THE SOCIETY OF RHEOLOGY

96TH ANNUAL MEETING
PROGRAM AND ABSTRACTS

Santa Fe Community Convention Center
Santa Fe, New Mexico
October 19 – 23, 2025

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Meeting Schedule

Monday, October 20, 2025

	SBA	*SBB*	*CD*	*PL*	*OM*	*SBC*	*SBD*
8:30			A. Q. Shen (PL1) - *SBEF*				
9:20			Coffee Break				
9:50	CS1	GN1	SM1	AR1	IR1	BL1	FI1
10:10	CS2	GN2	SM2	AR2	IR2	BL2	FI2
10:30	CS3	GN3	SM3	AR3	IR3	BL3	FI3
10:50	CS4	GN4	SM4	AR4	IR4	BL4	FI4
11:10	CS5	GN5	SM5	AR5	IR5	BL5	FI5
11:30	CS6	GN6	SM6	AR6	IR6	BL6	FI6
11:50			Lunch Break				
1:30	CS7	GN7	SM7	AR7	IR7	BL7	FI7
1:50		GN8	SM8	AR8	IR8	BL8	FI8
2:10	CS9	GN9	SM9	AR9	IR9	BL9	FI9
2:30	CS10	GN10	SM10	AR10	IR10	BL10	FI10
2:50	CS11	GN11	SM11		IR11	BL11	FI11
3:10			Coffee Break				
3:45	CS12	GN12	SM12	RG1	IR12	BL12	FI12
4:05	CS13	GN13	SM13	RG1	IR13	BL13	FI13
4:25	CS14	GN14	SM14	RG2	IR14	BL14	FI14
4:45	CS15	GN15	SM15	RG2	IR15	BL15	FI15
5:05	CS16	GN16	SM16	RG3	IR16	BL16	FI16
5:25	CS17			RG3			
5:45				End			
7:00			Monday Evening Reception				

Tuesday, October 21, 2025

	SBA	*SBB*	*CD*	*PL*	*OM*	*SBC*	*SBD*
8:30			A. N. Beris (PL2) - *SBEF*				
9:20			Coffee Break				
9:50	CS18	GN18	SM17	RG4	IR18	BL17	FI17
10:10	CS19	GN19	SM18	RG4	IR19		FI18
10:30	CS20	GN20	SM19	RG5	IR20		FI19
10:50	CS21	GN21	SM20	RG5	IR21	BL20	FI20
11:10	CS22	GN22	SM21	RG6	IR22	BL21	FI21
11:30		GN23	SM22	RG6		BL22	
11:50			Lunch Break / Society Business Meeting				
1:30	CS23	GN24	SM23	AR11	AM1	BL23	FI22
1:50	CS24	GN25	SM24	AR12	AM2	BL24	FI23
2:10	CS25	GN26	SM25	AR13	AM3	BL25	FI24
2:30	CS26	GN27	SM26	AR14	AM4	BL26	FI25
2:50	CS27	GN28	SM27	AR15	AM5		
3:10			Coffee Break				
3:45	CS28	GN29	FR1	AR16	AM6	BL27	TM1
4:05	CS29	GN30	FR2	AR17	AM7		TM2
4:25		GN31	FR3	AR18	AM8	BL29	TM3
4:45	CS31	GN32	FR4	AR19	AM9	BL30	TM4
5:05	CS32	GN33	FR5		AM10		TM5
5:25			FR6		AM11		TM6
5:45				End			
6:30			Bus to Santa Fe Farmers' Market Pavilion				
8:00			Awards Banquet				

Wednesday, October 22, 2025

	SBA	*SBB*	*CD*	*PL*	*OM*	*SBC*	*SBD*
8:30			L. Mahadevan (PL3) - *SBEF*				
9:20			Coffee Break				
9:50	CS33	GN34	SM28	AR20	AM12	ML1	TM7
10:10	CS34	GN35	SM29	AR21	AM13	ML2	TM8
10:30	CS35	GN36	SM30	AR22	AM14	ML3	TM9
10:50	CS36	GN37	SM31	AR23	AM15	ML4	TM10
11:10	CS37	GN38	SM32	AR29	AM16	ML5	TM11
11:30	CS38	GN39					TM12
11:50			Lunch Break				
1:30	CS39	GN40	SM33	AR24	AM17	ML7	TM13
1:50	CS40	GN41	SM34	AR25	AM18	ML8	TM14
2:10	CS41	GN42	SM35	AR26	AM19	ML9	TM15
2:30	CS42	GN43	SM36	AR27	AM20	ML10	TM16
2:50	CS43			AR28		ML11	TM17
3:10			Coffee Break				
3:45	CS44	SE1	SR1				TM18
4:05	CS45	SE2	SR2			ML13	TM19
4:25	CS46	SE3	SR3			ML14	TM20
4:45	CS47	SE4	SR4			ML15	TM21
5:05	CS48	SE5	SR5				TM22
5:25							TM23
5:45				End			
6:30			Poster Session & Reception				
6:30			Gallery of Rheology Sessions				

Thursday, October 23, 2025

	SBA	*SBB*	*CD*	*SBC*
8:00		S. Jamali (MP1) - *SBEF*		
8:40		Short Break		
8:45	CS49	SE6	SR6	ML16
9:05	CS50	SE7	SR7	ML17
9:25	CS51	SE8	SR8	ML18
9:45	CS52	SE9	SR9	ML19
10:05		Coffee Break		
10:35		SE10		
10:55	CS54	SE11		
11:15	CS55	SE12		
11:35	CS56	SE13		
11:55		End		

Session and Room Codes

AM = Additive and Advanced Manufacturing
AR = Applied Rheology for Industrial Applications
BL = Biomaterials, Bio-fluid Dynamics and Biorheology
CS = Colloidal Suspensions and Granular Materials
FI = Flow-Induced Instabilities and Non-Newtonian Fluids
FR = Special Session: Future of Rheology Speakers (Mini Session)
GI = Gallery of Rheology - Images
GN = Self-assemblies, Gels and Networks
GV = Gallery of Rheology - Videos
IR = Interfacial Rheology, Surfactants, Foams and Emulsions
ML = AI and ML in Rheology
MP = Metzner Presentation
PL = Plenary Lectures
RG = Special Session: Rheology in Geoscience (Invited)
SE = Rheology and Sustainability for Energy and Production
SM = Polymer Solutions, Melts and Blends
SR = Rheology for Soft Robotics and Use of Field-Responsive Materials
TM = Techniques and Methods: Rheometry, Tribometry, Spectroscopy and Microscopy

CD = Coronado + DeVargas
OM = O'Keeffe + Milagro
PL = Peralta + Lamy
SBA = Sweeney Ballroom A
SBB = Sweeney Ballroom B
SBC = Sweeney Ballroom C
SBD = Sweeney Ballroom D
SBEF = Sweeney Ballroom E+F

Shaded = Keynote

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Monday Morning

Symposium PL
Plenary Lectures

Monday 8:30 Sweeney Ballroom E+F PL1

Coupling rheology and microfluidics: Viscoelastic instabilities and emergent flow phenomena

Amy Q. Shen and Simon J. Haward
OIST, Onna, Okinawa, Japan

Viscoelastic fluids flowing through microfluidic geometries exhibit rich and often unexpected behaviors that arise from the interplay between material properties, flow conditions, and confining boundaries. In this talk, I explore how viscoelastic instabilities emerge in microscale flows and how they can lead to complex spatiotemporal patterns-including elastic turbulence. Drawing from experimental and computational studies, I will highlight flow transitions in polymeric fluids through microfluidic architectures such as cross-slot channels, micropost arrays, and porous media. These systems serve as tunable platforms for investigating how viscoelasticity, geometry, and imposed flow interact to produce synchronized oscillations, metachronal waves, symmetry breaking, and chaotic fluctuations. Using selective laser-induced etching (SLE), we fabricate robust 3D glass devices capable of sustaining high flow rates and strong deformation. To resolve the underlying flow structures and stress fields, we employ micro-particle image velocimetry (micro-PIV) and flow-induced birefringence (FIB), enabling visualization of velocity fields and stress profiles. We also examine how geometric disorder and confinement influence the onset and evolution of instability, offering insights into the control of mixing, transport, and particle manipulation. Coupling rheology with microfluidic design not only deepens our understanding of elastic instabilities in confined flows, but also establishes new principles for controlling complex fluid behavior in microscale systems with precision and efficiency.

Symposium CS
Colloidal Suspensions and Granular Materials

Organizers: James Gilchrist, Abhinendra Singh and Shravan Pradeep

Monday 9:50 Sweeney Ballroom A CS1

AI-powered Rheo-SAXS-XPCS analysis of cooperative rearrangement in dense colloidal suspensions

Hongrui He[1], Yuan Tian[2], Heyi Liang[2], Miaoqi Chu[3], Zhang Jiang[3], Juan de Pablo[2], Matthew Tirrell[4], Suresh Narayanan[3], and Wei Chen[1]
[1]Materials Science Division, Argonne National Laboratory, Lement, IL 60439, United States; [2]Tandon School of Engineering, New York University, New York, NY 11201, United States; [3]Advanced Photon Source, Argonne National Laboratory, Lemont, IL 60565, United States; [4]Pritzker School of Molecular Engineering, University of Chicago, Chicago, IL 60637, United States

Cooperative dynamics in materials like colloidal suspensions, gels, and polymer arise from complex surface interactions or structural variations. These collective motions drive critical behaviors such as yielding, failure, and avalanches, which are key to material performance. Traditional models, based on statistical mechanics and assuming uniform random particle motion, often miss the complexity of these systems. As a result, cooperative rearrangement regions (CRRs) in X-ray Photon Correlation Spectroscopy (XPCS) are frequently mistaken for noise due to limited coherence and inadequate theoretical models. To tackle this, we developed an AI-powered framework that treats dynamic bursts in two-time correlation functions as spatiotemporal "objects." Using deep learning, our approach detects and tracks these events, identifying the occurrence, duration, and intensity of CRRs. A lightweight deep-learning detector ensures efficient analysis. Validated through theory, simulations, and experiments, this method accurately captures CRRs and cooperative dynamics in soft matter. Our framework provides clear insights into these complex behaviors and serves as a robust tool for studying soft matter systems.

Monday 10:10 Sweeney Ballroom A *Keynote* CS2

Structure & dynamics of dense colloidal suspensions under oscillatory shear

Paulo E. Arratia
Mechanical Engineering & Applied Mechanics, University of Pennsylvania, Philadelphia, PA 19104-6393, United States

When stressed sufficiently, amorphous materials yield and deform plastically via reorganization of microscopic constituents. Despite much effort, understanding the interdependence of yielding, plasticity, and microscopic structure in non-equilibrium states (i.e. under stress) remains a challenge. In this talk, I explore this interdependence by cyclic shearing a dense colloidal suspension using a custom-built interfacial stress rheometer. This setup allows for simultaneous measurement of the bulk rheology (G', G'') and characterization of the suspension microstructure, and particle trajectories. We find that even when the deformation is globally reversible, local rearrangements are plastic, displaying hysteresis and altering rheology. The former is a sign that the self-organized steady state is in fact a limit cycle. This *reversible plasticity* vanishes at small strain

amplitude and is gradually overwhelmed by irreversibility as the yielding transition is surpassed. Next, the concept of (structural) excess entropy is used to investigate the relationship between sample dynamics & rheology and its microscopic structure both at the macroscopic and particle level. Overall, we find that measurement of sample *static* structure can provide quantitative predictive power on particle-scale rearrangements near yielding.

Monday 10:30 Sweeney Ballroom A CS3

Stored elasticity, emerging plasticity, and recovery of rigidity in yield stress fluids

Logan Bayer, H A Vinutha, and Emanuela Del Gado
Department of Physics, Georgetown University, Washington, DC 20057, United States

Yield stress fluids easily build-up residual stresses. We have used large-scale simulations of soft jammed particles to disentangle the role of stored elasticity and the emerging plasticity during stress relaxation to understand the build-up of residual stress [2]. Our simulations provide evidence of a power-law distribution of inter-times between plastic events which underpin the power-law decay in the stress relaxation. The plastic events are identified by the change in locally stiffer (icosahedrally-packed) regions. The number of icosahedrally-packed regions increase and rearrange over time as the system recovers mechanical equilibrium. Our results suggest that the recovery of rigidity may be related to a percolation of these locally stiffer regions which controls the residual stress build-up. We discuss these results in the context of elastoplastic models and recent experiments [1].

[1] Vinutha, HA et al., "Memory of shear flow in soft jammed materials", PNAS Nexus 3 (2024): 441 [2] Vinutha, HA, Bayer, L., and Del Gado, E., in preparation (2025)

Monday 10:50 Sweeney Ballroom A CS4

Memory in amorphous solids: From micro- to macro-rheology

Chloe W. Lindeman[1], Sidney R. Nagel[2], James J. Griebler[3], Penelope G. Kovakas[3], Simon A. Rogers[3], Suresh Narayanan[4], James L. Harden[5], and Robert L. Leheny[1]
[1]Department of Physics and Astronomy, Johns Hopkins University, Baltimore, MD 21211, United States; [2]James Franck Institute, University of Chicago, Chicago, IL 60637, United States; [3]Chemical and Biomolecular Engineering, University of Illinois Urbana-Champaign, Urbana, IL 61801, United States; [4]Advanced Photon Source, Argonne National Laboratory, Lemont, IL 60565, United States; [5]Department of Physics, University of Ottawa, Ottawa, Ontario K1N 6N5, Canada

Disordered materials like jammed solids can exhibit striking memory effects, including the ability to learn deformation types and amplitudes. Amplitude memory in particular highlights the ability of amorphous materials to return nearly or exactly to a previously visited configuration upon application of a particular strain protocol, a surprising feature given the extreme metastability of such systems. This configuration recall suggests a microscopic mechanism for the memory: particle rearrangements that occur as the system is sheared forward are undone as the strain is reversed. Here, we search for pairs of complementary rearrangements in simulations of jammed packings of soft spheres. We show that such pairs are easy to find but that their statistics exhibit unexpected features with implications for how materials form memories in the first place. Finally, we discuss ongoing work in nanocolloidal soft glasses that combines coherent x-ray scattering, which provides structural information, with rheology.

Monday 11:10 Sweeney Ballroom A CS5

Flow irreversibility for translational and rotational motion in dense colloidal suspensions

Austin H. Walker, Emanuela Del Gado, Jeffrey Urbach, and Daniel L. Blair
Physics, Georgetown University, Washington, DC 20057, United States

We study the flow reversibility of dense colloidal suspensions to link micro-structure to bulk material properties and elucidate the connections between fundamental ideas in statistical physics: chaos, reversibility, and predictability. The translational displacements of particles within granular and colloidal systems have been extensively studied under externally applied oscillatory shear [1,2,3]. Using confocal-rheology, we image particles once per cycle under oscillatory shear to experimentally verify the irreversibility threshold for translational motion and measure the corresponding threshold for rotational motion. Our in-house synthesized colloidal OCULI particles [4] have an offset core-shell construction, providing a real-space quantification of the rotational dynamics of each individual particle. This novel construction allows us to independently measure the critical strain amplitude for irreversible translational and rotational motion. Furthermore, we will demonstrate how concentration and OCULI surface roughness shift the threshold of flow irreversibility.

This work is supported by NSF DMR 2226485

[1] Hexner, D.; Levine, D. Hyperuniformity of Critical Absorbing States. Phys. Rev. Lett. 2015, 114 (11), 110602. https://doi.org/10.1103/PhysRevLett.114.110602. [2] J.R. Royer, P.M. Chaikin. Precisely cyclic sand: Self-organization of periodically sheared frictional grains, Proc. Natl. Acad. Sci. U.S.A. 112 (1) 49-53, https://doi.org/10.1073/pnas.1413468112 (2015). [3] Pine, D. J.; Gollub, J. P.; Brady, J. F.; Leshansky, A. M. Chaos and Threshold for Irreversibility in Sheared Suspensions. Nature 2005, 438 (7070), 997-1000. https://doi.org/10.1038/nature04380. [4] Yanagishima, T.; Liu, Y.; Tanaka, H.; Dullens, R. P. A. Particle-Level Visualization of Hydrodynamic and Frictional Couplings in Dense Suspensions of Spherical Colloids. Phys. Rev. X 2021, 11 (2), 021056. https://doi.org/10.1103/PhysRevX.11.021056.

Monday 11:30 Sweeney Ballroom A CS6

Unified microscopic theory of nonequilibrium aging, structural and stress relaxation, and residual stress in colloidal glasses after flow cessation

Kenneth S. Schweizer and Anoop Mutneja
Department of Materials Science and Engineering, University of Illinois, Urbana, IL 61801, United States

The re-solidification dynamics of dense amorphous colloidal solids after mechanically driven yielding from a nonequilibrium state is a fundamental science problem of broad relevance in soft matter physics, rheology, and materials science. We have formulated a microscopic statistical mechanical theory that includes activated Brownian dynamics under quiescent and stressed conditions which predicts in a unified manner the coupled time evolutions of structural and stress recovery following interruption of a continuous step shear deformation from a nonequilibrium state. A microrheological generalized Maxwell model framework self-consistently incorporates stress generation, constraint softening due to both direct external mechanical forces and structural deformation, and physical aging. After flow cessation, the theory captures the time dependent re-building of kinetic constraints and barriers that underlie structural recovery, stress relaxation, and re-solidification driven by relaxation and convective elastic backflow. The approach is general for particle-based materials, and quantitatively applied to dense hard-sphere colloidal suspensions as a paradigm for glass-forming materials. The theory properly captures the experimentally observed rich range of stress relaxation behaviors (exponential, stretched exponential, fractional power law) with increasing packing fraction upon shear cessation from the flowing nonequilibrium state. The emergence of residual stress on experimental timescales, power-law endless aging, sigmoidal recovery of the elastic modulus, pre-shear-rate-dependent mechanically imprinted memory effects, and a two-step structural relaxation process that can become decoupled from stress relaxation are also predicted. The revealed rich physics is relevant to materials processing, additive manufacturing and printing, and also provides new insights concerning the role of nonlocal collective elasticity on activated relaxation in quiescent glass-forming liquids.

Symposium GN
Self-assemblies, Gels and Networks

Organizers: Thibaut Divoux, Katie Weigandt and Ria Corder

Monday 9:50 Sweeney Ballroom B GN1

Rheology in microgravity to elucidate fundamental transport phenomena

Phillip Irace
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The flow of matter is strongly influenced by gravity-induced phenomena that affect everything from transport dynamics to structure. Microgravity provides a unique opportunity for researchers to decouple gravity-induced forces from other driving forces to investigate, and gain a better understanding of, fundamental transport phenomena in fluids using rheological measurements. For example, persistent microgravity provides the opportunity to obtain local thermophoretic and rheological data for microparticles in complex fluids that would otherwise sediment to the bottom of the container. The International Space Station (ISS) offers a unique platform in persistent microgravity to conduct such investigations. The ISS National Laboratory, managed by the Center for the Advancement of Science in Space(tm) (CASIS(tm)), sponsors and funds research investigations onboard the ISS, including through several partnerships with entities such as the U.S. National Science Foundation (NSF) Chemical, Bioengineering, Environmental, and Transport Systems (CBET) Division. Some relevant areas of investigation onboard the ISS have included colloidal systems (emulsions, gels, foams, nanoparticle suspensions, biomolecules, etc.), thermophoresis, protein mixing and aggregation, granular flows, and self-assembled structures. In this work, we will introduce the effects of gravity-driven forces on fluid systems and the importance of rheology in space. We will present case studies of rheology being conducted onboard the ISS, including mixing and aggregation of protein solutions in containerless systems and colloidal gelation and coarsening in bimodal attractive colloidal suspensions in which the size difference between the two particle populations is appreciable. We will also present opportunities for future microgravity experiments and access to ISS facilities through the ISS National Lab.

Monday 10:10 Sweeney Ballroom B GN2

Microstructure & rheology of thermoreversible colloidal gels by 4D-RheoSANS

Norman Wagner[1], Ted Egnaczyk[1], Quent Hartt[1], Mukund Kabra[1], Khushboo Suman[2], and Christopher Neal[3]
[1]University of Delaware, Newark, DE, United States; [2]IIT Madras, Chennai, India; [3]ORNL, Oak Ridge, TN, United States

Fundamental questions concerning the interplay between particle interactions, dynamical arrest and phase behavior are addressed by rheology and neutron scattering measurements on a model, thermoreversible, colloidal adhesive hard sphere (AHS) suspension. In contrast to monotonic aging observed for shallow quenches, deeper quenching leads to an anomalous rheological behavior in the form of a reproducible drop in shear modulus, which has been attributed to arrested phase separation. To provide a mechanistic understanding, a new instrument for time-resolved small angle neutron scattering measurements under rheological shear flow (4D-RheoSANS) is deployed on multiple neutron beamlines to interrogate the microstructure on the nano-to-micro-scale. Upon sudden reduction in temperature from a liquid state to gel state, shear-induced structural anisotropy is observed as butterfly scattering patterns and quantified in terms of alignment factor. Upon increasing the extent of thermal quench, the increased strength of interparticle attraction increases the viscosity as well as the degree of shear-induced anisotropy. SANS measurements as a function of time during various thermal quench are characterized in terms of an effective interaction strength and a Mason number. In this

manner, the interplay of gelation, phase separation, and glass formation is explored where steady shear and large amplitude oscillatory shear (LAOS) provide a means to explore the nonequilibrium nature of these transitions as well as the effects of shear rejuvenation. This behavior is characterized by Structure Lissajous plots connecting time-dependent gel structure and rheology. Industrial relevance in understanding how shear affects the flow behavior of colloidal gels is demonstrated by application of the learnings from this study to improve the processing of commercial materials, such as geopolymers for construction materials, will be presented.

Monday 10:30 Sweeney Ballroom B GN3

Yielding of dense protein-adjuvanted colloidal gels

Yug C. Saraswat[1], Rony Waheibi[1], Chris Glover[2], Dan Dixon[3], Alex Langford[2], and Lilian Hsiao[1]
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Colloidal adjuvants often aggregate and settle into a dense gel or suspension that requires fluidiziation prior to clinical applications. A mechanistic understanding of the complex interactions that influence particle packing in dense gels, and how these interactions govern their yielding behavior, is currently lacking. In this study, we use oscillatory shear rheology to investigate suspensions of colloidal adjuvants bound to proteins. Small and large amplitude oscillatory shear results show that an increase in packing fraction enhances the strength of the adjuvant gel microstructure and its yield stress, while confocal microscopy images show that sediments with higher packing fractions are more homogeneous. Rheological experiments reveal an exponential correlation between the weight fraction of sediments and the number of inversions required for complete resuspension of aluminum phosphate adjuvants formulated with varying ionic strengths (0 and 150 mM sodium chloride), protein types (bovine serum albumin and lysozyme), and protein concentrations (0, 0.5, and 1 mg/mL). These colloidal sediments possess greater inter-aggregate bond density, which strengthens the microstructure and resists its fluidization into a homogenous suspension. Salt-free formulations containing bovine serum albumin form sediments with the highest packing fractions. The colloidal suspensions continue settling under gravity and increasing in packing fraction until the yield stress is high enough to resist the gravitational stress. We speculate that formulations containing bovine serum albumin form large and polydisperse secondary aggregates, which lowers the yield stress and allows the aggregates to pack most efficiently, hence increasing the packing fraction and resuspension difficulty.

Monday 10:50 Sweeney Ballroom B *Keynote* GN4

Surface brush density as a structural and rheological tuning parameter in a colloidal gel

Calvin Zhuang[1], Robert Campbell[2], Paniz Haghighi[2], Safa Jamali[2], and Ali Mohraz[1]
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The surface properties of colloidal particles play a critical role in their interparticle interactions and self-assembly, particularly in attractive systems that undergo gelation. In this work, we investigate how varying the density of grafted polymer brushes on colloidal particles may influence brush-mediated noncentral interparticle forces, which in turn control the microstructure and rheology of a particular class of aqueous depletion-induced gels. Our experimental system consisted of 2,2,2-trifluoroethyl methacrylate-co-tert-butyl methacrylate copolymer particles suspended in an index-matching mixed solvent of water and glycerin, and gelation is induced by the addition of a non-adsorbing polymer, polyacrylamide. Confocal microscopy and particle tracking were used to characterize the gel microstructure and dynamics across a range of depletant and salt concentrations. These experiments were complemented by Dissipative Particle Dynamics simulations. Our results suggest that high brush density suppresses brush interpenetration and favors the formation of dense, compact clusters. In contrast, reduced brush density allows for smaller interparticle distances and greater brush overlap, leading to potential entanglements that introduce local resistance to angular displacements between neighboring particles. This additional constraint promotes the formation of extended, string-like gel networks with distinct mechanical characteristics, and can shift the gelation boundaries in this system. Our findings suggest that brush entanglements may offer a mechanism for kinetic arrest beyond classical depletion and electrostatic interactions. By modulating surface brush density, it becomes possible to tailor both the microstructure and mechanical response of colloidal gels. This work lays the foundation for future studies on more complex systems, including bimodal attractive suspensions, where the combined effects of size disparity and mixed brush densities are expected to further enrich the structural and rheological landscape.

Monday 11:10 Sweeney Ballroom B GN5

Simulating surface brush interactions in colloidal gel assembly using angular rigidity

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In experiments, model colloidal depletion gels typically rely on a thin polymer brush coating for steric stabilization and the approximation of hard-sphere interactions dominated by depletion. These brush coatings also affect particle charge, changing how electrostatic repulsion can be tuned with added salt. Recent experiments have found that reducing the amount of monomer used to produce this coating not only changes the measured colloidal charge but can also produce unexpectedly fractal gels that arrest at an average contact number ~3 instead of 6. This allows the user to manipulate gel structure and its resulting rheological properties with a single simple change to particle brush synthesis.

We present a companion simulation model that mimics this brush effect with a three-body angular rigidity. Using Brownian dynamics and standard depletion interactions with added electrostatics we allow particles to freely aggregate. When three or more particles form a cluster where brush regions interact, we introduce a non-central angular rigidty to restrict their rearrangement. By adjusting the strength of this rigidity and the range at which it activates we are can tune the resulting gel's average coordination number below 6. We also demonstrate how the effect of rigidity changes with different depletion and electrostatic conditions. The result is a relatively simple adjustment to traditional simulation methods that can mimic complex brush-brush interactions. We show how this method can represent experimental changes in brush synthesis with minimal information beyond the brushes' effective charge and approximate length.

Monday 11:30 Sweeney Ballroom B GN6

Rheological behavior of colloidal silica (Ludox) dispersion: Irreversible aging and thixotropy

Vivek Kumar and Yogesh M. Joshi
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Aqueous dispersion of colloidal silica, known as LUDOX, is made up of silica particles with a narrow particle size distribution and a mean diameter of 20 nm. It is known that this system undergoes physical aging, with its viscosity and elastic modulus increasing as a function of time elapsed since the cessation of shear melting (waiting time). Applying a deformation field results in a time-dependent decrease in both, demonstrating the thixotropic behavior. In rheological experiments conducted at a later date after preparation (rest time), we observe inherent irreversibility in the aging dynamics, which prevents the system from rejuvenating to the same state during shear melting and causes the evolution of dynamic moduli to shift to shorter time scales. We also observe relaxation time to show stronger than linear dependence on time, suggestive of hyper-aging dynamics. Interestingly, the power law coefficient defining this dependence decreases with an increase in rest time. All these observations imply that physical aging in the studied silica dispersion, while reversible over short time scales (of the order of hours), becomes irreversible over longer durations (days) owing to the inability of strong shear to break interparticle bonds that have strengthened over long durations. We also develop a thixotropic structural kinetic model within a time-dependent Maxwell framework that captures the experimentally observed rheological behavior well.

Symposium SM
Polymer Solutions, Melts and Blends

Organizers: Amanda Marciel, Ben Yavitt and Piyush Singh

Monday 9:50 Coronado + DeVargas SM1

Slip-link and tube models make different predictions about entangled, star-shaped polymer relaxation

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To describe the nonlinear rheology of entangled polymer melts and solutions two families of constitutive relations are currently commonly used. One family is based on the tube model of Doi and Edwards while the other one uses the concept of slip-links to model entanglements. Particularly noteworthy in this latter category is the single-chain, slip-link model which has been shown in over two decades of research to satisfy thermodynamic admissibility and is able to predict nonlinear rheology without adustable parameters. On the other hand, the tube model enjoys greater popularity despite the facts that (1) the GLaMM model violates energy conservation and the Roly-Polie model violates the second law of thermodynamics, (2) the parameters of tube models are typically fit to the experiments they are meant to describe, and have never been found from first principles, and (3) linear and star-branched chains are quite different mathematically. Moreover, slip-link predictions are in closer agreement with experiments. For example, we have shown, in contrast to tube models, that the slip-link model predicts all scaling observations for the inception of steady shear flow, for all chemistries studied experimentally. Here we show that the two theories make very different predictions about molecular-weight scaling for entangled, star-branched polymers---a difference that should be studied experimentally. We also give compelling evidence that a tube level of description is incapable of capturing the dynamics of the slip-link theory. Finally, the limited experimental data on star-branched support the slip-link theory, including no single scaling regime, as predicted by tube models. Relaxation of star-linear blends are also consistent with slip-link, but not with tube predictions.

Monday 10:10 Coronado + DeVargas SM2

Development of the Mead “Semi-Toy” polydispersity model for linear and/or star polymers in arbitrary flows

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Molecular constitutive models for entangled polymers have been in active development ever since Doi and Edwards posited the first serious attempt to model monodisperse linear polymers 45 years ago. Since that seminal work the subject has evolved more or less systematically by developing molecular models for model branched and linear polymers in various linear and nonlinear flows. With every new model polymer system studied additional heretofore unknown physics were discovered. It seemed that these phenomena associated with various special cases could not be generalized and simultaneously incorporated in a single unified theory for all entangled polymer systems in all flow configurations.

Such a unified approach is absolutely necessary when modelling polydisperse systems in general flow situations due to the extremely broad spectrum of orientational and stretch relaxation times inherent in polydisperse melts. The first issues we addressed in developing the new "Semi-Toy" model for polydisperse system was to assemble all the known physics in entangled linear and star polymers and develop a general model, and the code to simulate arbitrary flows, that simultaneously incorporated all known molecular relaxation mechanisms in entangled linear and star polymers. In addition to this feat, we have developed a new viable molecular model to simulate the entanglement destruction and creation dynamics that occurs in fast flows. Starting from the monodisperse Mead Model at the tube coordinate level, we demonstrate how we derive the polydisperse "Semi-Toy" by performing boundary layer analyses in an analogous manner to that used to derive the MLD Toy model from the MLD tube coordinate level model. The net result of these efforts is the "Semi-Toy" polydispersity model which contains all currently known polymer physics in addition to a newly proposed entanglement dynamics model that can simulate arbitrary flows. Simulations of polydisperse polymers in interrupted shear flow and other nonlinear flows are provided.

Monday 10:30 Coronado + DeVargas SM3

Shear banding in simulated entangled polymer melts depends on the effectiveness of flow-induced constraint release

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The Doi-Edwards tube theory of polymer dynamics predicts an unstable constitutive curve for all entangled polymer liquids, a signature of shear banding. However, experiments indicate that if banding does occur, it only does so for certain polymers and for large entanglement numbers Z. Incorporating convective constraint release (CCR) of entanglements into tube models can eliminate the constitutive instability for less-entangled polymers. The extent to which instabilities are eliminated depends on the CCR rate parameter β, which has recently been shown to increase with the stiffness of the polymer chain [1]. We use a recent extension of the Rolie-Poly tube model that incorporates CCR as well as the kinetics of entanglements [2] to predict which combinations of entanglement number Z and CCR rate parameter β lead to shear banding. We find that sufficiently high values of β (such as the value β~1 observed in United Atom Polyethylene simulations) can eliminate the instability for all experimentally accessible values of Z, and also observe a substantial dependence on an additional parameter related to the second normal stress difference. Comparing these predictions to non-equilibrium MD simulations of semiflexible bead-spring polymers of varying flexibility with β~0.1-0.4, we find surprisingly close agreement.

[1] Dolata, Cunha, O'Connor, Hopkins, and Olmsted, ACS Macro Letters 13, 896 (2024).
[2] Dolata and Olmsted, J. Rheology 67, 269 (2023).

Monday 10:50 Coronado + DeVargas SM4

Modelling the nonlinear shear rheology of entangled polymer solutions and melts

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In a recent work [1], we introduced a new approach based on the shear slit model [2] to describe the nonlinear shear rheology of unentangled linear polymer melts. This approach uses the concept of shear strands, which represent the confinement effect imposed by nonlinear shear flow on polymer chains, while the overshoot observed in the stress growth coefficient is interpreted as a transition from the linear envelope to the steady-state regime, driven by the progressive confinement of the chains. By assuming that confinement begins at the time corresponding to the boundary between affine and non-affine deformation of the chain, our predictions show quantitative agreement with experimental data.

In the present study, we extend our approach to describe the flow behavior of entangled polymer melts, where disentanglement processes influence the chain confinement. To further investigate this effect, we also study the flow properties of long entangled linear polymers diluted in oligomers, thereby modifying the effective molar mass between entanglements. When decreasing the polymer concentration, we observe a steady-state viscosity of this system going from the one of entangled chains towards the viscosity of unentangled chains. The responses of polymer melts and solutions with similar entanglement state are then compared to investigate how the reference unit governing the confinement depends on the entanglement state, and to establish the relationship between the molar mass between entanglements and the characteristic size of a shear strand. These new results allow us to better describe the evolution of the overshoot and refine our model to account for the presence of entanglements.

References

[1] M. Dalne, et al., Under review, *Macromolecules*, **2025**
[2] D. Parisi, et al., *Macromolecules*, **2021** 54 (6)

Monday 11:10 Coronado + DeVargas SM5

Mechanically accelerated depolymerization of entangled linear polymer melts

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Chemical Engineering & Materials Science, University of Minnesota, Minneapolis, MN 55455, United States

Mechanical forces can enhance the chemical depolymerization of synthetic polymers, when the shear flow induces chain scission. To quantify the extent of mechanically-induced scission, the effect of simple shear flow (its duration and strength) was investigated by considering the impact of the applied work in a rotational rheometer. Hydrogenated polyisoprene was chosen as a well-defined model for linear, entangled polyolefins. The conditions (strain amplitude, frequency, and shearing time) necessary to increase chain scission were assessed in the rubbery melt. Shear flow

induced faster chain scission at higher temperatures, suggesting an activated process. Isothermal scission vs. work curves were superposed by applying shift factors $a_{T,S}$, whose Arrhenius-like temperature dependence gave an apparent activation energy for chain scission of approximately 110 kJ/mol. A twin-screw micro-compounder with a more complicated flow pattern gave the same activation energy. Thus, the model system shows promise for designing processing flows to achieve controlled depolymerization by inducing a targeted amount of chain scission in entangled polymer melts.

Monday 11:30 Coronado + DeVargas SM6

Aging in natural gas activates the relaxations of polymer melts

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Although cast iron pipes carrying natural gas have been in service for several decades, they are prone to corrosion, cracks, and leaks. Polymeric materials such as polyethylene (PE), polyamide (PA) and polyvinylidene difluoride (PVDF) can serve as internal structural liners because of their high corrosion resistance, high strength-to-weight ratio, and impressive mechanical durability in hydrocarbon-rich and high-pressure environments. However, the impact of hydrocarbon environments on the properties of polymer liners is not yet fully understood. In this project, we characterize the properties of these materials after exposure to hydrocarbons at elevated temperatures and pressures, and over long periods of time to assess the stability of these liners in the presence of natural gas and contaminants. Dynamic mechanical analysis (DMA) and Fourier transform infrared spectroscopy (FTIR) were performed on both pre-aged and post-aged samples. Notably, the storage modulus indicates that the polymers generally maintain acceptable mechanical and chemical stability under typical natural gas compositions. However, using time-temperature superposition (TTS) indicates that hydrocarbon aging accelerates polymer relaxations and may lead to reduced mechanical performance. Thus, the activation energy governing polymer relaxation was identified as a sensitive indicator for benchmarking polymer performance and degradation. This minor change in polymer properties demonstrate that they are a viable alternative to cast iron for use as pipeline liners. However, hydrocarbon mixtures may contain reactive or corrosive contaminants. The next step of our study will focus on including these contaminants to observe their effects on mechanical and chemical properties and the activation energy.

Symposium AR
Applied Rheology for Industrial Applications

Organizers: Hammad A. Faizi and Antonio Perazzo

Monday 9:50 Peralta + Lamy AR1

Advancements in extensional rheology of polymer melts on a rotational rheometer with dual motors

James P. Eickhoff Jr.[1], Jan Haeberle[2], José Alberto Rodríguez Agudo[2], Joerg Laeuger[2], and Abhishek Shetty[1]
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Extensional rheology is critical for characterizing polymer melt behavior, revealing phenomena like strain hardening and softening that are not easily observed under shear flow. The Sentmanat Extensional Rheometer (SER) has enabled more accessible extensional testing, but it faces limitations at low strain rates and at Hencky strains beyond 4 due to its mechanical counter-rotation system and sample overlap after one full revolution. There has been prior discussion in the literature of achieving slightly higher Hencky strains by mounting the samples on the drum at an angle. This work introduces a modified setup using a rotational rheometer with an integrated secondary motor to overcome these challenges which has been described in previous studies as well. By decoupling the counter-rotating drums and leveraging air-bearing torque sensitivity, the system accommodates smaller sample sizes and enables testing at lower extension rates. To prevent sample overlap and extend measurable Hencky strains, one drum is vertically displaced during testing and the sample is also affixed at an angle. The method is validated against the SER using common polymers and further confirmed through optical tracking of sample deformation. This approach enhances extensional testing capabilities without requiring a separate instrument, offering a practical solution for advanced polymer characterization.

Monday 10:10 Peralta + Lamy *Keynote* AR2

Boosting flow-induced crystallization of polypropylene via vitrimerization

Carlos R. López-Barrón
ExxonMobil Technology and Engineering Company, Baytown, TX 77059, United States

Flow-induced crystallization (FIC) is a critical phenomena in many polymer processing operations as it determines the microstructure and properties of the final products. We studied the correlations between microstructure, nonlinear viscoelasticity and FIC of a series of polypropylene (PP) vitrimers prepared via reactive extrusion with a dynamic covalent cross-linker (diacrylate bis(dioxoborolane), DBDA). These vitrimers have a microstructure consisting of nano-clustered poly(DBDA) chains, grafted onto the PO backbones [Macromolecules 57, 2729 (2024)]. This unique microstructure correspond to nano-filled reinforced networks, which yield significant increase in melt strength (viscosity and elasticity) and extensional strain hardening (SH). The nanocluster also act as nucleants during quiescent crystallization. Under flow, the nanoclusters strongly delay the chain relaxation, which result in stronger alignment of the network strands, which greatly accelerates the FIC of the PP vitrimers, compared to PP homopolymers.

Monday 10:30 Peralta + Lamy AR3

Impact of polymer melt viscoelasticity on hollow fiber formation in segmented arc melt spinning

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Segmented arc melt spinning is a cost-effective, high throughput method for producing polymeric hollow fibers with applications in membrane technologies, medical drug delivery, and functional textiles. In this spinning method, molten polymer is extruded through a die composed of multiple arc-shaped segments arranged in a circular pattern. Upon exiting the spinneret, these segments coalesce to form an individual fiber with a hollow core. Formation of hollow fibers is found to be dependent on the viscoelastic stresses arising during extrusion and the rheological properties of the polymer melt. In this study, we use rheology to establish relationships between spinning parameters and fiber morphology, geometry, and mechanical properties. Polypropylene is used as a model polymer, with its molecular weight distribution systematically varied to investigate the effects of melt viscoelasticity on fiber formation and geometry. Small amplitude oscillatory shear (SAOS) experiments are carried out to obtain characteristic relaxation times at the conditions of spinning. Spinning parameters, including mass throughput, melt temperature, and polymer molecular weight distribution, are related to the fiber formation and flow behavior through the Weissenberg number (Wi). At higher Wi, fiber hollowness increases, but the circular uniformity of the fiber decreases. High speed imaging near the spinneret is used to quantify the die swell behavior of the extrudate and length to segment coalescence. A deeper understanding of the connections between spinning parameters and fiber properties enhances industrial design and optimization of hollow fiber production.

Monday 10:50 Peralta + Lamy AR4

Multiscale modeling, imaging, and rheology to understand crystallization pathways for resveratrol

Rekha R. Rao[1], Christine C. Roberts[1], Tesia Janicki[1], Helen Cleaves[1], Tyler R. Kennelly[1], Theron Rodgers[1], Monika Neal[2], and Zoltan Nagy[2]
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Crystallization of organic molecules from solution, though critical to applications from consumer projects to pharmaceutical production, is still a trial-and-error process where the morphology of the product is unknown until significant laboratory testing is carried out as a function of processing variables such as temperature, temperature ramp, concentration, and seeding. While classical crystallization proceeds via nucleation-and-growth in simple systems, more complicated molecular crystallization may follow a number of nonclassical transition pathways with more complex intermediate structures such as aggregated nanoparticles or mesocrystals. In this paper, we discuss multiscale models and experiments to understand solution recrystallization of resveratrol (3,5,4'-trihydroxy-trans-stilbene), a molecule with pharmaceutical interest due to its antioxidant and antimicrobial properties. We examine complex crystal growth and surface kinetics in resveratrol with a number of computational and experimental methods. Computationally, we will first introduce (1) a coarse-graining approach for resveratrol to implement crystal growth models in on-lattice kinetic Monte Carlo and (2) associated software development in the Stochastic Parallel PARticle Kinetic Simulator (SPPARKS) package. We also present a computational fluid dynamics model of a crystallizer coupled to a population balance equation to predict crystal size distribution as a function of time and space. Finally, single crystal studies of resveratrol growth are studied using microscopy and image processing while bulk crystallization is studied with light scattering and rheology.

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Monday 11:10 Peralta + Lamy AR5

Path-independent flow characterization of model yielding pastes

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Yielding pastes are a class of soft materials which mechanically transition between solid-like deformation and fluid like flow based on the level of mechanical loading. This phenomenology, particularly in cases where it is reversible, makes them ideal for use in additive manufacturing processes such as direct-ink-writing (DIW) 3D printing. To optimize materials for such applications, robust characterization of the flow behavior of these materials is needed. The most common means of doing this is the collection of a steady-shear flow curve, which consists of a series of constant shear rate tests across the desired deformation range, tracking the stress required for the deformation in each. The exact means by which this is accomplished however varies quite widely, with literature implementing tests with a variety of collection orders, preshear protocols, and end-of-test conditions. As many yielding pastes exhibit complex shear history, this variation in testing procedures creates a potential obstacle for obtaining reproducible results. To address this, we have developed a novel pre-shear protocol for yield stress fluids which results in a flow curve that is independent of the measurement path. The preshear flow curve results are presented in contrast to the flow curve results from preconditioning through shear-ramping, typical in cementitious measurement procedures. Our successful preshear uses a novel oscillatory/forced-recovery that is tuned for each sample using the viscoelastic properties of the specimen. The robustness of this protocol is demonstrated through measurements on several model yielding pastes.

Monday 11:30 Peralta + Lamy AR6

Psychophysical and rheological investigation of toothpaste tube squeezability

Baran Teoman and Andrei Potanin
Cross Category Research & Innovation - Rheology, Colgate-Palmolive Company, Piscataway, NJ 08854, United States

In this work, toothpaste tube squeezability was tested by three different methods: assessment by a human panel, a tactile glove, and several purely instrumental tests. The panelists characterized squeezability in terms of the acceptability of the product. The tactile glove was utilized to determine the maximum grip forces (GF) applied by the same panelists during their assessment. The instrumental tests consisted of emulative tests by a squeezing device and rheological tests. Along with commercial pastes, a series of samples were deliberately formulated and tested, so as to cover a wide range of squeezability. The study showed that it is possible to predict human sensory perception using either an emulative squeezing instrument or the rheological measurements of the pastes. The study also suggests that human perception of acceptable squeezability includes not only its low limit (pastes being hard to squeeze) but also its upper limit (pastes perceived as too runny) which may also be related to the inability of the paste to retain its shape on the brush. Based on this study consumer-acceptable ranges of rheological and squeezability parameters were defined. These results are expected to be useful, especially for oral/personal care product developers.

Symposium IR
Interfacial Rheology, Surfactants, Foams and Emulsions

Organizers: Manolis Chatzigiannakis, Carlos Martinez and Muchu Zhou

Monday 9:50 O'Keeffe + Milagro *Keynote* IR1

Complex thermodynamics, structure and mechanics of mixed surfactant "frenemies" on highly curved interfaces

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Surfactant mixtures and blends are ubiquitous in industrial practice (both intentionally and unintentionally) - yet little is understood about the molecular interactions they experience at fluid interfaces, and how these interactions control interfacial properties. In this talk, we report on the incredible complexity that mixed surfactants can exhibit, and our attempts to understand and control their interfacial thermodynamics, structure and mechanics to design and stabilize complex emulsion systems. We focus on relatively simple mixtures of surfactant "frenemies" - co-surfactants with homologous chemistry but dissimilar spontaneous curvature. Placing such mixtures on oil-water interfaces with nanoscale curvature (i.e., microemulsions and nanoemulsions) leads to complex vesicular structures, whose phase behavior can be readily tuned through the different spontaneous curvatures of the co-surfactant pair. Using contrast-variation neutron scattering, we demonstrate that the appearance of these structures correlates with interfacial demixing of the co-surfactants. Using a combination of experiments, theory and simulation, we provide a molecular explanation for this behavior, and use it to construct a model for the interfacial thermodynamics that simultaneously predicts the occurrence of demixing and the observed emulsion morphology phase behavior. Finally, we show that these systems exhibit highly non-trivial interfacial mechanics, opening new frontier questions and opportunities to explore how nonideal mixing/demixing and nanoscale curvature can be used to control the mechanics and rheology of mixed surfactant interfaces.

Monday 10:10 O'Keeffe + Milagro IR2

Controlled-release of additives to improve PFAS-free firefighting foam stability

Carlos J. Martinez, Elizabeth C. Malek, and Jeffrey Youngblood
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The military widely uses firefighting foam formulations (FFF) that contain perfluoroalkyl surfactants (PFAS) to rapidly extinguish fires. However, studies have shown that PFAS are detrimental to the environment and persist in the waterways and soil for significantly longer times than silicone- and hydrocarbon-based surfactants. The effectiveness of PFAS lies in their unique properties, including low surface tension (15 to 20 mN/m), high surfactant packing, and both hydrophobicity and oleophobicity. No single surfactant can replace PFAS in FFF formulations. A synergistic approach combining multiple surfactants and additives is necessary to identify a suitable replacement. One approach that could enhance the stability of firefighting foam is the controlled release of viscosifiers or other additives after the foam is applied. In this presentation, I will discuss our recent efforts in developing temperature-sensitive microcapsules that can be added to model firefighting foam formulations to enhance their stability. We used interfacial polymerization to make polyurea-shell microcapsules with aqueous Carbopol 940 solutions (viscosifier) and a gas-generating compound in the core. The microcapsules release the viscous Carbopol 940 solution upon heating during foam deposition, increasing the foam viscosity, potentially enhancing foam stability. The microcapsules also seem to provide improved stability due to their aggregation in the foam face lamellae and Plateau borders. I will discuss the feasibility of this approach and the current challenges we face in characterizing the performance of the microcapsules.

Monday 10:30 O'Keeffe + Milagro IR3

Dynamics of bubble pinchoff using mixed surfactants

Sibani Lisa Biswal
Chemical and Biomolecular Engineering, Rice University, Houston, TX 77005, United States

Surfactant formulations are widely used to stabilize foams by lowering the interfacial tension between gas and liquid phases. However, foam stability is not solely determined by interfacial tension; the dynamics of surfactant adsorption and the resulting interfacial viscoelasticity also play a critical role in bubble formation and longevity. In this study, we examine how mixtures of coco-betaine (a zwitterionic surfactant) and alpha olefin sulfonate (an anionic surfactant) influence interfacial rheology and bubble dynamics. Using a microfluidic device with a single constriction, we generate bubbles under controlled flow conditions and monitor the pinch-off process and subsequent foam formation. We find that specific ratios of coco-betaine to alpha olefin sulfonate enhance interfacial viscoelasticity, as measured by interfacial dilatational rheology. These changes correlate with delayed pinch-off times and more uniform bubble sizes, indicating increased resistance to interface deformation and drainage. Our results highlight the importance of tuning surfactant mixtures not only for interfacial tension reduction but also for optimizing interfacial viscoelastic properties. This work provides new insights into how molecular interactions at fluid interfaces govern foam generation in confined geometries.

Monday 10:50 O'Keeffe + Milagro IR4

Interfacial rheology and foam stability in pluronics and sodium dodecyl sulfate mixtures

Sarah A. Onyembe and Reza Foudazi
School of Sustainable Chemical, Biological and Materials Eng, University of Oklahoma, Norman, OK 73019, United States

Foam-templating is a promising method for synthesizing porous hydrogels with highly tunable properties. However, predicting and controlling foam stability before polymerization, as well as the resulting structure after polymerization, remain challenging. This research focuses on the interactions and properties of Pluronic-based triblock copolymers, including Pluronic F68 and Pluronic F127, combined with sodium dodecyl sulfate (SDS), in the formation of foam precursors. While the composition of Pluronic is kept constant, the concentration of SDS ranged from below its critical micelle concentration (CMC) to above the CMC to examine the effect of surfactants interaction on foam stability. This study investigates dilatational interfacial rheology to evaluate how its properties affect the formation and stability of foam. Results show that SDS influences the rate of coalescence in the foam precursor and allows for better control of foam stability. Additionally, as the SDS concentration approaches the CMC, the coarsening mechanism shifts toward Ostwald ripening. Below the CMC, the interface is more viscoelastic, while above the CMC, it becomes almost elastic. Then, the relationship between foam stability and interfacial rheology is discussed.

Monday 11:10 O'Keeffe + Milagro IR5

Stabilizing foams: Insights from thin film dynamics and interfacial rheology

Emmanouil Chatzigiannakis
Processing and Performance of Materials, Eindhoven University of Technology, Eindhoven, The Netherlands

The stability and rheology of multiphase materials, such as foams, are largely governed by the properties of their interfaces and the behavior of thin liquid films (TLFs) separating interacting droplets or bubbles. When two bubbles come into close proximity, a TLF forms between them and progressively thins through drainage. This thinning process, along with the overall stability of TLFs, is strongly influenced by interfacial stresses and intermolecular interactions driven by surface-active species. In this talk, we will discuss how experimental techniques, such as the dynamic thin film balance and interfacial shear rheometry, shed light on nano- and micro-scale physics of these materials. Particular attention will be given to films stabilized by low molecular weight surfactants, copolymers, and plant proteins, and how they impact key foam destabilization processes: drainage, coalescence, and Ostwald ripening. We will show that foam half-life is directly related to the type and magnitude of interfacial stresses, as well as to the thickness of the TLFs that separate two bubbles. A universal picture on foam stability emerges, which enables the rational design of sustainable foams.

Monday 11:30 O'Keeffe + Milagro IR6

Role of internal circulation in emulsion drops on microparticle morphology

Suryavarshini Sundar[1], Eric Hukkanen[2], Renato Chiarella[2], and Arun Ramachandran[1]
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We present our findings on understanding the effect of internal circulation in emulsion drops on the morphology of polymer microparticles used for drug delivery. Using a microfluidic extensional flow device, we captured the flow-driven dynamics within the polymer solution drops and observed the formation of drug-loaded microparticles by the solvent extraction process. We identified water-rich fluid pockets in the resulting microparticles, arising from the dissolution of water into the drop. During solvent extraction, this dissolved water phase separates, nucleates, and coalesces into larger droplets. However, circulation currents within the drop strongly influence the convection and distribution of these water droplets. Based on the strength of the internal circulation, we identified three distinct configurations of the microparticles with varying degrees of phase separation of the water phase. In drops with weak internal circulation, we saw a double-emulsion type of microparticles, with the nucleated water droplets present homogenously throughout the particle. We further compared our results with stagnant drop experiments, and again saw that in the absence of shear, or at low shear rates, the internal circulation within the drops is weak, and no significant phase separation of water was observed. However, in drops with strong circulation, we observed the formation of core-shell and Janus-type microparticles, with most of the water separated as a distinct water-rich lobe attached to a polymer and drug-rich lobe. We present a theoretical scaling to predict the formation of

these different configurations based on the coalescence time scales and Peclet number (Pe) from our experimental data. The water pockets in a microparticle become the pores of the particle after drying. This difference in the distribution of water in the microparticle, based on the internal circulation in the drop phase, directly affects the porosity of the dried particles, and in turn, the kinetics of polymer degradation and drug release.

Symposium BL
Biomaterials, Bio-fluid Dynamics and Biorheology

Organizers: Rae Robertson-Anderson, Travis W. Walker and Jairo Diaz

Monday 9:50 Sweeney Ballroom C *Keynote* BL1

Biofilm infections can use material from the infected organism to strengthen and protect themselves

Vernita Gordon
University of Texas, Austin, Austin, TX, United States

Biofilms are communities of microbes embedded in a matrix of extracellular polymeric substances. Matrix materials can be produced by the microorganisms themselves but can also originate from the environment and then be incorporated into the biofilm. Collagen is a human-produced protein that is abundant in many different infection sites. Pseudomonas aeruginosa, Staphylococcus aureus, and Burkholderia pseudomallei are human pathogens notable for forming biofilm infections in tissues rich in collagen, such as lung and skin. Here, we show that the incorporation of Type I collagen into P. aeruginosa, S. aureus, and B. pseudomallei biofilms significantly alters mechanical (and microstructural) properties of biofilms, measured using particle-tracking passive microrheology. Incorporating collagen also hinders white blood cells' ability to eat biofilm bacteria. Enzymatic degradation of collagen using collagenase reverses these effects, on both the microrheology and immune-clearance fronts. Our findings suggest that host materials play significant roles in stabilizing biofilms and may present promising targets for therapeutic interventions.

Monday 10:10 Sweeney Ballroom C BL2

Using exogenous polymers to engineer biofilm viscoelasticity

Bikash Bhattarai and Gordon F. Christopher
Texas Tech University, Lubbock, TX 79410, United States

Using Exogenous Polymers to Engineer Biofilm Viscoelasticity Abstract A large percentage of bacteria exist in sessile communities surrounded by self-secreted extracellular polymeric substances (EPS), better known as biofilms. Biofilms are increasingly found in applications in which their viscoelasticity influences outcomes including bioremediation, wastewater cleanup, and/or biofuel production. Ideally, to improve outcomes, biofilm viscoelasticity could be manipulated to achieve a desired response. Exogenous polymers are well known to impact planktonic bacterial behavior and previous work from our lab has demonstrated they can also substantially alter biofilm mechanics. However, the potential influence of polymers on biofilm viscoelasticity is largely unexplored. Building on previous results, we investigate how exogenous polysaccharides with varying charge and molecular weights can be used to impact biofilm viscoelasticity in a controlled manner.

Biofilms of Pseudomonas aeruginosa, which has a well characterized EPS, are grown in the presence of negative, neutral, and positive polysaccharides of varying molecular weight at concentrations where there is no planktonic antibacterial effect. Passive microrheology was employed to evaluate biofilms viscoelasticity. Results showed that neutral polymers had minimal impact on biofilms viscoelasticity whereas all charged polymers, both anionic and cationic, exhibited a stiffening effect on biofilms. In addition, the increase in stiffening is linked to the stiffness of the individual polymer incorporated into the biofilm.

Monday 10:30 Sweeney Ballroom C BL3

Whole-cell models of E. coli: How colloidal physics regulate ribogenesis and protein synthesis

Roseanna N. Zia[1], Vishal S. Sivasankar[1], Jennifer L. Hofmann[2], Theo S. Yang[2], Akshay J. Maheshwari[2], Harnoor S. Sachar[1], J. Galen Wang[1], and Drew Endy[2]
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We are interested in how physics at the colloidal scale instantiate life in biological cells. While principles from physics have driven recent paradigm shifts in understanding how collective biomolecular behaviors orchestrate life, many mechanistic aspects of key biological processes such as transcription, translation, and adaptation remain mysterious because understanding and controlling them requires unifying two disparate physical regimes: the atomistic (structural biology) and the microscopic (systems biology). Colloidal-scale modeling bridges this divide, linking molecular-scale phenomena to whole-cell function. I will discuss our computational models of the bacterium Escherichia coli in which we represent biomolecules and their interactions physically, electrostatically, and chemically, individually and explicitly. We have used these models to explain how colloidal physics drive speedup of protein synthesis during faster cell growth. I will also discuss how we are using AI-guided physics-based modeling to make progress with ribogenesis, one of the most notoriously difficult problems in synthetic biology.

Monday 10:50 Sweeney Ballroom C BL4

On growth and form: Living gels formed by bacteria growing in complex fluids

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Many bacteria live in complex fluids, such as mucus in the body, exopolymers in the ocean, and cell-secreted extracellular polymeric substances (EPS) that encapsulate biofilms. However, lab studies of bacteria typically focus on cells in simple homogeneous fluids that do not mimic real microbial habitats. How does inhabiting a complex fluid environment influence the behavior of bacterial communities? To address this question, we experimentally probe the growth of non-motile Escherichia coli cells in polymer and liquid crystalline solutions. When grown in a polymer solution or in a nematic liquid crystal, the cells grow in striking "cable-like" morphologies-in stark contrast to the random dispersions that are observed in simple fluids. Experiments and mathematical modeling elucidate how polymer-induced depletion attraction forces or liquid crystalline nematic elasticity, coupled with bacterial growth, lead to the emergence of cable structures in polymer and liquid crystalline environments, respectively. Our work uncovers quantitative principles governing the morphogenesis of bacterial colonies in diverse environments.

Monday 11:10 Sweeney Ballroom C BL5

Interpenetrated GelMA/PVA hydrogels with enhanced viscoelastic and structural properties for biomedical applications

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Hydrogels, due to their hydrated, crosslinked polymeric structures, offer significant utility in soft tissue engineering. However, a common limitation in traditional hydrogel systems lies in their inadequate mechanical tunability and restricted cellular infiltration. In this study, we report the synthesis and rheological analysis of a dual crosslinked Gelatin Methacryloyl/Polyvinyl Alcohol (GelMA/PVA) hydrogel system incorporating both covalent (UV-induced) and physical (borax-mediated) interactions. The use of PVA as a physical crosslinker introduces controlled porosity and tunable mechanical behavior upon dissolution, providing an avenue for enhancing cell migration and drug release dynamics. The interpenetrated crosslinked network contributed to increased ductility and flexibility in the final gel matrix. Oscillatory shear rheology was performed to evaluate the viscoelastic spectrum of the materials. Storage moduli (G') of ~8 kPa were observed, demonstrating elasticity sufficient for soft tissue applications. Frequency and amplitude sweep tests confirmed structural stability and resilience under physiological strain conditions. In addition to self-healing capacity, the hydrogels displayed high extensibility (~300%), which was corroborated by texture analysis. Further, the physical crosslinks allow for self-healing capabilities. The structure-property relationships were further probed through ongoing chemical and morphological characterization. These rheological findings are discussed in the context of their implications for cellular behavior, infiltration, and scaffold integration. Future work includes in situ electroimpedance rheometry to quantify the effect of dynamic shear and chain elongation on the conductivity of the gels, as well as correlating these features with biological outcomes. This study positions GelMA/PVA interpenetrated hydrogels as a versatile platform for the rational design of soft, robust, and bioactive scaffolds suitable for regenerative medicine.

Monday 11:30 Sweeney Ballroom C BL6

Measuring human mesenchymal stem cell migration and remodeling in hydrogels with a spatial change in elastic modulus

Zaid Imran and Kelly Schultz
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Human mesenchymal stem cells (hMSCs) can be delivered by implanted hydrogel scaffolds to wounded tissue to improve healing. To direct hMSC migration from a hydrogel scaffold to wounded tissue, physical and chemical cues can be presented to cells in the pericellular region. hMSCs undergo durotaxis, a process where cells migrate from softer to stiffer microenvironments. To leverage this behavior and spatially direct hMSC migration, we create an elastic modulus (G') gradient in a well-defined hMSC-degradable hydrogel. This photopolymerized scaffold is composed of 4-arm poly(ethylene glycol)-norbornene cross-linked with a matrix metalloproteinase (MMP)-degradable peptide. MMPs are cell-secreted enzymes. Hydrogels with a gradient in G' are formed by moving a photomask across a sample, which varies UV exposure time and, in turn, cross-link density. To characterize this G' gradient, we measure material autofluorescence spatially and use a calibration curve to calculate G'. In this work, we characterize cell-mediated degradation in the pericellular region of hydrogel scaffolds using multiple particle tracking microrheology (MPT). MPT measures the Brownian motion of probes in a sample to characterize the rheology of the material. On day 5 post-encapsulation, hMSCs have remodeled the soft region of the hydrogel ($G' < 460$ Pa), while minimal remodeling is measured in the middle ($460 < G' < 540$ Pa) and stiff ($540 < G' < 1000$ Pa) regions. This is due to the initial low cross-link density in the soft region. On day 6 post-encapsulation, all regions of the hydrogel have been remodeled due to cumulative degradation of the cross-linker by cell-secreted MMPs. However, the extent of remodeling across all regions is not significantly different, suggesting that both MMP activity and initial cross-link density differences lead to uniform degradation across the entire scaffold. These materials use the physical microenvironment, leveraging the rheology of the material, to direct hMSC motility to increase cell delivery after implantation.

Symposium FI
Flow-Induced Instabilities and Non-Newtonian Fluids

Organizers: Hadi Mohammadigoushki, Fardin Khabaz and Chenxian Xu

Monday 9:50 Sweeney Ballroom D *Keynote* FI1

GNFFTy model predictions of flow past a cylinder in the vortex-shedding regime

Robert J. Poole and David Geraghty
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A recently proposed viscosity equation which incorporates flow-type, but is otherwise inelastic, the so-called GNFFTy model (Generalized Newtonian Fluid model incorporating Flow Type pronounced "nifty") [1] is tested in a complex flow. We discuss predictions of this model in two-dimensional unsteady flow past a cylinder, i.e. in the vortex-shedding regime, and compare to experimental results for dilute polymer solutions [2]. The GNFFTy model is shown to be able to capture many of the features observed experimentally including a stabilizing effect on the von Kármán instability, with the critical Reynolds numbers pushed to higher values than the Newtonian fluid, and a reduction of the saturated vortex shedding frequency (Strouhal number). The increase in drag on the cylinder in the steady flow regime predicted by the GNFFTy model is also in good qualitative agreement with earlier classical experimental data [3].

References:
[1] Poole, R.J., 2024. On the use of the Astarita flow field for viscoelastic fluids to develop a generalised Newtonian fluid model incorporating flow type (GNFFTy). Journal of Fluid Mechanics, 987, p.A2.
[2] Pipe, C.J. and Monkewtiz, P.A., 2006. Vortex shedding in flows of dilute polymer solutions. Journal of non-newtonian fluid mechanics, 139(1-2), pp.54-67.
[3] James DF, Acosta AJ. The laminar flow of dilute polymer solutions around circular cylinders. Journal of Fluid Mechanics. 1970;42(2):269-288. doi:10.1017/S0022112070001258

Monday 10:10 Sweeney Ballroom D FI2

Asymptotic flow states in turbulent viscoelastic Taylor-Couette flow: The relationship between asymptotic drag states and large and small scale interactions

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Adding a small amount of long-chain flexible polymer leads to intriguing drag modification (DM) in turbulent Taylor-Couette flows (TCF). Specifically, our earlier studies show the existence of asymptotic maximum drag enhance- ment/reduction (MDE/MDR) flow states in wide-/small-gap turbulent viscoelas- tic TCF. These intriguing asymptotic flow states emerge from the complex inter- action between turbulent vortices and microscale polymer dynamics. However, the connection between MDR and MDE in TCF remains to be explored. To that end, we performed extensive direct numerical simulations over a wide range of polymer concentrations (viscosity ratio ß = 0.99 ~ 0.90) at W i of O(100) with the FENE-P model in a wide gap TCF at Reynolds number 6000. For different ß, asymptotic flow states, including both MDR and MDE are achieved by gradually increasing W i. Interestingly, the transition from MDR to MDE occurs with decreasing ß (increasing polymer concentrations). That is, asymp- totic flow states with DM of -11. 7% and 34. 6% are present at ß = 0.99 and 0.90, respectively. By examining the driving forces, we demonstrate that different degrees of DM arise as a result of the competition between Reynolds stress reduction and polymer stress development. Moreover, the state transi- tion is accompanied by the transition in the flow structures, namely, MDR and MDE states are dominated by large- and small-scale flow structures, respec- tively. This is because decreasing ß leads to enhanced elastic instability, which facilitates the generation of elastic Gortler vortices. Finally, we elucidate these transitions through a detailed examination of the inner and outer scales. Overall, this study has provided a comprehensive mechanisticunderstanding of DM that arises from the interaction of polymers with small-and large-scale flow structures.

Monday 10:30 Sweeney Ballroom D FI3

Viscoelastic effects in the bulge instability of inflated tubes

Sachin Velankar[1], Fatemeh Rouhani[2], Qihan Liu[2], and Brian Young[3]
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When a long balloon or rubber hose is inflated, it abruptly develops a bulge wherein a portion of the tube inflates much more than the rest. Such bulging is well-understood for fully-elastic materials. We show that inflation of polyurethane tubes deviates from this behavior. A variety of inflation pathways appear including multiple axisymmetric bulges, a single axially-propagating bulge, or homogeneous inflation. In all cases, the pressure rises to a maximum, and then gradually reduces towards a plateau with continued inflation. Unlike in elastic tubes, a pressure maximum can appear even if tubes inflate homogeneously, retaining a cylindrical shape. Finite element simulations show that most of the observations can be explained by viscoelasticity of the tube walls, specifically that a slow material response maintains a high pressure for long durations, which in

turn allows growth of multiple bulges. Simulations also show how a pressure maximum can appear purely due to constitutive behavior of the material regardless of mechanical instabilities.

Rouhani et al., Soft Matter, 2024, https://doi.org/10.1039/D4SM00241E

Monday 10:50 Sweeney Ballroom D FI4

Structure and dynamics of elastoinertial turbulence in channel and pipe flow

Manish Kumar and Michael D. Graham
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Addition of large polymer molecules to a fluid can lead to substantial reduction of energy losses in the turbulent flow regime characteristic of many flows in nature and technology. Recent studies have revealed two regimes of near-wall turbulence in viscoelastic polymer solutions. In the first, turbulence is sustained by quasistreamwise vortices. As viscoelasticity becomes more important, the second regime emerges, where these vortices are suppressed and a new type of flow, denoted elastoinertial turbulence (EIT), emerges. In the present study, direct simulations of turbulence in a dilute polymer solution, modeled with the FENE-P constitutive equation, are performed. The results are analyzed using a novel extension of spectral proper orthogonal decomposition (SPOD) based on the total mechanical energy in a viscoelastic fluid. The analysis demonstrates that although both channel and pipe flows are linearly stable in the parameter regime under consideration, nonlinear excitation of the dominant linear modes occurs. Furthermore, a new form of self-similarity is observed: nested patterns of self-sustaining nonlinear traveling waves sustained by viscoelasticity.

Monday 11:10 Sweeney Ballroom D FI5

Statistical analysis of laminar-to-turbulent transition in viscoelastic channel flows

Alexia Martinez Ibarra and Jae Sung Park
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The addition of small amounts of long-chain polymers to a turbulent flow has been well-reported thanks to its beneficial effects of drag reduction compared to Newtonian flows. However, this phenomenon in the transitional regime has yet to be fully explored. For this study, we perform direct numerical simulations of viscoelastic channel flows to investigate the susceptibility of laminar flow to finite-amplitude disturbances. First, the perturbation magnitude required for viscoelastic flows to transition is smaller than that required for its Newtonian counterpart. As Reynolds number is increased, the perturbation required to trigger a transition to turbulence decreases for both Newtonian and viscoelastic flows. The scaling of the critical perturbation magnitude as a function of Reynolds number is presented. We then investigate the survival probability of the laminar state as a function of Reynolds number and disturbance amplitude. The survival probability of the laminar state quickly reduces with increasing Reynolds number and perturbation amplitude for both Newtonian and viscoelastic flows. However, the difference between Newtonian and viscoelastic flows is more drastically observed with the effect of Reynolds number. These results are consistent with the observations of a destabilizing effect that arises from the addition of polymers to the flow. The effects of various disturbance types will be further discussed.

Monday 11:30 Sweeney Ballroom D FI6

Constitutive relations for modelling the viscoelastic response of fluids that exhibit non-monotonic steady-state response

Krishna Kaushik Yanamundra, Sreejith P. Pillai, Chandler C. Benjamin, and Kumbakonam R. Rajagopal
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Shear banding is observed in a wide range of complex fluids, including wormlike micellar solutions, colloidal suspensions, polymeric fluids, foams, and emulsions. While they are microstructurally diverse, many of these fluids exhibit a non-monotonic steady-state shear stress vs shear rate response, where stress becomes multivalued. This is also manifested as the "spurt" phenomenon. In this work, we present a thermodynamically consistent constitutive model that captures such a response through a non-convex rate of dissipation potential. We analyse the model in simple shear, Couette, and Poiseuille flows, and compare the results with experimental observations reported in the literature.

Monday Afternoon

Symposium CS
Colloidal Suspensions and Granular Materials

Organizers: James Gilchrist, Abhinendra Singh and Shravan Pradeep

Monday 1:30 Sweeney Ballroom A CS7

Particles to fields in viscoelastic fluids

Sachit Nagella, Dae Yeon Kim, Saksham Malik, Eric S. Shaqfeh, and Sho Takatori
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Many-body hydrodynamic interactions play an important role in the dynamics of fluid suspensions. Whereas fluid-mediated interactions among colloids have been studied extensively in incompressible Newtonian fluids, their many-body dynamics in nonlinear viscoelastic fluids are poorly understood. Ideally, there would be a "viscoelastic Stokesian dynamics" that allow arbitrary numbers of colloids to interact within a continuum field that contains the correct constitutive equation for the viscoelastic background fluid. In this work, we combine particle-based simulations, continuum field simulations, and optical laser tweezer experiments to quantify fluid-mediated colloidal interactions in viscoelastic fluids. We measure the hydrodynamic coupling between trapped fluorescently-labeled colloids as a direct reporter of few- to many-body hydrodynamic interactions in viscoelastic fluids. Our experiments and particle-based simulations reveal a breakdown of key basic assumptions present in all continuum field descriptions of viscoelastic constitutive equations. We aim to use our experiments and simulations to develop a framework to coarse grain from micro-to-macro (Langevin equation to a constitutive field evolution equation) for arbitrary viscoelastic fluids.

Monday 2:10 Sweeney Ballroom A CS9

Sedimentation of flocculating non-Brownian suspensions by high-order Stokesian dynamics

Alexander Z. Zinchenko
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Evolution of a monodisperse non-Brownian suspension from an initial well-mixed state to steady sedimentation is rigorously simulated by a novel algorithm of High-Order Stokesian Dynamics. Solid spheres interact through short-range van der Waals attraction and double-layer electrostatic repulsion with realistic colloidal parameters (particle size, Debye layer thickness, surface potential and Hamaker constant), resulting in temporary multiparticle clusters. Fluid velocity is sought as cumulative Lamb's multipole contribution from particle centers, with triply-periodic Green function of Hasimoto as a kernel. Within a 'lubrication zone', the force/torque balances are modified by explicit inclusion of exact 2-body hydrodynamic solutions, but this element is much different from the one in the traditional (low-order) Stokesian Dynamics; the 2-body correction zone gradually disappears as more multipoles are included. Rotational transformations of near-field multipole contributions, economical truncation (Zinchenko A.Z. 1994, J. Comput. Phys. 111, 120-135) and multipole acceleration facilitate efficient iterative solution, allowing simulations with N=500-4000 spheres in a periodic box, millions of time steps and multipoles of order 20-40 retained on each sphere. Macroscopic transient sedimentation rate U(t) (within 2-fold of the initial one for a well-mixed suspension) is obtained by ensemble averaging over initial configurations. The steady sedimentation speed requires much longer time averaging. For low suspension concentrations c=0.1-0.15, high-order multipole effects are less important than using large systems. In contrast, for higher concentrations c=0.25-0.5, the system-size effect is greatly reduced, and it is far more important to include high-order multipoles, than use large systems N>500, for accurate prediction of the steady sedimentation rate. This rate essentially depends on c and the maximum net adhesive force, but is almost insensitive to other details of colloidal interactions.

Monday 2:30 Sweeney Ballroom A CS10

Contactless inter-particle friction due to roughness and elasticity

Bhargav Rallabandi, Jake Minten, and Arash Kargar-Estahbanati
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Interactions between colloidal particles govern the rheology of dense suspensions. We discuss how the interplay between fluid flow, surface roughness and elastic deformation leads to friction-like behavior between suspended particles, even without solid-solid contact. We first discuss the hydrodynamics of rough particles in relative sliding, a scenario common in dense suspension flows. We show, using lubrication theory, that rough particles experience tangential hydrodynamic forces that grow as the inverse separation between the particles. Furthermore, we identify hydrodynamic torques that strongly couple rotational and translational modes of rough particles. These features are in contrast with smooth spheres, where the interaction forces and torques are much weaker. We understand these forces and torques quantitatively as the result of local squeeze flows between opposing asperities. We then briefly discuss how these effects are modified and enhanced when one of the particles is soft. We find that forces now depend non-monotonically on the roughness, reaching a maximum at a critical amplitude that depends on material properties. These features are generic hydrodynamic consequences of particle roughness and elasticity, and may be crucial in understanding suspension rheology.

Monday 2:50 Sweeney Ballroom A CS11

Three simple Stokeslet trajectories

Benjamin J. Landrum
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The rheology of particle suspensions, particularly under transient conditions, is governed by the evolving microstructure - shaped by the trajectories of individual particles. While many-particle systems are difficult to analyze due to chaotic motion and long-range hydrodynamic interactions, small systems often admit exact solutions that illuminate fundamental mechanisms. In this talk, I will present three such exact results for the sedimentation of small particle groups at low Reynolds number. Using the Stokeslet approximation for hydrodynamic interactions, I find that (1) the middle particle in a vertical trio sediments at a constant velocity indefinitely, (2) a horizontal pair near a no-slip wall experiences a finite lateral displacement even at large separations, and (3) a pair in a quadratic background flow undergoes periodic motion with a Hamiltonian structure. These results, drawn from my recent work [1], provide analytically tractable examples of long-range interactions and may help in understanding microstructural evolution and stress development in dilute suspensions.

Reference: [1] B. J. Landrum, "Three simple Stokeslet trajectories", Ind. Eng. Chem. Res. 2025, 64 (15), 7871-7877. https://doi.org/10.1021/acs.iecr.4c05014

Monday 3:45 Sweeney Ballroom A CS12

Dynamic response during solidification of dense suspensions

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Dense suspensions undergoing solidification via sintering or chemical reactions are very common in manufacturing. Their thixotropic behavior is often investigated in the liquid/paste-like state in relation to the "workability" of the material, i.e. the ability of delivering and forming the final object of interest. However, their ultimate solid mechanical response depends on the evolution of the underlying microstructure throughout the solidification process, which can be better probed by time-resolved linear viscoelastic measurements. In this talk we will focus on model and real systems, such as paraffin gels and cement pastes, and follow their solidification behavior via time-resolved mechanical spectroscopy to analyze in detail the liquid-to-solid transition. We do this both in quiescent conditions and under different imposed flow conditions to simulate real industrial applications, thus revealing the effect of stresses, strains and strain rates on the structure of chemically reactive dense suspensions. We conclude with a perspective on the modeling of these systems.

Monday 4:05 Sweeney Ballroom A CS13

Unified description of yielding in sheared soft particulate systems

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Fundamental understanding of shear-induced yielding in soft particulate systems is important in numerous applications, ranging from additive manufacturing of consumer products to generating hazard prediction models for environmental flows. Prior work in this area has been focused on bridging the understanding between microstructural signatures and macroscopic flow associated with the transition from rate-independent to rate-dependent plastic flow. Recent works from our lab (PNAS 2022, Nat Comms 2024) show that natural soil-based suspension systems exhibit two transitions: (a) elastic (shear-independent) to plastic (shear-dependent) and (b) plastic to viscous, across the entirety of non-inertial shear rates applied. Here, we generalize this framework to other soft particulate systems, such as colloidal suspensions, athermal suspensions, athermal gels, emulsions, and granular matter. We show that a universal yielding description for non-inertial yielding in soft particulate systems exist, where: (i) particulate systems can be classified either as frictional or non-frictional; (ii) there exists two critical points in every non-frictional particulate system that are a function of average interparticle interactions; and (iii) the rate-dependent yielding envelope is a function of the distance between the two critical points. Our results are supported by models for yielding of idealized amorphous solids and existing granular rheology framework, suggesting that the paradigm we developed to understand complex behaviors of Soft Earth suspensions can help generalize solid-fluid transition for soft particulate systems.

Monday 4:25 Sweeney Ballroom A CS14

Delayed yielding in soft glasses and gels, and the role of critical strain

Crystal E. Owens
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Soft materials exposed to constant stress during creep tests exhibit a deformation response that transitions from solid-like behavior (e.g., Andrade creep) to a flowing state. This transition is called fluidization, and for stresses near to the fluid yield stress it may occur suddenly after a delay in time, particularly apparent in thixotropic materials due to their time-sensitive microstructures. The onset of fluidization does not have a clear definition, and is often only apparent after full fluidization has occurred.

Focusing on tomato ketchup as a model thixotropic fluid, we introduce a parameter to locate the initiation time of yielding events from bulk rheological signatures. "Spurt", Sp, is defined as the log time derivative of the instantaneous shear rate. This term is nondimensional, and

mathematically represents the relative change in shear rate, appearing as a peak that becomes positive and increasing at the onset of fluidization. Using spurt, we cleanly delineate avalanche onset and duration, and reveal a power-law dependency in delay time as the applied stress approaches the creep yield stress from above, while the same onset occurs at a single critical yield strain (per material). This behavior is consistent for ketchup, a colloidal gel, and a bentonite solution, and we find direct agreement between fluidization times predicted using Sp and those made by local ultrasonic velocity profiles, for a range of creep stresses. Finally, we show the absence of the typical spurt response in two yield stress fluids shown to not exhibit thixotropy (carbopol and an aqueous foam), thus revealing the importance of thixotropy in yielding behavior.

Spurt allows for the mathematical definition of fluidization time and critical yield strain from bulk rheological measurements during creep experiments, which can advance our rheological understanding of this important phenomenon, and may be used to anticipate critical material failures more generally.

Monday 4:45 Sweeney Ballroom A CS15

A nested effective medium model for the rheology of crosslinking thermoset composites

Anthony P. Kotula and Stian Romberg
Materials Science and Engineering Division, National Institute of Standards and Technology, Gaithersburg, MD 20899-8542, United States

Accurate modeling of the chemical gelation process in thermoset composites is critical to the design and processing of materials for advanced processing. However, the addition of particle fillers can often obscure the critical gel relaxation phenomena that occurs during crosslinking, and models that adequately characterize the gelation of unfilled resins do not capture the salient viscoelastic features of crosslinking composites. Here, I demonstrate the use of "nesting" a generalized effective medium (GEM) model - embedding a GEM model describing a gelation process into a second GEM model describing the rheological properties of the composite. This nested GEM model reproduces many of the rheological transitions in crosslinking thermoset composites that are observed experimentally, which I demonstrate on a series of silica-filled epoxy resins that are relevant to semiconductor manufacturing. The nested GEM model is able to show when chemical gelation occurs, even in samples with high particle loadings where a critical gel power-law relaxation spectrum is not observed.

Monday 5:05 Sweeney Ballroom A CS16

Benchmarking the rheology of nanocellulose dispersions from multiple sources

Patrick T. Spicer and Maryam Hosseini
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Rod and fiber dispersions provide a popular basis for formulating yield stress fluids because high fiber aspect ratios enable the minimization of rheological modifier levels added to a product. As a result, the order of magnitude of the colloid aspect ratio can have a strong effect on the amount of additive needed to achieve a target rheology. Nanocellulose fibers are increasingly being explored for these purposes because they are a sustainable, biodegradable additive suitable for a wide range of products and materials. Nanocellulose fibers can be obtained from a number of disparate sources, including bacterial fermentation and chemical oxidation of bulk plant and waste materials. Recent experimental work has shown significant differences in the key performance characteristics, like the minimum threshold concentration where elasticity dominates viscosity, for nanocellulose materials from different sources. We demonstrate significantly lower threshold concentrations for bacterial cellulose than for cellulose produced by bulk material degradation, then use microscopy to provide structural evidence for the difference in performance. We conclude by suggesting ways to optimise all sources for efficient formulation of aqueous commercial products and materials.

Monday 5:25 Sweeney Ballroom A CS17

From double yielding in step-rate shear to two-step re-equilibration dynamics in colloidal attractive glasses and gels

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The combination of repulsive force caging and physical bond formation driven by short-range attractions in ultra-dense quiescent Brownian colloidal suspensions and glasses leads to intriguing phenomena such as re-entrant glass melting and non-monotonic evolution of the relaxation time and elastic modulus with attraction strength. When shear-driven, two-step versus one-step yielding can emerge with increasing attraction strength. Building on a quiescent microscopic theory that explicitly treats attractive bonding and thermally-induced activated hopping, we formulate a self-consistent theory for the coupled transient and steady-state mechanical response and structural correlations as a function of accumulated strain and deformation rate over a wide range of high packing fractions and attraction strengths and ranges. The theory predicts three qualitatively different transient responses under startup step shear: plastic-like, static yielding via a single stress overshoot, and double or 2-step yielding due to an intricate competition between deformation-induced bond breaking and de-caging. Upon shear cessation from the mechanically prepared non-equilibrium state, the rebuilding of kinetic constraints triggers activated aging dynamics and coupled structural and stress recovery. With increasing bond strength, the theory predicts one-step and then extremely slow two-step stress relaxation profiles for attractive glasses and dense gels. The initial faster process is driven by rapid re-bonding resulting in accelerated aging, followed by a slower second re-equilibration dynamics, akin to jammed suspensions. Overall, double yielding under shear is associated with deformation-induced structural softening, physical bond weakening, and cage disordering, and represents a nonequilibrium form of glass melting. After shear cessation, the inverse re-equilibration process results in two-step structural and stress relaxation. The theories are found to be consistent with experiments and simulations, and new predictions are made.

Symposium GN
Self-assemblies, Gels and Networks

Organizers: Thibaut Divoux, Katie Weigandt and Ria Corder

Monday 1:30 Sweeney Ballroom B GN7

Role of non-central forces on the structure and mechanics of colloidal gels

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Colloidal gels, known for their rich rheological features and broad applicability, have been extensively studied both experimentally and through simulations. Generally, the space-spanning network formed by physical bonds between individual colloids governs the mechanics of colloidal gels. As a result, topological changes of this particulate network directly influence the rheology and mechanics of the colloidal gel. On the other hand, meso- and macro-scale features of the network are direct results of interactions at the microscopic level. Beyond the strength of range of interparticle attraction, additional characteristics such as surface roughness, uneven charge distribution, or the presence of surface-bound polymers introduce geometric and energetic constraints that influence how and where bonds form. In this study, we investigate the extent to which particle connections in colloidal gels are truly random, and how built-in physical constraints influence the formation and architecture of the network. Specifically, we introduce a methodology that limits connectivity through bending rigidity, but without prescribing the number or angles of bonds that form. Although computationally expensive, this approach captures the disordered yet non-arbitrary nature of gel networks, offering a more realistic representation of interparticle forces. Our results demonstrate that this method not only improves the accuracy of network characterization but also reveals how different gel morphologies arise from the interplay of microscopic interactions and kinetic assembly processes.

Monday 1:50 Sweeney Ballroom B GN8

Investigating rough particle contact mechanics using optical tweezers

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Colloidal gels are widespread. They are found in natural materials like muds to consumer products like toothpaste. Gels are made of networks of particles in contact. These contacts ultimately govern the material's rheology. The elasticity and yielding of a colloidal gel can be related to the bending mechanics of a linear aggregate of particles by a micromechanical, three-point bending test [1]. This test gives us two key quantities: a single bond elasticity and a critical bending moment, which correlate to the storage modulus and yield stress of the bulk material. Particle contacts fail by a rolling frictional mechanism characterized by the depinning and rotation of particles [2]. While these experiments were conducted on model spherical particles, real world colloidal materials are often composed of particles with rough surfaces, which significantly alters the contact mechanics. Recent simulations have shown that the rotational friction between particles dictates and form the elastoviscous plasticity of colloidal gels [3]. As the rotational friction coefficient increases, the yield stress also increased. Roughness impedes the rolling of these particles resulting in an increase in the rotational friction barrier. Thus, the critical bending moment and yield stress increase as a function of the surface roughness. This work aims to experimentally validate the simulations by increasing the root-mean-squared (RMS) roughness of raspberry silica particles. Microscopic optical tweezer measurements combined with bulk rheology measurements elucidate the relationship between surface roughness and both microscopic interactions and bulk properties.

[1] Pantina, J. P.; Furst, E. M. Phys. Rev. Lett. 2005, 94 (13), 138301. [2] Bonacci, F. et al. Phys. Rev. Lett. 2022, 128 (1), 018003. [3] More, R.; Mckinley, G. arXiv March 21, 2025.

Monday 2:10 Sweeney Ballroom B GN9

Structure and dynamics of frictional vs frictionless colloidal gels

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Functional materials of diverse types can be fabricated through dispersions of colloids. The properties of the materials at the macroscopic scale originate from the microscopic features and, ultimately, to the particle level, including the surface functionality and surface topography of the particles. In most studies, the interactions between particles are modeled to be central, where attractive/repulsive forces are aligned with the centerline between two particles. However, in cases where particles having rough surfaces, noncentral forces (e.g., friction) become influential. In this presentation, I will discuss the formation of space-spanning particulate networks of attractive frictional and frictionless colloids, with an emphasis on the structural features of the resulting gels and their network characteristics. This is followed by rheological characterization of the gels and correlating the microscopic features and forces to macroscopic mechanics of the system.

Monday 2:30 Sweeney Ballroom B GN10

Shear-induced yielding and brittle-to-ductile transition in cellulose nanocrystal gels

Lise Morlet-Decarnin[1], Thibaut Divoux[2], and Sébastien Manneville[1]
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Cellulose nanocrystals (CNCs) are rod-like, bio-sourced colloidal particles that serve as essential building blocks for materials with advanced mechanical and optical properties. In pure water, CNCs form stable suspensions at low volume fractions; however, in the presence of salt, they aggregate and form reversible colloidal gels with time-dependent rheological behavior. In this work, we experimentally investigate the yielding behavior of CNC gels using shear start-up tests, combining rheology with ultrasound velocimetry. These gels exhibit a characteristic stress overshoot, whose magnitude and strain location are used to rescale stress-strain curves obtained across a range of shear rates. Remarkably, the rescaled responses reveal a counterintuitive trend: the gel yields more ductilely at higher shear rates. Local velocity measurements indicate that yielding initiates at the moving wall. In cases of brittle-like failure, the stress overshoot is followed by a pronounced elastic recoil and a transition to total wall slip. A similar brittle-to-ductile transition is observed when decreasing the sample "age," defined as the rest time following a high-shear rejuvenation step. These findings highlight the complex interplay between aging and yielding. Indeed, for a given sample age and under a small applied shear rate, it takes a significant amount of time to reach the critical deformation at which the gel breaks. During this initial stage, the material response remains solid-like, and the gel elasticity builds up due to aging, which leads to the formation of a consolidated network whose rupture is more brittle-like. To quantify the gel's brittleness, we introduce a parameter B, defined as the maximum slope beyond the stress overshoot in log-log stress-strain coordinates. We show that B decreases logarithmically with increasing shear rate. Finally, we compare our results with recent theoretical models and find notable deviations, indicating the need for refined theoretical descriptions.

Monday 2:50 Sweeney Ballroom B GN11

Adding MXenes to aqueous cellulose nanocrystal dispersions: Effects on rheology and dispersion microstructure

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We report the rheological and phase behavior effects of adding two-dimensional MXenes (Ti3C2TX) to aqueous dispersions of one-dimensional cellulose nanocrystals (CNC). There has been increasing interest in combining CNC and MXenes for electrochemical applications. Much of the research to date has focused on the final properties of assembled films, fibers, or 3D printed objects; less is known about the colloidal microstructure and rheological behavior that lead to the properties of the solid assemblies. Moreover, while the phase behavior of mixtures of 1D rods and 0D spheres is relatively well understood, much less is known about mixtures of 1D rods and 2D sheets, particularly for charged systems. In this research, various concentrations of aqueous MXene dispersions were mixed with aqueous dispersions of sulfated CNC dispersions with lengths of less than 0.2 μm and diameters on the order of 10 nm. A combination of cross-polarized optical microscopy and non-linear rheology was used to understand mixture microstructure and phase behavior. Even low concentrations of MXene sheets with a lateral dimension of L = 3 microns induced nematic liquid crystalline phase behavior instead of the chiral nematic behavior characteristic of aqueous CNC dispersions. However, the addition of smaller L = 0.3 micron MXene sheets had less impact. Most interestingly, some mixtures exhibited both chiral nematic fingerprints and bright purple nematic textures, while others appeared to be a colloidal glass. The results of this work are a first step toward an improved understanding of charged 2D/1D nanomesogen dispersions and achieving controlled nanomesogen orientation in advanced hybrid materials.

Monday 3:45 Sweeney Ballroom B GN12

Explicit simulation of depletion effects in colloid-polymer mixtures

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Colloidal gels driven by polymer-induced depletion forces-also known as depletion gels-serve as model systems for studying the rheology of disordered soft solids. There is a rich body of experimental literature characterizing the structure, dynamics, and flow behavior of depletion gels across a range of concentrations and size ratios. However, virtually all theoretical and simulation studies treat the polymers implicitly through effective potentials, or through representative physical forces that emerge from the presence of polymers. In this work, we perform explicit simulations of polymer depletants and colloidal particles to shed light on the anisotropic nature of forces that emerge in such systems.

The polymers are modeled as short bead-spring chains that interact with colloids via soft repulsions, resulting in a depletion-induced attraction without direct bonding. We compare these systems to reference gels with effective Morse pair potentials and examine the resultant equilibrium structures. Our work suggests that oversimplification of depletion forces via effective attractions between colloids can lead to structural differences-both under quiescent conditions and during flow. These findings highlight the importance of modeling microscopic interactions directly when predicting the flow behavior of colloidal gels, with implications for designing soft materials in formulations where polymer-colloid interactions cannot be accurately coarse-grained.

Monday 4:05 Sweeney Ballroom B GN13

Shear induced aging in polymer-silica composites

Destiny D. Gray[1], David Adrian[2], Dongchan Ahn[2], Shawn Chen[2], Froeschle Kalyn[2], Tyler Heyl[2], Matt Hodgson[2], Jyo Lyn Hor[2], and Simon A. Rogers[1]

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Fumed silica is added to polymers as a reinforcement filler to enhance their mechanical properties, such as strength, stiffness, and abrasion resistance. Studying the rheological aging effects of these polymer-silica composites is crucial because it helps assess long-term durability, stability, and performance, ensuring the material's suitability for various applications, from automotive to biological products. The effect of aging on the viscoelastic behavior of untreated silica filled polydimethylsiloxane (PDMS) is investigated experimentally by performing strain-controlled oscillatory shear tests at various times since preshearing. We show that the material is rejuvenated after fully yielding, but it can return to its aged state by either waiting sufficiently long times under zero-shearing conditions, or by shear-induced aging at intermediate strains. This aging process has also been found to be reversible, and dependent on the shear history. Shear-induced aging is accompanied by overshoots in both the storage and loss moduli and is only observed by controlling the oscillatory strain amplitude from small to large strains. Performing the tests from large to small strains results in an overshoot in the loss modulus, but only a monotonic change in the storage modulus. Thus, we interpret the overshoot in the loss modulus as a competition between shear-induced aging and rejuvenation and is not an intrinsic material property. This aging behavior is modeled by incorporating a time-dependent modulus that captures the nonlinear, transient rheological characteristics of the material.

Monday 4:25 Sweeney Ballroom B GN14

Polymer-nanoparticle composite gels to mimic muscle stiffness for cultured meat platforms

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Hydrogel scaffolds are being developed as biomimetic platforms to guide satellite muscle cell differentiation for cultured meat production. In native muscle, the extracellular matrix provides physical and chemical cues that result in organized muscle development. During myogenesis, satellite cells sense and respond to tissue stiffness, which regulates their progression into myotubes and mature fibers. Our work mimics tissue properties by incorporating thiol-functionalized silica nanoparticles (fSNPs) into a hydrogel scaffold to increase matrix stiffness. This is the first step in designing a tunable material system that recapitulates the stiffness of native muscle tissue to support the formation of contractile, meat-like structures. We synthesize silica nanoparticles and characterize size, morphology and thiol content using dynamic light scattering, scanning and transmission electron microscopy and Ellman's assays. These techniques confirm that the SNPs are uniform in size (D=38±5 nm, polydispersity 0.10±0.04). We tether fSNPs into a poly(ethylene glycol)-norbornene (PEG-N) hydrogel with an enzymatically-degradable cross-linker. The scaffold is photopolymerized using thiol:ene click chemistry. Bulk rheological properties measure how nanoparticle incorporation changes scaffold stiffness in both unswollen and swollen gels. fSNP content leads to higher storage moduli. Material degradation initiated with enzymes, specifically collagenase, is measured using multiple particle tracking microrheology (MPT). MPT is a passive microrheology technique that measures the displacement of embedded probe particles in the hydrogel to calculate rheological properties. This work develops a reproducible platform for incorporating physiologically properties into scaffolds that direct muscle tissue formation for cellular agriculture applications.

Monday 4:45 Sweeney Ballroom B GN15

Rheology and structure of multi-component attractive colloidal gels

Alexander I. Kaltashov[1] and Safa Jamali[2]

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To date, most rheological studies of colloidal gels have largely focused on model systems based on a single component, largely due to the complex rheological behavior of even the simplest of colloidal gels. Yet, many real-world systems of interest consist of multiple components, whose structural peculiarities often give rise to non-intuitive mechanical behavior. The study of multi-component systems is not only relevant to the understanding of existing complex systems, but can also inform the design of new materials whose mechanical and rheological properties can be tuned through the manipulation of different particle populations.

In this work, we study the rheological and mechanical properties of two-component colloidal gels whose inter-species and intra-species electrostatic attractions can be independently manipulated. Using mesoscale simulation techniques, we analyze the shear response of such gels. We observe that by simply tuning interparticle interactions and leveraging temporal controls via sequential gelation, we can construct a wide assortment of colloidal network structures that give rise to diverse and intriguing rheological properties.

Monday 5:05 Sweeney Ballroom B GN16

Tailoring evaporative patterns by hetero-aggregation of oppositely charged species

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Evaporation-driven assembly of colloidal particles often results in the coffee-ring effect, where particles are transported to and deposited at the drop edge due to capillary flows. In this study, we present a strategy to control and suppress this effect by using drying droplets containing mixtures of oppositely charged colloidal species. By tuning the mixing fraction (?$_f$), defined as the mass ratio of positively charged particles to total particle mass, and the total particle concentration (C_T), we engineer a wide range of deposit morphologies, including clustered deposits, uniform deposits with and without voids, and dome-like deposits. With the help of video microscopy, electrophoretic mobility measurements, particle-tracking microrheology, and ex-situ rheology, we examine how the interplay between sedimentation, capillary flow, and gelation during drying leads to the formation of distinct patterns. We present this work as a universal method to control evaporative patterns by extending it to particle-particle, particle-polymer, and polymer-polymer binary mixture systems. This work highlights how electrostatic interactions in colloidal mixtures can be harnessed to direct evaporation-driven assembly and tune final deposit patterns.

Symposium SM
Polymer Solutions, Melts and Blends

Organizers: Amanda Marciel, Ben Yavitt and Piyush Singh

Monday 1:30 Coronado + DeVargas SM7

Impact of molecular weight and polydispersity on concentration-dependent relaxation time in dilute polymer solutions

Ann M. Aisling[1], Donya Ghasemi[1], Nicolas J. Alvarez[1], Hans Werner Muller[2], and Lukas Brandfellner[2]
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This study examines the influence of molecular weight and polydispersity on the relationship between concentration and relaxation time in polymer solutions. Polyethylene Oxide (PEO) aqueous solutions with molecular weights of (4×106, 5×106, and 8×106 MDa), as well as Polystyrene samples (Mw = 2.24×106, 2.4×106, 2.75×106, 2.87×106, 3.62×106, 4.12×106 MDa) dissolved in dioctyl phthalate, were analyzed. Molecular weight distribution of the PEO samples was characterized using Gel Permeation Chromatography. Relaxation time was determined through VADER extensional flow under velocity control. Results reveal that in the dilute concentration regime, the widely used relationship between c/c* and relaxation time normalized by the Zimm relaxation time is significantly influenced by polydispersity and molecular distribution weighting, with larger molecules dominating bulk behavior. Furthermore, relaxation time is dependent on both molecular weight and concentration for polydispersity index (PDI) > 1.3, whereas monodisperse solutions exhibit concentration-independent behavior in the dilute regime. Due to material inhomogeneity and the complex interplay of polydispersity-driven relaxation effects, absolute rheological parameters lack significance unless the flow field for polydisperse solutions is specified. Notably, while monodisperse solutions maintain velocity-independent relaxation behavior, polydisperse solutions exhibit relaxation times that are inherently linked to velocity.

Monday 1:50 Coronado + DeVargas *Keynote* SM8

Viscoelastic properties of physical networks: From chain branching to sticky junctions

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Understanding and tailoring the viscoelastic response of polymer melts or concentrated solutions from the knowledge of their molecular structure (architecture) represents a formidable challenge and remains an important field of soft matter research. In order to further study the dynamics of these samples, we have developed a general coarse-grained approach based on the tube model, that we are now using as a tool to investigate the viscoelastic properties of complex, entangled polymer architectures. In the present work, we extend this approach to investigate the dynamics of reversible polymer networks, containing supramolecular junctions. The combination of stickers and entanglements as topological constraints provides a large room to modulate the viscoelastic response of the networks. On one hand, the network elasticity depends on the density of the reversible junctions but also on the entanglements trapped within the network, the proportion of which depends on the topology of the building blocks. On the other hand, the relaxation time of the network depends on the cooperative effects of the stickers, dangling ends and entanglements, their corresponding lifetimes being a function of the sample composition. Considering these different mechanisms, we show that it is possible to design very different transient networks but with exactly the same linear viscoelastic response at a specific temperature. But interestingly, these networks do not behave similarly at another temperature or under large deformation. This opens new possibilities to further control the networks dynamics, towards the design of samples with desired properties.

[1] Y Li et al., J. Rheol. 2022, 66 (6), 1203-1220.
[2] S Ghiassinejad et al. Macromol. 2021, 54 (13), 6400-6416.
[3] R Lyons et al., J. Rheol, 2022, 66 (6), 1349-1364.9
[4] P. de Wergifosse et al., Macromol. 2025.

Monday 2:10 Coronado + DeVargas SM9

Flow effects on associative polymers: From linear to ring macromolecule

John C. Bracewell[1], Rosita Sivaraj[1], Dvora Perahia[1], Thomas C. O'Connor[2], and Gary S. Grest[3]
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The unique shear and flow response of polymers is a compounded function of distinctive chemistries and topologies. Here, using a coarse grain bead-spring model, we probe the response of ring polymers decorated with associate groups in comparison with their linear analogues to extensional flow as the strength of the associative polymers is varied. The uniqueness of ring polymers lies in the fact that they have no free ends, a constraint that force ring chains to form globularly compact structures compared to linear macromolecules. Ring polymers are less entangled compared with linear chains with similar N, resulting in higher mobility and lower viscosity. Here we present results of non-equilibrium molecular dynamics simulations of extensional flow of entangled linear and ring melts containing associating groups along the backbone. We compare the effects of flow on chain conformation for linear and ring chains as well as the cluster characteristics as a function of flow rate. These are then correlated with extensional viscosity. We find that under flow for both linear and ring polymer melts, the clusters of associating groups are dynamic, continuously breaking and reforming. As the fraction of associating groups on the backbone or their interaction strength increases, the distribution of the chain extension becomes more heterogeneous as the associating groups restrict the response of the chains to flow. Even in the presence of strong interactions between the associating groups, the rings still form topological links, in which case the extensional viscosity is due to a combination of these linked rings and the associating groups.

Monday 2:30 Coronado + DeVargas SM10

Effect of chain length on shear and extensional rheology of polyampholyte ionomers

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Ionomers, polymers with a small fraction of ionic groups, self-assemble into nanodomains that serve as reversible crosslinks, controlling morphology, dynamics, and rheology much like permanent entanglements. To isolate the role of chain contour length, we modeled polyampholyte ionomers using coarse-grained molecular dynamics simulations with fixed spacing between ions and varied the total chain length, then probed each system under steady shear and uniaxial extension flow field. Under steady shear, longer chains produce larger, broader stress overshoots at higher strains, and the yield strain remains insensitive to shear rate, demonstrating that chain length, not deformation rate, sets the yielding threshold. At low shear rates, chains slide past one another slowly enough that unpaired ions along each backbone can reach across to bind with neighboring ions, adding crosslinks, densifying clusters, and modestly aligning the network before yielding. At high rates, they break more bonds at the stress peak but rapidly reform them during continued deformation, driving enhanced steady-state alignment. In uniaxial extension, all samples deviate from the linear viscoelastic behavior to exhibit strain hardening. Intermediate chain lengths fall within an optimal range where the segment-scale stretching and sticker dissociation time bracket our experimental window, producing a two-step viscosity plateau; shorter chains collapse both relaxation modes into one, while longer chains shift their crossover beyond accessible strains, erasing the second plateau. Throughout the extension, chains never lock into a fixed stretch; instead, they undergo persistent stretch-recoil-flip cycles, known as tumbling motion, as ionic bonds break and reform. This dynamic behavior shows how reversible ionic networks can mimic the toughness and ductility of permanently entangled polymers. By revealing how ionic associations and chain contour length jointly dictate rheological response, this work paves the way for tailored ionomer design.

Monday 2:50 Coronado + DeVargas SM11

Linking multiscale rheology and SANS study to performance of hierarchically structured PEM fuel cell catalyst layer

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Fluid-fluid interfaces containing nanoparticles provide a versatile platform for creating hierarchically structured materials with tailored properties. In this study, spinodal decomposition is employed for the first time as a template for fabricating catalyst layer (CL) in proton exchange membrane fuel cells (PEMFCs). Using phase separation of water/2,6-lutidine mixtures, this approach generates hierarchical pore structures and introduces a novel pathway for CL design. The structural evolution of these catalyst inks was examined through a multiscale approach, incorporating small-angle neutron scattering (SANS), microrheology, bulk rheology, and fuel cell performance testing. SANS study on ionomer dispersions with water/2,6-lutidine revealed a globular particle-like structure of the ionomer chains. Upon spinodal decomposition, long-range ionomer clusters appeared. However, the emergence of the clusters was suppressed in the presence of platinum-doped carbon (Pt/C) catalyst. Microrheology study indicated that this is due to jamming of both Pt/C and ionomer within the lutidine-rich domain by showing an increase in the local viscosity in the vicinity of Pt/C. Macro-rheology exhibited an enormous growth in bulk moduli stemming from the jamming and the evolution of the percolated structure. The moduli growth enabled the preservation of the formed structure against solvent drying stress, producing a CL with percolated pores. The formed structure facilitated mass transport and resulted in increased limiting current density. The spatial confinement of catalyst and ionomer improved catalytic activity. These findings establish spinodal decomposition as a powerful tool for fabricating hierarchically structured CLs. By offering new insights into ionomer chain behavior, catalyst interactions, and hierarchical structuring, this approach paves the way for optimizing material architectures in energy conversion technologies, particularly PEMFCs.

Monday 3:45 Coronado + DeVargas SM12

Shear response of ionizable polymer melts from ionomers to polyelectrolytes

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Nonlinear shear response of polymers is affected by inherent barriers for diffusive motion including entanglements and topology. In ionizable polymers, ionic clusters further constrain the intrinsic dynamics of the polymers, enhancing significantly their viscosity. Here we will present molecular level insight into the nonlinear shear response of ionizable polymers that are fundamental to controlling their processing into viable materials, using fully atomistic molecular dynamics simulations. The results for the ionomer regime, where distinctive clusters dominate the structure, will first be presented, followed by the cross over regime to polyelectrolytes where clusters percolate. The shear response of sulfonated polystyrene with sulfonation fractions of f = 0.09, 0.20, and 0.35, in pristine and THF swollen melts, will be discussed in comparison with polystyrene. On the molecular level, we find that polystyrene chains stretch under shear, while the ionic assemblies break and reform, affecting the macroscopic viscosity. For both the ionomer and polyelectrolyte regimes, the molecular level shear response strongly depends on the size of the ionic clusters resulting in distinctive response as the degree of sulfonation changes. Overall, the extent of stretching, and chain relaxation strongly depend on the confinement of the polymer, exerted by the ionic assemblies. For all systems, the shear viscosity displays initially an elastic response, followed by nonlinear shear stress. As THF is added, the chain interaction is modified and the shape and size of the ionizable domains changes, affecting their shear response. The correlations between shear viscosity and the molecular response will be discussed.

Monday 4:05 Coronado + DeVargas SM13

Microrheology of biosynthetic composites of DNA and NaPSS

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We engineer entangled bio-synthetic polyelectrolyte composites with judiciously matched critical concentrations that are tunable via solution conditions. We show that biological DNA polymers and synthetic sodium poly(styrene sulfonate) (PSS) polymers of comparable coil size in low salt conditions interpenetrate to form macroscopically miscible solutions across the dilute to semidilute to entangled regimes. Whereas PSS dynamics are highly dependent on salt concentration, DNA dynamics are largely insensitive, allowing for independent tuning of the critical concentration for entanglements. For all composites containing DNA (i.e., for DNA fractions wDNA > 0), the DNA entanglement concentration dictates the crossover from semidilute to entangled dynamics. The dynamic data on long and short time scales can be collapsed using the entanglement concentration in both low and high salt conditions, indicating that DNA entanglements appear to govern the crossover between dynamical regimes. In the entangled regime, the scaling behavior for the zero-shear viscosity monotonically transitions from the prediction for polyelectrolytes to that for neutral polymers as wDNA increases and is surprisingly insensitive to salt concentration for wDNA > 0 composites. We observe similar collapse in the short-time limit, where the composites exhibit shear-thinning and anomalous transport behavior in the entangled regime. By combining biological and synthetic polyelectrolytes we are able to span from semidilute to entangled regimes and from polyelectrolyte to neutral polymer behavior, with independent tuning knobs governing these transitions. The design principles can be leveraged for designing miscible blends with greater dynamic range and responsiveness.

Monday 4:25 Coronado + DeVargas SM14

Pinching dynamics and extensional rheology of dilute and entangled polymer solutions

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Concentration-dependent variation of macromolecular conformations and dynamics in polymer solutions are influenced by molecular weight, degree of overlap, solvent quality, persistence length, and number density of entanglements. In this contribution, we characterize the shear and extensional rheology response of flexible and semi-flexible polymer solutions using the broadest range of concentrations, spanning from ultra-dilute to highly entangled using solvent mixtures with varied volatility and solvent quality. We characterize the response to extensional flows realized in capillarity-driven pinching of liquid necks by using the dripping-onto-substrate (DoS) rheometry protocols. The concentration-dependent variation in shear vs extensional rheology response reveals distinct influence of polymer and solvent properties. Lastly, we find standard predictions of FENE-P or Oldroyd-B models are inadequate to describe the observed radius evolution datasets, and yet there are similarities in the response as dictated by dynamics and relaxation of stretched polymers.

Monday 4:45 Coronado + DeVargas SM15

Stringiness, spinnability, and sprayability of polymer solutions

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Stringiness, or a materials propensity to form long, thin, persistent threads, is a phenomenon which occurs all around us in everyday life. From the stringiness in nature that allows plants and insects to trap their prey, from food products like sauces, syrups, and other culinary creations that rely on stringiness for consistency and texture, from biological systems like saliva that transmit illnesses or help form cohesive boluses for mastication and swallowing processes, and paints, coatings, sprays and films which rely on stringiness to achieve desired application conditions,

stringiness controls how fluids in these applications behave. An understanding of stringiness is especially critical in applications such as spraying and fiber spinning, where formulation design dictates the performance of the product. To create sprayable or spinnable solutions, polymers are often used as rheological modifiers, leading to varying levels of stringiness. In this work, Dripping-onto-Substrate (DoS) and Dripping protocols are incorporated to observe stringiness and are utilized to collect extensional rheological properties. Shear and extensional rheological properties of polymer solutions are then measured and correlated to stringiness, sprayability and spinnability.

Monday 5:05 Coronado + DeVargas SM16

Extensional rheology of dilute suspensions of spheres in polymeric liquids

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Adding solid particles to a liquid typically increases its viscosity due to additional traction at particle surfaces. However, using a combination of semi-analytical methods and direct numerical simulations, we find that the extensional viscosity of polymeric liquids can decrease when a small concentration of spherical particles is added. This reduction occurs in regimes of large Hencky strain (H) and long polymer relaxation times-conditions where the host fluid exhibits large extensional viscosity due to highly stretched polymers. Our results qualitatively agree with the only available experimental observations, reported by McKinley et al. in space-based experiments aboard the International Space Station, for polymeric fluids at low concentrations (c). The mechanism involves polymer-particle interactions and local coil-stretch transitions in the suspending fluid. At low c, highly stretched polymers in undisturbed regions undergo a stretch-to-coil collapse near the particles, generating a negative particle-induced polymer stress. As c increases, this near-particle effect diminishes, but a new mechanism emerges: stronger coupling between polymer stress and velocity field induces widespread polymer collapse upstream of the particles, especially along the compressional axis. This results in an even more negative interaction stress that scales as c^2, exceeding the linear polymer stress increase seen without particles. Thus, in highly extensional regimes (large H, c, or relaxation time), adding dilute spherical particles can reduce extensional viscosity. This counterintuitive phenomenon-predicted by our simulations and observed even at higher c-motivates future lab-based extensional rheology experiments, where sagging of the fluid bridge in an extensional rheometer is expected to be minimal. The mechanism may reduce energy use in processes like fiber spinning and hydraulic fracturing, where particle-laden polymeric fluids experience strong extensional flows upon entering or exiting pores.

Symposium AR
Applied Rheology for Industrial Applications

Organizers: Hammad A. Faizi and Antonio Perazzo

Monday 1:30 Peralta + Lamy AR7

Functional Polysaccharides for Applications in Hair Care

Hammad A. Faizi

Dow Consumer Solution, The Dow Chemical Company, MIDLAND, MI 48611, United States

The home and personal care market has been experiencing revolutionary demand for sustainable alternatives to traditional synthetic materials used across market segments. Functionalized polysaccharides offer an attractive route to combat this challenge by providing natural, renewable, and biodegradable solutions. In this talk, I will focus on two areas in a shampoo formulation: polymers as a deposition aid and rheology modifier. The first part aims to compare the morphology of complexes of cationic polysaccharides such as cationic dextran (catDex), cationic guar (catGuar), and cationic hydroxyethyl cellulose (catHEC) with the anionic surfactant sodium lauryl ether sulfate (SLES) during dilution of model shampoos. Using a wide array of complementary techniques such as high-throughput phase studies, optical microscopy, dynamic light scattering, and liquid-phase transmission electron microscopy (LP TEM), we discovered the formation of unique, nanometric-sized catDex-SLES complexes as compared to the widely reported coacervate-driven deposition for catGuar-SLES complexes in driving large complexes on to hair. We explore the dynamics of the deposition on hair of these complexes using quartz crystal microbalance with dissipation (QCM-D). The results highlight the impact of the persistence length of cationic polysaccharide backbones on polymer-surfactant complex deposition onto negatively charged surfaces. Additionally, the rise in consumer preference for non-sulfate shampoos poses challenges for viscosity modification via traditional worm-like-micelle (WLM) mechanisms due to the high positive curvature of many non-sulfate surfactants (e.g., alkyl glucoside and amino acids). This talk will showcase how these challenges can be overcome using high-molecular-weight hydroxypropyl methylcellulose (HPMC) and biobased sulfate-free surfactants. Role of surfactants are well known to impact the shear rheology of hydrophobically modified Cellulose ethers. In this study, we investigated the role of HPMC-surfactant complex rheology under extensional flow via Capillary Breakup Extensional Rheometer (CABER). This is a critical parameter for consumer experience and formulation processing.

Monday 1:50 Peralta + Lamy AR8

Advanced tribological techniques for the personal care products

James P. Eickhoff Jr.[1] and Kartik S. Pondicherry[2]

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Characterization of materials via rheological techniques is a versatile tool for studying an array of personal care products. These measurements provide insight into the visco-elastic balance that can be used to exploit processability as well as stability. However, to garner a better insight from

a customer standpoint other technique can be employed. Measurements that monitor friction, wear, and even lubricity can often provide crucial information for adjusting the formulation to meet customer expectation. This can be measured through tribological means. In this talk, an array of tribological techniques are discussed for various personal care applications.

Monday 2:10 Peralta + Lamy AR9

Influence of cationic surfactant-fatty alcohol on the properties of moisturizing creams

Sophie Liu[1], Ritesh K. Sinha[2], Chung-chueh Chang[1], Brittany Lee[1], and Hy Bui[2]
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This study investigated some commercial skin moisturizing creams, marketed with claims comparable to CeraVe cream, and formulated as oil-in-water (O/W) emulsions containing similar ingredients, primarily cationic surfactants and fatty alcohols. Rheological analysis and differential scanning calorimetry (DSC) were used to characterize the creams, revealing variations in viscoelastic properties. These variations, along with morphological observations, suggest differences in surfactant concentrations and cationic surfactant-to-fatty alcohol ratios across the formulations. The influence of cationic surfactant concentration was further explored by examining product deposition on artificial skin and glass substrates, both before and after water immersion, using scanning electron microscopy (SEM), atomic force microscopy (AFM), and laser microscopy. Tribological analysis provided sensory evaluation data, supporting the observed relationship between surfactant-to-fatty-alcohol ratios and concentrations and the formation of lamellar gel networks and multilamellar vesicles within the O/W emulsions.

Monday 2:30 Peralta + Lamy AR10

Multiscale rheo-physical characterization and processing of concentrated surfactant solutions

Parth U. Kelkar[1], Kendra A. Erk[1], Emilio Tozzi[2], and Seth Lindberg[2]
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Consumer cleaning products contain a large amount of water, essential for their use but unnecessary for their production and transport. Since water in the shower dilutes these products effectively, shifting to concentrated formulas would reduce waste and environmental impact. However, simply removing water alters the microstructure and can compromise product performance. Further, scaling up processing of highly viscous pastes across the lab-to-manufacturing pipeline is challenging for conventional production methods. Real-time viscosity measurements coupled with robust multiscale material relationships are essential, as traditional benchtop methods may not fully capture rheological signatures influencing process performance. This university-industry collaboration developed fundamental relationships between rheology, microstructure, and processability of concentrated solutions. Industrially relevant aqueous complex fluids - entangled polyvinyl alcohol, spherical micelles, microfibrillated cellulose, and lamellar pastes (70 wt.% SLE_3S) were studied. Flow behavior and instabilities such as wall slip and plug flow were analyzed across multiple scales by integrating offline and in-line techniques. Benchtop rheometry and 1D velocity profiles from ultrasound speckle velocimetry (USV) at the lab scale were compared with pilot-scale pipe flow measurements, where pressure-based viscosity was measured using soft sensors and 2D velocity profiles were monitored using in-line magnetic resonance imaging (MRI). For the lamellar feedstock, effects of additives were studied to improve processability. Short-chain linear alcohols induced a transition to a lower-viscosity phase, reducing pressure drops and approaching micellar-like flow. Within the lamellar phase, propylene glycol enhanced wall slip, enabling higher flow rates for the same pressure drop. Outcomes from this study bridge the gap between lab-scale characterization and industrial processing, providing robust scale-up strategies for concentrated feedstocks.

Symposium RG
Special Session: Rheology in Geoscience (Invited)

Organizers: Sujit Datta, Meng Meng and Stephan Kolzenburg

Monday 3:45 Peralta + Lamy RG1

A dynamical model for the rheology of polycrystalline glacial ice

Alex Vargas, Ranjiangshang Ran, and Justin C. Burton
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The slow creep of glacial ice is essential to accurate predictions of future sea level rise. Glacial ice is polycrystalline, with millimetric grain sizes, yet understanding the transient deformation of polycrystalline ice remains a long-standing challenge. Historically, Glen's flow law-a simple power-law relation-has been used to describe ice rheology, but this empirical model fails to capture the transient regimes observed in laboratory experiments. Experiments on polycrystalline ice reveal three distinct creep regimes: primary, secondary, and tertiary, none of which can be fully described by a single power-law form. Here, we propose a physically motivated model that extends the Andrade creep framework to account for structural evolution in polycrystalline ice. Specifically, we replace the linear (viscous) term in the Andrade model with a structured dashpot that evolves between two limiting viscosities, representing the transition from a hardened isotropic state to a softened anisotropic fabric. This structure evolution is driven by the deformation of ice grains, whose strong crystallographic anisotropy causes the effective viscosity of the material to decrease as deformation proceeds. Our model captures the strain-rate minimum that emerges naturally during creep and reproduces key features

of all three creep regimes. We demonstrate that this approach offers a minimal, yet predictive, framework for describing transient creep in ice and may offer insights into more general anisotropic materials.

Monday 4:25 Peralta + Lamy RG2

Discovering the complex rheology of polar ice using AI and satellite data

Ching-Yao Lai and Yongji Wang
Geophysics, Stanford University, Palo Alto, CA 94305, United States

Can AI help uncover unknown constitutive laws from vast amounts of Earth data? In this talk I will discuss data-driven exploration of the rheology of ice shelves using physics-informed deep learning and remote-sensing observations (Wang, Lai, et al., Science (2025)). The constitutive law of ice directly governs the dynamics of land ice but is challenging to measure in the field. Thus, current models rely on results from decades-old laboratory experiments, conducted in idealized settings. Here, with physics-informed deep learning and remote-sensing observations, we identify constitutive models that differ from those previously assumed in ice-sheet models, including anisotropic behavior. Our results suggest the need to reassess the impact of ice flow laws on the future projection of sea-level rise, and highlights opportunities to study rheology of geophysical-scale Earth materials directly in their natural environment.

Monday 5:05 Peralta + Lamy RG3

Freezing flow in porous ice

Xiaojing Fu[1], Nathan Jones[1], Aman Eujayl[1], Benzhong Zhao[2], and Adrian Moure[1]
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Climate warming is altering hydrological processes in the cryosphere, yet these changes remain poorly understood. This study advances our understanding of fluid flow through subfreezing porous materials like snow, firn, and permafrost. Such flow involves complex interactions between interfacial flow, phase change, and thermal transfer, leading to diverse non-equilibrium phenomena from pore to field scales. We present ongoing numerical and experimental investigations into unsaturated water flow in porous ice. At the cm-to-m scale, we employ a thermodynamic nonequilibrium infiltration model to examine refrozen structures formed during gravity-driven water infiltration in subfreezing porous media. We identify two key freezing-induced mechanisms that slow infiltration. First, a portion of infiltrating water freezes, reducing the effective infiltration rate, which can be quantified using the freezing Damköhler number. Second, secondary fingers-new flow paths forming between primary channels-decrease flow channelization, weakening infiltration efficiency through flow field homogenization. At the mm-to-cm scale, we explore water imbibition into a subfreezing Hele-Shaw cell through experiments and modeling. Water at 0°C is injected at a constant flow rate into a radial Hele-Shaw cell cooled by a thermal-controlled aluminum block. By varying the cell gap thickness and flow rate, we analyze changes in solidification dynamics and flow. To model this process, we develop a gap-averaged two-phase Hele-Shaw flow model coupled with freezing dynamics. Finally, we compare preliminary experimental results with the model. This work enhances our understanding of unsaturated flow in freezing porous media, contributing to improved predictions of cryosphere hydrology in a warming climate.

Symposium IR
Interfacial Rheology, Surfactants, Foams and Emulsions

Organizers: Manolis Chatzigiannakis, Carlos Martinez and Muchu Zhou

Monday 1:30 O'Keeffe + Milagro IR7

Effect of interdroplet interaction on rheology of highly concentrated emulsions

Muchu Zhou, Babak Valipour Goodarzi, and Reza Foudazi
School of Sustainable Chemical, Biological and Materials Eng, University of Oklahoma, Norman, OK 73019, United States

The volume fraction of dispersed phase exceeds 74% in highly concentrated emulsions, also known as high internal phase emulsions (HIPEs). HIPEs have applications in many fields, such as cosmetics, foods, and production of porous polymers. HIPEs have elasto-viscoplastic behavior. However, the HIPEs stabilized by different surfactants behave differently under shearing due to the difference in the interdroplet interactions, inducing adhesive and non-adhesive droplets. In addition, the effect of droplet size on the rheological properties of adhesive and non-adhesive HIPEs has not comprehensively been investigated yet. Therefore, in the present work, the effect of droplet size on the dynamic moduli and yield stress of HIPEs with different interdroplet interactions are investigated. We show that strong interdroplet interaction can result in deviation of elastic modulus scaling with Laplace pressure.

Monday 1:50 O'Keeffe + Milagro IR8

A rigorous microinertia model for dilute emulsions under flow

Antony N. Beris[1] and Brian J. Edwards[2]
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As new materials are developed involving mesoscopic structures of larger sizes and interest grows in the modeling of inertial microfluidic flows, it is of interest to examine the proper form of macroscopic models that go beyond the local creeping hypothesis at the microscopic level. We call here those models, where the macroscopic characteristic length scale approaches closer to the microscopic one and where particle momenta become important, microinertial models. The use of the Single Generator Bracket Formalism (SGBF) of nonequilibrium dynamics, is particularly advantageous in properly representing the mathematical structure of microinertial models as demonstrated for the description of microinertial effects in nematic liquid crystals, an area where the first principles microinertia models were developed in the past [1]. The flow of dilute emulsions is an area where independent theoretical evidence of microinertial effects, based on both microscopic simulations [2] as well as theoretical asymptotic analysis results [3], is available. Emanating from a new evaluation of the mathematical structure of the governing equations of materials flow in the presence of microinertia, we present here an improved model to that discussed in the past [4] for the flow of dilute emulsions when microstructural inertia can be important. As in that work [4], all model parameters are independently fit to theoretical asymptotic analysis results [3]. Predictions with the new model are compared both against the older model [4] as well as against previous microscopic simulations [2] results at Reynolds numbers well beyond the creeping flow regime where inertial effects are expected to play a substantial role in the nonequilibrium dynamics of the system.

References: [1] A.N. Beris and B.J. Edwards, Thermodynamics of Flowing Systems, Oxford University Press, 1994. [2] X. Li and K. Sarkar, J. Rheol. 49, 1377 (2005). [3] R.V. Raja, G. Subramanian, and D.L. Koch, J. Fluid Mech. 646, 255 (2010). [4] P.M. Mwasame, N.J. Wagner, and

Monday 2:10 O'Keeffe + Milagro IR9

Formulation strategies for ZnO-containing emulsions with carbomer copolymers: Overcoming carbomer-electrolyte sensitivity

Brian S. Bodnar[1], Hy Bui[2], Abiral Poudel[3], and Anil Shah[1]
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Carbomer copolymers are essential rheology modifiers in various formulations, but their notorious sensitivity to electrolytes, particularly multivalent cations like Zn^{2+}, limits their compatibility with zinc oxide (ZnO), a critical ingredient in mineral sunscreens. ZnO, a common mineral UV filter, can release Zn^{2+} ions, potentially destabilizing carbomer-thickened emulsions. This study explores innovative formulation strategies to mitigate the adverse effects of Zn^{2+} on the rheological properties and stability of carbomer-stabilized oil-in-water sunscreens. We systematically investigated the influence of Zn^{2+} concentration on simple carbomer copolymer gels and model sunscreen formulations, employing microscopy and rheological analysis to characterize emulsion structure and stability. Our results define practical formulation tolerances for incorporating ZnO in carbomer-based systems, paving the way for the development of high-performance, stable mineral sunscreens with optimized rheological profiles.

Monday 2:30 O'Keeffe + Milagro IR10

Reducing emulsion drop deformation with low surface coverage: High yield particle interfaces

Arsalan Abutalebi and Gordon F. Christopher
Texas Tech University, Lubbock, TX 79410, United States

Due to their long-term stability, particle stabilized Pickering emulsions are used extensively across various industries. Commonly, stabilization is derived from fully particle covered, "armored" droplets. However, there is growing concern about the environmental impacts associated with increased global usage of micro- and nanoparticles, resulting in a desire to lessen their usage. It has been shown that particle laden bubbles with high yield stress interfaces can be stable at low surface concentrations. We wish to extend this mechanism to particle covered liquid droplets; however, creating high interfacial yield on o/w interfaces is challenging.

We build on our own previous work that demonstrated planar, o/w interfaces composed of charge bidisperse particles at low surface concentrations have larger interfacial yield stresses, viscoelastic moduli, relatively elasticity, and microstructure complexity compared to monodisperse interfaces. We than replicate bidisperse, planar, o/w particle laden interfaces onto dispersed water droplets in oil using a flow focuser microfluidic device that allows controlled delivery of bidisperse particle systems to the drop interface. Drop deformation during extensional flow and coalescence were studied. When comparing drops whose interfaces had high interfacial yield to those without, there was significant reduction in both deformation and number of coalescence events. This was observed to be true even at surface concentrations as low as 30%. In all cases, if interfacial yield was above 10-4 Pa*m, increased drop stability was observed. Such reduced deformation could significantly enhance emulsion stability and alter Pickering emulsion design.

Monday 2:50 O'Keeffe + Milagro IR11

Simulation of amphiphilicity-dependent aggregation and microstructural evolution of Janus particles at fluid interfaces

Masoumeh Pourasgharoshtebin[1], Bhaskar K C[2], Rajesh Khare[1], and Gordon F. Christopher[2]
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Pickering emulsions, which are widely utilized in healthcare, pharmaceutical, and industrial applications, are dependent on the properties of the particle laden interfaces around drops. Janus colloidal particles (JPs), characterized by their distinct surface properties on opposite faces, significantly influence self-assembly behaviors of particle fluid interfaces. Recent experimental work by the Razavi's research group [AIChE J. 2023;69:e18241], has posited that Janus particles with varying wettability on faces impact self-assembly due to altering the capillary interactions between particles to include distributions of capillary dipoles and hexapoles. Understanding these interactions is fundamental to advancing knowledge of their underlying physicochemical mechanisms. In this study, we employed computational simulations to examine the microstructural and mechanical properties of monolayers formed by particle systems with distributions of capillary hexapoles and dipoles and compared them to the experimental results of the Razavi research group. Analyzing particle local order, energy landscape, and pairwise interaction distributions, we found that simulated systems of hexapoles and dipoles in equilibrium correspond well to experimental results of Janus particles at specific surface concentrations. In addition, ongoing studies are investigating the mechanical response and structural evolution of these particle networks under externally applied compression, to find if predicted surface pressure evolution of these systems also corresponds to the experimental results of Janus particles.

Monday 3:45 O'Keeffe + Milagro IR12

Characterizing yield stress mechanisms in particle laden interfaces

KC Bhaskar[1], Simon A. Rogers[2], and Gordon F. Christopher[1]
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Particle Laden interfaces exhibit complex yielding behavior that has previously been identified but not sufficiently characterized. We use a unique combination of rheological and microstructural analysis to further investigate the yielding behavior of densely packed, particle-laden, air-water interfaces. Specifically, using a custom base with a double wall ring geometry, interfacial viscoelastic moduli were measured by extending the time resolved strain decomposition technique for bulk materials proposed by Donley et al [PNAS, 2020; 117:21945] and the microstructure was examined via tracking of interfacial particles.

Our results reveal that the G? overshoot originates from a peak in G?solid, followed by the growth of G?fluid, marking the transition from elastic energy storage to irreversible microstructural rearrangement, which has been similarly observed in bulk soft glass like materials. From particle tracking, we measure the accumulation of non-recoverable strain in the microstructure as well as the development of fractures in the interface. The accumulation of microstructural strain at the particle level is correlated to the rheometric strain, allowing us to identify the microstructural events that lead to the observed evolution of the decomposed G".

Monday 4:05 O'Keeffe + Milagro IR13

The rheology of Pickering emulsions - the effect of particle hydrophobicity

Natalie Finish Hakshur and Moshe Gottlieb
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The wide range of applications of Pickering emulsions require a fundamental understanding of their microstructure and rheological properties to enable control of their behavior during processing and properties in final use. Factors such as particle type and concentration, and volume fractions of the two liquid phases are known to directly affect the final emulsion microstructure and their rheological properties. Despite the great development achieved in the area in recent years, several questions remain unanswered regarding the microstructure of these systems, particularly under applied stress, and regarding its breakdown and recovery under shearing flows such as those encountered during processing.

In this study, water-in-oil (W/O) and oil-in-water (O/W) Pickering emulsions were prepared using surface-modified fumed silica nanoparticles with varying degrees of hydrophobicity. The effect of the different surface functionalities and the volume fraction occupied by the emulsion droplets on the properties of Pickering emulsions was systematically investigated. We used an array of rheological measurements, combined with microscopic visualization to provide insight into the mechanisms and structural features responsible for the observed rheological behavior of these emulsions. Furthermore, we examined to which extent the microstructure of these Pickering emulsions was able to rebuild following breakdown under a range of applied stress values.

We find that for the same particle concentration and similar emulsion volume fractions large differences in rheological behavior are exhibited by nanoparticles with different surface functionalities. These include order of magnitude difference in the value of the apparent yield stress, presence or absence of delayed yield, and different time scales for structure recovery.

Monday 4:25 O'Keeffe + Milagro IR14

Interfacial rheology of lung surfactants under relevant conditions

Jan Vermant[1], Maria Clara Novaes Silva[1], and Mariana Rodriguez Hakim[2]
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In this work, we explore how to best mimic the behavior of lung surfactants in the alveolar environment. To this end, we compare interfacial structures formed via spreading and adsorption, and assess interfacial rheology under dynamic conditions that mimic breathing. We study native, exogenous, and model surfactant systems, and identify exogenous replacements as effective physiological analogues. Thin film balance, shear, and dilatational rheology experiments are performed to characterize the most representative systems.

Monday 4:45 O'Keeffe + Milagro IR15

Effects of molecular architecture at liquid interfaces: Interfacial rheology and neutron reflectometry of linear, ring, and dendritic polymers

Damian Renggli[1], Benjamin Thompson[1], Jürgen Allgaier[2], Margarita Krutev[2], Dieter Richter[2], Ting-Chih Lin[3], Krzysztof Matyjaszewski[3], Dimitris Vlassopoulos[4], and Norman Wagner[1]
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Liquid-air interfaces provide confinement for insoluble polymeric networks to two-dimensional mono-molecular configuration where entanglements akin to three-dimensional (bulk) networks are not possible. In the absence of free ends, ring-shaped polymers accommodate topological constraints of their neighbors by adapting a loopy conformation that is described by the fractal loopy globule model. The loops are local double-folded segments. Dendrimers have the ability to interdigitate their dangling ends in two dimensions, and are known for their hierarchy of modes, where relaxation starts at the outermost dangling ends and moves sequentially to lower branching generations. These 'entangled' configurations will strongly influence the properties of said interfaces compared to linear polymers. A novel multimode interfacial rheometer (RheoSurfR www.stf-technologies.com) enables measurement of the isotherm as well as dilatational and shear interfacial rheology (both steady and dynamic), as well as in situ microstructural characterization by neutron reflectometry and Brewster angle microscopy. The latter enable determination of the surface excess and interfacial molecular structure, respectively. Contrast for neutron reflectometry is achieved by selective deuteration of the polymer and contrast variation of the water phase. We carefully investigate linear and ring conformations of poly(ethylene oxide) (PEO) and poly(methyl acrylate) (PMA) at varying compressions (i.e., confinement) and compare them to linear and Caley-Tree-like dendritic poly(methyl methacrylate) (PMMA). We observe strong changes in interfacial structure and hence compression isotherms (i.e., thermodynamic properties), while effects on interfacial rheology are more subtle, with dendritic PMMA having the strongest effect. The results of microstructural characterization are useful for interpreting these results. This work elucidates the effects of molecular architecture on interfacial entanglements; a concept not understood yet.

Monday 5:05 O'Keeffe + Milagro *Keynote* IR16

The life and death of far-from-equilibrium droplets

Lauren Zarzar
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Emulsions are kinetically stabilized, but thermodynamically unstable, mixtures of immiscible fluids. Far-from-equilibrium emulsion droplets have been shown to exhibit fascinating active behaviors, such as motility, self-organization, and communication. It is fundamentally important to understand how materials self-organize or evolve under dissipative conditions in synthetic systems, such as chemically minimal colloids. I will present work aimed at understanding the non-equilibrium properties of emulsions and liquid interfaces, including droplet chemotactic motions, solubilization, and partitioning, which impact emergent physical phenomena. For example, partitioning is usually defined under equilibrium conditions, but solubilizing active droplets are far from equilibrium; such droplets persist for extended times but ultimately disappear due to droplet dissolution and micellar solubilization. Consequently, equilibrium properties like oil-water partition coefficients may not accurately describe properties of out-of-equilibrium droplets. We believe that the study of such active solubilizing droplets provides a means to both uncover a chemically-tunable platform for probing active matter but also contributes to fundamental understanding of how fluid phases and interfaces behave when far from equilibrium.

Symposium BL
Biomaterials, Bio-fluid Dynamics and Biorheology

Organizers: Rae Robertson-Anderson, Travis W. Walker and Jairo Diaz

Monday 1:30 Sweeney Ballroom C BL7

Impact of integrin-ligand binding specificity on the dynamics of cell-material interactions: A rheological study of the cellular microenvironment

Faheem Hamid and Kelly Schultz
Davidson School of Chemical Engineering, Purdue University, West Lafayette, IN, United States

Synthetic hydrogel scaffolds can be designed as stem cell delivery vehicles in wound healing therapies. However, their effectiveness is limited due to low retention and poor motility of encapsulated cells post-implantation. Recent in vivo studies have shown that modulating cell adhesion by incorporating integrin (cell receptor)-specific ligands in hydrogels enhances the survival and engraftment of encapsulated cells, which improves reparative activities. In this study, we investigate how integrin-specific ligands tethered into a 3D poly(ethylene glycol)-norbornene (PEG-N) hydrogel change encapsulated human mesenchymal stem cells (hMSCs) adhesion, motility and cell-mediated material remodeling. The hydrogel scaffold used to encapsulate hMSCs is composed of 4-arm PEG-N cross-linked with a matrix metalloprotease (MMP)-degradable peptide by thiol-ene photopolymerization after exposure to UV light. We use multiple particle tracking microrheology (MPT), which captures the Brownian motion of fluorescent probe particles embedded in hydrogels using video microscopy, to quantify hMSC-mediated pericellular degradation and cell motility in different integrin-specific hydrogels. Initial storage modulus (G') of PEG-N hydrogels without hMSCs have no significant differences ($p>0.85$) regardless of the ligand tethered into the network. Cells encapsulated in fibronectin-derived RGD-tethered hydrogels begin remodeling the pericellular region 6 days post-encapsulation. The microenvironment of cells encapsulated in collagen-derived GFOGER-tethered hydrogels transition from a gel to a sol 8 days post-encapsulation. The quicker material degradation in RGD- compared to GFOGER-tethered hydrogels is attributed to distinct receptor-ligand interactions that result in increased MMP production. Our work determines how specific ligand-receptor interactions change cell-mediated pericellular remodeling, which can be used to tune dynamic hydrogel properties to enhance cell survival and migration in implantable hydrogels.

Monday 1:50 Sweeney Ballroom C BL8

Spatiotemporal mapping of dynamics and viscoelasticity in ligase-fueled DNA fluids

Ashlee D. McGovern, Emma Riggle, Dimitra Protopapas, Kaden Chang, Aysan Razzaghi, Ryan J. McGorty, and Rae M. Robertson-Anderson
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Naturally occurring ligase enzymes catalyze the formation of phosphodiester bonds between strands of deoxyribonucleic acid (DNA), playing a critical role in cellular replication and repair to maintain genomic integrity. In this work, we harness ligase activity to drive linear DNA solutions out of equilibrium. By leveraging real-time ligation of DNA, we dynamically alter chain length distributions within the solution, increasing both polydispersity and entanglement density. These molecular-level changes give rise to time-varying viscoelastic behavior and macromolecular diffusivity, which we characterize using epifluorescence microscopy, differential dynamic microscopy (DDM), and holographic optical tweezers (HOT) microrheology. This approach allows us to spatiotemporally resolve transport and rheological properties across decades of length and timescales during ligase activity. We investigate the role of DNA length and topology, as well as ligase concentration, on the time-varying rheological properties, focusing on the poorly understood crossover regime between semidilute unentangled to entangled polymer dynamics. Our findings demonstrate that in situ ligation can be used to precisely and tunably modulate the rheology of DNA-based materials in real-time. Incorporating photoresponsive ATP and photopatterning further equips this platform with responsiveness and switchability. Establishing spatiotemporally resolved composition-rheology relationships of ligase-fueled DNA fluids paves the way for the design of programmable active biofluids that can reconfigure, respond and self-heal for applications from wound-healing and tissue engineering to self-repairing infrastructure and mineral sequestration.

Monday 2:10 Sweeney Ballroom C BL9

Heterogeneity in red blood cell mechanics drives altered blood rheology in sickle cell disease

Hannah M. Szafraniec[1], Freya Bull[2], John Higgins[3], Howard A. Stone[4], Timm Krueger[5], and Dave K. Wood[6]
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In sickle cell disease (SCD), polymerization of hemoglobin under deoxygenated conditions causes red blood cells (RBCs) to stiffen, resulting in aberrant blood flow. At the continuum level, deoxygenated blood in SCD exhibits increased shear-thinning and wall friction, but it is not understood how the distribution of RBC properties contributes to whole-blood rheology. Therefore, we developed a novel microfluidic platform to probe the effect of oxygen-dependent RBC stiffness and volume fraction on the rheological properties of blood from patients with SCD. Using high-throughput single-cell measurements, we established that oxygen-dependent changes in red blood cell mechanics are highly heterogeneous. In parallel, we measured the effective rheology of the blood from spatially resolved flow fields and found that increases in effective resistances in

heterogeneous suspensions were driven by increases in the proportion of stiff cells, similar macroscopically to the behavior of rigid-particle suspensions. To explore mechanisms leading to the emergent rheology, we developed a computational model to simulate confined flow of heterogeneous mixtures of cells. This allowed us to probe the dynamics of the cells and measure the impact on rheology, which we confirmed experimentally. In the presence of deformable cells, the stiffened cells marginate towards channel walls, increasing effective wall friction. In fully deoxygenated conditions in which all cells are stiffened, significant heterogeneity in cell volume fraction along the direction of flow caused localized jamming, drastically increasing effective viscous flow resistance. Overall, our study directly links single cell properties to blood dynamics in microchannels across individual donors and establishes mechanisms for the apparent rheology of heterogeneous mixtures.

Monday 2:30 Sweeney Ballroom C BL10

Single cells are compactly and accurately described as Fractional Kelvin-Voigt Materials

Mohua Das[1], Jarno L. Waeterloos[2], Christian Clasen[2], and Gareth H. McKinley[1]

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The mechanobiology of single cells plays a crucial role in various biological processes, including embryonic development, cancer treatment, and wound healing. We show that the rheological response of single cells can be well described by the fractional Kelvin-Voigt model (FKVM) - a linear constitutive model consisting of two Scott Blair mechanical elements arranged in parallel. Unlike traditional power law models, which primarily fit the key features of the mechanical response at long timescales, the FKVM captures both short- and long-timescale mechanical responses with a minimal number of constitutive parameters. We use the Bayesian Information Criterion (BIC) to demonstrate the parsimony of the FKVM description and its credibility compared to other proposed models. As a complete (linear) constitutive formulation the FKV model also enables prediction of the rheological response of cells in other modes of deformation. Experimental small-amplitude oscillatory shear (SAOS) data for dividing canine kidney cells, creep data of human K562 erythroleukemic cells, and creep-recovery data of blastomere cytoplasm are all analyzed to showcase the accuracy and versatility of the FKVM. Additionally, for the first time, the continuous relaxation and retardation spectra corresponding to the fractional differential formulation of the FKVM are derived, and a number of special limiting cases are considered. The results establish a comprehensive framework for predictive analysis of single-cell rheology in both the time and frequency domains.

Monday 2:50 Sweeney Ballroom C BL11

How do crosslink dynamics alter the yielding transition and injectability of dynamic hydrogels?

Noah Eckman[1] and Eric Appel[2]

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Materials utilizing supramolecular assembly offer distinct advantages in applications requiring injection or extrusion, arising from the lack of permanent covalent crosslinks in favor of those which can dynamically rearrange. Dynamic materials may be used to directly deliver therapeutic cells and biologic drugs which are sensitive to the localized shear stress and inhomogeneities in the flow, highlighting the need for better characterization of the physics of capillary flow for these set of materials. A suite of rheological and mechanical testing tools exists to probe the linear and low-shear rate behavior, but unexpected behaviors may emerge at high shear rates, such as shear banding and wall-slip, even at low Reynolds number.

In this talk, I will utilize different dynamic hydrogel systems with hydrophobically-driven associations, ionic interactions, and dynamic covalent bonds in order to understand a spectrum of crosslink strength and material chemistry. By using LAOS experiments to determine the time-varying yielding transition, I will show that the yielding process of the dynamic hydrogels cannot be defined by a single yield stress value and is more accurately described by a range and velocity of yielding. Critically, I will connect the speed of yielding to cell viability measurements during high-shear rate injections in these materials.

I will then demonstrate the use of capillary flow rheology to explain non-monotonic trends in injection force with regards to crosslink dynamicity of a novel dynamic hydrogel system. By connecting measurements including rheometry, viscometry, and an in situ capillary microscope optical rheometer, we find that strong wall slip dominates the flow profile at high shear rate, leading to unexpectedly low injection forces, and nonuniform trends in injection force with respect to crosslink dynamics. Finally, we give new criteria for extrudability and injection force based on a rheological model which accounts for power law shear-thinning and wall slip.

Monday 3:45 Sweeney Ballroom C BL12

Mechanical phase transitions in articular cartilage

Itai Cohen[1], Lawrence Bonassar[2], Moumita Das[3], and Japheth Omonira[1]

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Articular cartilage is a remarkable material able to sustain millions of loading cycles over decades of use outperforming any synthetic substitute. Crucially, how extracellular matrix constituents determine mechanical performance, particularly in shear, remains poorly understood. Here, I will describe experiments and theory in support of a rigidity percolation framework that quantitatively describes the structural origins of cartilage's shear properties and how they arise from the mechanical interdependence of the collagen and aggrecan networks making up its extracellular matrix. This framework explains that near the cartilage surface, where the collagen network is sparse and close to the rigidity threshold, slight changes in the aggrecan concentrations, and therefore the rigidity of the secondary network, can dramatically alter the tissue modulus. Our results

suggest that cartilage is an actively tuned tissue where cells can change the modulus by modifying the production of the aggrecan molecules. More broadly, this framework provides a map for understanding how changes in composition throughout the tissue alter its shear properties and ultimate in vivo function.

Monday 4:05 Sweeney Ballroom C BL13

Non-equilibrium micromechanics of photo-responsive biopolymer composites

Rae M. Robertson-Anderson

Physics and Biophysics, University of San Diego, San Diego, CA 92110, United States

Active dynamics and out-of-equilibrium reconfigurability, at the heart of diverse biological processes, are widely studied across disciplines in efforts to infuse such properties into next-generation autonomous materials, and to understand the physics underlying living systems that are far from equilibrium. I will discuss our bio-inspired approaches to introduce non-equilibrium rheological properties, active dynamics and restructuring into biopolymer composites. Examples include using photo-activated crosslinking and ligation to spatiotemporally control gelation of DNA fluids, and using cyanobacteria cells to sculpt the structure and rheology of cytoskeleton scaffolds. I will also highlight some of the novel microrheology methods that we have developed to characterize the heterogeneous time-varying rheological and dynamical properties of these 'living' materials.

Monday 4:25 Sweeney Ballroom C BL14

Emergent stress transmission in active cytoskeleton composites

Aysan Razzaghi[1], Megan T. Valentine[1], Ryan J. McGorty[2], and Rae M. Robertson-Anderson[1]

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The cytoskeleton provides structural integrity to the cell and plays a critical role in regulating essential mechanical processes such as stiffening and softening, intracellular transport, and morphogenesis. To gain an understanding of the mechanical properties of the cytoskeleton, we prepare in vitro reconstituted cytoskeletal composites which consist of co-polymerized actin filaments and tubulin dimers along with motor proteins such as kinesin, which bind to and move along microtubules thereby inducing active contractile behavior. These active cytoskeletal composites (ACCs) have been shown to exhibit pronounced spatiotemporal heterogeneity, not only in their microstructure but also in their mechanical responses due in part to their viscoelasticity and the excess stresses generated by active contractions. To characterize the complex spatiotemporal response of ACCs to applied stress, we combine nonlinear micro-rheology and time-resolved differential dynamic microscopy (DDM). To apply perturbations, we employ holographic optical tweezers to oscillate a single or a pair of particles that can produce well controlled stress fields within the sample that locally approximate pure shear, simple shear, or compressional and extensional stress. Our findings reveal that while increasing the concentration of kinesin motors up to a certain threshold enhances local stress generation, it simultaneously leads to shorter-range stress propagation. Our powerful approach allows for the discovery of emergent rheological properties of ACCs that were found to directly be linked to the transport across cells membrane. Further, our method can be implemented to investigate other active matter with exquisite sensitivity across a broad range of length and time scales.

Monday 4:45 Sweeney Ballroom C *Keynote* BL15

In situ rheological monitoring of diffusion-driven bioink crosslinking in embedded 3D bioprinting

Audrey Shih[1], Stella J. Chung[1], Fotis Christakopoulos[2], Lucia G. Brunel[1], Noah Eckman[1], Yueming Liu[2], Junyi Tao[3], Sarah C. Heilshorn[2], and Gerald G. Fuller[1]

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In embedded 3D bioprinting, hydrogel bioinks are extruded into sacrificial support baths, where the diffusion of small molecules into or out of the support bath facilitates bioink crosslinking before its removal from the support bath. Despite the importance of tuning the mechanical properties of these bioinks to form stable tissues and organoids, there are currently no methods to predict bioink stiffness over time throughout the crosslinking process. Here, we use a custom-developed magnetic stress rheometer adapted for dual-layered bioink-support bath systems to continuously monitor diffusion-driven crosslinking in situ. Our approach reveals how gelation kinetics depend on the thickness of the bioink layer, and enables predictive modeling of mechanical evolution in these reaction-diffusion systems. These insights help inform the design of bioinks and timing of bioprinting protocols for tissue engineering applications.

Monday 5:05 Sweeney Ballroom C BL16

Investigation of shear and extensional rheology of silk fibroin in applications of tissue engineering

Laura Brunmaier and Travis Walker

Department of Chemical and Biological Engineering, South Dakota School of Mines & Technology, Rapid City, SD 57701, United States

Elastin is a critical component of vascular tissue, enabling dynamic expansion and recoil during the cardiac cycle. However, due to its limited availability and difficulty in extraction, elastin poses significant challenges for use in tissue engineering applications. Silk fibroin (SF), an elastic protein derived from silkworm cocoons, offers a promising alternative due to its excellent mechanical properties, tunable processing behavior,

and biocompatibility. Once extracted and purified, SF is transformed into a regenerated silk fibroin (rSF) solution; however, this solution can be unstable in aqueous environments, complicating downstream processing. The goal of this research is to develop a reliable and predictable method for extracting and processing rSF by characterizing its behavior at each stage of preparation. Rheological analysis plays a central role in this work. Shear rheology is employed to evaluate the viscoelastic properties of the rSF solution prior to processing, providing insight into its suitability for dip-coating. Tubes fabricated from the rSF solution are then characterized via burst pressure and compliance testing to assess their mechanical performance. To broaden the processing potential of rSF beyond dip-coating, extensional rheology is also performed to evaluate its processability for electrospinning. This technique is particularly sensitive to the molecular entanglements and extensional viscosity critical for fiber formation. By combining shear and extensional rheology, this research establishes a comprehensive framework for linking polymer solution properties to processability and final mechanical outcomes, ultimately guiding the selection of appropriate fabrication techniques for vascular tissue engineering.

Symposium FI
Flow-Induced Instabilities and Non-Newtonian Fluids

Organizers: Hadi Mohammadigoushki, Fardin Khabaz and Chenxian Xu

Monday 1:30 Sweeney Ballroom D FI7

Elastic turbulence and shear banding in entangled polymers and wormlike micelles

Theo Lewy[1], Suzanne M. Fielding[2], Peter D. Olmsted[3], and Rich R. Kerswell[1]
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Highly entangled polymer solutions and wormlike micelles are known to support instabilities in rectilinear geometries. We identify 2D elastic turbulence (ET) in both shear thinning and shear banding theologies using two numerical models, the Johnson-Segalman and the Rolie-Poly fluid. Both models sustain ET in planar Couette flow (pCf) and planar Poiseuille flow (pPf), both of which are devoid of curvature in their base states. We find a route to this turbulence via a shear thinning linear instability. Within pCf, the ET consists of a number of narrow shear bands with 2D structure that coalesce, split and interact with each other, with the complexity of the state growing with Weissenberg number Wi. Our results suggest that the shear banding plateau seen in experiments on wormlike micelles may be due to this 2D ET state within the high shear branch.

Monday 1:50 Sweeney Ballroom D FI8

Rheo-NMR of shear banding wormlike micelles

Alfredo Scigliani, Hadi Mohammadigoushki, and Samuel C. Grant
Chemical and Biomedical Engineering, Florida State University, Tallahassee, FL 32304, United States

Shear banding is a phenomenon in which distinct bands with different local shear rates form under the same applied shear stress. These discontinuities in velocity gradients have been extensively studied in wormlike micellar solutions (WLMs), which serve as model systems for understanding complex fluid behavior. A long-standing hypothesis suggests that shear banding in WLMs arises from flow-induced micellar chain scission, but direct experimental evidence supporting or refuting this mechanism has been limited. In this study, we employ a spatiotemporally resolved Rheo-DOSY-NMR approach, complemented by rheo-optical techniques, to investigate shear banding in CPyCl/NaSal WLMs in a Taylor-Couette (TC) flow. To test the micellar breakage hypothesis, we first measure the self-diffusivity of surfactants in quiescent micellar solutions and confirm that as micelle length increases, diffusivity decreases, finding a correlation between micellar length and diffusivity. We then conduct spatially resolved diffusivity measurements under shear across the TC cell gap over a wide range of imposed Weissenberg numbers, both below the onset of shear banding and within the stress plateau regime. Our results reveal that self-diffusivity remains unchanged across the shear-banded state, with no distinct differences between the high and low shear bands. This finding suggests that micellar length remains constant during shear banding flows. Additionally, we developed a rheo-qNMR technique to probe shear-induced concentration coupling in shear banding WLMs. By comparing concentration profiles across the high and low shear bands within the stress plateau regime, we assess whether coexisting bands exhibit compositional differences.

Monday 2:10 Sweeney Ballroom D FI9

Unraveling the dynamics of polymer scission in porous media

R. Craig Singiser and Sujit S. Datta
California Institute of Technology, Pasadena, CA 91125, United States

The flow of polymer solutions in porous media has tremendous utility for subsurface energy operations, water remediation, and packed bed reactors. The tortuous geometry of the pore space generates velocity gradients that, when sufficiently strong, cause polymers to undergo a coil-stretch transition where the polymer coils begin to extend. While this process has been studied in simplified geometries, how it manifests in more complex porous media is not well understood. It is crucial to understand what drives this process as fully extended polymers are subject to break, resulting in two lower molecular weight polymers. Continued degradation of polymer solutions ultimately reduces their efficacy. Here, we use pressure drop measurements of polymer solutions flowing through porous media to characterize the extent of scission during this process. We present a universal curve of scission that shows the generality of this process across various flow rates, pore sizes, polymer concentrations and

molecular weights. Improving our understanding of polymer scission will provide fundamental insights in complex fluid dynamics and will provide quantitative guidelines for the use of polymer solutions in the aforementioned applications.

Monday 2:30 Sweeney Ballroom D FI10

Finite-time blow-up: The importance of (and approximations for) marginal chain stretching effects

Joseph D. Peterson, Vickie Chen, and Charles T. Drucker
Department of Chemical and Biomolecular Engineering, University of Los Angeles, California, Los Angeles, CA 90024, United States

Highly entangled polymer melts will typically relax their orientation much more slowly than they relax their stretch. In such cases, it is often reasonable and convenient to approximate entangled polymer material as "non-stretching", provided strain rates everywhere in the flow domain remain small relative to the typical stretch relaxation rate. Unfortunately, for complex flows of strongly shear thinning viscoelastic materials one cannot always presuppose the validity of such a condition: even if a suitable steady state exists, transients may not! In this talk, we will share examples of Wi ~ O(1) flows that yield predictions of infinite shear rates in finite time when the effects of chain stretching are ignored. A perturbation expansion re-introduces the effects of marginal chain stretching and successfully suppresses the finite-time blowup pathology. Simulation results and some aspects of the perturbation model derivation will be discussed.

Monday 2:50 Sweeney Ballroom D FI11

Large amplitude oscillatory extension (LAOE) of complex fluids

Steffen M. Recktenwald[1], Thomas P. John[2], Robert J. Poole[3], Amy Q. Shen[1], Claudio P. Fonte[2], and Simon J. Haward[1]
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Complex fluids such as polymer melts and solutions, biological fluids, and food products often experience large and rapid deformations in practical applications and processing environments. Quantifying the nonlinear rheological properties of such fluids is therefore critical for predicting their behavior and optimizing their processing. With this aim, Large Amplitude Oscillatory Shear (LAOS) tests are used to obtain rheological fingerprints of soft materials undergoing nonlinear shear deformations. However, although in many industrial applications (e.g., fiber spinning, ink-jet printing, blow molding) the flow can be extension-dominated, the potential for elucidating the nonlinear rheological properties of complex fluids under oscillatory extensional flows remains largely unexplored. In this study we introduce a novel experimental method to investigate fluid responses to Large Amplitude Oscillatory Extension (LAOE). We use a microfluidic Optimized Shape Cross-slot Extensional Rheometer (OSCER) device to generate a homogeneous planar extensional flow driven by programmable syringe pumps operating in either oscillating or pulsatile sinusoidal modes. The applied time-dependent flow field within the OSCER is confirmed using micro-particle image velocimetry and the elastic stress response of the fluids is assessed from either the simultaneous pressure drop or the flow-induced birefringence, depending on the sample. We examine the time-dependent flow behavior of viscoelastic dilute polymeric solutions and rod-like colloidal systems under LAOE across a broad range of Weissenberg and Deborah numbers and compare our experimental results with numerical predictions. This investigation leads to a potentially promising new methodology for characterizing complex fluids under nonlinear extensional flow conditions.

Monday 3:45 Sweeney Ballroom D FI12

Recent advances in polymer viscoelasticity from general rigid bead-rod theory

Alan Jeffrey Giacomin
Mechanical Engineering, University of Nevada, Reno, Reno, NV, United States

One good way to explain the elasticity of a polymeric liquid, is to just consider the orientation distribution of the macromolecules. When exploring how macromolecular architecture affects the elasticity of a polymeric liquid, we find general rigid bead-rod theory to be both versatile and accurate. This theory sculpts macromolecules using beads and rods. Whereas beads represent points of Stokes flow resistances, the rods represent rigid separations. In this way, how the shape of the macromolecule affects its rheological behavior in suspension is determined. Our work shows the recent advances in polymer viscoelasticity using general rigid bead-rod theory, including the discovery of the first new materials functions from general bead-rod theory since the first, the complex viscosity of Hassager (1974). These include the steady shear material functions, large-amplitude oscillatory shear flow material functions, and the steady uniaxial, biaxial and planar extensional viscosities. We find each of these material functions to depend upon the same molecular feature: the ratio of the macromolecular moment of inertia about the molecular axis to that about the axes transverse to the molecular axis. We then use these new material functions to bridge the Oldroyd 8-constant framework (and thus all of its many special cases) to general bead-rod theory.

Monday 4:05 Sweeney Ballroom D FI13

The influence of fluid elasticity on the flow-induced response of a flexibly-mounted square prism

Han Gong, Umang N. Patel, Jonathan P. Rothstein, and Yahya Modarres-Sadeghi
Department of Mechanical and Industrial Engineering, University of Massachusetts Amherst, Amherst, MA 01003, United States

We numerically investigate how fluid elasticity can affect a canonical fluid-structure interaction (FSI) system. The system of choice is a flexibly mounted rigid square prism placed in viscoelastic fluid flow, with one degree-of-freedom in the cross-flow direction. The FENE-P (Finitely-Extensible Nonlinear Elastic) constitutive model is applied to solve for the polymeric stress field, while a two-way coupling scheme is implemented to accurately simulate the interaction between the fluid flow and the spring-mass system. We test square prisms with two very distinct mass ratios

m^*=2 & 20 under various reduced velocities U^*=3~45 at a Reynolds number of *Re*=200. For viscoelastic cases, we set our fluid to have a viscous ratio β=0.9, and the Weissenberg number is controlled to be *Wi*=2, which then yields an elastic number of *El*=0.01. We show that even a small amount of fluid elasticity can affect the flow-induced instabilities significantly. Through the simulations, we observe a substantial enhancement of galloping response on the prism in viscoelastic fluid compared to Newtonian fluid, especially for the small mass ratio case, where the critical reduced velocity for galloping decreases dramatically and the oscillation amplitude increases. Our results also show a suppression in vortex induced vibration (VIV) in viscoelastic fluid versus Newtonian fluid. We also propose some potential mechanisms that lead to these phenomena based on visualizations of the flow field and analysis of flow forces.

Monday 4:25 Sweeney Ballroom D FI14

Is there a relationship between the EOR polymer solutions' mechanical degradation and rheological properties?

Madhar Sahib Azad and Dhafer Al Shehri
Petroleum Engineering, King Fahd University of Petroleum and Minerals, Dhahran, Saudi Arabia

Polymer flooding is one of the most applied enhanced oil recovery (EOR) methods. During polymer flooding, the polymer powders are added to the injection water to make more viscous, thereby it retards the flow and thereby can contribute to the better sweep efficiency. For the same injection, the velocity of the polymer solutions around the wellbore will be highest and lower as the injection fluid gets exposed to a larger area of the reservoir. It is vital to maintain the viscosity of the injected polymer solutions, especially at lower velocities. However, there is a phenomenon called mechanical degradation that happens around the injection well where the velocity is higher. In this presentation, we compile the reported mechanical degradation of EOR polymer solutions with varying salinity concentration. The rheology of the used polymer solutions will be evaluated for its viscosity, linear relaxation time, and non-linear relaxation time to examine which aspect of rheology influences the mechanical degradation. It was found that the mechanical degradation of EOR polymer solutions has a direct relation with non-linear relaxation time.

Monday 4:45 Sweeney Ballroom D FI15

Holey sheet: Destabilizing fluids under extreme stress

Michelle Driscoll[1], Carly Galvin[1], Brendan Blackwell[2], and Sam Nielsen[3]
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The complex flow behavior of non-Newtonian fluids is linked to the arrangement of mesoscale structure (e.g. particles, emulsions, polymers, micelles) within the fluid. A large suite of tools and techniques have been employed to understand this structure, and quantitatively link structural changes to flow properties. However, all tools have limitations, and obtaining measurements at large stresses and a high density of additives remains a challenge. Here, I will demonstrate a complimentary technique: visualization of fluid destabilization in free-surface flows geometries. Looking at how fluids destabilize in falling drops, expanding sheets, and other geometries allows access to high stresses in boundary-free conditions, and offers a unique window into the mesoscale structure in non-Newtonian fluids. Here, I will present a novel technique for probing the mesostructure of a microgel (Carbopol) which employs high-speed imaging to visualize the destabilization of expanding liquid sheets. Newtonian fluid sheets are well-characterized, with breakup regimes set by the material properties such as surface tension and viscosity. Our findings show that complex fluids instead fragment when the sheet thins to the length scale of the mesosctructure present in the fluid. We find that the sheet breaks apart when it thins to a critical thickness, set by the scale of microgel aggregates in the complex fluid, and this critical thickness is independent of both jet velocity and the initial thickness at the stagnation point. Moreover, at high polymer concentrations, we find the sheet breakup thickness is independent of concentration, providing new evidence that the underlying mesoscopic structure is a space-filling network of jammed particles.

Monday 5:05 Sweeney Ballroom D FI16

Pressure drop in a deformable channel distinguishes Newtonian from Boger fluids

SungGyu Chun[1], Ivan C. Christov[2], and Jie Feng[1]
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We provide a comprehensive experimental-theoretical framework for analyzing the steady flow-induced deformation caused by an incompressible fluid flow in a deformable three-dimensional (3D) channel. We focus on how the flow-induced deformation reduces the pressure drop (for a fixed flow rate) as a function of wall compliance and fluid viscoelasticity. From the theory of Boyko & Christov (J. Non-Newton. Fluid Mech. 313, 104990, 2023), based on the Oldroyd-B model, we calculate the pressure drop of a steady weakly viscoelastic flow (small Deborah number) of a constant-shear-viscosity (i.e., Boger) fluid in a deformable channel. Building on the experimental platform of Chun et al. (Phys. Rev. Fluids 9, 043302, 2024), we measure the pressure drop for a solution of 300 ppm PAA into 10 wt% DI water (Boger fluid), as well as a viscosity-matched solution of 92.1 wt% glycerol into DI water (Newtonian fluid), over a range of Deborah numbers from ~0.01 up to ~0.1, finding good agreement between theory and experiment. Importantly, to ensure a proper comparison and cross-validation between theory and experiment, we perform independent rheological characterization of all fluids used (as well as elastic and geometric quantities). We also conduct experiments in an equivalent rigid channel, showing that both the Boger fluid and a viscosity-matched Newtonian fluid have the same pressure drop. Thus, the pressure drop in a deformable channel distinguishes Newtonian from Boger fluids, offering new ideas for microrheometry.

Tuesday Morning

Symposium PL
Plenary Lectures

Bingham Lecture

Tuesday 8:30 Sweeney Ballroom E+F PL2

Rheology magic

Antony N. Beris
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In a series of three stories referring to three different rheology investigations I will offer common elements and patterns as emerged from three different experiences with rheology studies that have persisted and are still on-going throughout my 40+ research career.

Starting with viscoplasticity and the analysis of the Bingham fluid flow around a falling sphere, I will outline its evolution to thixotropy with the development of one of the first structural models, leading more recently to the development of elastoviscoplastic and multiscale models with special application to blood rheology.

Second, with viscoelasticity, starting from the simulation and perturbation analysis of the flow between eccentric rotating cylinders, extended to the flow through undulating tubes, continued to the study of elastic instabilities to Taylor-Couette flow with the identification of three-dimensional critical instabilities, leading to the simulation of drag reduction in turbulent flows, I will outline most recent results obtained through the use of lubrication theory for flow through confined geometries.

The final tour starts with the modeling of the flow of polymeric liquid crystals, that led to the development of a systematic theory for modeling of material flows though non-equilibrium thermodynamics, eventually enabling complex flow applications such as the modeling of the flow of rod-like micelles, emulsions with most recently a significant extension involving the inclusion of microinertia effects.

The contributions of a significant number of collaborators consisting of undergraduate and graduate students, postdoctoral researchers and colleagues will be duly acknowledged.

Symposium CS
Colloidal Suspensions and Granular Materials

Organizers: James Gilchrist, Abhinendra Singh and Shravan Pradeep

Tuesday 9:50 Sweeney Ballroom A *Keynote* CS18

Non-simple flow geometries and granular rheology

Joel Clemmer[1], Ishan Srivastava[2], Gary S. Grest[1], and Jeremy B. Lechman[1]
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Whether through Couette cells in a laboratory or Lees-Edwards boundary conditions on a computer, simple shear is omnipresent in studies of granular, and non-granular, rheology. However, many essential industrial processes involve alternative geometries, flowing grains through a conical funnel or pressing powder into a die. These changes in the type of flow, often quantified in terms of a Lode angle, have a nontrivial impact on rheology yet are often overlooked. Here, we will illustrate this effect from discrete element method simulations, using both abstract periodic flows as well as experimentally-achievable geometries, and dissect how the rheology varies across strain rate, Lode angle, as well as material properties. Simulations result will also be related to new analytical models in the literature and connections will be drawn to the rheology of other non-granular systems.

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Tuesday 10:10 Sweeney Ballroom A CS19

Exploring effects of cohesive particles localization on μ(I)-rheology of highly polydisperse granular materials using GPU-accelerated DEM

Simon Yans, Michel Henry, Jonathan Lambrechts, and Vincent Legat
Institute of Mechanics, Materials and Civil Engineering, UCLouvain, Louvain-la-Neuve, Belgium

Contemporary industrial processes such as food processing, pharmaceutical production and battery electrode fabrication increasingly rely on the precise handling of particulate materials. These processes involve complex dense granular flows whose macroscopic behavior is notably dictated by interparticle interactions, size heterogeneity, and applied shear. The rheology of dry granular flows -particularly for monodisperse and small polydisperse assemblies and simple cohesive models- has been extensively characterized within the μ(I)-rheology over the past decades. In some cases, powder mixtures may exhibit high polydispersity ratios, and the introduction of fine cohesive agents or moisture can further complicates their flow behavior. The latter factors are known to have significant impact on bulk material response and processability by modifying microscopical interactions. Numerical simulations using the Discrete Element Method (DEM) provide a powerful tool for assessing the effects at the local scale on bulk rheology. In DEM, cohesive forces are classically represented through discrete force laws (capillary bridges, beam models). In this study, we present a GPU-accelerated DEM approach in which the cohesive agent is represented explicitly as a population of fine cohesive particles embedded among larger, inert grains. We perform simple shear simulations of highly polydisperse assemblies containing 0-10% vol. cohesive particles, spanning inertial numbers I = 10?4-10?¹ under controlled confining pressures. The effects of cohesive particle clustering and polydispersity on flow topology, shear resistance and compacity are assessed, and related to μ(I)-rheology.

Tuesday 10:30 Sweeney Ballroom A CS20

Shear reversal in dense frictional suspensions: A micromechanical description connecting microscopic physics with macroscopic physics via mesoscale frictional network

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Dense suspensions-dispersions of small particles in a Newtonian solvent-are ubiquitous in both natural and industrial settings. The interplay of surface interactions and particle properties such as size, roughness, interfacial chemistry, and shape gives rise to complex non-Newtonian behaviors, including yielding, shear-thinning, shear-thickening, and jamming. Recent studies have identified shear-thickening as a transition from a lubricated, unconstrained state to a frictionally constrained one. In this work, we employ discrete element method (DEM) simulations to investigate inertialess, buoyant particles in a Newtonian solvent, incorporating lubrication forces. We focus on shear reversal under fixed shear stress to isolate the roles of hydrodynamic and frictional interactions. We demonstrate that the dimensionless viscosity, defined as the ratio of the minimum to the steady-state viscosity, serves as a key metric for distinguishing between hydrodynamic and contact-dominated regimes. Remarkably, this ratio collapses onto a universal curve when the packing fraction is scaled by a stress-dependent jamming threshold. To probe the microscale, we analyze the frictional coordination number. Far from jamming, frictional contacts are transient; however, as jamming is approached through increasing stress or packing fraction, even 75% of contacts persist after reversal. At the mesoscale, network analysis reveals that third-order loops exhibit the strongest correlation with viscosity, even during transient states. This study presents a comprehensive multiscale framework for dense suspensions, linking microscale contact mechanics, mesoscale network topology, and macroscale rheology.

Tuesday 10:50 Sweeney Ballroom A CS21

Characterization of granular rheology using LAOS in Couette chute flow

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This experimental study explores the rheological transition between quasi-static and dense-inertial granular flows. The analysis combines Fourier Transform (FT) rheology, used previously for complex fluids, with inertial number scaling used for granular flows. We developed a concentric cylinder rheometer instrumented with multiple sensors for mass holdup, shear rate, torque, wall stress, and continuous flow rate, where the discharge flow is in the direction of the second normal stress. Oscillatory shear experiments were done over a range of amplitudes, collecting cyclic data that were explored using FT analyses of Lissajous-Bowditch plots. Self-intersection (i.e., crossover) was detected in the elastic part of the of the stress/strain-rate response, correlating with inertial number thresholds for transition between quasi-static and dense-inertial flows. Secondary crossovers within the quasi-static domain suggest elastic hysteresis in force chains affecting the friction-like response. Anticipated applications include boundary layer shear flows including thin-layer spreading for additive manufacturing.

Tuesday 11:10 Sweeney Ballroom A CS22

Unifying granular intrusion dynamics for space exploration applications

John G. Ruck[1], Shravan Pradeep[1], John Bush[2], Eric D. Sigg[3], Feifei Qian[4], and Douglas J. Jerolmack[1]
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Understanding the rheology of granular materials like planetary regolith is paramount for exploration success. We address the poorly understood link between granular friction and packing fraction, focusing on behaviors below and above the critical volume fraction that distinguishes compaction from dilation. Using quasi-static penetration tests using robotic legs on materials from uniform glass beads to complex lunar regolith simulant, we demonstrate that for non-cohesive media, changes in friction relative to the distance from this critical threshold can be described by a unifying master curve. This observation lends new support to the idea of a phase transition at the critical volume fraction. Furthermore, the introduction of cohesive dust, pertinent to lunar regolith, starkly differentiates the two regimes: while minimally affecting sub-critical behavior, it dramatically increases penetration resistance in the dilative state. Our results provide a refined understanding with practical implications for predicting regolith resistance, aiding the exploration and manipulation of granular materials on planetary bodies and Earth.

Symposium GN
Self-assemblies, Gels and Networks

Organizers: Thibaut Divoux, Katie Weigandt and Ria Corder

Tuesday 9:50 Sweeney Ballroom B GN18

Linear and non-linear rheology of Pluronic F127 self-assemblies in ionic liquid and water mixtures

Seyed Mostafa Tabatabaei and Reza Foudazi
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Water has been conventionally used as a solvent for self-assembly of Pluronic surfactants to form lyotropic Liquid Crystals (LLCs) with mesomorphic structures in the range of 2-50 nm. Ionic liquids (ILs) can also result in self-assembled structures with higher dynamic moduli than that of water due to their higher viscosity. The obtained ionogels can be used to produce sensors and electrolytes, and to control and retain the structure for templating applications. Ethylammonium nitrate (EAN) IL has been extensively used for self-assembly of Pluronics. Both F127/EAN and F127/water systems show sol-gel transition (i.e., disorder-ordered cubic transition). It has been shown that adding EAN to water can facilitate micellization and self-assembly of Pluronic block copolymers. In this work, the rheological behavior of Pluronic F127 mesophases is investigated in water and EAN mixtures. At low temperatures, samples show Newtonian behavior in the sol state, while elastoviscoplastic behavior is observed at high temperatures. LLCs show yield stress, shear banding, and Type III nonlinear behavior. Structural changes are studied using small angle x-ray scattering to analyze the effect of solvent mixture on rheological behavior.

Tuesday 10:10 Sweeney Ballroom B GN19

Thermodynamic origins of irreversible morphology transitions caused by flow-equilibration cycles in amphiphilic solutions

Senyuan Liu and Radhakrishna Sureshkumar
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Flow-induced morphology evolution in amphiphilic solutions is accompanied by the deformation, fragmentation, and reorganization of molecular assemblies. Shape deformation alters the energetic (e.g., interfacial area between the solvent and the solvophilic/solvophobic polymer blocks) and entropic (e.g., copolymer chain configuration) contributions to the system's free energy. Hence, equilibration of the deformed morphology after flow cessation could return the system to a state that minimizes the free energy in its local environment rather than to the initial (parent) structure. Such permanent or persistent equilibrated flow-induced morphologies have been shown to manifest in experiments in wormlike surfactant micelle solutions (Vasudevan et al., Nature Materials, 9, 436 (2010); Frounfelker et al., Langmuir, 25, 167 (2009)). However, computational discovery and analysis of this phenomenon in self-assembled amphiphiles in solution have been lacking. We perform molecular dynamics simulations to investigate morphology evolution of a unilamellar triblock copolymer vesicle subjected to startup and cessation of uniform shear flow. For O(1) values of the Weissenberg number Wi, an initially spherical vesicle deforms into a flow-aligned, tank-treading ellipsoidal bilayer. However, for Wi > 10 and sufficiently large strains, flow deformation produces a dumbbell-shaped bilayer with non-uniform membrane thickness. The thinner, middle portion of the bilayer contains highly stretched polymers while its thicker ends are composed of chains in their equilibrium (folded) configuration. Equilibration from this state results in the formation of a Novel Equlibrated Shear-Induced Structure (NoESIS) in which two vesicles are connected by a highly dynamic lamellar bridge (Liu & Rs, Langmuir, 41, 5083 (2025). The stability of NoESIS to thermal and mechanical perturbations is primarily attributed to a lowering of the interfacial energy achieved by the incorporation of copolymers into the multilayered molecular bridge.

Tuesday 10:30 Sweeney Ballroom B GN20

Life-like condensate networks formed by liquid crystal filament coiling

Christopher A. Browne and Chinedum Osuji
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Liquid-liquid phase separation, whereby two liquids spontaneously demix, occurs in many important industrial and biological settings. Many such fluids exhibit liquid crystalline ordering, which can drive the formation of condensates with intriguing non-spherical shapes and dynamics. Here, we report the formation of filamentous condensate networks, which spontaneously assemble during the demixing of a mesogen from a solvent. Condensing mesogens form rapidly elongating filaments, rather than spheres, to relieve distortion of an internal smectic mesophase. Growing filaments link to form sparse ramified networks, which continuously remodel themselves with life-like dynamics. We use a combination of high-speed microscopy, theory, and simulations to study this networking process. We find that new linkages are predominantly formed by an apparently adhesive interaction between straight filaments, which snap into contact and rapidly wind into helical coils with spontaneously selected chirality. We show that similar helical coils can be formed from single filaments, both within Hele-Shaw cells and within confining microdroplets, resulting in free-floating coiled droplets. We propose an internal smectic structure that rationalizes the partial coalescence of filaments and the coiling into helices, providing estimates for the energy barriers to form linkages within condensate networks. Understanding and controlling these dynamics may provide new avenues to direct pattern formation or template engineered and bio-inspired materials.

Tuesday 10:50 Sweeney Ballroom B GN21

Structure and rheology of self-assembled poly(styrene)-poly(ethylene glycol) block copolymers

Kathleen M. Weigandt[1] and Kelsi Rehmann[2]
[1]*NIST Center for Neutron Research, National Institute of Science and Technology, Gaithersburg, MD 20899, United States;*
[2]*University of Maryland, Gaithersburg, MD 20899, United States*

In this talk we will discuss recent results from rheology, scattering and simultaneous rheo-scattering experiments related to self-assembled block-copolymer micelle soft solid like materials. Self-assembling block copolymers have a broad range of applications including drug delivery, thermoplastic elastomers, nano-reactions, nanoparticle synthesis to name a few. Polystyrene-co-poly(ethylene glycol) micelles are self-assembled by immersing in water, mixing, and then annealing in an 80C oven for hours to days. The resulting micelles appear to be more homogeneous than micelles that were prepared at room temperature and left to age for days or weeks. At temperatures above 60C these polymer micelles remain liquid-like even for high concentration samples. When cooled to room temperatures, the higher concentration samples (roughly greater than 10 % by mass) form a soft solid with an FCC crystal lattice and undergo shear induced crystallization and melting when subjected to shear flow. In this talk we will focus on the characterization of the structure of these samples with small angle scattering and rheology within the linear-viscoelastic regime both at room temperature and as the materials are cooled from the annealing temperature.

Tuesday 11:10 Sweeney Ballroom B GN22

Modeling flow-driven disassembly of supramolecular telechelic polymers in elongational flows

Songyue Liu and Thomas C. O'Connor
Department of Materials Science and Engineering, Carnegie Mellon University, Pittsburgh, PA 15213, United States

End-linking telechelic polymers can self-assemble into large supramolecular chains that act as high molecular weight viscosity modifiers in linear response, but disassemble rather than degrade in nonlinear flows. However, the nonequilibrium dynamics and viscoelasticity of these self-assembling systems remain largely unknown. Here we apply coarse-grained molecular dynamics simulations to model the nonequilibrium dynamics of end-linking telechelics with bivalent associations during nonlinear elongational flows. Simulations vary bivalent association strengths from 9-18 kT and flow strengths from linear to highly nonlinear regimes. Simulations observe a pronounced slow-down in the growth of the steady-state extensional stress with increasing strain rate, resulting in much stronger rate-thinning of the extensional viscosity relative to analogous unassociative melts. Interestingly, the slow rise in stress coincides with an unexpected decrease in average chain extension with increasing rate, which arises as the tension carried by the elongating supramolecules drives them to dissociate. We find that the average molecular weight of ultralong supramolecules shows a power-law decrease with strain rate with a slope of about -1/2. As supramolecules break into smaller pieces, the number of self-associated single-chain loops increases, driving an overall decrease in average chain extension. We highlight the reach dynamics governing the nonlinear response of telechelic polymers and offer insights into how they might be used to engineer desirable rate-dependent flow behavior.

Tuesday 11:30 Sweeney Ballroom B GN23

Start-up response of wormlike micelles: Scission & banding

Ilaria Cusano[1], Afshin Azarpour[2], Nino Grizzuti[1], Giuliano Zanchetta[2], and Rossana Pasquino[1]
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[2]*Medical Biotechnology and Translational Medicine, Università degli Studi di Milano, Milano, Italy*

We present a comprehensive study of the linear and nonlinear rheology of a dilute wormlike micellar (WLM) solution composed of the common surfactant - cetylpyridinium chloride, and the penetrating salt - diclofenac sodium. The mesoscopic lengths of the WLMs were estimated through rheological measurements and confirmed via Cryo-TEM imaging.

Micrometer-long micelles were subjected to start-up flow experiments conducted with both a rotational rheometer and a linear strain-controlled shear cell coupled with microscopy.

In non-linear regime, two Weissenberg numbers can be defined, one related to the terminal relaxation time, Wi_d, and one connected to the breaking and reforming time, Wi_b. When Wi_d is lower than one, the measured stress response is monotonically increasing up to a steady state value, and the resulting velocity profile is stable. When Wi_d is higher than one, the WLMs behave as polymer chains in fast flows, aligning and stretching in the flow direction. When $Wi_b>1$, WLMs show a very pronounced strain hardening behaviour, with a stress peak typical of an elastic chain response, appearing always at the same value of the strain above a characteristic shear rate. A sudden stress decrease appears after the peak, suggesting a breakage phenomenon. The strain at which the stress peak appears permits the evaluation of the WLMs scission energy.

By reconstructing velocity profiles across the sample gap using a custom rheo-optical setup, we gain insights into the relationship between shear banding phenomena and micellar scission events.

Relevant references
Danino D., Current Opinion in Colloid & Interface Science 17, 2012
Guadino D. *et al*, Journal of Rheology 64, 2020
Inoue T. *et al*, Langmuir 21, 2005
Ito T.H. *et al*, Langmuir 30, 2014
Pasquino R. *et al*, Journal of Rheology 67, 2023

Symposium SM
Polymer Solutions, Melts and Blends

Organizers: Amanda Marciel, Ben Yavitt and Piyush Singh

Tuesday 9:50 Coronado + DeVargas SM17

Time-temperature superposition breaks down in extensional flow of polymer solutions

Joe Biju Joseph and Jonathan P. Rothstein
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Time-Temperature Superposition (TTS) is utilized extensively in shear rheology measurements to extend the range of shear rates that can be imposed on a fluid. The principle of time-temperature superposition is that temperature changes are equivalent to timescale or deformation rate changes. Extensional flows dominate many polymer processing techniques, imposing extension rates far exceeding the capable limits of filament stretching experiments. We present studies to validate the use of TTS to extend the measurable range of extension rates that can be imposed on polymer solutions using Filament Stretching Extensional Rheometry. We developed an environmental chamber to systematically vary the temperature of a sample from 25°C down to 5°C. Two different polymer solutions were then tested: a solution of high molecular weight polyacrylamide in glycerol-water and povidone in diethylene glycol. In both cases, using TTS, the imposed extension rates were increased by a factor of approximately four, with a 20°C decrease in temperature. In the low strain plateau, the shift factors calculated from the extensional viscosity were found to nicely correlate with those from the shear rheology. However, at the large strains, where the fluids approached their finite extensibility limit, the TTS shift factors calculated from the extensional viscosities variation with temperature did not align with those from the shear rheology. The extensional shift factors were consistently larger with a 20% discrepancy at the lowest temperatures tested. Changes to temperature affect the solvent quality and influence the radius of gyration at the initial coil configuration, which result in an increase in the finite extensibility, observed as an increase in the maximum extensional viscosity. TTS can therefore be used a technique to probe higher extension rates of filament stretching experiments. The shift factors from shear rheology can be used to shift extensional data only if changes to solvent quality and finite extensibility are accounted for.

Tuesday 10:10 Coronado + DeVargas SM18

Modeling the molecular dynamics of entangled polymer melts under biaxial elongational flow

Nattavipa Chongvimansin and Thomas C. O'Connor
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Biaxial elongational flows are commonly encountered in polymer processes like film blowing and blow molding. However, the molecular dynamics of melts undergoing nonlinear biaxial flows remain poorly understood, largely due to experimental challenges in sustaining and probing such flows. In this study, we employ molecular dynamics simulations to investigate the structural and dynamical properties of linear polymer melts during nonlinear biaxial elongation. By systematically varying deformation rates, chain length, and entanglement density, we comprehensively relate the microscopic melt structure to its nonlinear rheological response. Our results predict strain hardening and rate thinning behaviors consistent with experimental observations. At high strains, polymer chains become highly stretched and lie flat within the extension plane while undergoing continuous rotational diffusion. In contrast to uniaxial elongation, where entanglement effects diminish as chains elongate, primitive path analysis shows that intermolecular entanglements persist and localize along backbones even at large deformations, constraining the chains into distinctively bent conformations that are approximately hyperbolic. This results in novel and more complicated chain elongation dynamics than the simple Rouse-like stretching observed in nonlinear uniaxial flows.

Tuesday 10:30 Coronado + DeVargas SM19

Measuring the properties of a viscoelastic fluid using a tethered swimming rheometer

Eric S. Shaqfeh[1], Selena Chiu[1], Lingchun Yan[2], Adil Jussupov[3], and Manu Prakash[3]
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It is now known that normal stresses in a viscoelastic fluid can create propulsion of swimmers even in situations where there would be no propulsion in a Newtonian fluid[1]. Thus, the swimmer uses the nonlinearities of the fluid rheology to create propulsion. As a result, it has been suggested in the literature[1,2], that such propulsion can be used to measure the non-Newtonian properties of said fluid - i.e. a "swimming rheometer". In the present talk, we will demonstrate that by tethering a class of such swimmers, which generates such normal stress-driven propulsion, one can indeed make very sensitive measurements of the steady, primary normal stress coefficients in a viscoelastic fluid. The measurements can be made in a range of shear rate for which such measurements cannot easily be made on benchtop rheometers. In fact, the tethered swimming rheometer (TSR) allows for measurement of the asymptotic low Weissenberg number limit of these coefficients. The sensitivity rests on the notion that first, one is not limited to a viscometric flow and second, the entire area of the swimmer becomes the measuring area. Since the design space is "new" for such a rheometer, we will discuss and demonstrate various design changes (e.g. confinement) that increase the sensitivity of the rheometric measurement. Finally, we will demonstrate that dynamic measurements are also attainable via the same geometry.

[1] Kroo, L.A., J.P. Binagia, N. Eckman, M. Prakash, E.S.G. Shaqfeh, "A freely-suspended, robotic swimmer propelled by viscoelastic normal stresses", Journal of Fluid Mech. vol. 944, A20, (2022), doi:10.1017/jfm.2022.485 [2] Boon Siong, N., E.S.G. Shaqfeh, "Designing a Swimming Rheometer to Measure the Linear and Non-Linear Properties of a Viscoelastic Fluid", J. NonNewtonian Fluid Mech. 322, 105151 (2023) https://doi.org/10.1016/j.jnnfm.2023.105151

Tuesday 10:50 Coronado + DeVargas SM20

Interactive stress relaxation in polymers, fast and slow

H. Henning Winter
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Soft materials such as gels, pastes, and polymer liquids exhibit behavior that is partly solid-like and partly liquid-like. This mixed response, known as viscoelasticity, reflects how the material deforms over time when stretched, compressed, or sheared. Some internal structural parts respond quickly, others more slowly. To better capture this complexity, we propose a new perspective on two classical rheological measures: the Deborah number De and the Weissenberg number, Wi. These traditional, dimensionless numbers are based on just one "typical" timescale for the material and one "typical" timescale for the process. But this simplification masks the full spectrum of responses, and it neglects the dynamic interference between fast and slow eigenmodes. Instead, we introduce functions that span the complete range of relaxation times ($0 < t < t???$) and process timescales (from very short to very long). This approach reveals the detailed interplay between intrinsic material relaxation and external deformation. We call this framework SCOPE-Spectral Characterization of Process and Eigenmodes. It generalizes the scalar De and Wi concepts into their functional counterparts: the Deborah Function and the Weissenberg Function. In this presentation, we apply SCOPE to more fully describe the complex rheology of polymers and gels, fast and slow.

Reference: Winter HH 2025, Rheologica Acta.

Tuesday 11:10 Coronado + DeVargas SM21

A universal method to determine the molecular weight of polymers in semidilute unentangled solutions using SAXS, NMR diffusometry, and rheology

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Combining dynamic and structural properties of polymer solutions can be used to measure the molecular weight of the polymer. In this work, polystyrene samples over a wide range of molecular weights were studied in different solvents to evaluate the molecular weight determination methods based on the Rouse model for neutral polymer solutions in the semidilute unentangled regime. The weight-average number of Kuhn monomers per chain (Nw) was determined using specific viscosity (ηsp) and correlation length (ζ) measurements on solutions in tricresyl phosphate (TCP) and toluene. The number-average number of Kuhn monomers per chain (Nn) was determined from self-diffusion coefficient (D) and correlation length measurements in toluene and carbon disulfide. Correlation lengths were obtained by small-angle X-ray scattering (SAXS), analyzed using the Ornstein-Zernike function to fit scattering intensity as a function of wavevector. Self-diffusion coefficients were obtained by pulsed-field-gradient nuclear magnetic resonance (PFG-NMR) diffusometry on polystyrene solutions. The relation $Nw \approx 67.7 \eta sp(\zeta \hat{} 3)c$ was found to provide the weight-average molecular weight in good solvents like TCP and toluene (carbon sulfide is too volatile). Similarly, the relation $Nn \approx 14.9(\zeta \hat{} 2)kTc/6(\eta s)D$ can be used to determine the number-average molecular weight in good solvents like carbon disulfide and toluene (TCP 1H NMR resonances overlap with those of polystyrene). Moreover, the limits of these methods at low molecular weights, where the chain size approaches the thermal blob size, will be discussed.

Tuesday 11:30 Coronado + DeVargas SM22

Quantitative metrics to assess evidence of time-temperature superposition (tTS)

Atharva S. Modi[1], Nabil Ramlawi[1], Aaron T. Hedegaard[2], Evan L. Breedlove[2], John W. McAllister[2], Hansol Lee[2], Bahram Rajabifar[2], and Randy H. Ewoldt[1]

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Time-temperature superposition (tTS) has been one of the most ubiquitous techniques in rheology since its introduction 70 years ago, with applications ranging from broadening the time range of experimental data to understanding the interplay of complex relaxation mechanisms in linear viscoelasticity. However, validation of superposition has mostly relied on visual inspection, leading to subjective, binary labels of thermorheologically "simple" or "complex"- a distinction especially contentious for pseudo-tTS. We reconsider the problem with a Bayesian perspective and propose a continuous credibility measure of the tTS model. Unlike conventional model fitting, where there are natural metrics for credibility, the tTS model assumption does not involve an analytical function or residual form. Hence, we introduce quantitative criteria that compute the credibility based on the experimental scope, shift factor variability across material functions, and curve-similarity measures, e.g. between frequency sweeps. We validate the framework on synthetic datasets spanning canonical models of thermorheological behavior and identify key metrics for each model. The quantitative nature of the criteria also enables the propagation of experimental uncertainties through the criteria values. These criteria can be calculated on any material functions of linear viscoelasticity, reflecting the function's own sensitivity to thermorheological complexity. Additionally, they can be applied to superposed curves to identify localized regions of reliable superposition. By translating subjective judgments into a reproducible numerical gauge, the proposed method enables more rigorous reporting of thermorheological behavior through a low-dimensional assessment of the superposition.

Symposium RG
Special Session: Rheology in Geoscience (Invited)

Organizers: Sujit Datta, Meng Meng and Stephan Kolzenburg

Tuesday 9:50 Peralta + Lamy RG4

Flashing lights in speeding grains: Rheology of granular avalanches

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Flowing granular materials arise everywhere around us, in industry from pharmaceutical processes to bulk good transport lines, and in nature from snow avalanches to captivating dune fields. In landslides, we have an interesting interplay between microscale (grain-grain contacts) and macroscale processes (continuum behavior). In order to understand critical macroscale processes such as stability of a slope, creep and failure, we need to be able to visualize and characterize the microscale interactions. In this talk, I will introduce a laboratory technique called photoelasticity to visualize grain-grain contacts in time and space. Collisions between grains create a fascinating network of so-called force chains, which are responsible for the inhomogeneous distribution of stresses in a granular medium. We discover stress distributions in 2D granular avalanches, visualized with bespoke, superior-quality birefringent photoelastic particles. This technique gives for the first time access to the full velocity, density and stress fields inside of a dynamic avalanche, and allows us to experimentally validate granular rheological models. I would like to acknowledge the long list of students, postdocs and collaborators that I had the pleasure to interact with and learn from: without your inspiration, I would not have reached the point I am at now! These valuable people include Amalia Thomas, Rebecca Poon, Ben McMillan, Palmer Dick-Montez, Stephanie McNamara, Hale Burke, Krishnaroop Chaudhuri, Austin Hayes, Brandon Hayes, Ruby Gans, Zhu Tang, Karen Daniels, Alban Sauret, Stuart Dalziel.

Tuesday 10:30 Peralta + Lamy RG5

Viewing lobate patterns on Earth and Mars as climate-modulated fluid-like instabilities

Rachel C. Glade

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Hillslopes in cold regions commonly feature downslope-oriented wavelike patterns known as solifluction terraces, which often break into cross-slope fingers or solifluction lobes. Similar lobate patterns are observed on Martian crater walls in high latitude regions. While these features seem to form only in the presence of frost-heave processes, the specific ingredients required for their formation are not known, and it remains unclear why we only observe these patterns in cold places. Further, the persistence of these patterns challenges the prevailing diffusion-like view of soil creep in these landscapes. We present a case for viewing solifluction patterns as climate-modulated, fluid-like granular instabilities. Drawing on findings in soft matter and granular physics, fluid mechanics, and periglacial geomorphology, we use a combination of theory, remote sensing, numerical modeling, published field data and preliminary laboratory experiments to explore the nature of these enigmatic hillslope features on both Earth and Mars. We find that lobate patterns on both planets obey a simple theoretical first-order morphologic scaling similar to that of surface tension-induced fluid instabilities at flow fronts, albeit with much scatter. Data suggest that climate and gravity influence lobe morphology by dictating the thickness of soil available for motion. We explore several alternative working hypotheses for the conditions needed to initiate these non-inertial instabilities, including rheological origins, buckling instabilities, frost heave dynamics, and cohesion controls. Our work

highlights the importance of drawing from different fields to tackle challenging problems in hillslope geomorphology, and outlines many remaining open questions about the nature of soil creep in cold regions.

Tuesday 11:10 Peralta + Lamy RG6

Expanding the reach of fiber optic sensing: A new tool for environmental monitoring and characterization

Carly Donahue

Earth and Environmental Sciences, Los Alamos National Laboratory, Los Alamos, NM 87547, United States

Fiber optic sensors are highly robust, easily deployable, adapted to tight spaces, and often a cost-effective choice for long range data collection. Fiber optic interrogators come in a variety of designs, each leveraging different optical principles. Additionally, advancements in engineered fiber technology are becoming increasingly prevalent, expanding the capabilities and applications of fiber-based sensing. As the technology advances and costs decreases, these sensors are steadily being applied beyond borehole seismology to more fields including seismic hazards, structural health monitoring, and environmental monitoring. At Los Alamos National Laboratory, fiber optic sensors play a significant role across various programs, from energy research to national security. In this talk, I will provide a brief overview of fiber optic sensing technology, including key considerations for optimizing settings. I will then highlight recent scientific findings at LANL that have utilized fiber sensors, including applications in fluid flow characterization, nonlinear elasticity for well bore integrity monitoring, and planetary exploration.

Symposium IR
Interfacial Rheology, Surfactants, Foams and Emulsions

Organizers: Manolis Chatzigiannakis, Carlos Martinez and Muchu Zhou

Tuesday 9:50 O'Keeffe + Milagro IR18

Shear-induced deformation of MXene-covered droplets: Effect of interfacial viscoelasticity

Benedetta Attaianese[1], Ruth Cardinaels[1], and Ruth Cardinaels[2]

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Interfacially assembled conductive 2D nanoparticles can endow the interface with viscoelastic properties that can be leveraged to shape multifunctional materials into 3D architectures such as high internal phase pickering emulsions or bijels. To rationally tailor such microstructures, the relations between the interfacial assembly and the flow-induced structure dynamics should be known. In the current work, we focus on the deformation dynamics of single droplets covered with 2D MXene nanosheets subjected to shear flow. The MXene nanosheets are synthesized in house from the layered ceramics Ti3AlC2, using the MILD method. MXene-covered water droplets in a silicone oil matrix were investigated whereby the interfacial assembly is promoted by electrostatic interactions between the MXenes and either mono- or bi-amine terminated PDMS in the oil phase. The interfacial assembly is characterized by means of interfacial shear and dilatational rheology, using respectively a double-wall ring attached to a stress-controlled rheometer and pendant drop experiments. An interfacial network with a yield stress and limited frequency-dependency of the viscoelastic moduli is found whereby only the shear response is dominated by the particle-particle interactions. When using amine-terminated surfactants with a different number of charged heads, the interfacial network structure and resulting viscoelasticity is altered, with the bi-amine terminated surfactant leading to higher moduli but a slightly more brittle network. The shear-induced dynamics of MXene-covered droplets is investigated in a counter-rotating shear flow cell. The MXenes-covered droplets act as microcapsules, starting to deform only after a yield point, and exhibiting limited deformation as well as remaining deformation after flow cessation. Our analysis indicates that this behaviour is mainly dominated by the interfacial shear rheology whereby both the shear yield stress as well as the residual stiffness beyond yielding play a role.

Tuesday 10:10 O'Keeffe + Milagro IR19

Multiphysics modeling of long-term aging and deformation mechanisms in polyurethane foams

Kevin N. Long, Judith A. Brown, Christine C. Roberts, Brad H. Jones, and Rekha R. Rao

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Polyurethane foams are used in many industries to provide protection from impact, structural support and thermal insulation. Complex physical processes during both manufacturing and aging of these materials can cause part shape changes to occur over timescales of hours (during manufacturing) to years (part aging). A good understanding of what drives these deformations and the ability to model foam behavior is essential to enable production of parts with tight dimensional tolerances that remain acceptable over time. In this talk, we present a computational modeling platform that predicts shape change of foam parts over a multi-year lifetime period. The model is based on new experimental observations of aging mechanisms in polyurethane foams, which include water uptake-based swelling/deswelling and water reactions with isocyanate that releases carbon dioxide gas and leads to shrinkage over long time scales (years), complementing our work on modeling foaming, curing, and manufacturing warpage during polymerization and cool down. A new theoretical representation of the solid foam matrix constitutive behavior that couples water uptake and chemical species evolution with strain is developed. This model is based on a nonlinear viscoelastic formalism developed for manufacturing with the additional solution fields of water concentration and post-cure chemical reaction extent. Computational implementation uses the finite element method with an arbitrary Eulerian/Lagrangian representation of the transport phenomena including energy conservation and reaction kinetics that is loosely coupled with the Lagrangian momentum balance. The model is validated by matching displacements measured

through small-scale fiber Bragg gratings embedded in cylindrical polymer parts. The validated model is then used to predict long-term aging behavior and shape changes of a complex foam part that requires over 2 million elements to resolve. SNL is managed and operated by NTESS under DOE NNSA contract DE-NA0003525.

Tuesday 10:30 O'Keeffe + Milagro IR20

How does the airflow change the evaporation and deposition of droplets?

Dohyeon Jeon[1], Gun Oh[1], Seunguk Mun[1], Jae Sung Park[2], and Byungmook Weon[1]
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Sessile droplet evaporation draws much of scientific and engineering interest due to its distinguished characteristics from bulk liquid evaporation, such as the coffee-ring effect. Introducing airflow from well-controlled air nozzles can significantly reduce the time consumption of droplet evaporation. On the other hand, the airflow can alter the surface flux distribution, possibly affecting the formation of the coffee-ring or skin. This behavior has not been well studied for far, especially in the high-airflow range. Here, we investigated the evaporation and skin-formation dynamics under crosswind conditions with various imaging techniques. The result suggests that the airflow increases the evaporation rate by the square root of its velocity, due to the boundary layer kinetics. Moreover, these boundary layer kinetics force the droplet evaporation flux to be concentrated at the airflow-facing side, making the droplet deposition form an asymmetric pattern. This result will provide fundamental insight to the mass transportation in multiphase flow.

Tuesday 10:50 O'Keeffe + Milagro IR21

Dilatational response of soluble asphaltenes at the oil/water interface

Amanda B. Marciel
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Asphaltenes strongly adsorb to oil/water interfaces, forming viscoelastic films that result in solid-like mechanical properties and stabilize crude oil emulsions. It has been hypothesized that asphaltenes form the most stable emulsions close to their onset point of precipitation, where mixtures of soluble and insoluble asphaltenes are present in solution. Given their heterogeneity in chemical composition, molecular weight, and aggregation state, it remains challenging to identify the mechanisms that promote emulsion stability. Here, we study the influence of solvent quality on the size and interfacial behavior of soluble asphaltene nanoaggregate clusters and the model asphaltene molecule VO-79 using small-angle X-ray scattering (SAXS) and the oscillating pendant drop method, respectively. We observe that the radius of gyration of soluble asphaltene nanoaggregate clusters is independent of solvent quality until the onset point of precipitation where it then decreases with decreasing solvent quality. We show that the interfacial tension (IFT) at the oil/water interface is initially dependent on solvent quality. Transport of soluble asphaltene nanoaggregate clusters from the bulk to the interface may be described as a diffusion-controlled process that is dependent on solvent quality. After aging, however, the IFT becomes independent of solvent quality, suggesting that emulsion stability depends on other factors beyond IFT, including the rheological properties of asphaltenes, their colloidal stability, and reorganization at the oil-water interface. Using the oscillating pendant drop method, we observe that the complex dilatational modulus of soluble asphaltenes is dependent on solvent quality and increases with aging time. Lastly, we observe that formation of an interfacial film that wrinkles upon droplet contraction, revealing that soluble asphaltenes can form a partially incompressible interfacial film.

Tuesday 11:10 O'Keeffe + Milagro IR22

Flow assurance challenges through the lens of interfacial rheology

Tiphane A. Figueira[1], Eliana M. Castano[1], Jairo E. Leiva[1], Andrea Mora[1], Marcia C. Khalil de Oliveira[2], Osvaldo Karnitz[2], Priscilla R. Varges[1], Paulo R de Souza Mendes[1], and Monica F. Naccache[1]
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Flow assurance remains a major challenge in offshore oil production, particularly in deep and ultra-deep reservoirs, where extreme pressure and low temperatures significantly alter the physical and chemical properties of crude oils. Interfaces play an important role in the flow of complex multiphase systems, and understanding their rheological behavior is crucial for optimizing operations. In this work, we analyze the interfaces of water-in-waxy-oil emulsions by employing different experimental techniques simultaneously. Moreover, we compare results for different oils to assess the influence of chemical composition, such as paraffin and asphaltenes contents, on interfacial behavior. Paraffin and asphaltene deposition, which are highly sensitive to interfacial phenomena that precede bulk aggregation, are among the most critical contributors to flow instabilities. While bulk rheology has been widely investigated, interfacial rheology under critical conditions remains relatively underexplored. To address this gap, we studied crude oil films at several temperatures using techniques like the Langmuir trough and Brewster angle microscopy (MicroBAM) to analyze the interfacial behavior. In addition, we perform shear and dilatational oscillatory rheology using a rotational rheometer equipped with the double-wall ring accessory, as well as a drop tensiometer. Experiments with Brazilian crude oils exhibiting distinct SARA compositions were conducted at 4, 25?and 40°C to compare the effects of temperature and composition on interfacial film structure and dynamics. By improving our knowledge of molecular organization and rheological responses at complex interfaces, this research underscores the critical role of interfacial rheology in emulsion stabilization and gel formation. The findings highlight the potential of interfacial behavior as a predictive and diagnostic tool for addressing flow assurance challenges in offshore oil production.

Symposium BL
Biomaterials, Bio-fluid Dynamics and Biorheology

Organizers: Rae Robertson-Anderson, Travis W. Walker and Jairo Diaz

Tuesday 9:50 Sweeney Ballroom C BL17

Viscoelasticity of airway mucus by live-cell rheometry

Cody Moose[1] and Gerald G. Fuller[2]
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Mucus plugs occlude airways to obstruct airflow in cystic fibrosis (CF). These plugs form due to mucus stiffening as a result of dysfunction of the CF transmembrane conductance regulator (CFTR) protein, and studies in human airway epithelial cells (HAECs) show that CF cells autonomously generate this pathologic mucus. To determine how HAECs autonomously generate pathologic mucus and how CF treatments modulate mucus behavior, we used a magnetic microwire rheometer to characterize the viscoelastic properties of mucus secreted by HAECs under varying conditions. We found that normal HAEC mucus exhibited viscoelastic liquid behavior and mucus secreted by CF HAECs exhibited viscoelastic solid-like behavior. In addition, mucus secreted by CF HAECs treated with the CFTR modulator ETI or the mucolytic dPGS-SH exhibits viscoelastic liquid-like behavior, indicating a recovery of normal rheology. Furthermore, mucus secreted by IL-1ß- or IL-13-stimulated HAECs exhibits viscoelastic solid-like behavior. Together, our results show that CF HAECs generated pathologically stiffer mucus compared to normal HAECs which can be restored to healthy-like behavior with ETI or dPGS-SH, and that IL-1ß- or IL-13-treated HAECs autonomously generated pathologic mucus.

Tuesday 10:50 Sweeney Ballroom C BL20

The stress relaxation response of the porcine descending aorta under combined normal and torsional loadings

Chandler C. Benjamin and Luc Nguyen
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Understanding the mechanical properties of aortic tissue is crucial for improving future medical interventions related to cardiovascular diseases. Our group has previously investigated the uni-axial, bi-axial, and shear responses of the porcine thoracic aorta. In this study, we explore the stress relaxation of the porcine aorta under torsional shearing while maintaining a constant normal compressive load. Circular samples, measuring 0.5 inches in diameter, were extracted from the descending section of porcine thoracic aortas. Stress relaxation experiments were conducted at a constant shear strain ranging from 10 to 50% while maintaining a compressive strain ranging from 5 to 25%. We observed that the stress relaxation behavior differs between the normal and torsional shear directions. Moreover, results suggest that neither the normal or shear stress relaxation behavior of the porcine aorta is not significantly influenced by the degree of compressive strain or shear strain applied.

Tuesday 11:10 Sweeney Ballroom C BL21

A viscosity-based assay to screen blood diseases

Mahesh S. Tirumkudulu and Mahrukh A. Mir
Chemical Engineering, Indian Institute of Technology Bombay, Mumbai, Maharashtra 400076, India

We present a rapid, cost-effective screening assay that utilizes blood viscosity measurements from a single drop of blood to aid in simultaneous screening of anemia and SCD. The method leverages a standard blood smear, demonstrating that smear length correlates with blood viscosity, which is influenced by plasma viscosity, hematocrit and red blood cell (RBC) rigidity. The thickness of the film is determined by the capillary number, which measures the competition between the viscous force that smears the liquid over the glass slide and the surface tension that resists the deformation of the interface. We show that the length of the smear for a fixed sample volume is also set by capillary number and can be used as a reliable measure of fluid viscosity. Blood viscosity below a threshold due to low hematocrit indicates severe anemia, while a significant viscosity increase due to RBC hardening upon blood deoxygenation signals SCD. Our approach exhibits high sensitivity in screening severe anemia and SCD, positioning it as a reliable diagnostic tool at an affordable cost. Given the high accuracy of measuring blood viscosity, we anticipate the assay to be useful in screening and monitoring various disease conditions affecting blood viscosity, such as atherosclerosis, hypertension, diabetes, and COVID-19.

Tuesday 11:30 Sweeney Ballroom C BL22

Complex coacervate microemulsions

Samanvaya Srivastava
Chemical and Biomolecular Engineering, UCLA, Los Angeles, CA 90095, United States

This presentation will discuss our progress in creating stable membraneless water-water emulsions comprising complex coacervate microdroplets. Complex coacervation is a liquid-liquid phase separation phenomenon driven by the electrostatic association of oppositely charged multivalent macromolecules in water, creating coacervate microdroplets enriched with charged moieties. These aqueous membraneless microdroplets possess numerous attributes desired in colloidal reactors and protocell models. However, the membraneless coacervate-water interface that facilitates many of the bio(techno)logical functions of the coacervate microdroplets also promotes their coalescence, resulting in rapid coarsening and sedimentation. We will discuss our recently discovered strategy to stabilize complex coacervate microdroplets without introducing membranous

sheaths around the droplets by utilizing the assembly of anionic comb polyelectrolytes at the water(coacervate)-water interface. We will demonstrate the tunability of microdroplet size, its months-long stability, and its ability to withstand high ionic strength environments. Selective sequestration of charged (bio)molecules (proteins and enzymes) into the crowded environments of stabilized coacervate microdroplets will be argued to affect a significant (up to 10-fold) and sustained acceleration of enzyme-mediated bioreactions. Aided by the low cost of the constituent polymers and the simplicity of the formulations, we will argue that the stabilized coacervate emulsions serve as efficient enzyme-encapsulants in economical, large-scale flow bioreactors.

Symposium FI
Flow-Induced Instabilities and Non-Newtonian Fluids

Organizers: Hadi Mohammadigoushki, Fardin Khabaz and Chenxian Xu

Tuesday 9:50 Sweeney Ballroom D FI17

Evidence of an inertialess Kapitza instability due to viscosity stratification

Shravya Gundavarapu[1], Darish Jeswin Dhas[2], and Anubhab Roy[1]

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Gravity-driven falling films without an underlying microstructure are prone to a long-wave interfacial instability known as the Kapitza instability, which arises due to inertial stresses [1,2]. Recent investigations into the stability of colloidal falling films have revealed that the suspension rheology not only amplifies this instability but can also give rise to a purely inertialess mode of instability [3]. This novel instability has been attributed to shear-induced particle migration, which leads to a viscosity-stratified base state. Motivated by these findings, we investigate the dynamics of viscosity-stratified falling films to isolate and understand the role of viscosity gradients-arising from mechanisms such as particle migration or thermal variations-in driving interfacial instabilities. Through a combination of asymptotic analysis and numerical simulations, we demonstrate that even in the absence of fluid inertia, a prescribed base-state viscosity stratification, when coupled with viscosity perturbations, is sufficient to trigger interfacial instability.

References

[1] Yih, C. S. (1963). Stability of liquid flow down an inclined plane. *Physics of Fluids*, **6**(3), 321-334.
[2] Benjamin, T. B. (1957). Wave formation in laminar flow down an inclined plane. *Journal of Fluid Mechanics*, **2**(6), 554-573.
[3] Dhas, D. J., & Roy, A. (2022). Interfacial instability in gravity-driven colloidal films. *Journal of Fluid Mechanics*, **938**, A29.

Tuesday 10:10 Sweeney Ballroom D FI18

Shear-driven sedimentation of a rigid particle in soft suspensions

Rakan Alrashdan and Fardin Khabaz

School of Polymer Science and Polymer Engineering, University of Akron, Akron, OH, United States

Sedimentation, which is a phenomenon in which particles sink under the influence of gravity or pulling force, presents a major challenge in maintaining the stability of yield stress fluids which use rigid particles as functional additives, especially in formulations composed of soft deformable particles above jamming fraction. Here, we use particle dynamics simulations to explore the stability of a matrix of soft particles encompassing a single rigid particle under various pulling forces at different volume fractions and in the presence of cross shear flow at different shear rates. Our findings reveal that suspensions at higher volume fractions exhibit greater resistance to sedimentation, while higher pulling forces on the rigid particle increase the likelihood sedimentation. The shear rate influences the suspension stability, as stronger flows maintain the rigid particle in suspensions of soft particles, whereas lower shear rates coupled with higher pulling forces promote sedimentation. We determine the flow behavior of the background fluid, especially near the rigid particle and investigate its response to the pulling force acting on the particle. High shear rates maintain typical shear flow streamlines, while lower shear rates combined with a strong pulling force disrupt the flow, forming channel-like pathways that facilitate the sedimentation of the rigid particle. Next, we construct stability diagrams across various volume fractions and shear rates, identifying the critical force threshold characterized by dynamic yield stress and flow strength necessary to initiate sedimentation both under shear flow and in a quiescent condition. Finally, a universal stability diagram based on the applied shear rate and pulling force is provided. These results provide new insights into the control of sedimentation in suspensions subjected to external forces.

Tuesday 10:30 Sweeney Ballroom D FI19

Mechanics of multiple bubbles in yield stress fluids: Effect of hydrodynamic interactions and coalescence

Masoud Daneshi[1], Emad Chaparian[2], and Ian Frigaard[3]

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Bubbles in yield stress fluids are common in natural and industrial processes; examples are many, from gas emissions in tailings ponds to the entrapment of hydrogen bubbles in nuclear slurries. While beneficial in cases like foam cementing, they are often undesirable in cosmetics and pharmaceuticals. In this study, we investigate the mechanisms of bubble entrapment and release through experiments and computations. A vacuum chamber system was used to control the concentration and size of bubbles trapped in our model yield stress fluids, i.e., Carbopol and Laponite. We also used a rotational rheometer (Kinexus) to study the rheology of the fluids and link it to the flow dynamics in our system. Numerical

simulations using an adaptive finite element method based on an augmented Lagrangian scheme were also conducted to study the yielding mechanism around the bubbles. Previously, we investigated the stability of a single bubble and determined the critical yield number, the effect of elasticity on the final shape of the bubble, and the dynamic response of the gel during bubble growth [1,2]. We extend our study by examining the interactions of multiple bubbles at different orientations and proximities, aiming to understand how these affect the onset conditions. Additional phenomena, such as bubble coalescence, are also investigated in both our experiments and computations.

[1] Pourzahedi, Chaparian, Roustaei & Frigaard, J. Fluid Mech. 933 (2022) A21. [2] Daneshi & Frigaard , J. Fluid Mech. 957 (2023) A16.

Tuesday 10:50 Sweeney Ballroom D *Keynote* FI20

The mechanism of incomplete stress relaxation in brittle yield stress fluids

Jiye Lee, Gunnar B. Thompson, Brendan A. Harley, and Simon A. Rogers
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When the flow of yield stress fluids is stopped, the stress relaxes over some timescale but is eventually arrested, leading to finite residual stresses that are important in additive manufacturing, geological flows, foods, and consumer products. We study this phenomenon from the perspective of recovery rheology, where stress relaxation is seen to be an exchange between recoverable and unrecoverable deformation under conditions of fixed total strain. We combine traditional and recovery rheology experiments with predictions of the KDR model with brittility, which describes the rheology of yield stress fluids in a continuum manner with a rate-dependent relaxation time. In this model, plastic deformation is enhanced by rapid acquisition of recoverable strain scaled by a factor called the brittility, which allows for a sufficient exchange of recoverable strain for unrecoverable strain. The rate that the materials responds to, which we call the effective shear rate, can therefore be different from the total applied shear rate. It is this difference that allows for relaxation to take place, as the effective shear rate is small but finite even when the total shear rate is zero. The rate-dependence of the relaxation time allows for the construction of a relaxation master curve using shift factors that relate the initial shear rate to a reference shear rate. The results of our study have implications for numerous applications as well as understanding phenomena such as memory formation and retrieval and thixotropy.

Tuesday 11:10 Sweeney Ballroom D FI21

A universal relationship between linear and nonlinear responses in soft materials

Ryan Poling-Skutvik[1], Daniel Keane[1], Elnaz Nikoumanesh[1], and Simon A. Rogers[2]
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Yielding is a phenomenon in which a material transitions from elastic deformation to viscous dissipation when subjected to large deformations. This transition has been described and studied for over a century, but it remains elusive to predict in soft materials. Instead, rheologists characterize this transition empirically using a variety of protocols, the most common of which is large amplitude oscillatory shear. During this protocol, a material subjected to a sinusoidal strain (or stress) at a constant frequency with progressively larger amplitudes and the viscoelastic moduli are quantified by the proportional response in stress (or strain). The onset of nonlinearity in this response is often characterized by a peak in the loss modulus G", which precedes the crossover from a primarily elastic regime to a primarily viscous response. In this work, we show that the height of this peak can be fully predicted by tan(d) in the linear response. Additionally, the position of this peak is predicted by a combination of this linear viscoelasticity and flow stress. These relationships hold across material chemistry and structure and orders of magnitude in material elasticity. Our work therefore demonstrates that the same fundamental physics controlling the viscoelastic response under linear deformations is preserved across the yield transition. Furthermore, the direct relationship between the G" peak and linear material properties indicates that the G" peak is not an independent metric by which to classify the yield transition.

Tuesday Afternoon

Symposium CS
Colloidal Suspensions and Granular Materials

Organizers: James Gilchrist, Abhinendra Singh and Shravan Pradeep

Tuesday 1:30 Sweeney Ballroom A CS23

Microrheology in active suspensions

Boyuan Chen[1] and John F. Brady[2]
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Active matter systems generate self-propulsive motion by consuming energy, resulting in non-equilibrium behavior not seen in passive colloidal suspensions. Here, we study the microrheology of active Brownian suspensions where a probe particle moves through an active bath at constant speed. Full hydrodynamic interactions (HI) are incorporated using Fast Active Stokesian Dynamics. As a result of HI, the apparent viscosity experienced by the probe can become less than the solvent viscosity when the swimming activity is high compared to thermal Brownian motion. HI cause active bath particles to accumulate behind the probe, whereas in a passive bath particles accumulate in front of the moving probe. As a result, the active bath particles push the probe along, resulting in a reduction in drag and a reduced microviscosity. Can the drag be reduced to zero?

Tuesday 1:50 Sweeney Ballroom A CS24

Tuning the viscosity and shear-jamming point in active dense suspensions

Bhanu Prasad Bhowmik and Christopher Ness
School of Engineering, University of Edinburgh, Edinburgh, Scotland EH39NU, United Kingdom

Dense suspensions, such as blood, concrete, and molten chocolate, are mixtures of Brownian or non-Brownian solid particles and a viscous fluid in roughly equal proportions. Under external straining, the viscosity of these systems diverges, leading to a jamming transition at a critical solid volume fraction. Such viscosity divergence poses challenges in many industrial processes involving dense suspensions[1]. Here, using particle-based simulations, we study the rheological response of dense suspensions containing active particles. In one case, these active particles are modeled as run-and-tumble particles[2] with three different tuning parameters: the fraction of active particles in the system, an active force applied on the particles, and a persistence time after which the direction of the active force changes randomly. In another case, active torques are used instead of forces. Our simulations reveal that, in the strain-independent regime, the viscosity of the system depends on all three parameters associated with the active particles. The viscosity exhibits a monotonic decrease (up to an order of magnitude) with increasing active particle concentration, as well as a non- monotonic dependence on the magnitude of the active force/torque and the persistence time. We also observe a significant variation in the shear jamming volume fraction due to the presence of active particles. Moreover, we find that the rheology of active dense suspensions does not follow the conventional constitutive laws of μ-J rheology. To address this, we propose new constitutive laws to describe the rheology of active dense suspensions.

References: [1] C. Ness, R. Seto, and R. Mari, Annu. Rev. Condens. Matter Phys. 13, 97 (2022). [2] R. Mandal, P. J. Bhuyan, M. Rao & C. Dasgupta, Soft Matter 12, 6268-6276 (2016).

Tuesday 2:10 Sweeney Ballroom A CS25

Viscoelasticity of nanocolloidal suspensions from probe rheology: probe size and statistics

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Probe rheology has emerged as a versatile technique for characterizing the viscoelastic properties of soft matter systems at the microscale. Some advantages of probe rheology include its ability to determine local viscoelasticity and hence spatial structural heterogeneities, ability to sample a wide range of frequencies, requirement of a very small amount of sample, and its suitability for measuring the properties of confined systems. These capabilities make it an ideal tool for studying complex fluids under conditions where bulk rheological methods may be inadequate. In previous work [1], we demonstrated the applicability of the probe rheology simulation technique for determining the viscoelastic moduli of a nanocolloidal suspension. A particulate model of colloidal suspension was used in that work and the probe motion was tracked using molecular dynamic simulations. The results showed a dependence of the calculated values on the relative size of the probe compared to the colloidal particles. In this work, we have investigated this effect of probe particle size by studying probes covering a wide size range from a probe particles that is much larger than the size of the colloidal particles at one end, and a probe particle that has the same size as the colloidal particles (lower limit of probe size) at the other end. Probe rheology simulation results are compared with those obtained from oscillatory nonequilibrium molecular dynamics (NEMD) simulations, which are akin to bulk rheological measurements. The employment of smaller probes enables the usage of a larger number of probe particles in the same model system. The effect of the number of probe particles on the accuracy of the results is also investigated in this work.

[1] D. Sundaravadivelu Devarajan and R. Khare, J. Rheol. 66, 837-852 (2022).

Tuesday 2:30 Sweeney Ballroom A CS26

Probing the microstructure of a viscosity metamaterial

Anna R. Barth[1], Navneet Singh[1], Itai Cohen[1], Abhishek Shetty[2], Eric R. Dufresne[1], and Bulbul Chakraborty[3]
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The viscosity of a dense suspension can be manipulated with a rapid response time by applying ultrasonic acoustics. By cyclically switching the acoustics off and on, the suspension can be manipulated into a metamaterial with a time-averaged viscosity that is determined by both the acoustics-on and the acoustics-off state. Here we probe the microstructure of such a metamaterial by performing rheological measurements using a parallel plate geometry with a top plate that has been modified to introduce a barrier that the suspension must flow around. In the absence of acoustic perturbations, the effective viscosity of a dense suspension is strongly dependent on the size of this barrier, revealing a characteristic length scale associated with the suspension's microstructure. We show that viscosity metamaterials exhibit a characteristic length scale that is not simply the time-average of the length scales associated with the acoustics-on and acoustics-off states. Instead, the characteristic length scale can be tuned by the amplitude and frequency of the cycled acoustic perturbations. As a result, in viscosity metamaterials, the characteristic length scale and the average shear viscosity are no longer directly related, allowing the suspension to flow past the barrier at a surprisingly high rate even when the average shear viscosity is quite high.

Tuesday 2:50 Sweeney Ballroom A CS27

A discrete element framework for multibody collisions in wet granular systems

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Collisions between wet particles are central to the dynamics of dense suspensions and granular flows in both natural and industrial settings-ranging from debris flows to wet granulation in pharmaceutical and chemical processes. Accurate modeling of these interactions requires resolving short-range hydrodynamic forces while maintaining computational efficiency in many-body systems. We present a novel discrete element method (DEM) in which the relative motion between each pair of interacting particles is resolved in a rotating polar coordinate frame. This approach efficiently incorporates hydrodynamic interactions among neighboring particles without resorting to full finite element fluid simulations. The model explicitly captures lubrication and capillary forces arising from thin viscous film, which are coupled into the translational and rotational dynamics of the particles. Simulations of three-sphere collisions reveal a range of outcomes [1]-including full agglomeration, binary clustering, and complete separation-depending on the Stokes number, which governs the balance of inertia and viscous dissipation. The framework is extended to general N-body systems, and preliminary results for larger assemblies of wet particles will be presented. These findings provide insights into the collective behavior and microscale energy dissipation mechanisms in wet granular materials under dynamic conditions. These particle-scale interactions underlie the macroscopic rheological behavior of wet granular materials, particularly in regimes where capillary cohesion and viscous dissipation compete with inertial forces. This work will focus on extracting effective rheological parameters-such as apparent viscosity-from many-particle simulations under shear and compressive loading.

[1] Davis, Robert H. "Oblique collisions of three wet spheres." Phys. Fluids 35.10(2023)

Tuesday 3:45 Sweeney Ballroom A CS28

Teaching thixotropy and elastoviscoplastic materials

Christopher W. Macosko[1], Randy H. Ewoldt[2], and Gareth H. McKinley[3]
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At the SoR meeting in Chicago 2022 we proposed to add a new chapter on thixotropy to our 2nd edition of Macosko's rheology text. At that meeting and since we have distilled the vast complexity of observables and approaches to thixotropy. We have now completed that chapter, which we feel compactly teaches students and industrial practitioners the essential features of what we refer to as thixotropic elastoviscoplastic (TEVP) materials. We will share an outline of what we have written and test driven in recent short courses and in two university classes.

Tuesday 4:05 Sweeney Ballroom A CS29

Discriminating between viscoelasticity and thixotropy via constrained recoil experiments

Paulo R de Souza Mendes[1], Pedro H. Silva Paiva[1], Priscilla R. Varges[1], Ivan R. Siqueira[1], and Roney L. Thompson[2]
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If the shear stress is suddenly removed from a viscoelastic liquid undergoing steady simple shear flow-while maintaining a fixed gap between the plates-the liquid (and the upper plate) will recoil to a position it previously occupied. This reverse motion is characterized by the shear strain during recoil, measured relative to the moment the shear stress is removed. Over time, the recoil strain approaches a limiting value known as the ultimate recoil or recoverable shear. This asymptotic value depends on the shear stress applied during the preceding steady simple shear flow. Because the gap is held fixed, the removal of shear stress leads to a relaxation of the normal stresses over a timescale comparable to that of the recoil process [Bird et al. 1987, v.1, Wiley]. In this transient experiment we are able to obtain the recoverable strain as a function of the steady

shear stress. This experiment is particularly well-suited for characterizing the time-dependent behavior of a material-specifically, whether it behaves as a purely viscoelastic, thixoelastic, or purely viscous thixotropic liquid. In the case of thixotropic materials with purely viscous behavior, no recoil is observed, regardless of the magnitude of the preceding steady shear stress. For thixoelastic materials, the recoverable shear is finite at low to moderate steady shear stresses, but diminishes and eventually vanishes as the stress increases. In contrast, purely viscoelastic liquids exhibit increasing recoverable shear with increasing shear stress, often approaching a plateau. We conducted such experiments with various materials and successfully identified their time-dependent behavior in agreement with their constitutive characteristics.

Tuesday 4:45 Sweeney Ballroom A CS31

Rheology and microstructure of sticky yield stress fluids

Harry K. Yankah[1], Rakan Alrashdan[2], Michel Cloitre[3], and Fardin Khabaz[2]
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The rheology of yield stress fluids is influenced by attractive interparticle forces, which may arise from van der Waals interactions, depletion forces, or physical bridging through short alkane chains. These attractions introduce complex flow phenomena, including cluster formation and shear banding, which are particularly relevant in applications such as food, cosmetics, coatings, and pharmaceuticals, where precise control of flow and stickiness is essential. Here, we use discrete particle dynamics simulations to investigate the rheology of yield stress fluids with attractive interactions using a computational model that combines generalized Hertzian repulsion with a short-range sticky force to represent attraction. Our results show that increasing the strength of interparticle attractions raises the dynamic yield stress, reflecting enhanced resistance to flow. At low shear rates, the influence of attractive interactions is prominent, while at high shear rates, repulsive forces are dominant, and hence, the response of sticky suspensions to shear flow approaches that of purely repulsive systems in this regime. The microstructure of these suspensions shows there is increased formation and preservation of average number of contacts per particle with increasing stickiness, while there is a decrease in average number of contacts per particle as shear rates increase. Microstructural analysis reveals anisotropic contact distribution for particles featuring a second neighbor shell as the attraction degree increases, and its orientation aligns with the extension axis in shear flow. We construct a universal flow curve that collapses data across varying attraction strengths. These findings show how introducing sticky interactions into yield stress fluids governs their rheological and microstructural properties, offering an opportunity to control their rheological behavior.

Tuesday 5:05 Sweeney Ballroom A CS32

Flow-induced lamellar ordering in attractive suspensions

Esmaeel Moghimi, H A Vinutha, Austin H. Walker, Emanuela Del Gado, Daniel L. Blair, and Jeffrey Urbach
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We investigate microstructural changes that occur during oscillatory shear flow in an intermediate-volume-fraction colloidal gel, using rheo-confocal experiments and simulations. The system consists of a model depletion colloid-polymer mixture, composed of hard-sphere colloidal particles and non-adsorbing linear polymer chains. Our results reveal three distinct structural regimes depending on the strain amplitude and frequency of the applied oscillatory shear. At large strain amplitudes, the structure is fully broken, resulting in a more homogeneous dispersion. At low strain amplitudes, the system forms heterogeneous, amorphous structures. Remarkably, at intermediate strain amplitudes and very high frequencies, we observe the formation of a novel lamellar structure: particles organize into layers aligned with the flow direction, separated by solvent-rich regions. Rheo-confocal imaging shows that particles initially form monolayer sheets, which grow in thickness with continued shearing. These lamellar structures exhibit high stability even after flow cessation. Complementary simulations indicate that particle-particle friction is a key factor driving and stabilizing this layered organization. This discovery of flow-induced lamellar ordering in attractive suspensions reveals a new class of shear-induced structures with potential implications for processing and material design in soft matter systems.

Symposium GN
Self-assemblies, Gels and Networks

Organizers: Thibaut Divoux, Katie Weigandt and Ria Corder

Tuesday 1:30 Sweeney Ballroom B GN24

Effect of microgel elasticity on tracer dynamics in microgels

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The elasticity of polymer microgels governs both their bulk rheological response and the transport of embedded tracer particles. How elasticity and microgel concentration affect the tracer dynamics across different concentration regimes, however, remains incompletely understood. Here, we synthesize dual-stimuli-responsive poly(N-isopropylacrylamide-co-acrylic acid) (PNIPAM-co-PAA) microgels with tunable softness by varying the crosslink density. The microgels undergo a swelling transition near 32°C as they are cooled, and we exploit this transition to modulate microgel concentration in situ. We characterize the dynamics of 100nm fluorescent polystyrene tracers in microgel matrices as they are cooled from the collapsed to swollen state and reach final volume fractions of $\zeta \approx 0.4$ (dispersed), $\zeta \approx 0.6$ (contacting), and $\zeta \approx 1.0$ (jammed or compressed). Using differential dynamic microscopy and single-particle tracking, we determine relaxation times τ and diffusivities D for the tracer particles as functions of temperature and the final (swollen) ζ. At low $\zeta \approx 0.4$, τ and D of the tracers monotonically increase and decrease upon cooling, respectively, for both soft and stiff matrices. At intermediate $\zeta \approx 0.6$, however, τ and D exhibit non-monotonic dependences on temperature, with

local extrema near ~34°C, in stiff but not soft matrices. At high $\zeta \approx 1.0$, this non-monotonic behavior occurs in both soft and stiff matrices. Our results show how elastic compression modulates penetrant transport in microgel networks, which can inform the design of theranostics and biological scaffolds.

Tuesday 1:50 Sweeney Ballroom B GN25

Granular hydrogels as brittle yield stress fluids

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While granular hydrogels are increasingly used in biomedical applications, methods to capture their rheological behavior generally consider shear-thinning and self-healing properties or produce ensemble metrics such as the dynamic moduli while neglecting transient yielding and unyielding processes. Combining oscillatory shear testing with Brittility (Bt) via the Kamani-Donley-Rogers (KDR) model, we show that granular hydrogels behave as brittle yield stress fluids. We quantify steady and transient rheology as a function of microgel properties and granular composition for polyethylene glycol and gelatin microgels. The KDR model with Bt captures granular hydrogel behavior for a wide range of design parameters, reducing the complex rheology to a determination of model parameters. In granular mixtures, we observed monotonic dependencies of the elastic modulus, structural viscosity, and brittility upon granular composition, while the yield stress was lower for mixtures. Microgel size distribution and polymer fraction were the most influential parameters in monolithic granular hydrogels, while microgel size and packing density were less impactful. The model robustly captures self-healing behavior and reveals that granular hydrogel relaxation accelerates with an increased small-amplitude strain rate. This quantitative framework is an important step toward rational design of granular hydrogels for applications ranging from injection and in situ stabilization to 3D bioprinting.

Tuesday 2:10 Sweeney Ballroom B GN26

Rheological effects on rupture of polymer networks

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It is well-known that rupture of polymer network is sensitive to both loading rate and temperature. At temperatures far above glass transition temperature elastomeric stretching is only elastic, yet rupture occurs at higher tensile strength when stretched faster or stretched at lower temperatures. In this study, we examine rupture behavior of viscoelastic networks whose stress responses are both rate and temperature dependent. Using in-situ birefringence measurements, we show that viscoelasticity primarily arises from embedded entanglement due to chain uncrossability whose contributions increase with the applied stretch rate and are stronger at lower temperatures. This transient crosslink-like effect promotes non-Gaussian stretching of the network, boosting intrachain stress levels in the form of pronounced strain hardening. At temperatures sufficiently close to the glass transition temperature Tg, interchain interactions make a notable contribution to stress while producing greater participation of entanglement. We conclude that rupture characteristics such as tensile strength and rupture strain depend on how viscoelasticity in the form of transient entanglement affects chain tension buildup in network strands.

Tuesday 2:30 Sweeney Ballroom B GN27

The influence of network topology on the viscoelasticity of polyelectrolyte complex (PEC) hydrogels

Fahed Albreiki[1], Holly Senebandith[2], Defu Li[1], and Samanvaya Srivastava[1]
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Polyelectrolyte complex (PEC) hydrogels, which are formed by mixing oppositely charged block polyelectrolytes in aqueous media, have become attractive candidates as 3D printable inks and injectable wet adhesives owing to their highly tunable rheological properties. Their rheological behavior is known to be largely dictated by their self-assembled network structures. Yet, a predictive modeling approach that relates their chain exchange dynamics and their network topology with their viscoelastic properties remains elusive. In this contribution, we synthesize and prepare a library of PEC hydrogels by utilizing block polyelectrolytes with varying charged lengths to develop a comprehensive shear rheological investigation that elucidates how polyelectrolyte complexation and self-assembly leads to the observed viscoelastic properties. Based on transient network models, which were originally developed for hydrophobically associated block copolymers, an experimental and theoretical framework is established to capture the role of polyelectrolyte chain exchange dynamics and variation in the network topology in dictating the viscoelasticity of PEC hydrogels. We utilize experimental linear viscoelasticity results to demonstrate and quantify the evolution of PEC hydrogel networks from low bridging and faster chain exchange at low polymer concentrations to fully bridged networks exhibiting slowed chain exchange rates at high polymer concentrations. The proposed framework demonstrates how block polyelectrolytes self-assembly leads to hydrogels with precisely tailorable rheological properties and paves the way for designing better inks, adhesives, and injectable therapeutics.

Tuesday 2:50 Sweeney Ballroom B GN28

Exploring chemistries for hydrogel-based reversible adhesives

Jessica W. Kopatz[1], Koushik Ghosh[1], Elizabeth Larkin[1], Robert Secor[2], Rekha R. Rao[1], Micah Murphy[1], Warner Dorman[1], and Christine C. Roberts[1]

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Removable and reversible adhesives are tracking interest across a multitude of industries where there is a need to separate desirable and expensive materials (i.e. precious metals) from traditional encapsulant materials for recyclability. In contrast to exploiting carcinogenic burn pits, removable adhesives offer a safer-option by utilizing benign stimuli, such as water, for their release. Inspired by previous work (Cho et al., 2019, 10.1073/pnas.1818534116) focused on snail epiphragm-a mucus-derived structure enabling strong dehydration-activated bonding, we present a poly(2-hydroxyethyl methacrylate) (PHEMA) hydrogel crosslinked with polyethylene glycol methacrylate (PEGMA) that achieves strong adhesion through intrinsic hydration-dependent phase transitions. When hydrated, the softened gel conformally adapts to rough target surfaces through low-energy deformation. Upon drying, the gel's modulus increases locking in the adapted shape and enabling strong topographic interlocking with minimal residual stress. Rehydration, modulated by PEGMA content, triggers shape recovery, facilitating easy detachment and reversibility. This work provides an overview of the influence of polymer chemistry, photoinitiators, interpenetration, and chemical crosslinking on adhesive performance and water diffusion rates. Hydrogels stamped with various patterns are explored to investigate water uptake rates, which is optimized through a computational finite element model of capillary wicking. In conclusion, this study overcomes the traditional trade-off between adhesion strength and reversibility, offering potential applications in manufacturing, medicine, and temporary bonding processes where contamination-free detachment is crucial. Sandia National Laboratories is a multimission laboratory managed and operated by National Technology and Engineering Solutions of Sandia LLC, a wholly owned subsidiary of Honeywell International Inc. for the U.S. Department of Energy's National Nuclear Security Administration under contract DE -NA00035

Tuesday 3:45 Sweeney Ballroom B GN29

Time-resolved nonlinear rheology of interpenetrating biocomposite networks using the SPP framework: From experimental characterization to simulation models

Wayan A. Fontaine-Seiler[1], Daniel L. Blair[1], Emanuela Del Gado[1], and Gavin J. Donley[2]

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Functional biomaterials are often composed of multicomponent systems. Designing their biological and mechanical functionality depends on the precise control of their microscopic constituent properties on all relevant lengthscales. When utilized for 3D printing and cellular scaffolding applications, these hydrogel-based materials undergo large strain deformation which can dramatically alter their structure and mechanical properties. In this talk, we will present experimental rheological results for a biologically derived interpenetrating network composed of gelatin, fibrin and a non-specific enzymatic crosslinker along with Molecular Dynamics simulations models results. To quantify the nonlinear response, we apply the Sequence of Physical Processes (SPP) framework to Large Amplitude Oscillatory Strain (LAOS) rheology along with a statistical and geometric framework that we have created to interpret the time dependent moduli. Using this methodology, we will quantitatively describe the microscopic interdependence of the composite gels and also show the non-additive mechanical behavior at high strain amplitudes and discuss the mechanisms which underlie the transitions from linear to nonlinear behavior. Additionally, we explore and discuss Molecular Dynamics simulation models capable of explaining and predicting the experimental bulk nonlinear responses of as well as the potentially linked structural changes under high strains at different lengthscales at their origin. Finally, we show that our statistical analysis of SPP framework provides a more generic interpretation of LAOS rheology which can be applied to both experimental data and molecular dynamics simulations models.

Tuesday 4:05 Sweeney Ballroom B GN30

Modeling the viscoelastic mechanics of triblock copolymer thermoplastic elastomers with strong associative bonds

William T. Ferguson and Thomas C. O'Connor

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Coordinated associative interactions, such as hydrogen bonding, are known to enhance the dissipative stresses of adhesives and elastomers. However, the molecular mechanisms underlying this mechanical enhancement remain poorly understood. Here, we deploy a new class of coarse-grained molecular dynamics models that resolve the coordinated self-assembly and nonlinear rheology of associative polymers to explore how hydrogen bonds influence the self-assembly, mobility, and nonlinear mechanics of triblock thermoplastic elastomers. By varying the hydrogen bonding content within the rubbery midblock and glassy endblock fraction, we generate nanostructured elastomers with morphologies, thermomechanics, and mechanics that are consistent with experiments. We relate simulated stress-strain response to how hydrogen bonds alter the stretching of the rubbery chain segments and influence the plastic deformation of the glassy endblock domains. By linking associative chemical structure to trends in bulk mechanics, our models enable the molecular engineering of tough and thermally processable elastomers.

Tuesday 4:25 Sweeney Ballroom B GN31

Polyelectrolyte complex-interpenetrating polymer network (PEC-IPN) hydrogels: Influence of covalent network molecular weight

Holly Senebandith[1], Fahed Albreiki[2], Defu Li[2], and Samanvaya Srivastava[2]
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Polyelectrolyte complexes (PEC) hydrogels, formed by mixing oppositely charged block polyelectrolytes, feature versatile microstructures, rapid self-assembly, self-healing properties, and environmental responsiveness. Recently, interpenetration of PEC and covalent networks has emerged as an effective strategy to create polyelectrolyte complex/covalent interpenetrating polymer networks (IPN) hydrogels. However, the influence of cross-linkable precursor chain length or the covalent mesh size on the PEC-IPN hydrogel properties remains unclear. In this work, we employed photo-crosslinkable poly(ethylene glycol) diacrylate (PEG) with varying molecular weights to investigate the influence of PEG precursor molecular weight and network mesh size on the microstructures, shear moduli, and tensile properties. Introduction of PEG chains led to disorder-order and order-order transitions of PEC networks and resulted in lower shear moduli of the hydrogel. After photo-crosslinking, the resulting IPN hydrogels exhibited a higher shear and tensile strength, and these changes were strongly correlated with PEG molecular weight. A direct evidence of the role that cross-linkable polymers play was obtained using small angle neutron scattering (SANS) studies. This work establishes a simple relationship between cross-linkable chain length and PEC-IPN hydrogel properties - providing a reference for designing hydrogels with well-defined physical and mechanical properties.

Tuesday 4:45 Sweeney Ballroom B GN32

How gel architecture controls ductility and dissipation in single and double network gels

Mauro L. Mugnai, Rose B. Tchuenkam, and Emanuela Del Gado
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We study yielding and hysteresis in single and double network gel models. To this end, we perform mechanical tests and analyze the hysteresis under large shear deformation, strain localization, and subsequent failure or yielding [1,2,3]. In our simulations, the microscopic underpinnings can be identified in the different degrees of non-affine motion and local stresses, which can have significant implications for the formation of adhesive contacts, ductility and brittleness of the gels. We find that the hysteretic behavior qualitatively changes from a single network gel to a double network one, even when all is kept the same and only interspecies interactions are changed. We also find that the specific double network architecture also dramatically affects the ductility and brittleness. We discuss the possible implications for constitutive models and in the light of recent experiments.

References: [1] Colombo, Jader, and Emanuela Del Gado. "Stress localization, stiffening, and yielding in a model colloidal gel." Journal of rheology 58.5 (2014): 1089-1116. [2] Mugnai, Mauro L., Rose Tchuenkam Batoum, and Emanuela Del Gado. "Interspecies interactions in dual, fibrous gels enable control of gel structure and rheology." Proceedings of the National Academy of Sciences 122.19 (2025): e2423293122. [3] Rose Tchuenkam Batoum, Mugnai, Mauro L., and Emanuela Del Gado. "Hysteretic behavior in double networks." (In preparation 2025)

Tuesday 5:05 Sweeney Ballroom B GN33

Strain softening-stiffening of composite hydrogels composed of biopolymer and colloidal microfibrous networks

Chenxian Xu, Yug C. Saraswat, Mushtaq A. Shaikh, Nazanin Shakoury, Pedro Henrique Wink Reis, and Lilian Hsiao
Department of Chemical and Biomolecular Engineering, North Carolina State University, Raleigh, NC 27606, United States

Understanding the transient rheology of biopolymer hydrogels is crucial for applications in tissue engineering, pharmaceuticals, food science, biosensors, and 3D printing. Single-component hydrogels exhibit nonlinear rheological responses including strain softening-stiffening transition due to microstructure deformation, such as fiber bending, buckling, and sliding. However, the connection between the rheological behaviors of multicomponent hydrogels and the corresponding dynamic microstructure evolution remains poorly understood. In this study, we investigate a composite hydrogel system comprising two contrasting networks: a strain-stiffening agarose matrix and a strain-softening network of chitosan dendritic colloids. The chitosan colloids form microfiber bundles via van der Waals interactions in the composite hydrogels, and connect with the agarose networks through hydrogen bonding. Remarkably, the composite hydrogels exhibit a strain softening-stiffening transition with low agarose concentration (< 1 mg/mL), with the chitosan networks reinforcing the hydrogels without compromising fracture strain. Using confocal rheometry, we link the real-time microstructure evolution of the composite hydrogels with the rheological responses, revealing that the strain softening-stiffening transition arises from the interplay between agarose fiber stretching and chitosan microfiber bundle bending. These findings provide new insights into the design of multifunctional hydrogels with tunable mechanical properties, advancing their potential in biomedical and industrial applications.

Symposium SM
Polymer Solutions, Melts and Blends

Organizers: Amanda Marciel, Ben Yavitt and Piyush Singh

Tuesday 1:30 Coronado + DeVargas SM23

An elasto-viscoplastic approach to polymer rheology

Arturo Winters, Jan Vermant, and Theo A. Tervoort
Department of Materials, ETH Zurich, Zurich, Switzerland

This presentation explores the rheology of polymer melts and solutions through the lens of a standard elasto-viscoplastic Maxwell model. This simple one-mode building block emphasizes the role of recoverable strain-a tensorial measure of the elastic deformation stored in the material, which would be recovered upon removal of all external forces.

Building on the GENERIC (General Equation for the Non-Equilibrium Reversible-Irreversible Coupling) framework, we derive thermodynamically consistent evolution equations grounded in this recoverable strain concept [1]. From this foundation, we propose a particularly simple closed-form evolution equation for the stress tensor. Despite its simplicity, the model captures key nonlinear rheological behaviors using only linear material input data.

Analytical solutions are presented for stationary states under common flow conditions. The multi-mode version of the model is evaluated against experimental data from elongational, shear, and superposed flows of polymer melts. We benchmark its performance against established nonseparable constitutive models, particularly the Leonov model, which shares structural similarities, and we discuss the relation of our model to the well-known empirical Cox-Merz relation.

To enhance adaptability, we introduce two optional non-linear parameters to tailor the model to specific material responses. We also discuss thermodynamically consistent modifications, highlighting the model's flexibility and extensibility.

This work demonstrates that using recoverable strain as a central concept allows strongly nonlinear effects-such as shear thinning and strain hardening-to be incorporated within a framework that uses only linear viscoelastic input parameters.

References:
1. Markus Hütter and Theo A. Tervoort, *J. Non-Newtonian Fluid Mech.*, **152** (2008), 53-65.

Tuesday 1:50 Coronado + DeVargas SM24

Inherent spatial heterogeneity in polystyrene/polyisoprene block copolymers

Bret W. Tantorno and Gregory B. McKenna
Department of Chemical and Biomolecular Engineering, North Carolina State University, Raleigh, NC 27606, United States

Investigating the relationship between spatial and dynamic heterogeneity by leveraging the inherent heterogeneity in block copolymers can provide valuable insights into their dynamic behavior. This study focuses on the viscoelastic properties of unique polystyrene/polyisoprene (PS/PI) block copolymers [1], where the main chain consists of a randomly synthesized sequence of PS and PI monomers. Although random, this PSPI chain is considered a homogenous blend of the two components. Heterogeneity is then introduced by attaching a 10,000 g/mol block of either PS or PI to the PSPI chain, either at the end or in the middle. This structural heterogeneity occurs on a length scale of approximately 1.0 to 2.4 nm and may extend further due to block aggregation. Despite this built in heterogeneity, the viscoelastic behavior of these block copolymers shows little to no evidence of dynamic heterogeneity, except for a minor deviation near the glass transition temperature. This small deviation may be due to the blocks having a different temperature dependency in their relaxation behavior than the random chain. This observation is based on van-Gurp Palmen (vGP) plots, which are sensitive to the breakdown of time-temperature superposition (TTS). The absence of dynamic heterogeneity, despite the presence of distinct spatial heterogeneity, suggests that the two are not inherently linked. Since the spatial heterogeneity in these block copolymers exists on such a small scale, the samples appear to exhibit a single relaxation mechanism, rather than two distinct mechanisms for PS and PI that would otherwise lead to the breakdown of TTS.

[1]. L. W. Taylor, R. D. Priestley, and R. A. Register, "Control of Solution Phase Behavior through the Block-Random Copolymer Sequence," Macromolecules, 2024, **57**, 916-925.

We thank the US National Science Foundation under grant # 2219327 and Lauren Taylor, Richard Register and Rodney Priestley, from Princeton University for supplying the block copolymers.[1]

Tuesday 2:10 Coronado + DeVargas SM25

PEO/PMMA blend dynamics revisited - a van Gurp-Palmen analysis

Bret W. Tantorno, Tuyen T.T. Truong, Lori M. Hoover, and Gregory B. McKenna
Department of Chemical and Biomolecular Engineering, North Carolina State University, Raleigh, NC 27606, United States

The relationship between dynamic and spatial heterogeneities in polymer blends remains an important question in understanding their viscoelastic behavior. In this study, we examine the viscoelastic properties of poly(ethylene oxide) (PEO) and poly(methyl methacrylate) (PMMA) blends, including compositions traditionally regarded as miscible. Our results reveal that although time-temperature superposition (TTS) seems to describe the data, notable differences become evident through the lens of a van Gurp-Palmen (vGP) analysis. While earlier studies have concentrated on low-frequency (terminal) behavior, we extend the analysis into the glassy regime to investigate relaxation dynamics across a broader temperature range. Below 30 wt% PEO, the blends show thermal and dynamic miscibility in the rubbery and terminal regimes. However, near the glass

transition temperature (T_g), vGP plots indicate a failure of TTS, suggesting small-scale heterogeneities that would infer immiscibility. These observations were reinforced by complementary wide-angle X-ray scattering (WAXS) and ultra-small-angle X-ray scattering (USAXS) results, which reveal nano-scale heterogeneities. The findings demonstrate the sensitivity and usefulness of vGP plots for analysis of dynamic heterogeneity that relates back to spatial heterogeneity in the material's structure. Our analysis also considers the influence of residual solvent in the PMMA dominant regions, which modifies both T_g and the relaxation behavior.

We thank the US National Science Foundation under grant # 2219327 and Ran Tao and Fan Zhang from the Materials Measurements Science Division at the National Institute of Standards and Technology for the WAXS and SAXS measurements.

Tuesday 2:30 Coronado + DeVargas SM26

Immiscible polydimethylsiloxane and polybutadiene vitrimer blends

Nat Torres, Daniel C. Barzycki, and Ralm G. Ricarte
Chemical and Biomedical Engineering, FAMU-FSU College of Engineering, Tallahassee, FL, United States

Vitrimers are polymer networks cross-linked by dynamic covalent bonds that undergo associative exchange, wherein new bonds form before existing ones break. This mechanism preserves network connectivity while permitting topological rearrangements, leaving vitrimers insoluble yet readily reprocessable at elevated temperatures. Converting a conventional polymer into a vitrimer improves mechanical strength, increases chemical resistance, and enhances interfacial adhesion with other polymers. Consequently, vitrimers offer a promising route to compatibilize otherwise immiscible polymers. In this work, we investigate immiscible vitrimer blends of polydimethylsiloxane (PDMS) and polybutadiene (PB) containing dioxaborolane cross-links that undergo associative exchange. To form the blends, we use photo-initiated thiol-ene click chemistry to cross-link PDMS and PB in solution. We systematically varied the PB weight fraction (w_{PB}). Morphological characterization revealed multiscale structure. Scanning electron microscopy showed that the blends contain micron-sized droplets of the minor polymer within a matrix of the major component, whereas small angle X-ray scattering detected nanometer-sized aggregates at select w_{PB} values. For rheology, small amplitude oscillatory shear and creep were used to measure the rubbery plateau modulus (G_p) and rheological activation energy (E_{rh}), respectively. Surprisingly, both G_p and E_{rh} were essentially independent of w_{PB}. These findings suggest that cross-link exchange primarily governs the rheology of immiscible vitrimer blends.

Tuesday 2:50 Coronado + DeVargas SM27

Designing mercury-free photoelastic polyurethane particles

Krishnaroop Chaudhuri, Hale Burke, Brandon Hayes, and Nathalie M. Vriend
Paul M. Rady Mechanical Engineering, University of Colorado Boulder, Boulder, CO 80309, United States

Photoelastic polymer particles have been widely used to study the internal stress distributions in phenomena involving granular materials such as landslides, avalanches, hopper flow. Polyurethane remains a popular choice of material for fabricating photoelastic particles owing to its cost, tunability, optical and mechanical properties, and ease in particle molding. However, the state-of-the-art grade of polyurethane used to mold photoelastic particles contains a not-insignificant amount of toxic organomercury. This poses a risk to both users and the environment. In our work, we fabricated photoelastic particles from numerous commercially available polyurethane resins that are purportedly mercury-free. We tested the rheological and stress-optical properties of each and found an optimal candidate as a viable replacement for the state-of-the-art yet toxic material. To explore whether this new polyurethane resin can be tuned to improve its requisite stress-optical properties beyond what is currently possible, we studied its photoelastic dependence on its polymer microstructure and morphology using shear rheology, dynamic mechanical analysis (DMA) and differential scanning calorimetry (DSC). We altered the microstructure by creating blends of polyurethane and ethylene glycol fillers, which altered the crystalline domains of their networks. We then studied the consequent change in the photoelastic properties of these blends. These mercury-free polyurethane particles serve as a a viable replacement for the state-of-the-art materials, owing to being free of organomercury, and having similar rheological and stress-optical characteristics as the latter.

Symposium FR
Special Session: Future of Rheology Speakers (Mini Session)

Organizers: Matt Helgeson, Elise Chen and Arshiya Bhadu

Tuesday 3:45 Coronado + DeVargas FR1

Rigidity development in shear-thickened dense suspensions: Contact network and motion correlation analysis

Michel Orsi[1], Rahul Pandare[2], Bulbul Chakraborty[3], and Jeffrey F. Morris[2]
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We investigate discontinuous shear-thickening (DST) and the approach to shear jamming (SJ) in dense, non-Brownian suspensions composed of monodisperse and bidisperse particles, with size ratios up to 4:1. Simulations are performed using the Lubrication Flow-Discrete Element Method (LF-DEM), a well-established framework that combines hydrodynamic lubrication interactions with discrete particle contacts, incorporating frictional contact forces that activate above a critical stress threshold. Our analysis focuses on the evolution of the contact network during shear and its coupling to particle-scale dynamics, particularly spatial and temporal correlations in both translational and rotational fluctuations. We observe that, in the frictionally contacting regime, rotational motion becomes strongly correlated over long ranges, signaling the emergence of collective dynamics linked to the formation of system-spanning contact structures. To probe the origins of this behavior, we examine the onset of

contact percolation and the development of rigidity through geometric and topological measures of the network. Specifically, we relate changes in the stress response to evolving network features such as k-core structures and topological invariants derived from persistent homology analysis of the contact force network. These results provide a detailed picture of how microstructural evolution under shear governs macroscopic rheology, offering new insights into the dynamical signatures of DST and the critical transition to SJ.

Tuesday 4:05 Coronado + DeVargas FR2

Measuring and modeling deformations of topologically-defined polymers using in situ capillary rheo-SANS

Anukta Datta[1], Siobhan Powers[1], Xiaoyan T. Wang[2], Ryan P. Murphy[3], Kathleen M. Weigandt[3], Patrick T. Underhill[2], and Matthew E. Helgeson[1]

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Applications of high molecular weight dilute polymers typically involve extreme shear rates that cause nonlinear deformations and chain scission. Although various microscopy methods have successfully resolved single-molecule deformations for specific biopolymer systems, these techniques are inaccessible to conventional, synthetic polymers undergoing deformation in high shear flows. We present new in situ small-angle neutron scattering measurements using a high-shear capillary rheometer to simultaneously characterize the microstructure and rheology of topologically complex polymers. The resulting scattering is interpreted using a new modeling framework, Gram-Charlier analysis of polymer scattering (G-CAPS), that fingerprints nonlinear deformations of polymers through non-Gaussian moments of the segment density distribution. The method is validated using synthetic data from Brownian dynamics simulations, and applied to capillary rheo-SANS measurements on a series of topology-controlled polymers in high shear rate flows to test the influence of chain topology and extensibility on non-Gaussian polymer deformations. We anticipate that capillary rheo-SANS in combination with G-CAPS will provide powerful new tools to understand and engineer the molecular rheology of polymer fluids.

Tuesday 4:25 Coronado + DeVargas FR3

Nested traveling waves underlying elastoinertial turbulence

Manish Kumar

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Polymer additives are commonly used in pipeline transport of liquids to reduce turbulent drag and hence save pumping cost or liquid transfer time. The emergence of elastoinertial turbulence, a chaotic flow state resulting from the interplay between inertia and elasticity, restricts drag reduction through polymer additives beyond a limit. We investigate the dynamics of elastoinertial turbulence using a modal decomposition technique and discover that the chaotic dynamics of elastoinertial turbulence in channel flow is predominantly composed of a collection of self-similar nested traveling waves. The structure of the most dominant traveling mode exhibits shift-reflect symmetry similar to the viscoelasticity-modified Tollmien-Schlichting (TS) wave, where the velocity fluctuation in the traveling mode is characterized by the formation of large-scale regular structures spanning the channel height and the polymeric stress field is characterized by the formation of thin, inclined sheets of high polymeric stress localized at the critical layers near the channel walls. The formation of sheets of high polymeric stress at the critical layer of each structure acts like "walls" for the next-faster traveling structure and hence leads to the emergence of a nested family of traveling waves.

Tuesday 4:45 Coronado + DeVargas FR4

Strain shift measured from stress-controlled oscillatory shear: Evidence for a continuous yielding transition and new techniques to determine recovery rheology measures

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Understanding the yielding of complex fluids is an important rheological challenge that affects our ability to engineer and process materials for a wide variety of applications. Common theoretical understandings of yield stress fluids follow the Oldroyd-Prager formalism in which the material behavior below the yield stress is treated as solidlike, and above the yield stress as liquidlike, with an instantaneous transition between the two states. This formalism was built on a quasi-static approach to the yield stress, while most applications, ranging from material processing to end user applications, involve a transient approach to yielding over a finite timescale. Using stress-controlled oscillatory shear experiments, we show that yield stress fluids flow below their yield stresses. This is quantified through measuring the strain shift, which is the value about which the strain oscillates during a stress-controlled test and is a function of only the unrecoverable strain. Measurements of the strain shift are, therefore, measurements of flow having taken place. These experimental results are compared to the Herschel-Bulkley form of the Saramito model, which utilizes the Oldroyd-Prager formalism, and the recently published Kamani-Donley-Rogers (KDR) model, in which one constitutive equation represents the entire range of material responses. Scaling relationships are derived, which allow us to show why yield stress fluids will flow across all stresses, above and below their yield stress. Finally, derivations are presented that show strain shift can be used to determine average metrics previously attainable only through recovery rheology, and these are experimentally verified.

Tuesday 5:05 Coronado + DeVargas FR5

Rheology and dispensing of real and vegan mayo: The chickpea or egg problem

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The rheology, stability, texture, and taste of mayonnaise, a dense oil-in-water (O/W) emulsion, are determined by interfacially active egg lipids and proteins. Often mayonnaise is presented as a challenging example of an egg-based food material that is hard to emulate using plant-based or vegan ingredients. We characterize the flow behavior of animal-based and plant-based mayo emulsions seeking to decipher the signatures that make the real mayonnaise into such an appetizing complex fluid. We find that commercially available vegan mayos can emulate the apparent yield stress and shear thinning of yolk-based mayonnaise by the combined influence of plant-based proteins (like chickpea) and polysaccharide thickeners. However, we show that the dispensing and dipping behavior of egg-based and vegan mayos display striking differences in neck shape, sharpness, and length. The analysis of neck radius evolution of these extension thinning yield stress fluids reveals that even when the power law exponent governing the intermediate pinching dynamics is similar to the exponent obtained from the shear flow curve, the terminal pinching dynamics show strong local effects, influenced by interstitial fluid properties, finite drop size, and capillarity.

Tuesday 5:25 Coronado + DeVargas FR6

Size- and charge-dependent microrheology in live Escherichia coli: Impact of confinement and macromolecular interactions on particle dynamics and localization

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The crowded bacterial cytoplasm is comprised of millions of biomolecules spanning several orders of magnitude in size and electrical charge. This complexity is hypothesized as the source of rich spatial organization and apparent anomalous diffusion within cells, yet direct experimental and computational evidence for this remains limited. Here, we combine a colloidal whole-cell computational model with advanced three-dimensional single-particle tracking to study molecular localization and dynamics in live Escherichia coli cells. Using biplane microscopy, we track the 3D motion of bacterial Genetically Encoded Multimeric nanoparticles (bGEMs) with sizes from 20 to 50 nm and charges ranging from -3240 to +2700 e. Our computational model explicitly represents the size and charge distribution of cytoplasmic macromolecules and the porous bacterial nucleoid structure, enabling exploration beyond experimental spatial and temporal limits. We identify entropic (size-based) and electrostatic (charge-based) mechanisms that drive spatial segregation, finding smaller (20 nm) particles enriched within the nucleoid, while larger or positively charged particles are excluded. This localization emerges from the interplay of cytoplasmic polydispersity, nucleoid architecture, and interactions with cellular components such as ribosomes and DNA. Critically, we show that previously reported subdiffusive particle dynamics are primarily due to geometrical confinement rather than intrinsic anomalous diffusion. Although single-molecule tracking at moderate temporal resolutions suggests universal subdiffusion, simulations with higher temporal resolution clarify that confinement within the nucleoid and cell boundaries governs this apparent anomalous diffusion. Thus, our results provide new insight into intracellular transport, highlighting the crucial roles of confinement and macromolecular crowding in biomolecular localization and dynamics.

Symposium AR
Applied Rheology for Industrial Applications

Organizers: Hammad A. Faizi and Antonio Perazzo

Tuesday 1:30 Peralta + Lamy AR11

The evolution of parabolic focal conic defects in concentrated liquid crystalline detergent formulations

Matthew Kaboolian[1], Parth U. Kelkar[1], Marco Caggioni[2], Seth Lindberg[2], and Kendra A. Erk[1]
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Concentrated soap formulations reduce the amount of water used during manufacturing and could provide significant economic and environmental savings. Unfortunately, concentrated formulations can form liquid crystalline phases which significantly impact processability. These liquid crystals highlight a need to characterize the mechanical properties of these formulations at different length scales to understand both manufacturing and formulation design. Concentrated formulations of the common anionic surfactant sodium laureth sulfate (SLEnS), at 70 wt.% in water, forms an aligned lamellar bilayer phase under extreme confinement. Upon heating the aligned lamellae generate parabolic focal conic defects (pFCDs) whose structure and formation were analyzed using cross-polarized microscopy, oscillatory rheometry, and small angle X-ray scattering. The shape, periodicity, and onset temperature of pFCDs were shown to vary with degree of ethoxylation and low-concentration additives. Specifically,

the pFCD formation temperature decreased from 35°C (SLE1S) to 29°C (SLE3S) driven by a reduction in bilayer spacing. SLE3S was more deformable than SLE1S and was more affected by plasticizers (propylene glycol) whereas SLE1S was sensitive to the desiccants (sodium chloride). The analysis of defect morphology enables the separation of bilayer-scale bending and compression properties and provides a potential framework for analyzing other concentrated surfactant formulations, microlens arrays, and nano-templates.

Tuesday 1:50 Peralta + Lamy AR12

Tribo-rheological evaluation of facial cleansers for post-wash frictional sensory on synthetic skin templates

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We developed a vitro-evaluation to measure the "after-feel" effect for facial cleanser products by using rheo-tribology. While traditional rheological measurements are essential for formulation stability and flow behavior, they do not capture the dynamic skin-feel during and after product use. In this study, we integrate tribology with rotational Rheometry to quantify the frictional behavior of rinse-off facial cleansers post-application, simulating realistic use conditions. A synthetic template was used as the substrate for depositing cleansing products. The substrate was washed, rinsed and dried with different face cleansers and coefficient of friction (CoF) was evaluated as a function of sliding speed and normal force. A comparative analysis across different products revealed distinct frictional profiles correlating well with perceived sensorial feel (e.g. drag/ friction) on skin. This protocol may establish a new in vitro method towards designing desired face cleansing products.

Tuesday 2:10 Peralta + Lamy AR13

Microstructure-informed rheological models for effective formulation design

Julie Hipp, Marco Caggioni, and Ellie Martin
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In the cosmetic and pharmaceutical sectors, polymers are often used as active ingredients and rheological modifiers to improve the stability and performance of a formulation. Given the vast array of polymer types and variations available on the market, formulators often encounter a complex combinatorial challenge in choosing the right polymer type and concentration for their formulations. In this study, we propose a framework that facilitates the design of stable formulations by broadly classifying polymers as linear or cross-linked microgels. As part of this framework, we propose the integration of microstructure-informed rheological models (MIRMs) to characterize the effects of polymers in solution and, ultimately, to guide the formulation process. By combining models and measurement techniques for material properties, we show how the proposed approach can not only accelerate the formulation process but also extends the formulation space to include other colloidal rheology modifiers. This research is particularly relevant in light of new sustainability targets, which demand the substitution of traditionally used polymers from non-renewable sources.

Tuesday 2:30 Peralta + Lamy AR14

Linear and non-linear rheological behavior of ice cream

Azeem Alvi and Sergio I. Martinez-Monteagudo
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The complex multiphase ice cream structure is typically investigated by its texture, meltdown, viscosity, small amplitude oscillatory shear, and overrun. The whey-to-casein ratio in the ice cream is crucial as it significantly impacts the texture, mouthfeel, and stability of the final product. To understand the impacts of varying the whey to casein ratio in the ice cream mixes, it is imperative to study the structure of ice cream in the non-linear region under large deformation to provide practical insights for optimizing ice cream formulations and processing conditions. In this work, we will discuss three protein ratios of 20/80, 12/87, and 59/41 with a homogenization pressure of 3k Psi. Large Amplitude Oscillatory Shear (LAOS) was utilized to probe the non-linear rheological behavior of the ice cream mixes. The elastic stresses for the mixes exhibited strain rate softening behavior; at lower strain rates, there was a more significant viscous contribution, while as the strain rate increased, the mixes behaved more like an elastic solid. For viscous stresses, behavior at a low strain rate was dominated by the linear elastic response, but, as the strain rate increased, the curves became elongated ellipses, revealing a transition to viscous dominance and pronounced shear thinning.

Tuesday 2:50 Peralta + Lamy AR15

Small-volume protein solution rheology

Paul Salipante, Vivek Prabhu, and Steven Hudson
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The structure, rheology, and phase behavior of protein solutions are important for the manufacturing process of protein-based pharmaceuticals and for administration by sub-cutaneous injection. The viscosity and other properties of these solutions depend on temperature, pH, protein concentration, and the composition of excipients, because these variables affect the molecular interactions. Since the experimental variable space is significant, data collection requires significant labor and material. To improve throughput, we have automated measurements on the small-volume capillary rheometer (SVR) to make these viscosity measurements across a wide range of shear rate and as a function of temperature and composition routine while only using approximately 200 µL of sample. Similar automation methods are used to deliver samples to a flow cell for characterization using dynamic light scattering. Measurements with these automated methods are shown for different excipient conditions and compared to reference measurements.

Tuesday 3:45 Peralta + Lamy AR16

Bio-based additives as rheology modifiers for Hevea and guayule rubber latexes

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Colloidal rubber suspensions must flow through pumps and spray heads yet rapidly solidify after deposition, so tailoring their viscoelastic response with sustainable additives is a growing priority. Cellulose nanomaterials, sourced from agricultural residues and forestry side streams, offer renewability, low density, and a rich surface chemistry that can tune colloidal interactions without petroleum surfactants. Although many solid rubber composites show strength gains from cellulose reinforcements, the suspension-stage rheology that governs dipping, spraying, and printing remains underexplored, particularly for high-aspect-ratio cellulose nanofibrils (CNF) and shorter cellulose nanocrystals (CNC) in latexes. This study will build systematic rheological maps for commercial Hevea brasiliensis latex and centrifuge-purified Parthenium argentatum (guayule) latex formulated with CNF or CNC at solids levels used in production. Small-amplitude frequency sweeps will track shifts in storage modulus G', loss modulus, and relaxation spectra across processing temperatures. Steady-shear tests will determine zero-shear viscosity, shear-thinning index, and yield stress, establishing how each nanomaterial widens or narrows the workable window. Confocal laser scanning microscopy on shear-arrested droplets will visualize the spatial distribution of CNF and CNC inside the latex matrix, linking microstructure to rheological behavior and providing insight into depletion softening, reversible particle bridging, or percolated fiber networks. Comparing the complete data sets for CNF-filled and CNC-filled systems will reveal whether depletion softening, reversible bridging, or percolated fiber networks dominate, and whether guayule latex requires different modifier strategies from Hevea. The resulting charts will guide greener, allergen-reduced latex formulations and extend fundamental understanding of bio-particle suspensions as rheology modifiers.

Tuesday 4:05 Peralta + Lamy AR17

Charge transport trade-offs in colloidal suspension electrodes under flow

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Electrically conductive, redox-active, and/or energy-storing colloidal particles suspended in electrolyte solutions have been utilized as flowable suspension electrodes (FSEs) for electrochemical energy conversion and storage [1,2]. These flowable electrodes offer the potential to enable electrochemical reactor designs with high energy and power densities, making them promising candidates for grid-scale energy storage applications. However, a comprehensive understanding of the trade-offs among rheological behavior, charge transport, and electrochemical kinetics in FSE systems remains limited[3,4]. This knowledge is essential for the rational design and optimization of efficient electrochemical reactors using FSEs.

Attractive colloidal suspensions form dynamic particle networks under flowing conditions depending on colloid volume fraction, inter-colloid attraction, and shear rate. In this study, we combine Stokesian dynamics simulations, charge transport modeling, and rheological and electrochemical experiments to investigate electronic transport through particle networks and ionic transport through tortuous solvent pathways in flowing colloidal suspensions. As shear rate increases, particle contacts are broken, leading to a reduction in electronic conductivity[4]. Conversely, increased flow enhances mixing around the particles, which improves ionic transport[4]. In this talk, we will explore the trade-offs between electronic and ionic transport in the context of flowable suspension electrodes for redox flow batteries.

References:
1. Petek et. al., 2015, Journal of Power Sources, 294, pp.620-626.
2. Sinclair et. al., 2022, MRS Energy & Sustainability, 9(2), pp.387-391.
3. Lin et. al., 2022, Proceedings of the National Academy of Sciences, 119(29), p.e2203470119.
4. Majji et. al., 2023, Journal of The Electrochemical Society, 170(5), p.050532.

Tuesday 4:25 Peralta + Lamy AR18

Towards the rheological fingerprint of protein-enriched yogurts

Andrea G. Soler-Sanchez[1], Joy I. Agbawodike[1], Azeem Alvi[2], and Sergio I. Martinez-Monteagudo[2]
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Yogurts fortified with protein concentrates are increasingly used as a primary ingredient in beverages, frozen desserts, and novelty products, where they undergo large deformations during further processing. In this work, the linear and nonlinear rheological behavior of protein-enriched Greek-style yogurt (15% total solids) formulated with varying whey protein to casein ratios (13/87, 20/80, and 65/35) utilizing micellar casein concentrate (MCC85), milk protein concentrate (MPC80), and whey protein concentrate (WPC80) was investigated. Yogurts were prepared in triplicate via a standardized process: skim milk fortification (43-49°C, 30 min), heat treatment (90°C/10 min), cooling (43°C), inoculation with starter cultures (0.03% wt/wt), fermentation at 43°C for 5-6 h (final pH 4.6 ± 0.1), and cold storage (5°C, 21d). Compositional analysis presented crude protein contents of 29.40 ± 0.8%, 26.69 ± 0.5%, 27.13 ± 0.6%, for 13/87, 20/80, and 65/35, respectively. Small amplitude oscillatory shear test showed that the 13/87 ratio exhibited the longest linear viscoelastic region (critical strain ?c= 48.95%) compared to the 20/80 (30.46%) and 65/35 (35.83%). Frequency sweeps indicated weak gel-like behavior across all samples (G' > G"). Large amplitude oscillatory shear analysis indicated moderate nonlinear elasticity (e3/e1 > 0), with elastic Chebyshev coefficient ratios of 0.45, 0.60, and 0.50, for 13/87, 20/80, and 65/35 ratios, respectively. The 20/80 ratio showed an ability to recover from large deformations as indicated by the highest degree of intracycle strain stiffening (S = 0.69). Lissajous-Bowditch curves showed strain-thinning behavior for the three formulations. Scanning electron microscopy images displayed that the 65/35 yogurt had a compact protein network with small pores and dense crosslinks, which corresponded to the minimum syneresis (32.51 ± 2.54%)

and hardness (2.01 ± 0.08 N) after 21 d of cold storage. The outcomes of this investigation indicate that protein composition significantly influences the st

Tuesday 4:45 Peralta + Lamy AR19

Oscillation thermo-rheometry as a tool to study the melting behavior of high protein ice creams

Nana Tweneboah, Kevin Pizarro, John Olatunde, and Sergio I. Martinez-Monteagudo
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High-protein ice cream consists of a protein increment of about 4 to 6-fold compared with regular ice-cream. Industrially, these ice creams are formulated with blends of proteins to achieve the desirable concentration of protein (6-8%). Such concentration of protein alters the flow behavior of the mix and therefore the resulting quality of the ice cream. This work aims to model the melting curves (torque vs temperature) of ice creams formulated with four different sources to achieve 7.5% of protein, including WPC-80, MPC-85, MCC, and calcium caseinate. The melting behavior was evaluated through oscillatory thermorheometry within the temperature range of -20 to 10ºC. All samples exhibited three distinctives zones: zone I (-20 to -10ºC), zone II (-10 to 0ºC) and zone III (0 to 10ºC). The tangent loss factor (tan d=G''/G') was also used to evaluate the melting curve, where the temperature corresponding to the highest value of tan d varied from -4.4 to 9.8ºC, depending on the protein source. For instance, the highest value of tan d (0.61 ± 0.02) was found at -5.4 ± 0.15ºC when WPC-80 was added. Contrary, the highest tan d (0.59 ± 0.03) was found at -9.8 ± 0.18ºC when calcium caseinate was used as a protein source. The melting curves were modeled using four equations: Logistic model, the Gompertz model, the Richard model, and the Hill model. The experimental melting curves were adequately represented by the Logistic model, judging by a number of criteria (R2=0.999, adjusted R2=0.999, and Akaike probability = 0.294). The analysis of the oscillatory curves can be used to classify the melting behavior of high-protein ice creams.

Symposium AM
Additive and Advanced Manufacturing

Organizers: Anthony Kotula and Xiaoyu Tang

Tuesday 1:30 O'Keeffe + Milagro AM1

Printability and rheology of colloidal inks under high-frequency pulsed strain histories

Laurel Kroo[1], More Rishabh[1], Tri Tuladhar[2], and Gareth H. McKinley[1]
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Complex time-varying strain histories are commonly used in industrial inkjet printing and paint-deposition technologies to facilitate droplet ejection, but the physical mechanisms that underpin "optimal" waveforms for ejection efficiency (especially in the presence of viscoelasticity) remain elusive. In this study, we investigate the transient rheological response of particle-laden viscoelastic fluids using a piezo-electric high-frequency rheometer (TriJet Limited). Specifically, we study a "model paint" formulated from polyisobutylene, polyalphaolefin and colloidal particulates (carbon black), suspended in a paraffinic oil-based solvent. The high-frequency compressional rheometer squeezes a thin disk of this fluid between two parallel plates at exceptionally high-frequencies (under sinusoidal oscillations up to 10,000 Hz), while simultaneously measuring the dynamic response of the system.? Using a lumped-parameter model of the squeeze flow rheometer, we begin by isolating the response of the fluid from the "plant", while the fluid is subjected to rapid trains of step-pulses (parameterized through the duty cycle, ramp time, period, and number of pulses). From the rheological characterization at high frequency, we find that this category of highly-filled colloidal fluid is well-represented with a fractional Kelvin-Voigt constitutive model. Using this model as a "virtual" fluid with a relaxation spectra representative of real, industrially relevant printing inks/paints- we systematically study the linear system response to a variety of waveform parameters. Finally, we explore the question of rheologically-meaningful objective functions for identifying an optimal waveform that maximizes droplet ejection performance. We compare this with observations on a range of fluids that vary in concentration of carbon black from 2% to 10% wt. and connect to potential mechanisms that affect printability.

Tuesday 1:50 O'Keeffe + Milagro *Keynote* AM2

Printability criterion for highly-filled inks for direct-ink write additive manufacturing

James J. Griebler[1], Jessica W. Kopatz[2], Simon A. Rogers[3], Alex S. Tappan[2], and Anne M. Grillet[2]
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Additive manufacturing enables the creation of unique, custom-designed hardware in a relatively timely and inexpensive manner. Direct-ink write operates by extruding a particle-filled "ink" onto a substrate in a desired pattern via extrusion through a syringe. The ability of an ink to be extruded onto a substrate in many layers and maintain the desired shape is what defines printability. Printability of inks has historically been investigated in an iterative manner by formulating and printing inks and then performing postmortem analysis of final parts. Our goal is to predict what range of particle loadings will print a high quality part. For applications with functional fillers, the challenge is to formulate inks with the highest possible particle loading that can still be printed. We have proposed a printability criterion based on the particle filler's maximum packing fraction calculated from small amplitude oscillatory shear experiments. This printability criterion is demonstrated to predict the range of optimal particle loadings over a range of hard particle fillers and blends. We then utilize statistical methods to develop a filler characteristics model to predict the maximum

packing fraction from particle analysis alone. These two methods paired together can significantly speed up development of new inks, increase the performance of material extrusion printing, and improve the stability of printed parts, with less wasted time and materials.

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Tuesday 2:10 O'Keeffe + Milagro AM3

Impact of polymer molar mass on stability of dense pastes during additive manufacturing

Blair Brettmann

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Improving the processing of dense paste composites is pivotal for the production of novel material formulations that meet performance demands and integrate with new technologies. There is a need in the field to define fundamental formulation-processing relationships that can be leveraged to address the challenging nature of developing and processing highly loaded particulate composites/dense pastes, especially in the area of additive manufacturing. One important challenge is the formation of heterogeneities in the particle spatial distribution of the dense pastes during processing. Dense pastes undergo particle network deformation under the complex shearing and pressure forces experienced during processing. Applied stresses that exceed the viscoelastic yield stress cause irreversible particle migration and heterogeneous particle microstructures. Heterogeneities are then solidified into the final composite and can hinder mechanical properties and performance. In this work, we examine the influence of polymer molar mass on heterogeneity formation during paste processing through rheological testing. The effects of polymer molar mass are deconvoluted from the effects of polymer solution viscosity by tuning polymer concentration to achieve viscosity matched binder solutions. Model bimodal suspensions of inert glass microparticles are employed and the total solids content is kept consistent at 61.4 vol%. Polymer binder concentration and molar mass are systematically varied using polyvinylpyrrolidone and polyethylene oxide polymers dissolved in water. We show that low molar mass binders at high concentrations have improved stability against settling and shear migration. The improved stability is attributed to balanced viscous dissipation and elasticity at small particle length scales. Elucidating the formulation-processing relationships between polymer formulation parameters and paste stability during additive manufacturing enables informed polymer selection during formulation development.

Tuesday 2:30 O'Keeffe + Milagro AM4

Embedding cell-Like rheology into 3D printed scaffolding for active and adaptable materials applications

Thomas E. Angelini

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Tissue cells probe their environment and, in response, modulate their own elasticity, shape, migration speed, and adhesiveness. In the case of mechanical sensing, cell elasticity is controlled by cytoskeletal pre-stress driven by molecular motors. While inspiration for autonomous materials can be drawn from the cell, relying on molecular motors involves challenges like the stability and distribution of motor proteins and a supply of ATP. To sidestep these limitations, we leverage materials that hold their configuration after large applied strains: packings of soft particles. One of the most useful rheological properties of packed micro-scale hydrogel particles (microgels) is their ability to quickly relax stress after imposing large strains, in contrast to polymer networks that store elastic energy and work to return to zero strain. In this talk I will show how combining the non-linear elasticity of biopolymers with the reconfigurability of microgels enables the development of 3D printable materials that exhibit dramatic changes in material properties in response to mechanical stimulus, with the ability to "lock in" a finite strain after stress is applied and then removed. The biopolymer network provides a shape memory effect, while the packed microgels provide a programmability effect. We demonstrate the shape-programmability and stability of these materials over the course of several days after imposing large deformations on molded structures. I will conclude by discussing how this material represents an athermal analog of the living cell - the canonical tunable biomaterial - and how we can add activity to these "cell mimicking" materials by seeding them with cells as sources of mechanical energy.

Tuesday 2:50 O'Keeffe + Milagro AM5

Stabilizing liquid threads in embedded 3D printing

Mohammad Tanver Hossain, Wonsik Eom, Sameh H. Tawfick, and Randy H. Ewoldt

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The stability of a liquid filament embedded within a yield-stress medium is governed by a balance between interfacial tension and the resistance of the supporting matrix. We asked a fundamental question: What is the smallest stable filament diameter achievable in embedded 3D printing, given a supporting matrix with a known yield stress? We found that the minimum diameter is governed by a previously unidentified critical plastocapillary number (yield-capillary number) [1], which captures the competition between capillary forces and the yield stress of the surrounding viscoplastic medium. When the plastocapillary number falls below a critical threshold, filaments break up due to capillary-driven instabilities. We were also motivated by another question: how can we push beyond this limit? To do so, we created a new embedded printing technique that rapidly solidifies the liquid filament upon deposition using a solvent exchange mechanism [2]. This strategy enables the formation of stable, ultra-thin filaments far below the predicted critical diameter, expanding the resolution frontier of embedded 3D printing additive manufacturing.

[1] Hossain M. T., W. Eom, A. Shah, A. Lowe, D. Fudge, S. H. Tawfick and R. H. Ewoldt, "The critical plastocapillary number for a Newtonian liquid filament embedded into a viscoplastic fluid," Journal of Non-Newtonian Fluid Mechanics, in revision. DOI: 10.2139/ssrn.5120697
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Tuesday 3:45 O'Keeffe + Milagro AM6

Rapidly recoverable yield stresses in Direct-Ink-Write printing of weight-supporting structures using polymers containing fumed silica and polyethylene glycol

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This study investigates the rheological properties that determine Direct Ink Writing (DIW) printability of weight-bearing structures in the absence of chemical reaction or temperature change. Such printability requires that the material possess a yield stress that can re-develop rapidly after the material microstructure producing the yield stress has been broken down through flow through a 3D printing nozzle. We explore the rheology and 3D printability of room-temperature thermoplastics containing structure-forming fumed silica, with particular focus on the ability of polyethylene glycol (PEG) to aid in rapid recovery of yield stress following high shear rates, including those in the printing nozzle. We show that ramp-up of shear rate to 1000 s-1 followed by ramp-down to low shear rates in a rheometer provides a measure of yield stress following high shear that correlates well with 3D printability. In melts of polydimethylsiloxane, polyisoprene, and polybutadiene, suitably high initial yield stress is obtained by adding fumed silica, but that in all cases, yield stress is lost and not readily recovered unless polyethylene glycol (PEG) is also added. The addition of PEG leads both to rapid recovery of yield stress in a rheometer and to 3D printability of tall slump cones, when neither is observed when PEG is absent. Additionally, we address reproducibility challenges caused by sensitivity to mixing and degassing protocols, and find a procedure that ensures consistency in rheological measurements. Our findings contribute to a generalized framework for linking rheological behavior with DIW printability, providing insights into material formulation strategies for advanced additive manufacturing applications.

Tuesday 4:05 O'Keeffe + Milagro AM7

Bridging microstructural information and swelling performance of emulsion-based edible films

Ezgi Pulatsu and Chibuike Udenigwe
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Film formation relies on creating cohesive molecular networks between the macromolecules, such as proteins, polysaccharides, lipids, and other film components. These networks are critical to obtaining good barrier properties to gases and good mechanical properties in edible packaging applications that will contribute to the shelf stability of food products. On the other hand, novel applications of edible films have emerged as substrates in four-dimensional (4D) printing, soft actuators, or wound healing, where different physicochemical and mechanical properties may be desired. Hence, establishing structure-function relationships based on microstructure and rheological information will be beneficial in evaluating their use and performance in their specific application. This study focused on creating oil-in-water (O/W) emulsion-based edible films, stabilized by gelatin and lecithin. Film-forming emulsions were prepared at three oil-to-water (O:W) ratios (1:99, 5:95, and 10:90 v/v). The film-forming emulsions were yield stress fluids, following the Herschel-Bulkley model, with solid-like properties in the linear viscoelastic region. Network strength and connectivity of emulsions were significantly different based on complex modulus as a function of frequency obtained via Power law model fitting ($p < 0.05$). The films were characterized by thickness (0.19-0.66 mm), weight (0.41-1.2 g), moisture content, and color. The dried films were then submerged in distilled water for 1 h to assess their swelling behavior. The film matrix properties and the volume of phases affected the response behavior of the samples, which is evident in the photomicrographs of film cross sections. Swelling rates of the films differed ($p < 0.05$), and their governing diffusion mechanism was less Fickian. Understanding the effects of the oil phase and surface-active agents on the response behavior provides insights for repurposing these films for future applications as novel substrates in 4D printing.

Tuesday 4:25 O'Keeffe + Milagro *Keynote* AM8

Addressing process challenges in direct chip attachment process

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Engineering Technology, Avery Dennison, Azusa, CA, United States

Direct chip attachment (DCA) is a semiconductor packaging process of connecting a microchip directly to a circuit board. One avenue to accomplish it is by jetting uncured anisotropic conductive adhesive onto designated connection spots on the board followed by depositing the microchips on top of the adhesive. The chips-adhesive-board assembly are then undergoing press and cure step in order to solidify the adhesive, hence cement the connection between the chips conductive pads and the board mechanically and electrically. Optimizing the process requires full understanding of all of the steps involved. In this paper, we are presenting studies in two steps of the process: Adhesive jetting and chips deposition. In adhesive jetting step, we are studying how nozzle geometry, adhesive rheology, and jetting rates can be tuned to deliver optimum drop volume consistently in prescribed locations. In microchips deposition step, we are studying sensitivity of adhesive spread and fill dynamics as function of deposition speed, alignment, and adhesive rheology. We will then present gaps in knowledge and technology needed in order to speed up the process.

Tuesday 4:45 O'Keeffe + Milagro AM9

Additive manufacturing of bidisperse ceramic suspensions

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The most promising ceramic additive manufacturing techniques rely on feedstocks containing small ceramic particles suspended in a solvent. The ideal feedstock will have two contradictory properties. First, the feedstock should have low viscosity, so it flows easily during processing, and second, the feedstock should have high solids loading to reduce shrinkage and increase final part density after sintering. Bidisperse suspensions circumvent some of the difficulties encountered in formulating ceramic feedstock, because a bidisperse suspension will have a lower viscosity

than a monodisperse dispersion at the same volume fraction due to more efficient packing. However, with this reduction in viscosity comes new manufacturing challenges; particles in bidisperse suspension can separate by size due to shear-induced migration. We examine the suitability of bidisperse suspensions as ceramic feedstocks through a combined experimental and computational approach. The feedstocks are characterized through detailed rheological measurements. We then use x-ray scattering combined with particle-level simulations to investigate the migration of particles during direct-ink write printing of our formulations. We determine how particle migration during printing is influenced by feedstock formulation and printing conditions and discuss strategies to minimize shear-induced migration during printing.

Tuesday 5:05 O'Keeffe + Milagro AM10

Formulation of ceramic clays and glazes with local materials of the Black Hills

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The Black Hills of South Dakota is a region that is rich in both geological (mineral) resources and culture. Among its geological assets is Fuson shale, which contains valuable industrial minerals, such as quartz, kaolin, and muscovite. These minerals make the shale potentially useful for a variety of applications of clay-based ceramics, including art, bricks, and surface coatings. Historically, the region was home to the Lakota tribes, who followed bison herds across the plains. Modern bison harvesting incorporates a commitment to sustainability by ensuring that all parts of the bison are used. One specific challenge was the utilization of bison bones, which became a central focus of this research. Leveraging both the mineralogical availability within the region and the available bison bones, this project developed two ceramic products: a clay body and a glaze (ceramic coating). While rooted in historical and cultural relevance, the project utilized modern manufacturing techniques and methods for material characterization. The clay body was processed using various techniques, including additive manufacturing, slip casting, and pressing. The glaze formulation was tailored to produce a vitreous bone-ash coating that enhances the mechanical properties of the material. Pre-firing characterization of the clays includes testing with shear rheology (viscosity, dynamic oscillatory shear, yield stress, and compression), and post-firing characterization includes microscopy, 3-point bend testing, microconstituent characterization, and densification. Rheological characterization was used to direct and optimize gum concentration in the glaze formulation.

Tuesday 5:25 O'Keeffe + Milagro AM11

Development of an experimental protocol for the evaluation of the buildability of fresh 3D printable concrete

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3D printing of concrete requires the material to exhibit both fluid-like and solid-like properties to be effectively pumped, extruded, and layered. Traditional evaluation methods primarily address the flow behavior of fresh concrete or the strength of hardened concrete, leaving a gap in understanding the printability during intermediate stages. Standard evaluation methods like slump tests and compressive strength measurements fall short in characterizing time-dependent deformation during printing. This study focuses on the buildability of 3D-printed concrete, defined as its ability to maintain structural integrity under self-weight and the load of successive layers. To assess buildability, the creep response-deformation under a constant load-was analyzed using short-term, long-term, and incremental creep tests. These methods were chosen to capture the immediate, progressive, and step-wise deformation behaviors that are critical for layer stability; providing insights into the time-dependent deformation characteristics. The primary objective is to quantify how creep behavior influences the stability of 3D-printed layers during the build phase. Results show that fresh concrete under a 250N load deforms about 3.5 times more than under a 25N load at the same age (30 minutes after mixing). Larger time gaps between load increments significantly reduced total deformation, with each subsequent increment showing diminished rates. Additionally, over long periods of applying low loads (12 hours), the long-term effects of deformation were found to be negligible. These findings highlight the nonlinear creep behavior of fresh concrete, suggesting that conventional models may underestimate its time-dependent effects. These insights can drive the development of enhanced predictive models, optimizing construction efficiency and reliability in large-scale 3D printing applications.

Symposium BL
Biomaterials, Bio-fluid Dynamics and Biorheology

Organizers: Rae Robertson-Anderson, Travis W. Walker and Jairo Diaz

Tuesday 1:30 Sweeney Ballroom C BL23

Micro-confinement drives the separation of active and passive matter

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Bacteria must navigate complex mechanical environments while swimming. Motility provides a significant evolutionary advantage, enabling access to narrow and confined regions that would otherwise be inaccessible to non-motile bacteria. This distinction has important implications for host infections caused by motile and nonmotile bacterial pathogens. Given the widespread occurrence of both bacterial types, understanding their behavior under confinement is of significant interest. In this study, we employed a microfluidic platform to confine and quantify their behavior. Motile cells readily penetrated narrow micro-channels of the device, overcoming drag through flagellar-driven hydrodynamic thrust, while non-motile cells were largely excluded. This led to the steady accumulation of motile cells within channels, regardless of reversals, highlighting their

natural tendency to segregate under confinement. Using fluorescence microscopy, we quantified channel occupancy in mixed populations, finding that confinement effectively separated mixtures over the timescale of a few minutes. Based on these observations, we designed a colloidal column with bead spacings mimicking micro-channel dimensions. The column achieved ~100% separation efficiency for mixed suspensions of motile and nonmotile E. coli. These results demonstrate a powerful bioseparation strategy for active and passive matter.

Tuesday 1:50 Sweeney Ballroom C BL24

Multicomponent vesicles in simple shear flow

Yiding Li[1], Anirudh Venkatesh[2], Charles Schroeder[3], and Vivek Narsimhan[2]
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In biology, cell membranes are often multi-component in nature, made up of multiple phospholipids and cholesterol mixtures that give rise to interesting phase separation and coarsening dynamics. In this talk, we consider the motion of a nearly spherical, giant unilamellar vesicle (GUV) in shear flow, where the lipid membrane is made up of a ternary mixture of a saturated phospholipid, an unsaturated phospholipid, and cholesterol. The bending energy of the vesicle is governed by the Helfrich model and the mixing energy is governed by a Landau-Ginzburg model with an order parameter that represents the phospholipid composition. We use spherical harmonics basis sets to come up with reduced order equations that solve the fluid flow (Stokes equations) in the limit of small deformations (small excess area), as well as the nonlinear Cahn-Hilliard equations for phospholipid distribution on the membrane surface. We observe a wide range of dynamical regimes for shape and concentration, including tank treading, phase treading, swinging, and tumbling depending on the characteristic dimensionless numbers governing the line tension, average bending stiffness, and shear rate. This talk discusses what gives rise to the observed shape and phase separation behaviors. We conclude by comparing our results to preliminary experiments involving giant unilamellar vesicles (GUVs) composed of DOPC:DPPC:cholesterol. Using advanced microfluidic platforms and optical techniques, we tracked fluorescently labeled GUVs under simple shear flow, enabling precise control of shear rates. These experiments provide insight into how membrane phase behavior and coarsening dynamics are influenced by nonequilibrium forces and flow.

Tuesday 2:10 Sweeney Ballroom C BL25

Up, up, and away: Microbes use biogenic bubbles to escape confinement in yield stress environments

Babak Vajdi Hokmabad[1] and Sujit S. Datta[2]
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Microbial communities often inhabit confining three-dimensional environments, such as soils, sediments, foods, and biological gels and tissues. While some microbes can spread through their surroundings using motility, many are non-motile. Here, we show that even these non-motile microbes can escape their localized environments and disperse over long distances by riding bubbles generated through their metabolic activity. In our study, we focus on non-motile yeast growing in transparent three-dimensional granular hydrogel matrices. As the yeast ferment, they produce bubbles of carbon dioxide that grow, deform the surrounding matrix, and ultimately yield the matrix and rise, entraining yeast cells in their wake over large vertical distances. We show that the sequential entrainment of yeast cells by the train of rising bubbles ultimately culminates in the formation of a conduit within the matrix, encapsulating the colony and giving rise to a distinct columnar morphology. Our findings provide quantitative insights into the entrainment process driven by biogenic bubbles and demonstrate its connection to microbial dispersal. This research highlights the critical role of biogenesis in the proliferation and transport of living matter within complex environments, reflecting many biogeological processes observed in nature.

Tuesday 2:30 Sweeney Ballroom C BL26

Locomotion in viscoplastic yield stress fluids: Investigation of force balance and geometry effects

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The ability of microorganisms to navigate complex biological media is crucial to their survival and often has direct implications for human health. A prominent example is Helicobacter pylori, whose movement through gastric mucus is closely linked to the onset of ulcers. At low pH, this mucus behaves as a yield stress barrier, hindering bacterial motion. Building on our prior work that identified three distinct locomotion stages in such fluids, the current study investigates the mechanical forces and the effect of the swimmer geometry underpinning these stages. Using a custom-designed rotational Helmholtz setup, we imposed a controlled torque to drive artificial swimmers mimicking microbial propulsion. We systematically varied swimmer geometry including head shape, surface texture, tail thickness and pitch angle to quantify how these parameters influence thrust and drag in yield stress media. Our results reveal that pressure related resistance at the onset of motion diminishes nonlinearly with decreasing Bingham number (Bi), while the propulsive thrust from the helical tail grows with increased rotational speed which highly depend of the tail geometry. Notably, swimmers with tail pitch angles between 12° and 32° exhibited insufficient thrust to overcome resistance, resulting in no net motion. However, once Bi dropped below a critical threshold (~1), or when pitch angles exceeded 37°, thrust consistently surpassed the pressure, enabling effective propulsion. Swimmer geometry shows significant influence on the pressure at the onset and drag forces while the swimmer's locomotion is underway. Surface roughness was also found to increase drag, particularly at higher Bi, with fluid flow visualization suggesting reduced slip near roughened surfaces. These findings provide new insights into the interplay between swimmer design and nonlinear fluid rheology, shedding light on conditions necessary for locomotion in biological yield stress environments.

Tuesday 3:45 Sweeney Ballroom C BL27

Hyaluronic acid/cellulose nanocrystal suspensions as a potential viscosupplement composition for osteoarthritis

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Osteoarthritis (OA) is a degenerative joint disease characterized by the breakdown of cartilage. During OA, oxidative stress resulting from increased levels of reactive oxygen species (ROS) leads to the oxidative breakdown of hyaluronic acid (HA), an essential component that contributes to the lubricating properties of synovial fluid. This degradation results in decreased lubrication in the joints and reduced mobility. One of the temporary treatment methods for OA is the use of an HA-based injection called a viscosupplement to restore the properties of synovial fluid. However, due to the presence of ROS, the effect of the commercial viscosupplement does not last long. Cellulose nanocrystals (CNCs) are rod-like, biodegradable nanoparticles that possess antioxidant properties and can enhance both the flow behavior and lubricity of HA-based suspensions. The current study investigates the effect of using HA/CNC suspensions as a potential viscosupplement. Steady shear and oscillatory sweep tests revealed non-Newtonian shear-thinning behavior and improved viscoelasticity with increasing CNC content in HA/CNC suspensions. At 2 wt.% CNC, the suspension showed dual-yielding and a dominant elastic modulus (G' > G?) at frequencies relevant to human joint motion. Further, the in vitro addition of this formulation to synovial fluid collected from patients undergoing total knee replacement surgery demonstrated a significant improvement in viscoelastic properties, compared to the commercial viscosupplement Monovisc, suggesting a better load-carrying capacity. Tribological tests demonstrated reduced friction and wear with CNC concentrations, attributed to CNC's mending effect, which facilitates smooth joint motion and protects cartilage from wear. In-vitro oxidative degradation studies show higher oxidative stability than Monovisc. Further, the hydrogel is observed to be biocompatibility. The results suggest that HA/CNC suspensions exhibit superior properties making them promising candidates for the treatment of OA.

Tuesday 4:25 Sweeney Ballroom C BL29

Microfluidic cell-free layer and yield stress measurements of blood

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The rheological properties of blood are linked to some cardiovascular diseases, suggesting its use in diagnostic screening. One challenge in implementing blood rheology measurements for diagnostics is the accessibility of the information to physicians. The goal of this research is to create a microfluidic device that measures relevant rheological information. The thixotropic behavior of blood induced by red blood cell aggregates, called rouleaux, is one rheological characteristic of interest to cardiovascular diseases. The yield stress is a key characteristic of thixotropy that is also connected to the rouleaux structure. The rouleaux aggregation occurs at low shear rates; therefore, this study aims to measure low shear rate behaviors of blood in a microfluidic channel to interrogate the thixotropic behavior and yield stress created by rouleaux. An experimental setup was created to control low pressure drops (<100 Pa) with a hydrostatic head in a 1.5 mm wide microfluidic channel to produce low shear rates. Equine red blood cells are resuspended in the polymeric depletant dextran 500 to induce aggregation and phosphate buffered saline to inhibit aggregation. The presence of a 10 μm cell-free layer, significantly larger than the one induced from isolated red blood cells, has been shown in our previous work to be a direct result of rouleaux formation. There the effect of the cell-free layer was studied using rheometry and supported by a two fluid model and initial microfluidic measurements. In this work, additional microfluidic measurements provide further evidence for the cell-free layer. Moreover, observations and quantification of blood's yield stress were obtained and are consistent with the yield stress inferred from rheometry. This work provides two potential methods for measurement of low shear rate blood rheology parameters that could have clinical diagnostic capabilities in the future.

Tuesday 4:45 Sweeney Ballroom C BL30

Suspension balance modelling of microcirculatory blood flows capturing cell free layer

Hugo A. Castillo Sanchez[1], Weston Ortiz[2], Rekha R. Rao[3], and Leo Liu[1]
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Microcirculatory blood flow is featured by red blood cells (RBCs) migrating away from the vessel wall. This process leads to a cell-laden core and a near-wall cell-free layer (CFL), causing the Fåhræus-Lindquist effect, which is largely neglected by existing continuum models of blood flows. In this work, we develop a modified suspension balance model (SBM) for capturing the CFL in microcirculatory blood flows. Specifically, we introduce a lift-force flux term operated on the RBC phase to capture the hydrodynamic "lift" effect generated from the wall on the RBCs. Two different open-source solvers, OpenFOAM and Goma, are adopted to implement the new SBM formalisms for cross-validation. The results are validated against existing experiments and cellular blood flow simulations in terms of velocity and hematocrit profiles. It is shown that the new SBM can well capture the CFL and the Fåhræus-Lindquist effect in various hemorheological conditions. Blood flows through microvascular bifurcations are also explored to capture the hematocrit splitting rules governed by the Zweifach-Fung effects. The new SBM blood flow model allows computationally efficient, yet accurate capture of hemorheology in microcirculatory blood flows.

Symposium FI
Flow-Induced Instabilities and Non-Newtonian Fluids

Organizers: Hadi Mohammadigoushki, Fardin Khabaz and Chenxian Xu

Tuesday 1:30 Sweeney Ballroom D FI22

Extensional deformation of a drop with an elastoviscoplastic interface

Patrick D. Anderson[1], Martien Hulsen[2], Markus Hutter[2], Mick Carrozza[2], and Leon Bremer[3]
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A numerical implementation of two-phase flows of Newtonian fluids with a non-linear viscoelastic interface is validated and applied to uniaxial extension of a drop in a matrix fluid. Dimensionless groups based on viscoelastic interfacial extra stress, interfacial tension, and bulk viscous stress are used to analyze the flow problem. After fitting the intrinsic viscoelastic stress-strain behavior of interfaces in shear to experimental results, the influence of interfacial rheology on drop shape and stress is investigated using a Lagrangian-based interface tracking finite element method. The drop shape is not significantly influenced by interfacial viscoelastic properties if the stress, tension, and bulk viscous stress are comparable. However, distinct stress profiles emerge for varying properties. For large interfacial viscoelastic stress compared to tension and bulk viscous stress, simulations become unstable, and interfacial stress exceeds tension and possibly buckles due to compressive stresses at the drop tip.

Tuesday 1:50 Sweeney Ballroom D FI23

Fiber suspension flow with wall-slip in hyperbolic symmetric geometries

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We investigate the steady flow of a semi-dilute fiber suspension in symmetric hyperbolic channels and axisymmetric cylindrical pipes with wall slip. The rheology of the matrix fluid is defined solely by a Newtonian matrix fluid with a fixed velocity profile to evaluate the fiber orientation. We use the most accurate velocity profile according to the high-order lubrication theory derived by Sialmas & Housiadas (2024) by considering Navier's linear slip along the wall(s). The flow exhibits purely extensional characteristics in the midplane, whereas slip along walls diminishes its purely shear characteristics along the wall(s). We use the Advani & Tucker (1987) model to evaluate the spatial evolution of the second order orientation tensor, whereas the 4th-order orientation tensor which appears in the equation is approximated with a hybrid closure (Advani & Tucker 1987). The final equations for the orientation tensor are solved numerically using finite difference and spectral methods developed by Housiadas et al. (2025). We conducted a parametric study to investigate the effects of the channel's aspect ratio, the contraction ratio, the interaction coefficient, and the slip coefficient. The results show a reorientation of the fiber alignment from their initial state to a more aligned configuration at the channel exit. This alignment becomes more pronounced near the midplane, due to the purely extensional nature of the flow in that region.

Tuesday 2:10 Sweeney Ballroom D FI24

Impact dynamics of non-Newtonian drops

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Drop impact provides a unique setting to explore the rheological response of non-Newtonian fluids at high shear rates, exceeding those accessible by conventional rheometry. In this work, we investigate two key aspects of the impact dynamics of non-Newtonian liquid drops. (1) By combining simulations, experiments, and scaling analyses, we establish a general framework for predicting the maximum spreading of drops of generalized Newtonian liquids, encompassing both shear-thinning and shear-thickening behaviors. Through an analysis of the energy budget at maximum spreading, we identify a characteristic shear rate that governs the viscous dissipation during drop impact. The finding allows us to map the spreading of non-Newtonian drops onto that of Newtonian drops, revealing the quantitative dependence of the maximum spreading diameter on various impact parameters and rheological properties of liquids. (2) We investigate the impact forces of drops that exhibit discontinuous shear thickening and shear jamming. The interplay between inertia and impact-induced solidification gives rise to complex dynamics, reflected in distinctive features of the impact force. We develop a simple model that quantitatively captures both the peak impact force and the timing of its occurrence across different impact regimes. Taken together, our findings address the long-standing challenge of understanding the impact dynamics of non-Newtonian drops and offer guidance for tailoring fluid rheology to achieve desired impact outcomes---relevant for applications such as printing, coating, and material processing.

Tuesday 2:30 Sweeney Ballroom D FI25

A causality-abiding constitutive relationship for a wide class of thixotropic materials

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In this work, we present a rigorous thermodynamically consistent framework to model the thixotropic behavior of a broad class of complex fluids using an internal "structure" parameter. While structure-based models have long been employed in the rheological modeling of thixotropic materials, their formulation has typically lacked a foundation grounded in the fundamental principles of continuum thermodynamics, particularly those respecting causality. To address this gap, we develop a novel constitutive model by introducing a Gibbs free energy function and a rate of entropy production function, which is maximized to derive an evolution equation for the structure parameter that is inherently stress-driven. Our analysis reveals that the structure evolution is governed not merely by strain-rate or deformation history, but by the thermodynamic forces conjugate to the internal variables- the applied stress. The model predicts that the fully unstructured state corresponds to a thermodynamically unstable reference configuration, while a structured state is associated with residual stress and thermodynamic stability. This insight provides a mechanistic basis for spontaneous structure formation in stress-free configurations, offering a natural explanation for structural recovery in these materials. Importantly, the model also captures the non-monotonic stress-strain-rate response observed experimentally in many thixotropic systems, which is often a hallmark of structural hysteresis and flow instabilities. Finally, to demonstrate the versatility and predictive capability of our framework, we apply it to two distinct material systems: cellulose nanocrystal (CNC) gels and cementitious suspensions.

Symposium TM
Techniques and Methods: Rheometry, Tribometry, Spectroscopy and Microscopy

Organizers: Sara Hashmi, Jeffrey Richards and Qi Li

Tuesday 3:45 Sweeney Ballroom D *Keynote* TM1

Confocal and colloidal probe microscopy for characterizing adhesion, friction, and wetting of multi-phase elastomers

Jonathan T. Pham

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Soft elastomeric materials are found in a host of applications, from adhesives and coatings to natural and synthetic biomaterials. Many of these materials comprise a lightly crosslinked polymer network, which can also be infused with a compatible liquid (i.e., swelling). Swelling offers additional functionality, like molecular transport, lubrication, and control over mechanical properties. However, understanding the behavior of soft and swollen interfaces is an ongoing challenge. For example, when crosslinked solids are sufficiently soft, or the characteristic size scale is small, they display liquid-like characteristics like capillarity, even without an infused liquid. When the networks are swollen, the swelling liquid itself provides true liquid behavior, creating multi-phase situations that are even more complex. Here we will demonstrate the use of confocal microscopy, colloidal probe microscopy, and customized positioning as a route to understand the adhesion, friction, wetting, and phase behavior of such interfaces, primarily focused on microscopic size scales. Leveraging these tools, we will show how combinations of solid and liquid characteristics control static and dynamic wetting and microscale friction of swollen surfaces.

Tuesday 4:05 Sweeney Ballroom D TM2

Mapping of the multiaxial failure envelope of model soft elastomers to develop a failure criterion

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Characterization of multiaxial mechanical behavior of soft solids is crucial in understanding their behavior in systems, where complex stress states develop upon loading. The large strain constitutive response, yield stress, and ultimate failure point of materials are all sensitive to the stress state that develops upon loading. However, most studies from the available literature do not venture into characterizing the failure response of soft solids under multiaxial loadings. We explore the biaxial failure behavior of silicone networks using cruciform specimens and perform combined tension/torsion loading on soft cylinders. Cruciform sample designs provide a controlled approach to biaxial deformation. However, stress concentrations at the sample corners can lead to premature failure due to localization effects. To improve stress uniformity, modifications such as increasing center compliance relative to the legs, segmenting the legs to mitigate lateral traction effects, and replacing sharp corners with rounded features are examined. Along with the response of soft cylinders to combined tension and torsion deformation, we gain insight into soft solids' deformation mechanisms, stress distribution, and failure modes under real-world loading conditions. The aim is to more broadly map the failure envelope of these networks to establish a failure criterion. A failure criterion can aid in soft material selection for applications in biomedical devices, flexible electronics, and other systems with complex features and stresses.

Tuesday 4:25 Sweeney Ballroom D TM3

Rheo-impedance and Tribo-impedance spectroscopy of lubricating greases for electric vehicles

Paul Staudinger[1], Julius Heinrich[2], Kartik S. Pondicherry[1], and Joerg Laeuger[2]
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Lubricants for electromobility must meet additional criteria, that go beyond the traditional requirements. The discharge of stray currents, which are generated by frequency converters to control the motor speed, via the associated ball bearings can lead to damage to the bearings in the long term. Lubricants for electric vehicles must also take electrical parameters such as conductivity, permittivity and breakdown voltage into account and conductive greases must be developed. Combined rheological and impedance measurements on conductive and non-conductive greases in a parallel-plate geometry show that the electrical properties of both greases do not change significantly under shear, but the conductive grease shows some electrical degradation at constant shear rate and elevated temperatures. To simulate real application conditions, a temperature-controlled setup was designed in which a rolling bearing can be mounted and the electrical properties of a grease filled in the bearing can be measured, while a rheometer geometry acts as the bearing shaft and drives the bearing. In speed ramps, the torque signal of the rheometer, i.e. the friction coefficient of the system, shows the typical progression of extended Stribeck curves with the states of boundary friction, mixed friction and the hydrodynamic regime. Impedance increases due to film formation during the transition from mixed friction to the hydrodynamic region, while the conductive grease exhibited an order of magnitude lower impedance over almost the entire speed range. The new tribo-impedance setup is an efficient laboratory-scale test method for the characterization of greases in real ball bearings, accounting for the electrical properties, and allow differentiation between them in terms of their frictional behavior and the electro-tribological response of the system. It will help to develop a model for understanding the tribological and electrical behavior of grease-lubricated ball-bearing systems under dynamic conditions.

Tuesday 4:45 Sweeney Ballroom D TM4

Tribological flow transitions in soft elastomers with colloid-laden lubricants

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Particle-laden lubricants are increasingly relevant in friction-sensitive applications such as cosmetic formulations and soft robotic bearings. When compliant materials like poly(dimethyl siloxane) (PDMS) are used, high surface deformation induces nonlinear sliding stresses that alter the mixed and elastohydrodynamic lubrication (EHL) regimes. Here, we report steady-state tribology curves for PDMS-PDMS interfaces lubricated with colloidal suspensions of hard sphere-like poly(methyl methacrylate) (PMMA) particles dispersed in squalene and diisodecyl phthalate (DIDP). Friction data were collected using a ball-on-three-plates geometry mounted on a stress-controlled rheometer under a constant normal load of 1.5 N, with sliding velocities ranging from 0.001 to 100 rad/s. Separately, steady shear viscosity was measured using parallel plate geometry. We evaluated the friction coefficient across particle sizes (diameters 2a = 0.43 μm, 1.0 μm, 2.54 μm, and 3.1 μm) and volume fractions ranging from 0.01 = ? = 0.5. A distinct plateau appears in the Stribeck curve between the mixed and EHL regimes, marking an extended friction regime with low sensitivity to sliding speed. This regime broadens with decreasing particle size and solvent viscosity, particularly in squalene-based suspensions at low volume fractions (? = 0.01). In higher-viscosity solvents like DIDP, the friction coefficient within this regime exhibits a linear relationship with volume fraction, while only minimal effects are observed in the lower-viscosity squalene. Low friction coefficients persist across a broader sliding speed range in these systems. To investigate the extension of the mixed regime, we performed relaxation experiments by halting PDMS sliding and monitoring lubrication film thickness over time. These tests revealed that larger particles exhibit shorter retention times in the contact zone in DIDP, suggesting that frictional behavior is influenced by a sustained lubrication film that persists after flow cessation.

Tuesday 5:05 Sweeney Ballroom D TM5

Pressure driven flow of polymer melt in elliptical dies

Martin Zatloukal[1], Levente Szántó[2], Jiri Drabek[1], and Philip Rolfe[3]
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In this work, various elliptical dies were used to determine the flow behavior of polymer melt using a high-pressure capillary rheometer. The major and minor semi-axes of the elliptical capillary cross-sections and their lengths were systematically varied and the obtained results were compared with a reference circular capillary die. Measured data were used to validate the general equations for flow channels of elliptical cross-section proposed by Kozicki et al. [1]. The obtained results provide deeper insight into how possible inaccuracy in the manufacturing of circular capillaries can affect measured rheological data and how to correct them.

Acknowledgement: MZ and JD wish to acknowledge the Grant Agency of the Czech Republic (Grant No. 24-11442S) for the financial support and NETZSCH Gerätebau GmbH for providing the Rosand RH10 capillary rheometer.

References:
1. Kozicki, W., Chou, C.H., Tiu, C. Non-Newtonian flow in ducts of arbitrary cross-sectional shape (1966) Chemical Engineering Science, 21 (8), pp. 665-679.

Tuesday 5:25 Sweeney Ballroom D TM6

Determining viscoelastic properties of soft microscale rods by capillary aspiration

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Characterizing mechanical properties of hydrogels and other soft materials on the microscale presents significant experimental challenges. Atomic force microscopy (AFM) requires specialized equipment, faces reduced sensitivity in liquid environments, and may damage sensitive samples, while conventional rheology demands sample volumes larger than are often available for microscale materials. We present a novel capillary-based bending technique to measure the mechanical properties of soft microscale rod-shaped specimens in solution using standard laboratory equipment. Our method aligns rod-shaped samples across the opening of a glass capillary, with the opposite end of the capillary connected to a vacuum pump and flow meter. When the pump is activated, the flow of water into the capillary exerts quantifiable forces on the sample, causing deflection measurable via optical microscopy. By measuring deflection as a function of the applied viscous forces, we can determine flexural moduli using the Euler-Bernoulli beam theory. Additionally, analyzing the time-dependent responses of shape deformation at constant applied force enables viscoelastic measurements of creep. We demonstrate this technique's versatility by measuring rods made of various materials including alginate and gelatin hydrogels and natural biomaterials such as downy feather barbules. All rods range from 300 to 2000 μm in length with diameters between 4 and 200 μm, tested using glass capillaries with diameters of 200 or 600 μm. This method enables measurements of bending moduli ranging from O(100) Pa to O(100) MPa. Comparative analysis with bulk rheology and AFM measurements validates our approach. Capillary aspiration offers a simple, accessible approach to the mechanical characterization of microscale rod-shaped materials, particularly hydrogels and biomaterials in their native hydrated state.

Wednesday Morning

Symposium PL
Plenary Lectures

Wednesday 8:30 Sweeney Ballroom E+F PL3

Shaping the future using folding (origami), cutting (kirigami) and printing (coiling)

Lakshminarayanan Mahadevan

Applied Mathematics, Physics, Organismic & Evolutionary Biol, Harvard University, Boston, MA, United States

How can we design shape (for function)? I will describe a few inverse problems that this question raises, all inspired by art in one form or another. These include kirigami tilings for planar and three-dimensional shapes, origami tessellations for complex curved surfaces, and 4d printing and growing strategies to create complex filamentous surfaces, using a combination of experimental, computational and theoretical approaches.

Symposium CS
Colloidal Suspensions and Granular Materials

Organizers: James Gilchrist, Abhinendra Singh and Shravan Pradeep

Wednesday 9:50 Sweeney Ballroom A CS33

Clogging of interlocking particles in a 2D microfludic hopper

Anke Lindner, Jules Tampier, Lars Kool, and Philippe Bourrianne

PMMH, ESPCI, Paris, France

When particles are forced through a narrow constriction, clogging can occur, leading to an intermittent or permanent drop in discharge. Many parameters influence the probability of clog formation, among which the particle shape plays a critical role. In this study, we experimentally investigate the influence of particle geometry on clogging by examining the flow of a dense suspension of non-convex particles in a 2D microfluidic hopper. The particles are fabricated using a photolithographic projection method, enabling precise control over their 2D shapes. For each particle shape considered, we analyze the packing morphology and estimate the average number of particles discharged before a clog occurs. Our results show that interlocking between non-convex particles significantly increases the likelihood of clogging by promoting the formation of stable structures near the constriction.

Wednesday 10:10 Sweeney Ballroom A CS34

Shear-rheology of colloidal rods with hydrodynamic interactions in semi-dilute concentrations: Brownian Dynamics simulations

Lucas H P Cunha[1], Paul Salipante[2], and Steven Hudson[2]

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Colloidal rods are present in various biological systems and are extensively used in industry to adjust the mechanical behavior of composite materials. The elongated shape of the particles and their orientation dynamics under flow contribute to complex viscoelastic responses in the bulk material, which can result in flow instabilities even at low Reynolds numbers. At the microscale, particle dynamics are influenced by factors such as flow conditions, particle geometry, Brownian motion, external fields, and interparticle interactions. While hydrodynamic interactions (HI) are known to significantly affect the rheology of systems like spherical particles and emulsions, their impact on fiber suspensions remains less well understood. To investigate this, we use Brownian Dynamics simulations to study how HI affect orientation dynamics and bulk rheology in semi-dilute colloidal rod suspensions. Our results, derived from this simplified model, reveal a cascading effect: the tumbling of an individual rod disrupts the local flow, prompting nearby rods to tumble as well, thereby amplifying the system's overall stress.

Wednesday 10:30 Sweeney Ballroom A CS35

Two-step yielding in nematic glasses of rigid rods

George Petekidis and Mohan Das

IESL and Department of Materials Science and Engineering, FORTH and University of Crete, Heraklion, Greece

Structure and rheology of dense suspensions of rod-like silica particles is studied using a combination of rheology and confocal microscopy. Confocal microscopy revealed formation of long range nematic ordering at high rod volume fractions (f> 0.20). Linear rheological measurements show that dense rod suspensions behave like Wigner glass due to long range electrostatic repulsion between charged silica rods. Steady shear measurements reveal different regimes of flow instabilities such as wagging and gradient-banding at low shear rates and a flow aligned Newtonian

regime at high shear rates. Transient measurements in step-rate and step-stress measurements indicate a two-step yielding process. Rheo-confocal investigation connects the first step increase in stress with "tube renewal" of individual rods and second step increase with an interaction between domains leading to wagging of rods in the flow-vorticity plane. Velocimetry measurements show that the wagging regime is also accompanied by shear banding and plug flow.

Wednesday 10:50 Sweeney Ballroom A CS36

Average stress in a dilute suspension of rigid spheroids in a second-order fluid in a linear flow

Tanvi Mahendra Apte[1], Arezoo Ardekani[2], and Vivek Narsimhan[1]
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The microhydrodynamics of particle suspensions in polymeric fluids has a wide range of applications in industry and biology. To discern the dynamics of particles in such systems, it is important to analyze the stress response of the suspension to applied flow fields. While such investigations have been theoretically done for suspensions of rigid spheres in weakly viscoelastic fluids, the effect of non-sphericity of particles on the stress remains relatively unexplored. The interplay between the response of the polymeric fluid and the particle orientation yields rich physics. The viscoelastic torques make the particle inhabit a preferred orientation in a given flow, resulting in time-dependent stresses. In this paper, we determine the average extra stress in a dilute suspension of rigid, non-Brownian spheroids in a second-order fluid subject to shear and extensional flows. We perform this task by examining the flow around a single spheroid in the limit of small Weissenberg number (Wi"1) and perform an ensemble average of the stress tensor over all particle configurations. There are two contributions to the extra stress: one from the force dipole on the particles (stresslet) and another from the fluctuations in the velocity in the bulk fluid (fluid-induced particle stress), the latter of which does not arise in a zero Reynolds number Newtonian fluid. We present results for the O(fWi) corrections to the long-time effective shear viscosity, normal stress coefficients, and extensional viscosities in the suspension in shear, uniaxial extensional, and planar extensional flows, where f is the particle volume fraction. To elucidate the effect of particle shape on the effective viscosity, we repeat this analysis for different aspect ratios (AR) for prolate (needlelike) and oblate (disk-like) spheroids.

Wednesday 11:10 Sweeney Ballroom A CS37

Shear flow of colloidal bent-core liquid crystals

Nicholas Hackney, Joel Clemmer, and Gary S. Grest
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Manifestations of dense packings of anisotropic rods are ubiquitous across a wide variety of physical systems. Knowledge of how they order and flow in response to applied stress is important for understanding a diverse range of phenomena including debris flow in landslides, biological transport of rod-like viruses and industrial processes such as additive manufacturing. Unlike their more symmetric counter parts, rod-like particles tend to align nematically in response to applied shear stress. This ordering can be frustrated by introducing a constant curvature that breaks the azimuthal symmetry of straight rods. The preference for uniform bend must be accompanied by additional splay or twist deformations, leading to unique states of nematic splay-bend or twist-bend order. Additionally, this situation has recently been shown to be compatible with the existence of exotic topological defects such as Skyrmions. In this talk, results from molecular dynamic simulations will be presented to investigate the effect of curvature and applied shear stress on the behavior of dense packings of rigid rods, with a particular focus on understanding how the frustration of local order can lead to novel ordered states and opens up potential mechanisms to control the structure and functionality of complex material.

Wednesday 11:30 Sweeney Ballroom A CS38

Frictional contacts in rigid rod suspensions allow for large stress oscillations

Christopher Quinones and Peter D. Olmsted
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Coulomb-like frictional contacts between particles in sheared suspensions have been suggested as the genesis of discontinuous shear thickening, or DST, as well as shear thinning and jamming. Much work has addressed the effect of frictional contacts in suspensions of spheres, but rod-like particles have received less attention. We perform simulations of sheared, frictional non-Brownian rigid rods in LAMMPS, exploring the interplay between nematic order, contacts, and stress. We discuss average contact numbers, how the presence of frictional forces tends to increase nematic order, and the role of volume fraction and aspect ratio. For the concentrated regime, we also show that under certain conditions the rods enter a "wagging" regime that requires frictional forces to persist. In this phase, there are significant stress oscillations in step with the director deviating from flow alignment.

Symposium GN
Self-assemblies, Gels and Networks

Organizers: Thibaut Divoux, Katie Weigandt and Ria Corder

Wednesday 9:50 Sweeney Ballroom B GN34

Modelling the increased failure toughness of double network hydrogels

Samuel B. Walker and Suzanne M. Fielding
Department of Physics, Durham University, Durham, County Durham DH1 3LE, United Kingdom

Double network hydrogels exhibit an exceptional combination of stiffness, strength and fracture toughness. The mechanisms behind these remarkable properties are poorly understood. Here, we use a simple mesoscale model of a double network material to show that load sharing between the two networks delocalizes stress, thereby preventing crack propagation. Importantly, our model is capable of addressing bulk macroscopic cracking behaviour (and its inhibition), yet is detailed enough still to capture the microphysics of individual plastic bond failures. This allows us to resolve the reduction in the Eshelby stress propagator and the corresponding inhibition of stress concentration around failed sacrificial bonds, which suppresses the cascading failure of bonds. Instead, we find that the brittle failure seen in single networks is replaced by ductile deformation in double networks, where damage occurs diffusely through distributed microcracking. By varying the length scales and fracture stresses of the two networks, we demonstrate that it is possible to design a material with exceptional stiffness and high resistance to mechanical failure. These insights provide a first step to understanding why double-network hydrogels are so tough.

Wednesday 10:10 Sweeney Ballroom B *Keynote* GN35

Mean-field and critical scaling of polymer clusters near the gel point

Jian Qin
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The number, size, and relaxation dynamics of polymer clusters formed by random cross-linking are highly susceptible to the degree of gelation. Depending on the distance to the gel point, either mean-field or critical exponents is expected. The crossover between these two regimes has been indirectly employed to rationalize the rheological responses of physical gels in the linear regime, but has not been directly probed, partially because the gelation window is narrow. Here, we present a hybrid MC/MD simulation model, a configuration-biased cross-linking protocol, and simulation results on the statistics of cluster number and size. By varying the length, stiffness, and bulkiness of the precursor chains, it is shown that an emergent length scale, a thermal blob, can be identified, below which mean-field scale works and above the cluster swells. Upon normalization by the thermal blob, all the results collapse onto a master curve, which exhibits an surprisingly gradual crossover from the mean-field to critical scaling regimes. The connection between the thermal blob and the Ginzburg number identified by the space-filling argument, and the implication on the shift of gel point are discussed.

Wednesday 10:30 Sweeney Ballroom B GN36

Protorheology à la critical gel

Maxwell C. Marsh, Mohammad Tanver Hossain, and Randy H. Ewoldt
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The significance of the critical gel point has been known for decades. However, no prior study has combined a comprehensive rheometric dataset paired with non-trivial flow observations that demonstrate the consequences of critical gel rheology, such as spreadability, high damping, and extensional thickening. Here, we select a realistic model material with thermal gelation and mutation, widely accessible and colloquially understood (egg yolk), and present a detailed library of temperature-dependent linear and nonlinear oscillatory, creep, and stress relaxation data [1]. Furthermore, in the spirit of protorheology [2] we provide high quality visuals of the flow consequences of being a realistic critical gel. These materials mutate during testing, complicating gel point determination. Moreover, any claim of "solid" behavior depends on the timescale of observation (diverging zero-shear viscosity and emerging equilibrium modulus in the case of a critical gel). Our work highlights the mutation timescale in this material as well as the observation timescale present in any rheological test. One common test to approximate a gel point is to measure the dynamic moduli in oscillation and observe when they cross over. While the rheological community has known for decades that this is not a true critical gel point, many outside our community continue to use the moduli crossover as a metric. We propose an alternative way to interpret the same data: using diverging dynamic viscosity eta' with careful consideration of the timescale of observation (oscillatory time scale). By integrating protorheology observations with rigorous rheometric data and new interpretation techniques, this work enables a deeper understanding of critical gel behavior.

[1] Marsh M. et al., "Egg yolk as a model for gelation: from rheometry to flow physics," Phys. Fluids 37, 043114 (2025). https://doi.org/10.1063/5.0255929
[2] Hossain, M. et al., "Protorheology," J. Rheol. 68(1), 113-144 (2024). https://doi.org/10.1122/8.0000667

Wednesday 10:50 Sweeney Ballroom B GN37

On gelation and form: Linear & nonlinear rheology of gelling networks during fluid-mediated shape formation

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Many natural and man-made soft materials obtain their shape and form through fluid-mediated fabrication processes. Interfacial flows, hydrodynamic instabilities, or flow kinematics during stretching flows can all generate transient patterns in a liquid precursor. These patterns gradually evolve towards their final state as the underlying network ultimately cures into a viscoelastic solid via gelation. By performing a series of experiments on different curing elastomeric networks and combining linear & nonlinear rheological measurements we capture the essential features of such complex mutating systems as they approach the critical gel point. We magnify our probing window through time-connectivity superposition principle, and develop appropriate constitutive models that form a quantitate universal framework for predicting both the behavior of curing networks in strong flows and the ultimate shapes & patterns that form in soft assemblies: a rheologist's almanac for gelling systems.

Wednesday 11:10 Sweeney Ballroom B GN38

Enhancing the re-processability of photo-recyclable polymer networks using molecular design and in situ photo-rheology

Eleanor L. Quirk[1], Camily Pereira dos Santos[1], Michael C. Burroughs[1], Brendan M. Wirtz[1], Tracy H. Schloemer[2], Daniel N. Congreve[2], and Danielle J. Mai[1]

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Polymer networks are versatile materials used in consumer products, biomedical materials, and 3D printing. The ubiquity of manufactured polymer networks leads to plastic waste generation and environmental harm, as these networks are built to last and rarely designed for sustainable end-of-life reprocessing. To investigate polymer network recycling, we report the time-resolved material evolution of model photo-responsive polymers during network formation, deconstruction, and re-formation using in situ photo-rheology. The model system comprises multi-arm star polyethylene glycol end-functionalized with the photo-crosslinking molecule anthracene (PEG-anthracene). PEG-anthracene undergoes network formation upon irradiation with ultraviolet light (UVA, 365 nm) and network deconstruction upon irradiation with short-wavelength ultraviolet light (UVC, 265 nm). PEG-anthracene recyclability is increased by reducing anthracene crosslink density and maximizing un-crosslinking. Thus, by reducing the number of arms per polymer star, the concentration of polymer in solution, and the duration of UVA light exposure to the minimum values required for network formation, PEG-anthracene recyclability is enhanced. These findings demonstrate an opportunity for spatiotemporal-control of reprocessible photo-responsive polymer networks.

Wednesday 11:30 Sweeney Ballroom B GN39

Rheological characterization of hydrogels with both adaptable and non-degradable cross-links

Gautam Khare[1], Kristi Anseth[2], and Kelly Schultz[1]

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The extracellular matrix (ECM) is viscoelastic, which influences cellular processes such as spreading and motility. Covalent adaptable networks (CANs) can mimic this viscoelastic behavior due to the ability to reversibly reorganize the network microstructure. 3D encapsulated cells remodel viscoelastic substrates by applying cytoskeletal tension, causing local network rearrangement. However, this applied tension causes reversible material remodeling rather than allowing the cell to pull itself through the network. This reduces motility, which leads to the cell depleting nutrients and reduces viability. Designing a viscoelastic hydrogel that retains some microstructure will enhance motility and viability. We characterize composite CANs with adaptable cross-links which provide viscoelasticity and non-degradable cross-links which maintain structure. Our networks consist of 8-arm polyethylene glycol (PEG)-thiol cross-linked with PEG-thioester norbornene (PTNB, adaptable) and PEG-norbornene (PNB, non-degradable). We characterize networks with varying ratios of cross-linker concentration: 100%, 75%, 50%, 25% and 0% PTNB. Multiple particle tracking microrheology (MPT) is used to characterize the evolving network microstructure during incubation in L-cysteine, which degrades PTNB cross-links only. MPT measures the Brownian motion of fluorescent probes in the material to characterize the microstructure and rheology. Time-cure superposition is used to identify network microstructure at the phase transition by calculating the critical relaxation exponent, n. We measure network rearrangements in 100%, 75% and 50% PTNB networks before complete degradation. 25% PTNB networks partially degrade without a phase transition and 0% PTNB networks do not degrade. A decrease in adaptable cross-linker concentration leads to a more elastic and tightly cross-linked network. The variation of the cross-linker ratio enables hydrogels to mimic the dynamic nature of the ECM while retaining structure to enable cytoskeletal tension.

Symposium SM
Polymer Solutions, Melts and Blends

Organizers: Amanda Marciel, Ben Yavitt and Piyush Singh

Wednesday 9:50 Coronado + DeVargas SM28

Mechanical reprocessing of PA 11 and PA 11–LDPE blends followed via rheological methods

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This study reports on the mechanical recycling (closed-loop twin-screw extrusion) of virgin PA 11 and post-consumer PA 11-low density polyethylene (LDPE) (90/10) blend over ten cycles. The samples were first analyzed via Fourier transform infrared spectroscopy (FTIR) and proton nuclear magnetic resonance (^{1}H NMR) to detect any changes associated with possible chain scission and/or molecular rearrangements. In particular, a carbonyl band was observed in the virgin PA 11 after reprocessing, indicating thermo-oxidative degradation. Then, mechanical testing (solid state) showed gradual reductions of the elastic modulus, stress at break, and impact strength, with significant drops after the third cycle. Finally, rheological analyses were performed to get more information in the melt state. The results showed continuous decreases in the storage modulus (G'), loss modulus (G?), complex viscosity (?*), and damping factor (tan?d), reflecting lower molecular weight and modified viscoelastic behavior. This was further confirmed via Cole-Cole and van Gurp-Palmen plots. But most importantly, scanning electron microscopy (SEM) showed progressive coalescence of LDPE droplets in the PA 11-LDPE blend with reprocessing, leading to reduced interfacial area and lower impact resistance. In general, these results showed that virgin PA 11 retains acceptable performance up to three cycles, while the post-consumer blend exhibits faster property losses.

Wednesday 10:10 Coronado + DeVargas SM29

Revisiting structure-property relations in PP/HDPE blends: From processing to performance with recycled polyolefins

Stan F.S.P. Looijmans[1], Sujith D. Namnidi[1], Michelle M.A. Spanjaards[2], Lambèrt C.A. van Breemen[1], and Patrick D. Anderson[1]
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The United Nations predicts that plastic waste could reach 23-37 million tonnes by 2040, with only 9% currently recycled. Around 60-70% of this waste consists of polyolefins such as LDPE, HDPE, LLDPE, and PP. These materials are challenging to separate due to their similar densities, leading to mixed PP/HDPE waste streams. Recycling these blends results in downgraded mechanical properties compared to virgin materials. While thermal and rheological characterizations of these blends have been partially addressed, the effects of impure material compositions on melting behavior and structure formation under controlled processing conditions are largely unexplored. Typically, only melt-state properties are considered, but these fail to account for the solid-to-melt transition. In this study, we demonstrate that the dominant heat source during this transition is plastic deformation, specifically from compression, with negligible contribution of shear. Heat generation is governed by the yield stress in the solid state, which varies between different polyolefins, complicating the recycling of mixed plastic waste and often leading to partial melting or degradation. Our investigation extends to the thermal and rheological properties of controlled PP/HDPE blends, utilizing extended dilatometry to simulate near-processing conditions, including pressure and shear. Microstructural analysis through X-ray diffraction and mechanical testing reveals that under quiescent conditions, increasing polyethylene concentration reduces strength and elongation-at-break. However, under shear, polyethylene enhances the yield stress due to increased flow strength, especially when rapid melt solidification occurs, leading to more oriented polypropylene structures. This research advances the understanding of melting and crystallization behaviors in polyolefin blends, providing key insights for optimizing polymer recycling processes through precise control of processing conditions and blend composition.

Wednesday 10:30 Coronado + DeVargas SM30

Synergistic role of long chains and shear on the crystallization of poly(ethylene oxide) (PEO)

Arshiya Bhadu[1], Elijah J. Mumau[2], Nora C. Lee[3], Kirt A. Page[4], Xiaoshi Zhang[5], Alicyn M. Rhoades[5], and Ralph H. Colby[1]
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Winter and Pogodina postulated that polymer crystallization is analogous to a physical gelation phenomenon. During isothermal crystallization, tan(δ), the ratio of the loss to storage modulus, becomes independent of oscillation frequency (ω) and can be defined as the physical gelation point or the crystallization time. We applied various levels of shear on neat 100 and 44 kg mol^{-1} PEO and their blends with 0.5-9.5 wt% 1000 kg mol^{-1} to investigate the impact of shear and long chains on the crystallization of PEO. Small-amplitude oscillatory shear was conducted before and after shear to measure the changes in the Winter and Pogodina crossover time while monitoring the birefringence in-situ during nucleation and crystal growth. The Winter-Pogodina crossover time decreases after applying weak shear flow accompanied by an increase in nucleation density, where the strongest effect occurs in the blend with the highest weight% of long chains. At stronger levels of shear, especially in the blends with long chains, a strong isotropic to anisotropic morphological transition occurs in addition to a decrease in the crossover time. The morphological

transition is corroborated by the formation of higher order structures via ex-situ small-angle X-ray scattering. Shear is implicitly assumed to impact only the nucleation rate and is neutral towards the growth rate. We find that this assumption is incorrect, and the growth rate of crystals changes after shear or the addition of long chains.

Wednesday 10:50 Coronado + DeVargas SM31

Rheology during crystallization of poly(ethylene oxide) in gel polymer electrolytes

Fatemeh Naderi Samani and Reza Foudazi
School of Sustainable Chemical, Biological and Materials Eng, University of Oklahoma, Norman, OK 73019, United States

This study investigates the rheological behavior of gel polymer electrolytes (GPEs) composed of short-chain block copolymers, specifically poly(ethylene oxide)-block-poly(ethylene) (PEO-b-PE), blended with ionic liquids (ILs) and different salts. Block copolymers are well-known for their ability to undergo microphase separation, resulting in nanostructured morphologies where the PEO-rich domains serve as continuous ion-conducting pathways. Rheological analysis is employed to probe the temperature-dependent structural transitions and crystallization kinetics of PEO in the GPEs. The crystallization behavior of the samples is systematically investigated while also considering different salts. This is achieved by applying oscillatory shear while cooling GPEs from temperatures above the melting point to below the crystallization temperature, enabling a comprehensive analysis of the crystallization kinetics. During crystallization, the storage modulus (G') and loss modulus (G") exhibit frequency-dependent features, including a maximum in G" against temperature. The incorporation of ILs and salts increases G' in the crystalline phase, indicating enhanced ionic interactions within the ordered domains. Notably, G' values are higher for systems containing multivalent cations compared to those with monovalent cations, suggesting stronger coordination and network formation in the crystalline matrix. These findings contribute to a deeper understanding of the structure-property relationships in GPEs and offer critical guidance for the molecular design and performance optimization of polymer electrolytes for advanced electrochemical energy storage systems.

Wednesday 11:10 Coronado + DeVargas *Keynote* SM32

Role of the energy conversion factor in flow birefringence and polymer crystallization kinetics

Arshiya Bhadu[1], Evan P. Moffett[1], Shaojie Xu[1], Alicyn M. Rhoades[2], and Ralph H. Colby[1]
[1]Materials Science and Engineering, The Pennsylvania State University, University Park, PA 16802, United States; [2]School of Engineering, Penn State Behrend, Erie, PA 16563, United States

Shearing a high-density polyethylene (HDPE) melt stretches chains in the high molecular weight tail of the molecular weight distribution. Size exclusion chromatography data in that tail are fit to $\exp(-M/M_{max})$ to estimate the volume fraction of chains E that get stretched at a given shear rate, that exceeds the reciprocal of their Rouse time. Hence, a sheared polymer melt undergoes de Gennes' first-order coil-stretch transition; the longest chains are stretched and coexist with shorter chains that are only partially oriented. We find that E is proportional to the measured birefringence at each shear rate. While the applied specific work (W) seems to be the control variable for acceleration of nucleation kinetics at intermediate shear rates, that is not the case for low or high shear rates. Shear rates from 1 - 70 s^{-1} were applied, resulting in W levels of up to 60 MPa by varying the shearing time. A flow-induced nucleation model is applied based on Flory's entropy reduction model and Hoffman and Lauritzen's isothermal heterogeneous nucleation model. We find that the acceleration in crystallization after shear plotted as a function of EW collapses all data to the same curve, making the volume fraction of chains E that get stretched the effective energy conversion factor. Shorter chains that do not stretch dissipate the rest of the applied specific work as heat. The critical crystal nucleus volume V* is quantified using the model and found to increase with temperature in the range of $122^oC \leq T_C \leq 126^oC$. We find the quiescent V* = 7.5 - 10.4 nm^3, containing 23 - 37 Kuhn monomers of HDPE. The sheared V* is 2/3 of the quiescent V* at all temperatures and shearing conditions thus far explored.

Symposium AR
Applied Rheology for Industrial Applications

Organizers: Hammad A. Faizi and Antonio Perazzo

Wednesday 9:50 Peralta + Lamy AR20

Predicting spinnability of hydrocarbons from extensional rheology and thermal-flow simulations

Thamires A. Lima, Rondes F. Torin, Amir A. Yancheshme, and Nicolas J. Alvarez
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The development of carbon fibers from hydrocarbons has remained a challenge, with limited predictive tools linking isothermal extensional rheological properties to spinnability parameters. In this work, we defined a stretchability window for hydrocarbons by systematically varying the isothermal temperature and applying constant extensional velocities in a commercial extensional rheometer, resulting in different strain rates and final draw ratios. Using a custom-built melt spinning apparatus, we established a corresponding spinnability window by changing nozzle temperature (viscosity), and spool velocities, keeping nozzle velocity constant. Simulations performed in COMSOL Multiphysics accurately replicate the filament's shape and temperature profile as it exits the nozzle. Our results demonstrate that optimal spinning conditions are governed by both the material's stretchability and the temperature gradient along the filament during melt spinning. Specifically, we found that the sample exhibiting the highest stretchability at 230?&degC achieved superior spinnability starting at 270?&degC (nozzle temperature) and maintaining a spool velocity below 1000 mm/s (maximum strain 1.8). We further integrate shear and extensional rheology, differential scanning calorimetry, and FTIR to assess the thermal and oxidative stability of the samples, confirming the importance of inert conditions during processing. This study

offers a robust framework for the rational design and optimization of fiber spinning protocols for hydrocarbons, significantly reducing material waste and development time.

Wednesday 10:10 Peralta + Lamy AR21

Identifying efficient polymer processing aids

Xiaohan Jia[1], Amir Malmir[1], Jourdain H. Piette[1], Ziyue Zhang[1], Antonios K. Doufas[2], Gerrits Nicole[3], and Savvas G. Hatzikiriakos[1]

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A novel model of polymer flow with processing aid (PPA) is developed to predict the adsorption-desorption kinetics of PPA on the wall, gradually altering the slip boundary condition. The coating dynamics of the die surface with PPA are captured through the pressure transient and the progressive change in polymer slip velocity. This model incorporates several physical parameters, which are found to be related to the PPA/polymer/metal wall interfacial energetics. The physical model can aid in developing/identifying appropriate polymer processing aids based on their surface energetics. The model is validated using experimental results to address the effects of die length, apparent shear rate, PPA concentration, and surface energetics on the flow dynamics and melt fracture performance of PPAs.

Wednesday 10:30 Peralta + Lamy AR22

Rheological behavior of fresh ultra-high-performance concrete enhanced with cellulose nanofibers

Xiaoli Xiong and Chengcheng Tao

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Nanoadditives have been widely used in cement and concrete materials to improve the rheology of the fresh materials. Cellulose nanofibers (CNFs), typically derived from wood pulp through a chemical-free process, are promising additives to cement and concrete. Studies have shown that adding CNFs reduces the yield stress and plastic viscosity of cement paste. And cement pastes with higher CNF concentrations exhibit shear-thinning behavior. Ultra-high-performance concrete (UHPC) is a specialized class of concrete known for its outstanding mechanical properties. UHPC exhibits compressive strengths exceeding 120 MPa, which is approximately five times that of conventional C25 concrete. CNFs can be used as viscosity modifying agent in UHPC for better reinforcing fiber alignment, resulting in excellent mechanical and durability performance. This study aims to investigate the rheological behavior of fresh UHPC enhanced by CNFs through both experimental and computational approaches. We measure the rheological properties of CNF-enhanced UHPC using the modular compact rheometer, and evaluate the workability and consistency of the fresh concrete through mini-slump tests. UHPC mixtures with varying contents of high-range water reducers and CNFs are tested. The addition of CNF is found to influence the yield stress, viscosity, and shear-thinning or shear-thickening behavior of the UHPC. Based on the experimental results, we model the CNF-enhanced UHPC as a non-Newtonian fluid to further investigate flow behavior. A modified power-law model is utilized to demonstrate the dependency of the UHPC viscosity on the shear rate and volume fraction of the concrete and the CNF particles. The findings from the study can help the design of a sustainable, high-performance construction material with optimal rheological properties and workability.

Wednesday 10:50 Peralta + Lamy AR23

Impact of wellbore inclination and rheological properties on barite sedimentation: Using a new visualization technique

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Unlike traditional drilling, directional drilling increases the well productivity. With the aim of optimizing drilling operations, oil industries are increasingly investing in technologies both in the way of drilling wells and in the fluids to be used during drilling. Drilling fluids contain insoluble solids, such as barite, which can sediment over time or when their flow is interrupted. Therefore, particle sedimentation is an undesirable phenomenon for the oil sector. Barite is widely employed to control the density of drilling fluids. Although, in inclined wells, the Boycott effect occurs, meaning that barite particles tend to laterally deposit in the mud, quickly accumulating near the wellbore wall. Over time, these deposited particles form unstable barite beds that periodically slide down, inducing fluctuations in bottom hole pressure. Originating various challenges during drilling. Understanding the effects that the wellbore inclination angle can have on particle sedimentation is still a poorly understood phenomenon. In this context, this study aims to improve the understanding of the influence of wellbore inclination and fluid behaviour during sedimentation of solids in Newtonian and non-Newtonian fluids. To this end, suspensions will be prepared after rheological characterization of the fluids. The video monitoring technique will be used to observe the behaviour of solids during sedimentation in both fluids and to monitor the volumetric concentration of solids over time at 5 different inclinations relative to the horizontal axis. According to the literature, with an increase in the inclination angle, the sedimentation velocity of solids will also increase, and there may be changes in sedimentation dynamics related to container inclination and fluid rheological characteristics, associated with the Boycott effect and gelation of biopolymeric structures. Thus, the use of video monitoring technique will enable observation and analysis of the difference in Boycott effect behaviour in both fluids.

Wednesday 11:10 Peralta + Lamy AR29

The flow fingerprint: A relativistic framework for characterizing complex fluids and predicting performance

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Understanding and optimizing the pumpability of concrete is critical for efficient construction, especially in modern projects requiring rapid placement and long-distance or high-rise pumping. Traditional methods for assessing pumpability, such as slump and flow table tests, often fail to capture the complex rheological behavior of concrete under actual pumping conditions. This study investigates the pumpability of various concrete mixes using the Sliding Pipe Rheometer (SLIPER), a novel device designed to closely replicate real-world pumping processes in a laboratory setting. The SLIPER employs a vertical pipe filled with fresh concrete, where a piston equipped with a pressure sensor measures the resistance as the pipe slides downward, simulating the pressure and flow encountered during pumping. This setup enables direct measurement of key parameters influencing pumpability, such as pressure loss and flow resistance, under controlled conditions. A comprehensive series of tests was conducted on concrete mixes with varying water-to-binder ratios, aggregate types and gradations, and admixture contents. Results demonstrate clear correlations between mix composition and pumpability, highlighting the effects of aggregate shape, water-cement ratio, and admixtures on pressure requirements and flow stability. The findings support the use of SLIPER as a practical tool for optimizing concrete mix designs to ensure efficient, blockage-free pumping, and for predicting field pumping pressures with high accuracy. These insights contribute to improved quality control and cost savings in concrete construction by enabling targeted mix adjustments prior to full-scale application.

Symposium AM
Additive and Advanced Manufacturing

Organizers: Anthony Kotula and Xiaoyu Tang

Wednesday 9:50 O'Keeffe + Milagro AM12

On the roles of die swell, boundary coalescence and crystallization kinetics in material extrusion-based additive manufacturing of thermoplastic polymers

Trystan Domenech[1], Pierre Ovlaque[2], Yves Trolez[3], Dominique Olivier[3], Benjamin Bujeau[4], Sébastien Charlon[2], and Jérémie Soulestin[2]

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Die swell is a well-known phenomenon occurring when a polymer melt is subjected to a constriction flow, resulting in an expansion of the melt as it exits an extrusion die. This flow-induced effect is ubiquitous in the field of extrusion-based polymer processing, including material extrusion-based additive manufacturing such as fused filament fabrication (FFF). However, its implications in FFF remain poorly understood, notably because the melt strand deposition flow occurs quite close to the printing nozzle exit, where the die swell does not happen freely (as for a simple extrusion flow) but in a confined layered flow. To better describe the relevance of this phenomenon in the context of FFF processes, we propose an examination of die swell in both free extrusion and confined flow conditions, where we underline the influences of the polymer molecular weight and processing conditions. Furthermore, we also explore the influence of physical parameters like bead cross section geometry, partial bead fusion (also called bead coalescence or bead welding) and crystallization kinetics on the 3D printing of isotactic polypropylene as a model semicrystalline polymer. New methods for the characterization of printed stacks cross sections, interlayer cohesion and viscoelastic coalescence are introduced and discussed.

Wednesday 10:10 O'Keeffe + Milagro AM13

Advanced manufacturing and deconstruction of polymer networks using stimuli-responsive microcapsules

Brad H. Jones[1], Oleg Davydovich[1], Samuel C. Leguizamon[1], Clarissa Westover[2], and Francesca M. C'de Baca[1]

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Microencapsulated functional compounds have been studied extensively for the development of stimuli-responsive materials, such as self-healing composites and coatings with sensing capabilities. In contrast, there are comparatively few examples of their use in advanced manufacturing and chemical recycling techniques, despite reliance on various external stimuli (e.g., light) to drive critical processes underpinning such techniques. This presentation will illustrate how microencapsulated catalysts can be leveraged to create polymer networks with programmable transformation profiles. We rendered highly active catalysts effectively latent by sequestration within glassy particles. These particles were used to create olefin resin systems for energy-efficient frontal polymerizations having exceptional shelf stability. The particle composition and design were varied to create both temperature- and light-activated systems. In other work, we created polybutadiene elastomers loaded with microencapsulated catalysts that were released in situ to induce rapid depolymerization of the elastomer. The depolymerization products were reprocessed, without any separation, purification, or workup, into a new elastomer bearing minimal loss of mechanical properties. More recently, we have extended these approaches to alternative polymer chemistries, such as polyurethanes. In all cases, we relied heavily on rheological and dynamic mechanical characterization to assess the performance of these unique, stimuli-responsive systems.

Wednesday 10:30 O'Keeffe + Milagro AM14

A rheological perspective into digital light projection printability of colloidal suspensions

Ejajul Hoque[1], Sarah Barber[2], Anna Klear[2], and Benjamin M. Yavitt[2]
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In digital light projection (DLP) 3D printing, the use of colloidal suspensions, such as nanoparticle-filled resins, offers opportunities for functional materials but presents significant processing challenges due to complex rheological behavior. High viscosity and yield stresses limit flow and recoating in many DLP setups, while time-dependent phenomena like thixotropy can cause layer inconsistency and defects. This study aims to bridge the gap between rheological characterization and DLP printability by exploring how transient rheological properties influence print quality. We hypothesize that efficient DLP printing occurs when the material's rheological time scales align with process time scales, and that both microstructure and final part properties are strongly governed by these dynamics. We use a model system of fumed silica dispersed in a commercial acrylate-based resin, enabling control over a broad range of viscosity, yield stress, and thixotropic behavior. Samples were printed with varying rheological profiles to determine critical thresholds for viscosity and yield stress beyond which printing becomes unreliable. We introduced controlled wait times prior to light exposure in the 3D printer to probe the effects of thixotropic recovery on dimensional fidelity and mechanical strength. An integrated photo-rheology set up was used to simulate printing conditions in the shear rheometer to see how standard rheological tools can be predictive of print performance under relevant conditions. Together, these findings contribute to a framework for evaluating and formulating colloidal suspensions for DLP, emphasizing the importance of matching rheological behavior to printing dynamics for optimal part quality.

Wednesday 10:50 O'Keeffe + Milagro AM15

Effect of functional groups on acrylate photopolymerization kinetics and rheological properties during UV cure

Robin Crownover and Eric Beckel
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It has been previously shown that secondary functionalities on monoacrylate monomers have a profound effect on the photopolymerization kinetics of these materials. While the previous research showed a polymerization rate increase with the addition of specific secondary functionalities, we have identified alternative secondary functionalities that reduce the polymerization kinetics. This study investigates the effect of these particular functional groups on the kinetics via UV cure during oscillatory rheometry, through the time to G'/G" crossover and time to final modulus. This study additionally examines how these functional groups affect rheological properties like storage and loss moduli, in particular the final storage modulus. Since the monomers under investigation are monoacrylates, there should be no crosslinking; therefore the differences in modulus strength are indicative of entanglement and the length of the polymer chains. These rheological studies will assist in the elucidation of the particular mechanism that may be contributing to the slower polymerization kinetic rates of these monomers.

Wednesday 11:10 O'Keeffe + Milagro AM16

Pinch-off, impact, and spreading dynamics of fiber-suspension droplets

Alban Sauret[1], Sreeram Rajesh[2], Nathan Vani[3], and Virgile Thievenaz[3]
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The pinch-off, impact, and spreading of drops of particulate suspensions on solid surfaces is relevant in various industrial applications such as inkjet printing or spray coating. The capillary dynamics of elongated particles, such as fibers, are also important in extrusion-based additive manufacturing when bioprinting cells or fiber suspensions used for fiber composites. However, the role and dynamics of fiber suspensions during capillary flows remain elusive. In particular, fibers can influence the ligament pinch-off from a millimetric nozzle, leading to the formation of a drop. During pinch-off, the liquid neck evolves through an effective-Newtonian stage, a grain-dislocation stage, and a pure fluid final pinch-off. Then, the presence of fibers also modifies the impact of the droplet, from its spreading to splashing. We experimentally investigate the impact of droplets of fiber suspensions on a hydrophilic surface. We report the evolution of the spreading dynamics, thresholds for splashing, film thickness, and fiber orientation as a function of the radial distance for fiber suspensions of varying mass fraction and aspect ratios. Our experiments show a substantial modification in the spreading dynamics of the drop due to the presence of fibers. Together, the two canonical experiments, pinch-off and drop impact, illustrate how fiber geometry and concentration modify breakup, spreading, and splashing.

Symposium ML
AI and ML in Rheology

Organizers: Vikram Jadhao, Shamsheer Mahammad and Hassan Pouraria

Wednesday 9:50 Sweeney Ballroom C ML1

Comprehensive data sets for machine-learned constitutive equations for temperature-dependent thixotropic waxy oils

Samuel A. Ogunwale[1], Khalid Mateen[2], Palermo Thierry[3], Abhishek Shetty[4], Luqman Mahir[1], Annie Fidel-Dufour[3], and Ronald G. Larson[1]

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The development of constitutive equations through Machine Learning and AI tools is an extremely promising, but difficult to achieve for frame-invariant three-dimensional tensorial constitutive equations. However, for some classes of fluids, scalar shear rheology is of greatest importance, and is in itself very complex. The example presented here is that of waxy oils, whose rheology under shear during and after cooling controls whether plugging of oil occurs in oil pipelines. A constitutive equation that can reliably predict shear viscosity and yield stress for temperature and shear histories in a pipeline would therefore be of great value. To help develop such constitutive equations, we have generated a wide range of shear flow data, under multiple shear and temperature histories, as well multiple wax compositions on well formulated wax oils. We achieve well-defined shearing conditions by starting at temperatures above that needed for wax crystals to form, so that the fluid is initially Newtonian. From this high temperature, we cool to final temperatures at different rates, and under different shear conditions. We find that shear strains of around 10 5 strain units during and/or after cooling are needed to achieve steady-state viscosities, which are non-Newtonian with yield stress. Studying these oils in different labs show that reproducible data is achievable with care, especially above 1 Pa shear stress. The thermal and shear thixotropic times dependences are very complex, but physics informed neutral networks (PINNs) represent a promising path towards capturing this behavior. Our methodology for data acquisition and development of constitutive equations helps define an approach that can be applied to other fluids exhibiting yield stress, thixotropy, and complex temperature history dependence.

Wednesday 10:10 Sweeney Ballroom C *Keynote* ML2

Accelerating physics discovery with machine learning

Amanda Howard

Pacific Northwest National Laboratory, Seattle, WA, United States

We use physics-informed neural networks (PINNs) to learn viscosity models of two non-Newtonian systems (polymer melts and suspensions of particles) using only velocity measurements. For synthetic velocity data generated with the power-law viscosity model, the PINN-inferred viscosity model agrees with the analytical model for shear rates with large absolute values but deviates for shear rates near zero where the analytical model has an unphysical singularity. Once the viscosity model is learned the PINN method can solve the momentum conservation equation using only the boundary conditions.

Wednesday 10:30 Sweeney Ballroom C ML3

Rheo-Former: A generative platform for reliable rheological and non-Newtonian fluid mechanical modeling

Maedeh Saberi and Safa Jamali

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Rigorous and accurate prediction of complex fluids' flow behavior in different scenarios has been a central objective of rheological sciences. Rheologically-relevant fluids often exhibit strong dependence on the history of flow, anisotropic stress responses, and nonlinearities that are nontrivial to capture using conventional numerical solvers, and thus non-Newtonian fluid mechanical platforms have been constantly evolving to alleviate such challenges. With unprecedented progress in development of data-driven techniques, reliable ML-based platforms that are capable of accurately modeling non-Newtonian fluids are generally lacking, or suffer from limited generalizability and computational inefficiencies when applied across varying flow conditions and geometries.

In this work, we develop a novel modeling platform based on neural operators-specifically, a Transformer-based architecture called OFormer-designed to learn the full operator mapping from system inputs (e.g., shear rate or velocity fields) to stress responses in complex fluids. This method integrates attention-based mechanisms with a latent time-marching propagator, enabling efficient and accurate prediction of both spatial interactions and temporal evolution within a reduced latent space. We evaluate our OFormer on multiple constitutive models (Thixotropic Elasto-Viscoplastic, Giesekus, and Oldroyd-B) and assess its performance on two categories of problems: (1) rheometric experiments involving prediction of scalar and tensorial stress responses from applied shear rates, and (2) full-field flow simulations in complex domains such as contraction channels and flow past obstacles. OFormer results suggest that it can serve as a robust surrogate for high-fidelity simulations, accurately resolving the entire flow of different complex fluids using minimal training data.

Wednesday 10:50 Sweeney Ballroom C ML4

Unveiling non-Newtonian flow dynamics and rheology: Data-driven constitutive modeling through differentiable simulations

Alp M. Sunol[1], Mohammed G. Alhashim[2], Wenyun Wang[1], James V. Roggeveen[1], Henry S. Bae[1], Kaylie Hausknecht[3], David A. Weitz[1], and Michael P. Brenner[1]

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Non-Newtonian and viscoelastic flows are ubiquitous in industrial processes and biological systems, yet modeling their behavior in realistic geometries and complex flow conditions remains a significant challenge. Differentiable simulations, by enabling automatic gradient computations throughout fluid simulations, present a transformative approach for solving inverse design problems and discovering constitutive relationships directly from diverse flow data. In this work, we introduce a fully differentiable non-Newtonian fluid solver developed using JAX. Leveraging differentiability, our solver enables end-to-end training of machine-learning models directly within the simulation pipeline, supporting efficient, data-driven parameterization of complex rheological behavior in arbitrary geometries. We incorporate a novel tensorial basis neural network that maps invariants of the flow to non-Newtonian and viscoelastic stress tensors, from which we extract bulk fluid properties such as viscosity and viscoelastic moduli. Our machine-learning framework's interpretability allows for direct comparison to established constitutive models via Bayesian Information Criterion (BIC), facilitating model selection and parameter refinement from sparse experimental data. To validate this framework, we first demonstrate its efficacy in flow scenarios where traditional constitutive models frequently fail due to complex deformation patterns and intricate boundary effects, namely contracting channels and porous media. Then, we present results from a new "rheofluidics" framework, where we learn the frequency-dependent rheology of droplets in microfluidic channels with oscillating walls from their deformation images. Ultimately, this work lays a data-driven groundwork for advanced digital rheometry to characterize the behavior of complex fluids under diverse and realistic in-situ conditions.

Wednesday 11:10 Sweeney Ballroom C ML5

Inferring viscoelastic model parameters from complex flows using physics informed neural networks

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Viscoelastic constitutive models often entail many parameters, and are difficult to calibrate using standard rheological measurements. We present a deep learning inverse calibration framework based on physics-informed neural networks (PINNs) that combines full-field data from multiple data sources to infer constitutive parameters. We demonstrate our approach using simulation data from the extensional and static phases of a capillary break extensional rheometry (CaBER) flow simulation. The use of full-field velocity and stress data yields adequate inference of rheological parameters for both a Newtonian and linear Phan-Thien-Tanner (LPTT) fluid, with improvements in the latter case achieved by combining data from the static and extensional phases. We explore the robustness of this approach to the amount of available data, as well as to Gaussian noise in the data, in order to assess the potential for use with experimental datasets. Using velocity and stress data only on the boundary leads to incomplete parameter identification for the single-mode LPTT model. However, by augmenting the dataset with measurements from a simple Poiseuille flow experiment, we obtain accurate parameter estimates even with limited data. The ease of using multiple data sources in a PINNs framework demonstrates the usefulness of this approach for augmenting traditional model calibrations, and potentially combining full-field measurements with standard rheological measurements for improved model parameter inference. This method provides a crucial step towards efficient and accurate characterization of complex fluids, circumventing many limitations of conventional methods that rely on idealized flow conditions and simplified geometries.

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Symposium TM
Techniques and Methods: Rheometry, Tribometry, Spectroscopy and Microscopy

Organizers: Sara Hashmi, Jeffrey Richards and Qi Li

Wednesday 9:50 Sweeney Ballroom D *Keynote* TM7

New advancements in techniques for investigating lava rheology

Martin A. Harris[1], Stephan Kolzenburg[1], Magdalena O. Chevrel[2], Magdalena O. Chevrel[3], and Magdalena O. Chevrel[1]
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Viscosity is a fundamental physical property that controls lava flow dynamics, runout distance, and velocity, which are critical factors in assessing and mitigating risks associated with volcanic eruptions. Laboratory rheometry on remelted rocks is the standard technique for measuring lava properties. This approach enables precise measurements but struggles to recreate natural lava characteristics: three-phase suspension made of a temperature and redox-dependent magmatic melt, crystals, and bubbles. Specifically, these techniques (concentric cylinder) are unable to retain bubbles that escape through the melt and thus fail to capture the multiphase nature of lavas. Measurements performed in the field, directly in active lava flows, are the only way to fully capture lava's viscosities, but these are scarce due to a lack of easy-to-use, portable devices. Here, we present new devices, in-situ field measurements, and a first comparison of field and laboratory lava viscometry. In-situ field viscosities were measured using home-made portable field viscometers and are integrated with data on the same lava measured in the laboratory at subliquidus temperatures, constant crystal fraction (thermal equilibrium), and under constant cooling and crystallization (disequilibrium), measured at conditions relevant to natural processes (log fO_2 of -8.7; shear-rate of ~3 s^{-1}). At lava natural temperatures (1150-1165 °C), we show, for the first time, that disequilibrium laboratory measurements run at 0.5-1 °°C/min closely match the rheological evolution of flowing lava measured in the field: ~1.5 to 3.5 Log Pa s. Lastly, we find that the laboratory experiments run at equilibrium thermal conditions are capable of recovering natural lava viscosities but only at dilute crystal volumes <30%, limiting this laboratory method's applicability to crystal-rich lavas.

Wednesday 10:10 Sweeney Ballroom D TM8

Oscillatory rheometry procedures for highly loaded suspensions

Patrick Stanton
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Oscillatory rheometry is a critical experimental tool for characterizing a new material and understanding its behavior during a manufacturing process, additive or traditional. Specifically of interest are the linear storage moduli. Traditional rheological procedures for obtaining accurate data on these properties do not work for highly loaded suspensions due to slip, edge fracturing, or in-gap flow. In this discussion the development of oscillatory rheometry procedures for highly loaded suspensions are reported.

Wednesday 10:30 Sweeney Ballroom D TM9

Extensional rheology and stringiness of yield stress fluids

Somayeh Sepahvand, Nadia Nikolova, Louie Edano, and Vivek Sharma
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Many commercial formulations that appear to flow only beyond a critical stress value are classified as yield stress fluids. The apparent yield stress can be computed from a large variety of measurements that rely on transient, oscillatory, or steady shear response. Despite the wide availability and applications of such fluids, there is a considerable lack of studies that characterize their response to extensional stress and flows, motivating this study. Here we investigate the flow characteristics of extruded filaments using dripping and dripping-onto-substrate. We analyze the transition from solid to liquid in a neck to estimate the extensional yield stress and after yielding, characterize the neck pinching dynamics. The yielding transition, neck shapes, radius evolution as a function of time, and shape and size of dispensed drops are characterized and analyzed for prototypical yield stress fluids formulated using densely packed microgels, particles, drops, or macromolecules. We seek a deeper appreciation of the diversity in extensional response of formulations as influenced by their microstructure, and challenges involved in the characterization using methods based on free-surface flows.

Wednesday 10:50 Sweeney Ballroom D TM10

Boger yield stress fluids in gravity-driven filament stretching

Thomas A. Livesay, Mohammad Tanver Hossain, and Randy H. Ewoldt
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Yield stress fluids can be highly extensible [1]. However, current methods to characterize this extensibility with filament stretching can suffer from boundary adhesion issues, unstable or asymmetric filament formation, artifacts from delayed necking, and difficulties in accessing high strain rates. Here, we study how extensional gravity-rheometry (EGR), developed for simple yield-stress fluids [2], can be extended to more complex yield stress fluids with high elasticity including "Boger yield stress fluids" with tunable extensibility [3]. Thin filaments are often generated; we derive and test how to incorporate surface tension effects into the working equations and identify operational limits where key assumptions are violated. We consider a range of fluids, including Newtonian fluids, archetypal yield stress fluids, and model extensible yield stress fluids formulated with polyethylene oxide (PEO) and Carbopol microgel particles [3]. Using quantitative video image analysis, we track filament

deformation during extrusion to calculate the instantaneous strain rate and tensile stresses at the minimum filament radius, enabling inference of instantaneous, local extensional rheological properties. We demonstrate this technique can be used to reveal high extensibility and extensional thickening in these model extensional yield stress fluids, beyond what has typically been observed in filament stretching tests, made possible by probing higher strain rate regimes [4]. These results broaden the applicability of the extensional gravity-rheometry test to a wider classification of fluids, enabling advancements in high throughput, in situ material characterization, as well as in construction, additive manufacturing, and 3D printing applications.

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Wednesday 11:10 Sweeney Ballroom D TM11

Rheology of Carbopol in a benchmark experiments: Flow around a rising bubble

Omid Hajieghrary[1], Masoud Daneshi[2], and Ian Frigaard[1]
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Rising bubbles in liquid occur in natural and industrial processes such as tailing ponds, swamps, food processing, drilling fluids, etc. More often than not, the material surrounding the bubbles shows complex rheological properties. When modeling these flows, simplified constitutive equations are often used. In controlled lab settings, rising bubbles in elasto-viscoplastic materials exhibit numerous phenomena that simple viscoplastic constitutive models fail to predict. Creation of preferential paths for subsequent bubbles released and sharp tails in certain parameter regimes are two of these effects. Accurately modeling these effects requires more sophisticated constitutive laws, which in turn depend on detailed rheological characterization. This study aims to provide comprehensive rheological measurements for benchmark flows involving rising bubbles in elasto-viscoplastic materials. Particular attention is given to recoverable rheology, which has attracted attention in recent years. This data set and the experimental protocols will be invaluable to developing constitutive models that try to model the full aspect of bubble rise in such material.

Wednesday 11:30 Sweeney Ballroom D TM12

Marsh funnel protorheology for yield stress fluids - operational limits and design insights

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The Marsh funnel [1] is an incredibly useful test standard, a type of protorheology test [2], to infer fluid rheology (yield stress, viscosity) by observing gravity-driven discharge from a funnel. However, corrupt data and practical limitations can cause data misinterpretation, an issue in both protorheology [3] and rheometry more generally [4], and a quantitative framework to address these limits is lacking. In this work, we derive explicit limit equations for yield stress fluid tests with funnel viscometers (Marsh Funnel and other standard geometries) based on non-idealities due to fill height and stagnation height resolution, discharge time, fluid inertia, assumptions of laminar, fully developed flow, and negligible surface tension effects. These equations help identify an "operational window" on material function plots (e.g., viscosity vs stress) informing where working equation assumptions are valid. While previous studies reported fewer limitations for specific funnels, we derive general and extensive equations dependent on funnel geometry and fluid properties. Inversely, this provides an opportunity to design new funnel geometries to extend the measurement range of existing standard funnels (e.g., yield stress of 12 - 50 Pa) to practical applications like drilling and construction which encounter a wider range of rheology (e.g., yield stress of 5-100 Pa). We propose quantitative insights for designing new funnel geometries to achieve specific rheological targets, enabling broader applications of these tests.

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Wednesday Afternoon

Symposium CS
Colloidal Suspensions and Granular Materials

Organizers: James Gilchrist, Abhinendra Singh and Shravan Pradeep

Wednesday 1:30 Sweeney Ballroom A CS39

Coherent x-rays reveal dynamics inhomogeneity in shear thickening colloids

Xiao-Min Lin[1], James P. Horwath[2], Hongrui He[3], Jonghun Lee[2], Zhang Jiang[2], Suman Chakraborty[1], Qingteng Zhang[2], Eric M. Dufresne[2], Mark Sutton[4], Alec Sandy[2], and Suresh Narayanan[2]

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Shear thickening is a ubiquitous phenomenon that plays an important role in many industrial processes. Despite its importance, the intrinsic mechanism that drives shear thickening has long been under debate, particularly the role of friction between the particles. One phenomenological theory proposed by the Wyart and Cates suggests that discontinuous shear thickening (DST) may arise from part of the sample overcoming finite electrostatic, steric repulsion, or Brownian stress and developing frictional contact. However, little experimental evidence exists to support this model directly. Here, using x-ray photon correlation spectroscopy (XPCS), we show the existence of an intrinsic heterodyne feature during shear cessation, which originates from the relative motion of mobile particles against an aggregated or jammed network induced by shear thickening. Upon removing the shear, the shear stress dissipates rather quickly in a two-step fashion, whereas the heterogeneous particle dynamics persist much longer with the relative velocity decaying slowly with time as t^-1. More importantly, both continuous shear thickening (CST) and DST show similar heterodyne features, indicating the intrinsic mechanisms causing shear thickening are similar in nature.

Wednesday 1:50 Sweeney Ballroom A CS40

Scaling of structural and rheological properties in shear thickening suspensions

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Based on an established simulation approach for dense suspensions, the clusters defined by frictional contacts are considered for a suspension of repulsive particles that undergo a lubricated-to-frictional shear thickening transition as the imposed stress increases. Here, the focus is on the scaling behavior of both structural and rheological measures. First, the development of progressively more rigid motion of the clusters as the degrees of freedom are restricted by contacts is described, with a focus on discontinuously shear thickening (DST) conditions. The statistics of these clusters as a function of the stress imposed, and their relation to the observed DST response, are studied, with special attention to observed critical scaling behavior of rigid clusters [1]. In addition, the relation of rigid clusters to network measures of contact, include contact percolation, is considered. Second, based on the prior finding [2] that the rheology of shear thickening suspensions cross-over scaling, between regimes controlled by the frictionless and frictional jamming points, we explore the cross-over scaling for different particle stiffness.

1. A. Santra, M. Orsi, B. Chakraborty & J. F. Morris 2025 Rigid clusters in shear-thickening suspensions: a nonequilibrium critical transition. Phys. Rev. Research 7, 013275. 2. N. Malbranche, A. Santra, B. Chakraborty & J. F. Morris 2022 Scaling analysis of shear thickening suspensions. Frontiers in Physics 10, 946221.

Wednesday 2:10 Sweeney Ballroom A CS41

Large intruders in a shear-thickening suspension

Alice Pelosse and Heinrich Jaeger

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Shear-thickening in suspensions, characterized by an increase in viscosity with strain rate or applied stress, is a phenomenon observed in a variety of systems, including starches, dense colloidal suspensions, confined granular materials, and suspensions of functionalized particles. This effect typically emerges at relatively high particle volume fractions, where it is intrinsically tied to the jamming of the solid phase. Depending on the underlying mechanisms, shear-thickening can manifest as either continuous (CST) or discontinuous (DST). DST, in particular, is thought to arise from the onset of frictional interactions at the particle level, which lead to the formation of rigid, system-spanning clusters. These frictional clusters are central to the dramatic viscosity increase observed during DST. It follows that perturbations disrupting this rigid network, such as the introduction of foreign large granules, could alter the strength of the shear-thickening response. In this work, I investigate how the inclusion of intruders-large granules embedded in the shear-thickening suspension-affects its rheology. My results indicate that the effects of granules observed in previous studies on cornstarch-based suspensions do not generalize to all shear-thickening systems, in particular in terms of CST and DST

trends. I therefore analyze how the rheology is influenced by the composition and microstructure of the suspension, as well as by the size, volume fraction, and surface chemistry of the granules. This study sheds light on the multiscale nature of shear-thickening and highlights key parameters that govern the interplay between intruders and the raw shear-thickening suspension.

Wednesday 2:30 Sweeney Ballroom A CS42

Shear thickening and time-dependent rheological behavior in graphite/CMC slurries

Hyunjoon Jung, Cheolheon Hyun, and Jaewook Nam
Chemical and Biological Engineering, Seoul National University, Seoul, Republic of Korea

A detailed understanding of the rheology of dense, non-Brownian slurries is essential for optimizing lithium-ion battery electrode manufacturing. This study examines the shear thickening behavior of aqueous graphite suspensions, serving as a model system for anode slurries. At high graphite concentrations, the suspensions exhibit pronounced shear thickening accompanied by anti-thixotropy-a time-dependent increase in viscosity under sustained shear. Flow reversal experiments reveal that both phenomena originate from forming a frictional contact network, with contact stresses increasing as a function of shear rate and shearing time, while non-contact stresses remain largely unchanged. Flow cessation tests show that this network partially persists after shear removal, as evidenced by residual stress and a marked increase in storage modulus. Supporting this observation, rheo-impedance measurements indicate an irreversible increase in electrical impedance following shear, providing additional evidence for the persistence of the contact network. These findings suggest that hydrophobic interactions contribute to the network's slow relaxation. Overall, this work advances the understanding of shear thickening in non-Brownian suspensions and offers insights relevant to the processing of battery electrode slurries.

Wednesday 2:50 Sweeney Ballroom A CS43

Effects of non-adsorbing polymer molecular weight on the rheology and microstructure of dense, colloidal, ceramic suspensions

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Dense suspensions with high solid volume fractions (?=0.5) are prevalent in nature and throughout industry. These highly loaded suspensions can exhibit complex rheological behaviors, including both shear thinning and subsequent thickening with increasing shear rate. Understanding the mechanisms behind these rheological behaviors can improve the design of materials systems to behave as predicted and desired under process flows. Here, we present a study on an industrially relevant, dense (?=0.55), colloidal alumina suspension and show how the addition and loading of non-adsorbing polyvinylpyrrolidone (PVP) at different molecular weights can be used to tune and control its rheological properties. PVP was added at varying concentrations spanning the dilute and semi-dilute, non-entangled regimes for each molecular weight. The addition of PVP at concentrations in the dilute regime was shown to increase the viscosity of the suspension and induce discontinuous shear thickening (DST). However, further increases in PVP loading particularly within the semi-dilute, non-entangled regime and at higher PVP molecular weights also increased the dynamic yield stress of the material, made the suspension more shear thinning, and delayed the onset of DST. Rheological measurements were coupled with insights on the relevant particle and polymer length scales from small angle neutron scattering (SANS), including Rheo-SANS measurements, to inform on the mechanisms by which non-adsorbing polymers influence suspension rheology across multiple flow regimes.

Wednesday 3:45 Sweeney Ballroom A CS44

Capillary rheology of high concentration CNT solutions

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Solution processing of carbon nanotube (CNT) is a scalable way of producing conductive, strong macroscopic materials like fibers and tapes via wet spinning or casting. The best solvents are corrosive, hygroscopic, or otherwise unstable in air, requiring environmental isolation during processing. While these challenges can be simply handled in manufacturing, they complicate rheological characterization due to exposed free surfaces that can lead to solution degradation. Capillary rheology offers a promising approach to measuring solution properties because samples are fully enclosed during measurement; however, commercially available capillary rheometers are typically designed for melt extrusion, with single-pass operation and extrudate ejection into air, preventing their use in this case. We present a simple, low-cost, sealed multi-pass capillary rheometer suitable for studying CNT solutions in various solvents. With this rheometer, we study the effect of CNT concentration and molecular structure (length and diameter) in chlorosulfonic acid solutions (0.5 to 10 wt% CNT). In this range of concentrations and CNT aspect ratio (length to diameter), the solutions are liquid crystalline, with a polydomain morphology. The solutions ranged in viscosity from ~0.001 Pa s (0.1 wt% CNT sheared at 1000 s^{-1}) to ~100 Pa s (10 wt% CNT sheared at 1 s^{-1}). The viscosity and power law index increased with increasing CNT aspect ratio and concentration. At lower concentrations (1%), longer CNT solutions have about 10x higher viscosity than shorter ones. At the highest concentrations (10%), the viscosity was nearly independent of CNT length at low shear rates, suggesting that these solutions began exhibiting

behavior dominated by CNT liquid crystalline domain dynamics. This method and results are a pathway towards deeper understanding of CNT liquid crystalline solutions that can be used to process CNTs into fibers, tapes, and other macroscopic structures.

Wednesday 4:05 Sweeney Ballroom A CS45

Microscopic structure and dynamics of dense suspensions of a stimuli-responsive core-shell latex

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Suspensions of responsive polymers have been developed for various applications including biomedical scaffolds, paints and coatings, water treatment, and commercial personal care products. The particles in these systems respond to external environmental changes, such as temperature, solvent, pH, ionic strength, etc., via changes in their internal microstructure and intraparticle interactions. These microstructural responses manifest as changes in macroscopic properties such as viscosity or elasticity allowing for tunable material properties. In previous work, we linked the rheology in the dilute and semi-dilute regimes of a resin consisting of an aqueous suspension of core-shell latex particles to the particle architecture and investigated the response to changes in pH and solvent conditions. We discovered a unique architecture of the shell component and provided insight into predicting the rheology of the resin showing that the particles can be modeled as effective hard spheres due to charge repulsion. We extend this work into the concentrated regime where the dilute and semi-dilute predictions no longer hold. In this regime, we find through Small Angle Neutron Scattering (SANS) that the intensity of the initial structure factor peak is enhanced by added stimuli, suggesting particle clustering contrary to the repulsion-dominated regime in dilute suspensions. We gain dynamical information from X-ray Photon Correlation Spectroscopy (XPCS) confirming the complex interplay in particle interactions in concentrated suspensions. This insight allows us to ultimately connect the rheological response of the resin to stimuli with the microstructure and dynamics.

Wednesday 4:25 Sweeney Ballroom A CS46

From sedimentation to suspension: Critical strain as a predictor of particle resuspension under shear

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The resuspension of sedimented particles in a viscous fluid plays a critical role in environmental and industrial processes-from riverbed erosion to blood flow and industrial mixing. While prior studies have focused on turbulence-dominated regimes, less is understood about particle dynamics and related models in laminar flows where gravitational and shear forces are comparable. These conditions are common in riverbeds, biomedical flows, and seismic-induced sediment transport, where particle mobilization shows thresholds, hysteresis, and memory effects. In this study, we investigate the resuspension of dense, non-Brownian spherical particles in a Newtonian fluid subjected to both steady and oscillatory shear flows. Using bulk rheology and in situ rheo-microscopy, we examine a range of particle volume fractions (? = 0.30-0.55) and identify shear strain as the primary control parameter for resuspension. Our results reveal a strain-driven transition from a stable sediment bed to a homogeneously suspended state, which is mediated by effective particle-particle collisions and collective motion, and it is independent of the applied shear rate. We further introduce a theoretical model that correlates critical strain with particle concentration, enabling the prediction of resuspension thresholds under different shear conditions. Based on this, we make universal state diagrams that classify sedimented, resuspension, and full suspension regimes under both steady and oscillatory shear flow. These findings provide a new framework to understand and control resuspension dynamics in low-Reynolds-number flows, with implications for environmental, biomedical, and functional materials.

Wednesday 4:45 Sweeney Ballroom A CS47

Fluid flow modulation via shape-evolving colloids

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This work introduces a colloidal platform for temperature-dependent rheological control, utilizing elastic colloids and thermo-responsive polymers. Viscous dissipation in these colloids arises solely from their deformability, avoiding the need for chemical functionalization to drive binding interactions. We will demonstrate that temperature can be employed to dynamically manipulate particle interactions and packing, providing versatile structural control of the fluid. Furthermore, we will present examples illustrating how colloidal shape variations can precisely tailor the suspension's flow properties. This platform offers a promising route for future manipulation of complex fluid rheology.

Wednesday 5:05 Sweeney Ballroom A CS48

Influence of particle morphology and fluid matrix on the rheological response and microstructure of non-colloidal suspensions

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The rheological behavior of non-colloidal suspensions is strongly influenced by the interplay between particle characteristics and the fluid's microstructure. This study investigates the effect of particle morphology on the rheological response of suspensions formulated with porous PSP

particles dispersed in a viscoplastic Carbopol® matrix. The objective is to understand how particle shape, size, and surface roughness modulate the yield stress, viscoelastic properties, and flow behavior of these systems. Rheological characterization was performed through steady shear tests, oscillatory measurements, and creep experiments using a rotational rheometer with appropriate geometries. The microstructural arrangement of the suspensions under flow was evaluated via rheo-microscopy. Preliminary results reveal that PSP particles significantly alter the Carbopol® network, enhancing elastic moduli and affecting thixotropic recovery, due to increased particle-fluid interactions. These findings contribute to a deeper understanding of the microstructure-rheology relationship in viscoplastic suspensions, providing a basis for tailoring formulations in applications requiring controlled yield stress and structural recovery.

Symposium GN
Self-assemblies, Gels and Networks

Organizers: Thibaut Divoux, Katie Weigandt and Ria Corder

Wednesday 1:30 Sweeney Ballroom B GN40

Viscoelasticity of model polyisoprene vitrimers

Russo Arcangela[1], Bhaumik Saibal[2], Ntetsikas Konstantinos[2], Hadjichristidis Nikolaos[2], Loppinet Benoit[3], and Dimitris Vlassopoulos[4]

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Vitrimers are known to combine the desirable properties of both thermoset and thermoplastic materials. The key feature is the presence of associative dynamic covalent bonds. At high temperatures, the material becomes easily processable due to the fast kinetic rate of bond exchange reactions, while upon cooling it acquires a thermosetting behavior. Given that vitrimes often suffer from parasitic reactions following preparation, to understand their rheology and in particular the intricate interplay between bond dynamics and mechanical response, we investigate well-characterized vitrimers. They are based on polyisoprene precursors whose molar mass varies systematically from the unentangled to the well-entangled regime. We analyze the evolution of storage and loss moduli across a range of frequencies and temperatures, unraveling the unique rheological fingerprint of these materials. The vitrimer network exhibits a broad transition from elastic response to viscoelastic flow, governed by the activation of bond exchange reactions. A strong aging is observed and monitored. Lower molar masses lead to a stiffer and disordered material, whereas for higher molar masses two plateau moduli can be discerned. These results, combined with information from systematic X-ray scattering measurements support the hypothesis of cluster formation due to the microphase separation of the crosslinkers (bonding groups) in samples with lower molecular weights. We further analyze the frequency shift factors from the rheological master curves and find a transition from WLF to Arrhenious behavior which should occur at the vitrimer temperature Tv. These insights pave the way for designing vitrimers having tunable mechanical properties, with emphasis on their possible use as compatibilizers for polymer blends.

Wednesday 1:50 Sweeney Ballroom B GN41

Microstructural and rheological insights into polysaccharide-protein complex gels

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Galactomannans-plant-derived polysaccharides composed of mannose and galactose units-are widely utilized in food, pharmaceutical, and cosmetic formulations due to their thickening, stabilizing, and gelling capabilities. Their functional performance is closely tied to their mannose-to-galactose (M/G) ratio, which varies by botanical source. When combined with proteins, galactomannans influence structural and mechanical properties, yet the nature of these interactions, particularly under processing conditions such as heat and shear, remains underexplored. This study investigates the interactions between whey protein isolate (WPI) and two galactomannans-guar gum (GG) and locust bean gum (LBG)-to understand their effect on thermal gelation, rheological properties, and microstructural development. WPI alone and its mixtures with GG or LBG were subjected to controlled thermal and shear treatments. Rheological measurements revealed that both GG and LBG enhanced the viscosity and viscoelasticity of WPI systems, with GG showing a more pronounced thickening effect even at ambient conditions. Although the presence of galactomannans did not alter the thermal denaturation profile of WPI, GG slightly accelerated gelation compared to LBG. Oscillatory frequency sweeps indicated that all systems formed stable gels, with storage moduli (G') consistently exceeding loss moduli (G"). The magnitude of viscoelastic moduli followed the order: WPI+GG > WPI+LBG > WPI, highlighting the stronger rheological influence of GG. Confocal images of the complexes were consistent with rheological results while isothermal titration calorimetry (ITC) provided molecular-level interactions between the components. Temperature ramp experiments further confirmed the stability and enhanced rigidity of the protein-polysaccharide gels, particularly under thermal cycling. These findings suggest that while galactomannans do not modify the fundamental denaturation mechanism of WPI, they significantly influence the resulting gel network through segregative inter

Wednesday 2:10 Sweeney Ballroom B GN42

High-pressure rheology of a thermoreversible protein sol-gel

Eric M. Furst, Susana Teixeira, Brian Paul, Norman Wagner, and Abraham Lenhoff
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Protein gels are ubiquitous in pharmaceutical, biomedical, and food science for which protein formulations undergo a complex series of processing steps, including high hydrostatic pressure, for which the rheological effects on protein gelation are largely unexplored. With the growing need for soft biomaterials with precisely designed structural and mechanical properties, an expanded understanding of pressure-tunable protein gel behavior is highly desirable. With this goal in mind, we studied the rheology through the sol-gel transition of gelatin, a model thermoreversible protein gel. We report measurements using rotational rheometry at atmospheric pressures and microrheology measurements using a high-pressure cell. The latter significantly extends the measurement regime of these materials to process pressures. We find that the thermal gel boundary increases approximately 4C for every 100 MPa of pressure. More importantly, we find that temperature and pressure can be used to control the final gel microstructure, for instance using stepwise pathways to travel back and forth across the critical gel line to achieve the desired initial cross-linking density before quenching to lower temperature. The potential tunability of gel properties by this approach can be a powerful solution for optimizing gel characteristics for biomedical applications, where greater gel strength is not necessarily desirable, and pressure-temperature controlled manufacturing steps can yield the desired gel properties at ambient temperature.

Wednesday 2:30 Sweeney Ballroom B GN43

Novel rheological transitions and ordering in hybrid emulsion-hydrogels for treating otitis media

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Chemical Engineering and Materials Science, University of Minnesota, Minneapolis, MN 55455, United States

Despite many recent advances in treatment options for acute otitis media (AOM), there still exists a specific need for stable delivery systems to facilitate direct, non-invasive delivery of antibiotics through the ear drum (TM). However, parameters such as antibiotic release profile, formulation stability, and mechanical properties remain difficult to efficiently control without compromising treatment efficacy. To address this, we have developed thermoresponsive formulations consisting of a triblock polymer, antibiotic, and chemical permeation enhancer (CPE) to enhance flux across the TM and deliver antibiotics. These formulations exist as liquids at room temperature - rendering them easily applicable to the TM via syringe - and undergo a solution-to-soft solid transition upon contact with the warm TM. Unlike prior formulations, here the CPE methyl laurate (ML) is an oil that complexes with antibiotics such as ciprofloxacin to enhance drug permeation. Because ML is not water-soluble, a hybrid emulsion-hydrogel structure forms when these systems self-assemble, leading to unique multi-step rheological transitions with increasing temperature. Beyond rheology, differential scanning calorimetry and small-angle X-ray scattering are used to elucidate the complex structure-formation mechanisms behind this unique thermoresponsive gelation and ordering. While analogous systems without ML typically have sharp, single step rheological transitions with respect to temperature, these materials undergo multiple structural transitions during heating leading to broad rheological transitions. Further, cubic ordered micelle packings form in these hybrid materials at dynamic moduli that are orders of magnitude lower than observed in systems without ML. By establishing these structure-property relationships, optimal formulations for treating AOM and other diseases can be developed without hindering drug diffusion or mechanical stability.

Symposium SE
Rheology and Sustainability for Energy and Production

Organizers: Rekha Rao, Joseph Samaniuk and Phillip Irace

Wednesday 3:45 Sweeney Ballroom B SE1

Coating and extrusion models for viscoelastic fluids

Weston Ortiz[1] and Rekha R. Rao[2]
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Viscoelastic materials are often found in many industrial coating processes from electrode inks to polymer melts and solutions. For these processes, a material is extruded from a die and subsequently deposited on a substrate. The material can often experience high shear-rates and stresses during deposition, which can result in unstable flow leading to defect formation. Computation fluid dynamics (CFD) models can be used to help inform process choices and find stable flows, such as determining the low flow limit for coating flows. CFD of viscoelastic flows can often be difficult due to both the increased computational costs and numerical issues like the high Weissenberg number problem (HWNP), where we see loss of convergence as the amount of elasticity in the fluid is increased. The simulations utilize a DEVSS/SUPG stabilized finite element formulation using a symmetric square root conformation tensor transformation for the viscoelastic constitutive equation, which can alleviate the HWNP and handle constitutive equations with multiple modes. An arbitrary-Lagrangian-Eulerian (ALE) approach is used for interface tracking of the evolving geometry. In this paper, we investigate several viscoelastic flows free surface flows relating to industrial processes, including die swell from fiber spinning, blade coating, film casting, and slide coating. When available, comparison to experimental results are shown.

Wednesday 4:05 Sweeney Ballroom B *Keynote*…..SE2

Microstructure investigations of electrocatalyst inks towards manufacturing scaling-up of fuel cells and electrolyzers

Sunilkumar Khandavalli[1], Jae H. Park[2], Diego D. Soetrisno[1], Megan Bassinger[1], H. Henning Winter[3], Deborah J. Myers[2], Michael Ulsh[1], and Scott A. Mauger[1]

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Polymer electrolyte membrane fuel cells and water electrolyzers are two prominent electrochemical energy conversion technologies with many applications including in transportation and industrial sectors, but are currently adopted on a limited scale. Their wide-scale commercialization requires reduction in their manufacturing costs, along with enhancements in their performance and durability to meet application demands. The catalyst layers are critical components of these devices that provides transport pathways for reactants and products to-and-from the catalyst active sites, impacting the device performance. They are composed of a mixture of catalyst and ionomer, acting as a binder and an ion-conducting agent. The catalyst layer is commonly fabricated by solution-processing a catalyst ink. The ink design as well as coating and drying processes greatly impact the catalyst layer morphology, and thereby affecting the device performance and durability. Understanding how these impact the catalyst layer morphology and in turn the device performance is critical to efficiently control and tailor the catalyst layer morphology during scale-up and advancing these technologies, but are not well-understood. This is presenting a bottleneck for scale-up efforts. The talk will focus on recent and ongoing foundational investigations analyzing how the dispersion media properties impact the microstructure of IrOx-based electrolyzer inks as well as neat ionomer dispersions using a combination of rheology and USAXS. Investigations revealed the dispersion media composition - the ratio of water and isopropanol (IPA) - to strongly impact the viscosity scaling, viscoelastic non-linear response, including shear thickening, and interchain aggregation of ionomer dispersions. Likewise, dispersion media composition was also found to dramatically affect the aggregation kinetics and microstructure of electrolyzer inks, suggesting modification of ionomer-catalyst interactions, which has been rationalized using extended-DLVO theory.

Wednesday 4:25 Sweeney Ballroom B *Keynote* SE3

Edge profile control in battery electrode slot-coating

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Edge profile control in slot-coating processes remains a critical challenge for lithium-ion battery electrode manufacturing. Edge defects, particularly elevated edges, cause electrode wrinkles and lead to significant material waste due to necessary edge trimming. Despite its importance, controlling edge profiles in thick-film anode coatings remains challenging due to complex flow phenomena. This research investigates edge profile control strategies and the underlying formation mechanisms using a dataset of over 500 high-quality edge profile measurements across diverse process conditions. Through systematic variation of operating conditions, slot-die configurations, and slurry rheological properties, our data-driven analysis identified the optimal parameters for achieving desired edge profiles. Further investigation identified two distinct physical mechanisms governing edge formation: pressure distribution within the coating bead and downstream leveling flow. These insights provide manufacturers with clear guidelines to reduce edge defects and improve production yield, while offering the underlying physical rationale that supports these guidelines.

Wednesday 4:45 Sweeney Ballroom B SE4

Effect of time-dependent thixotropic fluids on slot-die coater flow dynamics, viscosity recovery, and operating conditions

Tyler R. Kennelly[1], Rekha R. Rao[1], Weston Ortiz[2], Chance Parrish[3], Kristianto Tjiptowidjojo[4], and Randy Schunk[2]

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Slot-die coating is a precise, scalable, and pre-metered technique widely used to deposit thin, uniform films onto substrates. It is suitable for applications across industries such as photographic film, battery electrodes, photovoltaics, transparent conductive films, and catalyst layer deposition in Polymer Electrolyte Membrane Fuel Cells (PEMFCs). Because of its versatility, slot-die coating is commonly employed for a broad range of complex inks, many of which are multicomponent mixtures comprising polymer solutions, alcohols, metallic solids, and colloidal suspensions. These complex formulations form microscale networks of particles and entangled polymer chains that give rise to diverse non-Newtonian behaviors, including shear-thinning, extensional thickening, viscoelasticity, viscoplasticity, and thixotropy. In this presentation, we investigate the thixotropic behavior of platinum-on-carbon (Pt/C) ink used in proton exchange membrane fuel cells (PEMFCs) and its impact on flow dynamics, wet-film viscosity recovery, and slot-die coating windows using Goma, a finite-element multiphysics simulation code. To evaluate the influence of time-dependent viscosity on operating conditions, we compare two rheological models: a steady-state Carreau-Yasuda model and a time-dependent first-order structural kinetics model. Simulations for the baseline PT-C ink reveal that while overall flow characteristics within the die and coating gap remain similar between models, the thixotropic model exhibits markedly reduced viscosity recovery. Further simulations for a fluid of slower structure recovery and breakdown rates show a significantly altered vortex formation within the die. This changes the viscosity

distribution throughout the slot and wet film and leads to the development of a persistent viscous strand. These structural effects culminate in a substantial increase of up to 15% in the vacuum pressure required to maintain stable, defect-free coating.

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Wednesday 5:05 Sweeney Ballroom B SE5

Effect of polymer additives to Nafion solutions on shear and extensional rheological behavior, coating deposition, and drying defects

Mariah J. Gallegos and Nelson S. Bell
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Nafion properties have been widely studied to help further improve the performance of proton exchange membranes (PEMs). This ionomer displays interesting properties due to its hydrophobic tetrafluoroethylene backbone and hydrophilic sulfonic acid side chains. There are still fundamental questions on the intra-ionomer behavior, structure, and ionomer dynamics. Recent studies have shown that addition of polymers leads to a decrease in crack formation during the drying process of the PEMs cathode catalyst layer. Induced hydrogen bonding between Nafion and the polymers leads to the formation of agglomerated catalyst networks thereby affecting the morphology but doesn't impact MEA electrochemical performance. Understanding the extensional properties in ionomer-polymer suspensions may give further insight on coating parameters and drying deflects. Here, we look to further investigate the role that polymer additivities have on Nafion behavior. By the rheological behavior, the process-property relationship for PEM manufacturing will benefit by improvement in rheological properties needed in slot-die coating quality and coating operating windows, as well as in drying processes and microstructural development. In this study, we induce hydrogen bonding of different cationic and rigid polymers with Nafion to investigate the effects of shear and extensional rheological behavior, wettability, and aggregation of the ionomer polymer suspensions. We also investigate the effect of temperature on these parameters to see the effect of possible de-solvency of the ionomer-polymer suspensions. We further study how film thickness and drying rates are affected by the addition of a polymer to the solutions.

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Symposium SM
Polymer Solutions, Melts and Blends

Organizers: Amanda Marciel, Ben Yavitt and Piyush Singh

Wednesday 1:30 Coronado + DeVargas SM33

Shear induced crystallization of concentrated, PEGylated nanoparticles

Kelsi Rehmann[1], Kathleen M. Weigandt[2], Steven Hudson[3], and Paul Salipante[3]
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Nanoparticles stabilized with poly(ethylene glycol) (PEG) are widely studied for their efficacy in a variety of applications in therapeutics, diagnostics, and wearable electronics. The COVID-19 vaccines produced by Pfizer and Moderna, for instance, are lipid nanoparticles stabilized with PEG to deliver mRNA and were deployed world-wide. As the demand for soft nanoparticles increases, it becomes critical to understand how these materials change as they undergo processes necessary for translating technologies from the bench to the factory. Many of these industrial processes involve deformation under high shear, such as injection through needles, lubrication, and spray coating or drying. Thus we are interested in measuring the structure of PEGylated nanoparticles using capillary rheoSANS, a technique developed at NIST to simultaneously measure the high shear rheology (with shear rates as high as ~ 106 s-1) and the nanomaterial structure with small angle neutron scattering (SANS). Our preliminary study has observed shear induced crystallization of model nanoparticles in this unique sample environment. At high concentration, the nanoparticles have many 'disordered' crystals which give rise to isotropic 2D scattering in the static experiment, analogous to powder diffraction. Under shear, the crystals align and give distinct peaks in the 2D scattering data, analogous to single crystal diffraction. Although similar results have been shown previously in conventional rheoSANS, this is the first measurement of shear induced crystallization in a capillary rheometer, which probes different shear planes than the conventional sample environment. We present results and analyses of these experiments, as well as complimentary static SANS and conventional rheoSANS experiments, to highlight interesting observations of these samples under high shear.

Wednesday 1:50 Coronado + DeVargas SM34

Combined influence of pressure and shear flow on the crystallization of isotactic polypropylene

Benson Jacob[1], Joerg Laeuger[2], Xiaoshi Zhang[3], Marcus Thiele[2], Markus Nemeth[2], Kirt A. Page[4], Alicyn M. Rhoades[3], and Ralph H. Colby[1]

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In many melt processing techniques, polymers undergo rapid melting and deformation under pressure, followed by a rapid cooling or quench to solidification - conditions far from equilibrium and difficult to explore using traditional rheology instrumentation. To better understand polymer flow and crystallization under pressure, we studied with a commercial isotactic polypropylene using new rheological tools capable of applying simultaneous rotational shear flow and pressure. As expected, the combination of flow and pressure accelerated crystallization kinetics. However, the most striking finding was the profound impact that pressure seems to have on the crystallization mechanism and resulting morphology. At moderate pressures (~2 bar), typical shish kebab morphologies resulted after shear flow. However, at elevated pressures of 100-180 bar alignment was suppressed, and morphologies were more isotropic despite the same level of shear flow. This shift may suggest a transition to a different crystallization pathway that is not simply accelerated but fundamentally altered by pressure. Unexpectedly, crystallization occurred above nominal melting conditions, indicating a pressure-induced suppression of chain mobility. X-ray scattering revealed the presence of a new crystalline peak exclusive to samples produced under the shear/pressure combination, potentially indicating a pressure-induced polymorphism. These morphologies resulted in melting temperatures that were up to 10 K higher than their quiescently crystallized counterparts. Together, these results point to pressure-driven processes that influence not only crystallization kinetics and resulting morphology, but also bulk properties that are potentially important for industrial adoption.

Wednesday 2:10 Coronado + DeVargas SM35

Extensional flow-induced crystallization in metallocene and Ziegler-Natta high-density polyethylenes

Kashyap Sundara Rajan and Jonathan P. Rothstein

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Flow-induced crystallization (FIC) in semi-crystalline polymers like high-density polyethylene (HDPE) has profound implications in the polymer processing industry, particularly in film-formation applications. In this study, we examine how extensional flow parameters, specifically the imposed strain and extension rate, affect the crystallization behavior of two HDPEs synthesized via metallocene and Ziegler-Natta catalysts. Rheological characterization was first performed using shear flow and extensional flow using a filament stretching rheometer at multiple temperature so that time-temperature superposition could be used to establish viscoelastic baselines. For FIC, samples were melted at 180°C to erase thermal history, quenched to 120°C, and held to equilibrate before undergoing deformation, as per the Janeschitz-Kriegl protocol. Crystallinity was evaluated using differential scanning calorimetry (DSC) and morphological evolution was assessed by small-angle X-ray scattering (SAXS) and polarized light microscopy. Both materials exhibited shear thinning and mild strain hardening at Hencky strains greater than 5. FIC responses showed an increase in crystallinity from ~50% to ~60% with increasing strain rate, followed by a decline at higher rates, suggesting a competition between alignment-driven crystallization and deformation-induced disruption. SAXS confirmed the emergence of shish-kebab structures at intermediate strain rates, corresponding to higher crystallinity. The ZN-based HDPE exhibited a more pronounced FIC response, indicating catalyst-type dependency in the formation of crystals. These results provide critical insight into how molecular architecture and deformation parameters govern crystalline morphology and content. This understanding can guide the design of HDPE films with enhanced structural order and physicochemical properties, thereby addressing key challenges in packaging and industrial applications.

Wednesday 2:30 Coronado + DeVargas SM36

Flow-induced suppression of crystallization in polymer blends

Naomi Deneke and Kalman B. Migler

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Flow induced crystallization (FIC) in polymers is widely studied due to its relevance in processing and final mechanical properties. Here we demonstrate for the first time that the opposite effect can occur in polymer blends - flow induced *suppression* of crystallization (FISC). This suppression can occur in the droplet component when flow induces a reduction in droplet size to the extent that the density of droplets become comparable to, or greater than, the density of active nucleating agents - thus a fraction of droplets will not contain nucleating agents. At still higher flow rates, FIC is recovered. Under intermediate conditions, both FISC and FIC can be observed *iin the same experiment* - the FIC manifests as an increase in kinetics while FISC manifests as a decrease in overall crystallinity. We utilize scaling arguments within the specific work hypothesis to explain the results.

Symposium SR
Rheology for Soft Robotics and Use of Field-Responsive Materials

Organizers: Laurel Kroo, Ryan Poling-Skutvik and Bhuvnesh Bharti

Wednesday 3:45 Coronado + DeVargas *Keynote* SR1

From tunable shear thickening to viscosity metamaterials

Itai Cohen

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The past decade has produced dramatic advances in our ability to tune the viscosity of flowing suspensions by orders of magnitude using external fields. Here, I will describe some of the tuning knobs for achieving these behaviors that our group has been investigating including orthogonal shear, acoustic perturbations, and activity. I will then describe how we are using these knobs to create a new materials class - viscosity metamaterials. To create these metamaterials, we rapidly drive large viscosity oscillations in a shear-thickened fluid. Because the time scale for these oscillations can be orders of magnitude smaller than the timescales associated with the global material flow, we can construct metamaterials whose resulting viscosity is a composite of the thickened, high-viscosity and dethickened, low viscosity states. Such viscosity metamaterials can be used to engineer a variety of unique properties including flow rectification, as well as negative, infinite, or zero viscosities - responses that are inconceivable with conventional fluids. The high degree of control over the resulting viscosity, the ease with which they can be accessed, and the variety of exotic properties achievable by viscosity metamaterials make them attractive for technologies in which control over fluid flows and their instabilities is critical including robotics, cloaking, and 3D printing.

Wednesday 4:05 Coronado + DeVargas SR2

Controlling the rheology and thixotropy of colloidal gels with an electric field

Seyed Mohammad Hosseini and Jae Sung Park

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Colloidal gels are networks of interconnected particles dispersed in a fluid, exhibiting solid-like behavior under small deformations. The rheology of these systems is strongly influenced by the history of their stress and microstructure, a phenomenon known as thixotropy. Due to their widespread applications in nature and engineering, the ability to actively and effectively tune their properties is of great importance. Here, we use Stokesian Dynamics simulations to explore the controllability of colloidal gels and their time-dependent properties via an electric field. As a baseline, we first examine the rheology and thixotropy of colloidal gels in the absence of an electric field. We then explore the use of dielectrophoresis (DEP) to control colloidal gels, a technique similar to electrorheological (ER) fluids. At high electric-field strengths and shear rates, we observe the formation of lamellar structures leading to an increase in viscosity, which is a similar behavior observed in typical ER fluids. Interestingly, at lower electric fields and shear rates, DEP interactions disrupt bond formation between colloidal particles, resulting in a reduction in viscosity, also known as a negative ER effect. DEP enables fast, particle-level manipulation of both the microstructure and stress distribution within the gel. A detailed analysis of the microstructural evolution and its correlation with rheological behavior is presented to elucidate the mechanisms. Lastly, we discuss the use of induced-charge electrophoresis (ICEP), where ICEP interactions seem to decrease the viscosity by disrupting the network of gels. Our findings demonstrate that both DEP and ICEP can serve as effective means to tune the properties of colloidal gels.

Wednesday 4:25 Coronado + DeVargas SR3

Nonreciprocal rheology in living and robotic chiral active matter

Tzer Han Tan

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Nonreciprocal interactions in active matter yield unconventional rheological responses, including odd elasticity, directional stiffness, and self-sustained wave propagation. I will present recent results on living chiral crystals composed of thousands of spinning starfish embryos, where hydrodynamic coupling and developmental dynamics govern formation, dissolution, and emergent oscillations. These crystals exhibit deformation behaviors characteristic of odd elastic media. Inspired by this, we built a bioinspired robotic swarm with programmable nonreciprocal interactions. Tuning interaction strength drives transitions from solid-like states with vibrational modes to fluid-like phases with surface fluctuation characteristics of odd mechanical response. These findings link biological development, robotic design, and nonreciprocal rheology, revealing new avenues for engineering chiral active materials with direction-dependent mechanical response.

Wednesday 4:45 Coronado + DeVargas SR4

Activity driven jamming

Navneet Singh[1], Anna R. Barth[1], Edward Y. X. Ong[1], Abhishek Shetty[2], Bulbul Chakraborty[3], James P. Sethna[1], Eric R. Dufresne[1], and Itai Cohen[1]

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Active systems, which harness energy from their environment, offer a promising pathway for designing functional materials with tunable bulk properties through engineered microscopic interactions. However, to date, most active systems have been constrained by either their manufacturing scalability or their ability to generate sufficiently large stresses to influence bulk behavior, making the investigation of 3D bulk properties challenging. In this study, we overcome these constraints by engineering three-dimensional active solids composed of micron-scale Quincke rotors, enabling the observation of adaptive bulk behaviors through detailed imaging and rheological experiments. Our experiments reveal that, in the absence of shear, Quincke rotation induces dynamic, porous, percolating structures that continuously evolve due to active rotation. At high volume fractions, Quincke rotors accumulate in regions where they move more slowly and undergo motility-induced phase separation between dense and dilute fluid phases. Once they phase separate, these active disordered systems undergo orders of magnitude changes in viscosity, transitioning under shear to significantly thickened or jammed suspensions, depending on the ratio of active stress to applied shear stress. Finally, we present a phase diagram for activity jamming as a function of volume fraction and applied stress. These findings could provide new insights into jamming mechanisms in biological systems and unlock new possibilities for programmable state transitions in viscosity metamaterials.

Wednesday 5:05 Coronado + DeVargas SR5

Measuring thermophoretic and Brownian motion using multiple particle tracking microrheology in ground and microgravity conditions

Nazrin Hasanova[1], Maria Chiara Roffin[1], Xuanhong Cheng[2], Kelly Schultz[3], and James F. Gilchrist[1]

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To help create single-step diagnostic devices, we aim to develop a separation technique to concentrate viral particles for easier detection. One method for bulk separation of charged particles is thermophoresis, or directional motion in response to a temperature gradient. Thermophoretic motion depends on fluid properties in the immediate area, which will vary in complex biological fluids in a temperature gradient. Simultaneous measurement and correlation of local properties to thermal gradient-driven motion is essential to optimize thermophoresis-based separation. To achieve this, we use 2D multiple particle tracking microrheology (MPT), a passive rheological technique that correlates particle motion with fluid properties. We separate MPT measurements into two 1D components to simultaneously measure local fluid properties (y-direction) and particle velocity under an applied 1D temperature gradient (x-direction). On Earth, a temperature gradient causes buoyancy-induced recirculation, masking thermophoretic motion. We conduct experiments in both ground and microgravity conditions on the International Space Station to eliminate recirculation. Viscosities of glycerol-water solutions in both ground and microgravity increase with addition of glycerol and match tabulated data. In ground conditions, x-directional velocities are consistent with viscosity-dependent recirculation. In microgravity, near-zero velocities are measured, indicating motion in gravity conditions is due to recirculation. We also present preliminary results for polyethylene oxide (PEO) solutions under and over the overlap concentration C^*. Under C^*, recirculation velocity decreases with an increase in polymer molecular weight. Above C^*, velocity decreases with increasing molecular weight due to elasticity of the fluid. Simultaneous measurements of local rheology and thermal gradient-driven motion can help optimize thermophoretic separation in complex fluids.

Symposium AR
Applied Rheology for Industrial Applications

Organizers: Hammad A. Faizi and Antonio Perazzo

Wednesday 1:30 Peralta + Lamy AR24

Fighting bad rheometry: Lessons from compliance limits and protorheology

Mohammad Tanver Hossain[1], Ramdas Tiwari[1], Christopher W. Macosko[2], Gareth H. McKinley[3], and Randy H. Ewoldt[1]

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Rheological data are only as trustworthy as the tools and interpretations that generate them. This talk integrates insights from two recent studies [1,2] that identify and address distinct but complementary challenges in rheological measurement and inference.

The first challenge arises from instrument compliance artifacts, which can systematically depress apparent viscoelastic moduli below their true values. This risk is especially important with curing systems on a rotational rheometer, as well as with dynamic mechanical analysis (DMA) devices. We present a framework for identifying and avoiding such errors using operational limit lines, G_{max} and E_{max}, that enable

immediate visual assessment of data credibility and error estimation, even without access to raw displacement or force data. These limit lines also provide a proactive tool for experimental design, instrument selection, and retrospective data evaluation.

The second challenge emerges in the broader and less controlled domain of protorheology, where informal or opportunistic observations are used to infer rheological properties. While protorheology offers accessibility, creative insight, and a sanity check for rheometric data, it also carries significant risks of misinterpretation, e.g. confusing viscosity with elasticity, flow time with relaxation time, or capillary pinning with yield stress. With several realistic examples, we illustrate how to avoid these pitfalls and apply protorheological reasoning responsibly.

Together, these two perspectives reinforce a central message: good rheology requires not just good data, but vigilance against both instrumental artifacts and interpretive overreach. By applying operational limit lines and critically evaluating assumptions, we can avoid common errors and enable more reliable insights into rheological behavior.

[1] Hossain, Macosko, McKinley, Ewoldt (2025). DOI: 10.1007/s00397-024-01481-9
[2] Hossain, Tiwari, and Ewoldt (2024). DOI: 10.1016/j.cocis.2024.101866

Wednesday 1:50 Peralta + Lamy AR25

Making rheology developments interesting again and again

David J. Moonay
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Industrial rheology and viscometry typically require very practical solutions to various challenges. A wide variety of materials need to be processed and, therefore, measured in different ways. Relative measurements for suspensions at different concentrations have been obtained with geometries such as offset-flag impellers, for example. The results are typically in turbulent flow. However, 3-D printing or Additive Manufacturing techniques now allow significantly easier creation of more complex shapes, such as helical impellers, at different size scales. These can provide different flow fields within moderately small samples. Budget considerations may influence rheometer development, as well. Therefore, maximizing the range with various geometries can help. Larger surface area should allow greater sensitivity, for example, because of the increased friction or torque enabled with a particular sample. However, the design, including the material used for the part and internal mechanical construction, must be carefully considered, as well. The size and weight influence the moment of inertia - a significant consideration for oscillatory shear measurements, for example. This presentation presents some new developments in rheometry, with representative data for various commercial products, such as suspensions, weak gels and soft solids.

Wednesday 2:10 Peralta + Lamy AR26

Role of powder rheology in dry battery electrode processing

Abhishek Shetty[1], Helena Weingrill[2], and Tamara Ebner[2]
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The novel dry battery electrode (DBE) process has several advantages compared to conventional and established solvent-based coating procedures for battery production including energy savings, environmental benefits, reduced costs and enhanced battery performance. In the DBE process, the active material, conductive additive, and polytetrafluoroethylene (PTFE) binder transition from fine powder to the free-standing electrode under high shear and elevated temperature, enabled by PTFE fibrillation. This transformation is critical for processability and the final battery performance, requiring a homogeneous mixture with the appropriate fibrillation before calendering. The goal of the study was to apply well-established powder rheological methods for characterizing the powder behaviour during this innovative battery production route as well as to develop a new method to characterize the fibrillation process of the PTFE binder. During the first part of the study, conventional methods such as deaeration time, segregation, shear and compressibility testing were applied. For this purpose, mixed anode materials (graphite, carbon black, and PTFE) were characterized both before fibrillation (as premixes) and after fibrillation (as grinded particles) with varying binder contents. The binder content played a significant role on the segregation behaviour where a higher binder proved to prevent segregation and was therefore preferable. The second part of the study focused on developing a method for characterizing PTFE fibrillation. Pure PTFE samples were investigated. Wall friction measurements with an underlying temperature ramp revealed a strong increase in shear stress only once PTFE's crystalline transition temperature below 20 °C was transgressed (which is the prerequisite for fibrillation). This increase in shear stress could be successfully correlated with the powder's fibrillation by scanning electron microscope pictures taken during the different stages of the temperature-controlled wall friction test.

Wednesday 2:30 Peralta + Lamy AR27

Powder rheological properties of pharmaceutical excipients: Lactose monohydrate and carboxymethyl cellulose

Behbood Abedi
TA Instruments - Waters LLC, New Castle, DE 19720, United States

Powder rheology is crucial in the pharmaceutical industry for characterizing excipients and optimizing drug formulations. It involves studying the flow behavior and deformation of powders, directly impacting manufacturing processes and product quality. Flowability, compressibility, and cohesion measurements provide a comprehensive understanding of powder flow behavior and particle interactions. This study examines the rheological properties of lactose monohydrate and carboxymethyl cellulose (CMC), common pharmaceutical excipients. Lactose exhibited over three times higher compression and cohesion values compared to CMC. Both powders showed rate-dependency, with flow energy decreasing as tip speed increases. Rheological properties were also examined at 45°C, simulating sunlight exposure, and at 4°C, simulating refrigeration. At

4°C, lactose monohydrate's flow function shifted towards cohesive flow. Under high stress, CMC flows better, while under moderate to low stress, lactose monohydrate flows better. Under very low stress, both exhibit similar flowability. Lactose monohydrate demonstrates easy flow, relatively low confined flow energy, moderate cohesion, and excellent compressibility. CMC exhibits lower cohesion but higher confined flow energy, which should be considered when using CMC as a filler. Understanding these properties is essential for optimizing formulations and ensuring consistent product quality in pharmaceutical manufacturing.

Wednesday 2:50 Peralta + Lamy AR28

Rheological insights into coffee powders: Unveiling the impact of grind size, roast degree, and origin

Behbood Abedi

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This study investigates the rheological properties of coffee powders, focusing on how grind size, roast degree, and origin influence their behavior. Using Scanning Electron Microscopy (SEM), fine and coarse grounds of medium roast coffee, as well as coarse grounds of medium and dark roast coffee from Colombia and Brazil, were compared. Fine grounds exhibited smaller, more uniform particles with smoother surfaces, while coarse grounds showed rougher surfaces and greater porosity. Rheological tests revealed that fine grounds have higher wall friction, compressibility, and cohesion, impacting dosing, tamping, and brewing. Higher wall friction in fine grounds can lead to slower flow and potential clogging, while higher compressibility results in denser packing and slower water flow during brewing, potentially causing over-extraction. Conversely, coarse grounds with lower wall friction and compressibility allow for faster flow and lighter brews. Confined flow energy measurements indicate that Brazilian coarse grounds require more force to be tamped effectively due to their irregular shapes, while fine grounds of both origins show similar confined flow energy. Flow function and cohesion tests reveal that Brazilian coffee powders exhibit slightly lower flow function and higher cohesion, attributed to higher surface oil content, which promotes particle clumping and resistance to flow. Wall friction measurements show that Colombian coffee powders have lower friction against stainless steel, facilitating flow during dosing and tamping. These rheological differences influence the brewing process, affecting extraction efficiency and flavor profile. Understanding these properties allows for the optimization of grind size, roast degree, and brewing techniques, ensuring a consistent and desirable coffee beverage.

Symposium AM
Additive and Advanced Manufacturing

Organizers: Anthony Kotula and Xiaoyu Tang

Wednesday 1:30 O'Keeffe + Milagro AM17

Shear-induced nanoscale morphologies in 3D-printed structural color

Kyle George and Monirosadat Sadati

Chemical Enginnering, The University of South Carolina, Columbia, SC 29208, United States

Liquid crystalline systems based on hydroxypropyl cellulose (HPC) present a promising framework for hierarchical material design by enabling spontaneous chiral nematic self-assembly with helicoidal architectures analogous to those observed in natural photonic structures. In this study, we leverage the intrinsic rheological behavior of HPC-based inks to engineer structurally colored, three-dimensional constructs via extrusion-based 3D printing. Blending HPC with polyethylene glycol (PEG) induces kinetic arrest during solvent evaporation, allowing precise modulation of the helical pitch and access to structural colors spanning the visible spectrum. Comprehensive rheological characterization of these viscoelastic inks identified a pseudo-nematic flow regime at shear rates around 23 1/s, wherein HPC domains align with their helical axis normal to the substrate, yielding maximal reflectance intensity and uniform structural coloration. At elevated shear rates (~100 1/s), alignment reorients along the print path, producing anisotropic coloration and angular-dependent optical effects. These insights were translated into optimized printing protocols for fabricating high-resolution, architected materials with embedded nanoscale optical functionality. This work establishes a rheologically guided strategy for precision control of chiral nematic alignment in HPC-based systems, enabling scalable fabrication of multifunctional photonic architectures through the coupling of flow-driven self-assembly and additive manufacturing.

Wednesday 1:50 O'Keeffe + Milagro AM18

The competition between nucleation agents and flow-induced crystallization in material extrusion additive manufacturing

Jonathan E. Seppala[1], Kirt A. Page[2], Jacob Crossno[3], Paul Roberts[1], and Anthony P. Kotula[1]

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In material extrusion additive manufacturing (AM) of semicrystalline polymers, the interplay between shear-induced crystallization and nucleation agents can significantly impact the resulting microstructure. This study employs micro-focused small-angle X-ray scattering (SAXS) and wide-angle X-ray scattering (WAXS) to investigate the layer-wise crystallinity and orientation in 3D-printed isotactic polypropylene (iPP). Neat iPP, iPP with a strong nucleating agent, and iPP with a clarifier were printed at varying Weissenberg numbers. SAXS/WAXS analysis reveals spatial variations in lamellar structure and crystalline orientation within each printed layer, highlighting the competition between flow-induced

crystallization and nucleation efficacy. These findings underscore the importance of processing-structure-property relationships in AM, offering insights into optimizing nucleation agents and printing parameters to achieve tailored microstructures in printed iPP.

Wednesday 2:10 O'Keeffe + Milagro AM19

A multi-modal rheological characterization approach to determine the flow mechanisms during material-extrusion AM of polymer-composite type precursors

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The application domain of Material Extrusion-based Additive Manufacturing (MatEX AM) has expanded to metals, ceramics and advanced composites with the development of polymer-composite type precursors. These material systems include solid particles of metals or ceramics as well as reinforcing fillers dispersed in a liquid phase polymer matrix facilitating printability. In these applications, green parts produced through additive manufacturing are often sintered through thermal post-processing to obtain metallic or ceramic parts. Final microstructure, porosity and density of the parts produced have been shown to be strong functions of the shear and extensional flow the precursors experience during the MatEX AM process. As such, success of these applications relies heavily on understanding and controlling the material flow fields. Several key challenges remain in this regard. Firstly, high solid loading of these precursor materials lead to high yield stresses and imposes difficulties in characterizing their shear rheology in the high strain rate range relevant to the MatEX AM process. Secondly, significant wall-slip that occurs between the material and the nozzle walls renders flow modeling and prediction very difficult.

In this study, we aim to address these challenges through a multi-modal rheological characterization and flow modeling approach, focusing on ceramic matrix composite precursors consisting of a preceramic polymer binder, ceramic matrix particles and microfiber reinforcements. We combine rotational shear, squeeze flow and capillary rheometry to capture low, intermediate and high rate material rheology coupled with wall-slip characteristics, respectively. We implement a sophisticated flow model to decouple the wall-slip and shear flow contributions to the material flow. This talk will detail the techniques to overcome several characterization challenges and present results on the flow mechanisms observed during MatEX AM as a function of flow rate and nozzle size.

Wednesday 2:30 O'Keeffe + Milagro AM20

Fabrication of functionally graded core–shell structures via material extrusion additive manufacturing

Ahmad Naqi[1] and Michael Mackay[2]
[1]Chemical Engineering Department, Kuwait University, Kuwait City, Kuwait; [2]University of Delaware, Newark, DE, United States

Additive manufacturing (AM), or 3D printing, enables the creation of complex geometries through a layer-by-layer process, offering unparalleled design freedom and customization. Fused filament fabrication (FFF) is the most accessible AM method due to its low cost and simplicity. However, FFF parts often suffer from weak interlayer bonding, limiting their mechanical performance. Most commercial FFF thermoplastics have high melt viscosity, causing them to solidify before achieving sufficient surface contact and molecular interdiffusion. In contrast, high-density polyethylene (HDPE) exhibits low melt viscosity and a short reptation time, promoting strong interlayer bonding and interface healing. Yet, its high crystallinity leads to significant warping during cooling, making dimensionally accurate HDPE prints feasible only when anchored to an HDPE substrate-an impractical solution for most applications. This study introduces a novel coextrusion die capable of simultaneously extruding two polymers in a core-shell configuration to enhance interlayer adhesion. A low-viscosity shell improves surface contact and welding, while a high-viscosity core maintains structural integrity and helps counteracting the crystallization induced warpage of HDP. Polyethylene terephthalate glycol (PETG), an amorphous thermoplastic with a low coefficient of thermal expansion, is used as the core material to mitigate stresses induced by HDPE crystallization, thereby enhancing dimensional stability. Composite objects having HDPE shell and PETG core architecture were successfully printed with full interlayer surface contact and an adequate dimensional accuracy. Additionally, gradient structures were fabricated by dynamically adjusting core/shell flow rates, and their mechanical properties were compared to neat polymers.

Symposium ML
AI and ML in Rheology

Organizers: Vikram Jadhao, Shamsheer Mahammad and Hassan Pouraria

Wednesday 1:30 Sweeney Ballroom C ML7

Non-local physics-informed neural networks for forward and inverse solutions of granular flows

Saghar Zolfaghari and Safa Jamali
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Understanding/predicting dense granular flows remains a major challenge due to the inherently nonlocal nature of grain interactions, especially in quasi-static or slowly sheared regions. Traditional local rheological models fail to capture spatial cooperativity effects that are prominent in many granular systems. The nonlocal granular fluidity (NGF) model addresses this limitation by introducing a diffusive-like partial differential equation for a fluidity field, governed by a key material-dependent parameter: the nonlocal amplitude A. However, determining A from experiments or simulations is known to be difficult and typically requires extensive calibration across multiple geometries. In this work, we present a data-driven platform based on Physics-Informed Neural Networks (PINNs) embedded with the NGF model, capable of solving granular flows in a forward or

inverse manner. By training the model on transient flow in a planar shear configuration under gravity, we infer the full velocity, pressure, and stress fields. We observe that small variations in the nonlocal amplitude *A* possibly lead to sharp, bifurcation-like transitions in flow behavior, transitioning from localized shear zones to bulk flow regimes. To further address the challenge of identifying *A*, we also implement an inverse PINN architecture that treats *A* as a trainable parameter and learns its value directly from velocity data. This approach demonstrates the feasibility of data-driven parameter inference in complex nonlocal models and opens up new possibilities for characterizing granular materials from sparse experimental observations.

Wednesday 1:50 Sweeney Ballroom C ML8

Augmenting machine learning of universal viscoelastic constitutive relationships through curriculum learning using first normal stress difference measurements in LAOS

Nicholas King[1], Eugene Pashkovski[2], Reid Patterson[2], Paige Rockwell[2], and Gareth H. McKinley[1]
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Large amplitude oscillatory shear (LAOS) is a key technique for characterizing nonlinear viscoelasticity, from the response of polymer melts to foods and other soft materials. For highly elastic materials such as polymer melts, the first normal stress difference (N1) can become much larger than the shear stress at sufficiently large strains, serving as a sensitive probe of the material's nonlinear rheological characteristics. The LAOS shear stress and N1 responses thus together provide an extended rheological fingerprint of a complex fluid. We use the Fourier-Tschebyshev framework recently introduced by King et al (2025) to determine the N1 material functions for a silicone oil (PDMS) and a thermoplastic polyurethane (TPU) melt. Experiments are performed using the Gaborheometry strain sweep technique, enabling rapid and quantitative determination of experimental N1 data from small to large strain amplitudes. The measured material response for PDMS is well-described by a conventional multimode differential constitutive equation. However, for the TPU we observe a local 'band gap' at which there is a finite but non-oscillatory N1 response at a specific angular frequency and strain amplitude. This cannot be predicted by the widely used Giesekus model for polymer melts, and motivates the search for new constitutive equations that can describe such nonlinear fluid behavior. We use machine learning techniques to learn a tensorial constitutive equation (a Rheological Universal Differential Equation (RUDE)) that can describe the fluid's extended rheological fingerprint, taking a step towards a more accurate digital fluid twin that enables the prediction of the fluid response under different processing conditions. The framework we outline for analyzing N1 is complementary to the established framework for analyzing the nonlinear shear stresses in LAOS, and is helpful for augmented feature representation in machine learning, hence more fully quantifying the nonlinear viscoelastic properties of a wide range of soft materials.

Wednesday 2:10 Sweeney Ballroom C ML9

Deriving data-driven rheological constitutive models with a sparse identification algorithm

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This study investigated a method for deriving constitutive models (CMs) from rheological data with a sparse identification method. The sparse identification method used in this study was originally formulated by Brunton and coworkers as the Sparse Identification of Nonlinear Dynamics (SINDy), a technique for discovering symbolic representations of governing equations from time-series data [*Proc. Natl. Acad. Sci. U.S.A.*, **113**, 3932 (2016)]. SINDy assumes the time derivatives of time-series data are approximated by a product of a library matrix containing predefined candidate functions and a coefficient matrix. We applied this technique to rheological data to test (i) whether it can recover the phenomenological CMs from numerical data generated by these models, (ii) whether the method can derive an approximate CM from time-series data generated by mesoscopic simulations, and (iii) whether the approximate CMs obtained by the proposed method can predict spatially inhomogeneous flows. For test (i), we demonstrated that our method successfully reconstructed several viscoelastic CMs by appropriately selecting the sparsity-promoting algorithm. In test (ii), we employed a dumbbell model with a finitely extensible nonlinear elastic (FENE) spring, for which an analytical CM is unavailable. Using the optimization method shown as effective in test (i), we derived an approximate CM for the FENE dumbbell model. The obtained model accurately captured the rheological properties for the interpolation and moderate extrapolation regimes. For test (iii), we compared the flow simulation results obtained by a multiscale simulation (MSS) method with the simulation results obtained with data-driven CMs. In the MSS method, the FENE dumbbell model was embedded in a macroscopic computational domain to obtain polymeric stress. We confirmed that the flow simulations with the data-driven CMs reasonably reproduced the full MSS results. These findings demonstrate the effectiveness of the SINDy framework to model viscoelastic fluids.

Wednesday 2:30 Sweeney Ballroom C ML10

A general machine learning framework for accurate detection of cluster formation: A case study of polymer crystallization from molecular dynamics simulations with supervised and unsupervised approaches

Elyar Tourani, Brian J. Edwards, and Bamin Khomami
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In this study, we present an integrated machine learning workflow for the detection and quantification of structural transformations, such as crystallization, in polymeric systems using molecular dynamics simulation data. We construct a high-dimensional feature vector for each atom, combining thermodynamic-like variables (local entropy and enthalpy), geometric descriptors, and invariant bond orientational order parameters,

and apply dimensionality reduction techniques (PCA, UMAP, and VAE) to project this space into low-dimensional embeddings, exposing latent structural fingerprints.

Unsupervised clustering methods (KMeans, GMM, and HDBSCAN) are then used to label atoms as crystalline or amorphous, with UMAP and subsequent HDBSCAN yielding the highest cluster quality metrics. To validate and interpret these clusters, we train supervised binary classifiers (logistic regression, random forest, and gradient boosting) on the same feature set and demonstrate that the clustering-derived label is markedly more predictable than any individual physical threshold. Feature importance analyzes reveal that q_6, local entropy, and p_2 contribute most strongly to classification performance.

We use these insights to define a composite crystallinity parameter, C, by fitting a logistic model to the top three descriptors. The resulting C distribution is robustly bimodal in all simulation time steps, providing a sensitive, generalizable indicator of crystalline versus amorphous environments. Crucially, C can be calibrated using just one or a few representative snapshots and then efficiently computed throughout the trajectory to track the crystallinity evolution. We further show that the time-dependent growth rate extracted from C closely matches the values reported in the literature for the kinetics of polymer crystallization.

Wednesday 2:50 Sweeney Ballroom C ML11

Suspension-balance neural networks for modeling concentrated suspension rheology in confined flows

Michael Davis[1], Hugo A. Castillo Sanchez[2], Rekha R. Rao[3], and Leo Liu[2]
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Understanding the complex rheology of concentrated particle suspensions in confined geometries is critical for applications ranging from biomedical microfluidics to industrial coatings. However, traditional continuum models often fail to capture the intricate coupling between hydrodynamics, particle interactions, and confinement effects, especially at high volume fractions. In this work, we introduce Suspension-Balance Neural Networks (SB-NNs), a physics-informed machine learning framework that integrates particle-scale stress balance principles with neural network architectures to model the flow behavior of concentrated suspensions in confined geometries. Our approach learns spatially resolved stress and velocity fields directly from sparse datasets from direct numerical simulations and microfluidic experiments, while embedding conservation laws, particle migration tendencies, and non-Newtonian constitutive behavior into the model structure. We validate the SB-NNs across a range of particle concentrations and confinement ratios, demonstrating superior accuracy in predicting shear-induced particle migration and plug-flow development compared to traditional continuum or empirical models. Furthermore, the framework captures emergent features such as micro-structural heterogeneity that arise uniquely under confinement. These results offer new insight into the mesoscale physics of suspension flows and highlight the potential of hybrid physics-ML tools to serve as surrogate models for complex rheological systems. The implications of this work extend to improving process design in suspension-based technologies and enhancing diagnostic capabilities in biomedical suspension flows such as blood.

Wednesday 4:05 Sweeney Ballroom C ML13

Graph neural network for multitask prediction of rheological and microstructural behavior in suspensions

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Fast prediction of suspension rheology is vital for optimizing process and performance across various applications. Traditional experimental methods face limitations in terms of reproducibility and scalability and conventional computational techniques are hindered by high computational cost and time requirements. Machine Learning (ML) has emerged as a powerful approach for modeling and predicting the behavior of particulate systems; this study presents a novel multitask learning framework leveraging Graph Neural Networks (GNN) to simultaneously predict both microstructural and rheological properties of suspensions, specifically focusing on particle pressure, viscosity, and friction coordination. We simulated semi-dilute to dense suspension systems exhibiting complex rheological behaviors, including continuous and discontinuous shear thickening up to jamming, using Lubrication-Flow Discrete Element Modeling (LF-DEM). Then the configurations were converted into graph representations where particles were defined as nodes and interparticle interactions as edges. GNN models were trained separately for various packing fractions f and a wide range of normalized shear stresses spanning from 0.1 to 200. The results from multitask interpolation demonstrate high correlation coefficients (R^2 = 0.99) and narrow mean absolute error for packing fractions up to f = 0.80. Performance shows a slight decrease at higher packing fractions approaching jamming, attributed to significant fluctuations in system behavior, but prediction yields results within 15% error for f = 0.80. Fitting curves of viscosity, particle pressure and coordination number as a function of shear stress all demonstrated very good agreement, closely following the trend of the curves obtained from direct simulations. Overall, this GNN-based multitask learning approach offers a promising and efficient tool for exploring and predicting the properties of particulate systems across a broad range of conditions.

Wednesday 4:25 Sweeney Ballroom C ML14

Clustering and measurement methods for quantitative microstructural analysis using molecular dynamics data: A case study of polymer crystallization

Elyar Tourani, Brian J. Edwards, and Bamin Khomami
Chemical and Biomolecular Engineering, University of Tennessee, Knoxville, TN 37996, United States

Accurate characterization of local symmetry, order, and connectivity is essential for linking microstructural evolution, like crystallization, to mechanical behavior in molecular dynamics (MD) simulation data. This study introduces a novel, physically informed clustering framework

tailored to MD-driven data and designed to systematically identify and track evolving structural domains. Our method integrates the desired variables, specifically the measures of the crystallinity index, into a grid-based clustering architecture within a Connected Component Analysis (CCA) framework.

To address the common locality and sparsity issues in spatial datasets, we develop a de novo diffusion-based imputation technique, enabling robust reconstruction of missing or noisy local ordering information in physical systems without introducing artificial biases. Compared to conventional clustering methods, our approach demonstrates unparalleled superior efficiency, consistent precision in spatial resolution, and interpretability of clustering parameters. We assess biases, establish best practices for clustering, and perform sensitivity and error analysis in various procedures. Our framework avoids heuristic parameter tuning and ensures consistent cluster identification across diverse datasets by using physically motivated variables. The computational complexity is retained at O(n log n), matching or exceeding that of widely used algorithms while improving the sensitivity to subtle ordering transitions.

The clustering framework is applied to MD simulations of supercooling-induced and flow-induced crystallization in polyethylene melts, serving as case studies. Our method effectively captures anisotropic nuclei evolution and provides key metrics (volume, surface area, and convexity) for understanding structure-property relationships. Although focused on crystallization, this methodology is broadly applicable for studying microstructural transformations in polymeric and soft matter systems.

Wednesday 4:45 Sweeney Ballroom C ML15

Isolating the MAOS regime via data-driven constitutive modeling

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The MAOS or asymptotically nonlinear regime is attractive because it rests on a firm theoretical foundation. However, experimentally probing this regime presents a delicate balancing act: the narrow window of accessible strain amplitudes is confined by instrument sensitivity on one end and the risk of contamination by higher harmonics on the other. Thus, extraction of MAOS moduli is a highly labor-intensive task. We present a data-driven method that shifts the burden almost entirely from the experimenter to the computer. Our novel approach relies on first inferring a constitutive model that strictly obeys symmetry and frame-invariance via sparse polynomial approximation. We demonstrate the convenience and effectiveness of the proposed method on a series of worm-like micellar solutions.

Symposium TM
Techniques and Methods: Rheometry, Tribometry, Spectroscopy and Microscopy

Organizers: Sara Hashmi, Jeffrey Richards and Qi Li

Wednesday 1:30 Sweeney Ballroom D *Keynote* TM13

Statistical mechanics of aramid fiber structure and rheological properties subject to rheometric and high-rate impact deformations

Michael A. Ploch[1], Michael R. Roenbeck[2], Jacob L. Pretko[3], Christopher W. Seay[3], Kenneth E. Strawhecker[2], and Steven R. Lustig[1]
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The design of advanced, protective materials requires statistical mechanics methods capable of concurrently assessing structural, topological, and rheological changes in polymeric materials under complex, multi-axial deformations. We introduce a two-dimensional statistical mechanics framework to study aramid fibers subjected to controlled rheometric deformations and high-rate impact deformations. Utilizing multichannel AM-FM atomic force microscopy, we obtain spatially resolved measurements of key nanostructural features including fibril widths, void widths, crystal misorientation angles, and pleat component lengths. Microscopy accurately resolves and quantifies morphological and topological alterations within fibrils at length scales significantly smaller than the polymer's average molecular length. Statistical analyses of the measured feature distributions reveal detailed morphological shifts that elucidate structural dynamics at the nanoscale. Our analyses demonstrate that both tensile and compressive deformations-axial and transverse-contribute significantly and independently to the fibrillar mechanical response during high-rate impacts. This finding contrasts traditional assumptions and manufacturing practices predominantly focused on tensile properties. Further, by evaluating entropy variations of the fibrillar network, we calculate the minimal mechanical work absorbed during deformation, highlighting entropy as a direct indicator of structural reorganization and energy absorption. This statistical mechanics analysis underscores the importance of simultaneously enhancing tensile and compressive properties in woven aramid materials. The results provide direct insights for engineering fibril-based protective systems with improved mechanical performance under varied high-rate deformation conditions.

Wednesday 1:50 Sweeney Ballroom D TM14

Chebyshev polynomial approach for first normal stress difference interpretation in LAOS

Aaron T. Hedegaard
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First normal stress differences in shear rheology are useful for understanding processing phenomena like die swell and predicting axial loads during shearing of soft solids in a confined geometry, such as the sliding of two plates bonded with an adhesive. These stresses can become particularly acute in large-strain applications. When investigating the resulting shear and normal stresses in large strain oscillatory shear (LAOS) using an approach utilizing Chebyshev polynomials of the first kind, the shear stress response is described using the odd-ordered polynomial terms. However, when attempting to naively apply a similar approach to the resulting normal stresses via the even-ordered polynomial terms, the analysis fails to capture the in-phase component of the normal stresses, suggesting a fundamental limitation of the approach. This manuscript describes an alternative approach that continues to employ Chebyshev polynomials of the first kind to describe the out-of-phase (rate-dependent) response of the normal stresses but employs Chebyshev polynomials of the second kind for the in-phase (strain-dependent) response. This reproduces the results from a Fourier transform approach but retains the advantages of Chebyshev polynomials such as readiness for physical interpretation and a data-fitting procedure that is agnostic of the collected time data. The manuscript closes with worked examples for materials of interest.

Wednesday 2:10 Sweeney Ballroom D TM15

Long windowed chirps to probe low frequencies

Kevin J. Whitcomb and Yuan Tian
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This presentation will demonstrate and discuss utilizing windowed chirps of exceptionally long duration (= 5,000 seconds) to probe low frequencies associated with the timescale of the chirp duration. These experiments are conducted on current generation combined motor transducer instruments. Polymer materials will be examined to demonstrate the utility of long windowed chirps. This presentation will also explore the relationship between the duration of a windowed chirp and the frequency content that can be extracted during that duration. Additionally, the range of frequencies that can be contained in a single chirp will also be explored.

Wednesday 2:30 Sweeney Ballroom D TM16

Nonlinear chirp rheology

Jarno L. Waeterloos and Christian Clasen
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Chirp signals have proven to be highly efficient for acquiring small amplitude oscillatory shear (SAOS) data of viscoelastic materials sampling wider ranges of frequencies. By significantly reducing experimental times, chirps enable in particular the measurement of fast time-evolving systems. Recently, their popularity has grown with the development of chirp protocols which are directly implemented in both stress and strain controlled rheometers. While initially designed for measurements within the LVE regime, chirps are now also being considered for nonlinear rheological measurements where materials also undergo microstructural changes.

Advanced techniques like parallel and orthogonal superposition rheology allow the use of chirps for the characterization of nonlinearly deformed materials. In this work, we go further by demonstrating that chirps can directly be used to obtain nonlinear viscoelastic properties in medium amplitude oscillatory shear (MAOS) and large amplitude oscillatory shear (LAOS) measurements. Unlike single frequency sine waves, where the harmonics are easily separated by means of Fourier transform rheology, chirp signals present a challenge due to spectral overlap of the harmonics. In light of the recent development of Gaborheometry for the extraction of the Fourier-Tschebychev coefficients [1], a similar strategy is employed using the Gabor transform to extract the nonlinear viscoelastic harmonics from chirp signals. We show that additional corrections are required due to the inherent phase of the chirp waveform itself and demonstrate with simulations and experimental verification that with these corrections this method is highly efficient and reduces nonlinear measurement times by orders of magnitude. Finally, the possible use of the more extensive Frenet-Serret framework [2] is investigated for the determination of nonlinear viscoelastic moduli using chirp signals.

[1] Rathinaraj and McKinley, JOR 67, 2, 479 (2023).
[2] Rogers, Rheol Acta 56, 5, 501 (2017).

Wednesday 2:50 Sweeney Ballroom D TM17

Application of improved optimally windowed-chirps (OWCh) to curing systems

Sarah Cotts and Kevin J. Whitcomb
TA Instruments, New Castle, DE 19720, United States

Traditional methods of monitoring curing reactions and polymer time-temperature superposition experiments are time intensive and frequency limited. Recent developments [1,2] in optimally windowed-chirp (OWCh) signals allow users to quickly collect frequency-dense data from time evolving systems. Data from curing reactions of commercial epoxies from low viscosity uncured states through curing will be presented along with time-temperature superposition experiments performed with windowed chirps. Additionally, advancements in commercially available OWCh methods will also be discussed. Prior methods of conducting chirp-based rheometry relied on user-built equations entered into the software that

limited the fidelity of the rheometer's input stimulus. The latest innovations that provide a higher-quality material stimulus across a much wider frequency range will be presented.

References: (1) Phys. Rev. X 8, 041042, 2018. (2) J. Non-Newton. Fluid Mech, 333, 105307, 2024.

Wednesday 3:45 Sweeney Ballroom D TM18

Dripping-on-Substrate (DoS) dos and don'ts

Lucas N. Warwaruk[1], Randy H. Ewoldt[2], Macosko Chris[3], and Gareth H. McKinley[1]
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Capillarity-driven rheometry techniques are a well-established means of measuring the relaxation time of long-chain polymer solutions. One such technique, known as Dripping-on-Substrate rheometry or DoS, has become a popular method of particular utility for low viscosity solutions [1]. The energy released by a pendant droplet of a complex fluid spreading across a partially-wetting substrate drives rapid formation of a neck, which leads to strong transient extensional flow even in very low viscosity fluids. However, a clear set of guidelines on the capabilities and limitations of DoS rheometry is lacking. In the current technical presentation, we establish the key ``Dos and Don'ts"; of DoS rheometry; discussing critical parameters that influence the quality of the measurements and the accuracy of the resulting estimates of the extensional relaxation time. Dilute solutions of a 2 MDa and 8 MDa polyethylene oxide (PEO) polymer, as well as a 20 MDa polyacrylamide (PAM) polymer, are used as test fluids for probing the role of different experimental control parameters. We develop two instrumental constraints, relating to the spatial and temporal resolution of the DoS setup. Provided these constraints are satisfied, DoS rheometry is able to measure small relaxation times, on the order of 0.1 ms. Such values are markedly smaller than the range of values accessible with other common techniques, such as capillary break-up extensional rheometry (CaBER) [2]; however, care must be taken to ensure that fitting of the elasto-capillary regime covers a sufficiently long duration (in dimensionless time) and that digital video images are recorded at an appropriate acquisition rate and spatial magnification. These instrumental constraints can be combined to provide a figure of merit that allows inter-laboratory comparison of different approaches to capillarity-driven rheometry.

[1] Dinic, J., Zhang, Y., Jimenez, L.N. & Sharma, V. 2015 ACS Lett. [2] Rodd, L.E., Scott, T.P., Cooper-White, J.J. & McKinley, G.H. 2000 Appl. Rheol.

Wednesday 4:05 Sweeney Ballroom D TM19

A low-cost 3D-printed rotational viscometer for rheology and fluid mechanics education

Benjamin M. Yavitt, Miriam Knutson, Sasanka P. Weerakoon, C.J. Ticknor, and Aashish Priye
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The high cost of commercial viscometers limits hands-on learning opportunities for the public. We present the development and implementation of a Low-Cost Rotational Viscometer (LC-RV) utilizing 3D-printed components and off-the-shelf materials for educational purposes. The LC-RV replaces expensive rotary torque sensors with a linear force sensor mounted on a stationary cup. The LC-RV consistently measures viscosity over 3 orders of magnitude for Newtonian fluids (like mineral oil and glycerol solutions) and non-Newtonian fluids (like soap) at various shear rates. The education impact of the LC-RV was demonstrated in an undergraduate fluid mechanics course, providing students with practical hands-on experience in viscosity measurement. A cognitive assessment based on thematic analysis of the responses indicated that most students effectively grasped key concepts in viscosity and rheology, with many demonstrating high levels of cognitive engagement. The design files, program codes, and assembly instructions are publicly available, enabling others to implement, expand, and adapt LC-RV for diverse pedagogical and research applications beyond classroom demonstrations.

Wednesday 4:25 Sweeney Ballroom D TM20

Fast, cheap, and predictably wrong: Quantitative limits of tilted vial protorheology

Ramdas Tiwari[1], Connor D. Armstrong[2], Mohammad Tanver Hossain[2], Michael Zakoworotny[2], Ignacio Arretche[2], Nancy R. Sottos[2], Phillipe Geubelle[2], Sameh H. Tawfick[2], and Randy H. Ewoldt[1]
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We assess physics-based viscosity inference equations for the tilted vial test and propose criteria for when and why they fail.

High-throughput characterization of the mechanical properties of materials accelerates material discovery in both industrial and academic contexts. To this end, the tilted-vial test was proposed as a quick and cost-effective method for inferring viscosity [1]. While images of inverted vials of material are abundantly used in literature to indicate fluidity (or lack thereof), they are rarely used for the quantitative inference of properties [2]. The proposed test involves tilting a vial of material by a set angle and observing the evolution of the liquid-air interface. Driven by gravity and opposed by viscous effects, the interface levels out. Hossain et al. proposed a scaling law relating the timescale of this 'leveling flow' to the viscosity of the fluid. Importantly, this scaling law assumes ideal conditions (Newtonian flow and negligible inertial and surface tension effects), which are not always valid [3]. In this work, we predict when these assumptions break down and propose mathematical expressions for such limits. Pairing these with practical conditions on observable deformation rates and the maximum imposable shear stress fixes an operational window which serves as a quick and intuitive way to judge the reliability of inferred data. We validate the proposed operational window by

comparing inferred viscosities with rheometer measurements and analyze the error variation with the Reynolds and Bond numbers. Our results show that the tilted vial test can accurately measure viscosities over several orders of magnitude and inference fails in a predictable fashion, thereby making it a candidate method for quantitative high-throughput characterization.

[1] Hossain et al.; J Rheol, (2024) DOI: 10.1122/8.0000667
[2] Lessard et al.; JACS, (2024) DOI: 10.1021/jacs.4c01578
[3] Hossain et al.; Curr Opin Colloid Interface Sci, (2024) DOI: 10.1016/j.cocis.2024.101866

Wednesday 4:45 Sweeney Ballroom D TM21

Errors matter when measuring Poisson's ratio of nearly incompressible elastomers

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School of Polymer Science and Polymer Engineering, The University of Akron, Akron, OH 44325, United States

Elastomers are a class of materials where their bulk modulus is orders of magnitude larger than their shear or Young's moduli. This difference results in nearly incompressible behavior where the value of Poisson's ratio approaches the incompressible limit of 0.5. Due to this limit approaching behavior, nearly incompressible materials require characterization methods with high degrees of precision. Recently, researchers have suggested that inferring Poisson's ratio from measurements of Young's modulus and shear modulus is an appropriate method for quantifying Poisson's ratio. This claim is examined by comparing such a method to other established methods including digital image correlation (DIC) and radially confined compression (RCC). It is found that too much error propagates from the measurement of the shear and Young's moduli to distinguish Poisson's ratio from the incompressible limit. Notably, it is also found that small cumulative errors (5-10%) in moduli measurements can result in estimates of Poisson's ratio in the 0.45-0.35 range. Similar error analysis is performed with DIC and RCC. These findings have strong implications for the mechanics of rubber gaskets, coatings, and seals where hydrostatic stresses develop.

Wednesday 5:05 Sweeney Ballroom D TM22

Imaging intermittent flows in capillary channels using widefield spatiotemporal analysis of attractive nanoemulsions

Cormak Weeks, Wentao Tang, and Lilian Hsiao
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Confined extrusion of colloidal gels produces complex flow instabilities that are challenging to resolve with conventional rheometry alone, necessitating microscopy-based spatiotemporal analysis to link microstructure to macroscopic behavior. Unlike Newtonian fluids, colloidal dispersions display shear-dependent behavior and stress-induced microstructural evolution, resulting in emergent phenomena such as demixing, droplet clustering, and dynamic network formation. Conventional rheological models (e.g., Herschel-Bulkley, power-law) fail to capture these evolving multiphase structures and are inadequate for predictive control during extrusion-based processing. We present an integrated experimental-computational approach to characterize and actively regulate flow in thermoresponsive colloidal gels extruded through a cylindrical capillary (1 mm diameter, 45 mm length) across temperatures from 25 to 60°C and wall shear rates from 0.21 to 6.2 s?¹. The formulation includes 20 vol% fluorescent poly (dimethyl siloxane) (PDMS) nanoemulsion droplets in an aqueous phase with 200 mM sodium dodecyl sulfate (SDS) and 33 vol% poly (ethylene glycol) diacrylate (PEGDA), a thermal crosslinker. Heating induces a thermoreversible sol-gel transition via temperature-dependent interfacial attractions, forming percolated gel networks with hierarchical structure. This self-assembly makes the system highly responsive to local thermal and shear conditions, ideal for probing microstructural dynamics. To capture these effects, we develop a finite difference transport model solving the coupled Taylor flow equations, parametrized with experimentally measured rheological and structural data. Real-time image analysis yields dispersion metrics linked to microstructural heterogeneity and functional outcomes. This work establishes a closed-loop, physics-informed strategy for microstructural control during extrusion, advancing precision fabrication in biomanufacturing and soft materials processing.

Wednesday 5:25 Sweeney Ballroom D TM23

Characterization of length-scale dependent rheology using bi-disperse multiple particle tracking during cell-material interactions

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hMSCs re-engineer their microenvironments across length-scales to enable basic cellular processes, including motility and differentiation, during wound healing and tissue regeneration. During hMSC-mediated scaffold remodeling single cross-links break on the nanometer scale, cellular extensions pull material and degrade paths through the scaffold to enable motility on the micrometer scale and bulk scaffold degradation occurs on macroscopic scales. We measure length-scale dependent rheology during cell-mediated remodeling of the pericellular region using bi-disperse multiple particle tracking microrheology (MPT). Bi-disperse MPT measures the Brownian motion of two different probe sizes to characterize length-scale dependent rheology. 0.5 and 2 micron particles are embedded in the same sample and are tracked separately using a brightness-based squared radius of gyration. We measure hMSC-mediated scaffold degradation in a well-defined hydrogel scaffold composed of 4-arm star PEG-norbornene cross-linked with a matrix metalloproteinase-degradable peptide. An adhesion ligand, CGRDS, is included to enable cellular adhesion to the network during motility. We measure that cells preferentially re-engineer their microenvironment across length-scales using enzymatic secretions (irreversible degradation) and cytoskeletal tension (reversible degradation). Using bi-disperse MPT we identify the area where the cell

is applying force by tracking probe particles and extending their trajectories to points of intersection. From these measurements, we identify that 2 micron particles are stuck in a loose gel network that has been partially degraded and is being reversibly remodeled by the hMSC. At the same time, 0.5 micron particles are measuring irreversible scaffold degradation due to cell-secreted enzymes and diffuse through the larger network structure cells are pulling on. By characterizing evolving length-scale dependent rheology, new materials can be designed which better mimic native tissue and instruct cell behavior.

Thursday Morning

Symposium MP
Metzner Presentation

Metzner Award Presentation

Thursday 8:00 Sweeney Ballroom E+F MP1

Rheoinformatics: Seamlessly integrating theory, computation, and experiment through data-driven rheology

Safa Jamali

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The scientific community has witnessed a plethora of developments in the area of machine learning and artificial intelligence in the last few years. Many scientific and engineering disciplines have adopted these advanced techniques under the general umbrella of scientific machine learning. Rheology community is also rapidly adopting a series of different data-driven techniques. I will present some of the recent advances in data-driven rheology, as a seamless pathway to bring theory, computation, and experiments together. These techniques will range from physics-informed machine learning platforms for meta-modeling complex fluids, to more advanced generative AI platforms for robust and reliable non-Newtonian fluid dynamics. Finally, I will discuss some of the future directions and outlooks, given the pace of developments in the ML/AI sciences.

Symposium CS
Colloidal Suspensions and Granular Materials

Organizers: James Gilchrist, Abhinendra Singh and Shravan Pradeep

Thursday 8:45 Sweeney Ballroom A CS49

Rheology and crystallization behavior of natural basaltic melts at conditions relevant to lava flow emplacement

Stephan Kolzenburg

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Natural basaltic melts exist between liquidus and solidus conditions during storage, transport, eruption, and emplacement on Earth and other Planets. In these environments, where melts crystallize, they encounter a range of non-equilibrium thermal and environmental conditions, such as lower oxygen fugacities (fO2) than in the atmosphere. The thermal path and -history, as well as the oxygen fugacity within the melt influence the onset, phase-dynamics, and kinetics of crystallization. Thus, they have profound effects on rheologic properties and the transition from a flowing suspension to a solid rock. Yet, the influence of these environmental conditions on both rheology and solidification behavior remains largely uncharted, and most data derive from measurements at atmospheric conditions. This contribution presents new data that constrain both rheology and solidification behavior of crystallizing basaltic melts at subliquidus temperatures, and reduced conditions. The data show that at reduced conditions 1) the onset of crystallization is delayed 2) the crystallization kinetics are more sluggish. 3) the effective suspension viscosity is reduced as a result of a decrease in the volume fraction of crystals. 4) the crystallizing phases change. 5) variations in major element melt composition can extend / narrow the solidification window.

Thursday 9:05 Sweeney Ballroom A CS50

Acoustic forces in colloids: Microstreaming effects and particle-scale modeling

Shreyas Sudhaman and Roger T. Bonnecaze

McKetta Department of Chemical Engineering, The University of Texas at Austin, Austin, TX 78712, United States

Ultrasonic waves are known to reduce the viscosity of colloidal suspensions and gels by disrupting particle aggregates, enabling control over their rheological properties. However, the mechanisms responsible for this effect are not fully understood. In this study, we quantify the acoustic forces acting on suspended particles and identify microstreaming as the dominant force for particles smaller than one micron. We also present a particle dynamics model to explore how these forces may contribute to structural changes in colloidal systems under sonication. These results offer a step toward understanding how ultrasound influences suspension microstructure and flow behavior.

Thursday 9:25 Sweeney Ballroom A *Keynote* CS51

Rheology of dense fiber suspensions

Arezoo Ardekani
Mechanical Engineering, Purdue University, West Lafayette, IN, United States

We use high-fidelity computational model of fiber suspension to investigate suspension rheology. We investigate the interplay between the hydrodynamic, noncontact attractive and repulsive, and interfiber contact interactions. The shear-thinning viscosity and finite yield stress obtained from the Immerse Boundary Method simulations align quantitatively with experimental findings from the literature. The study demonstrates that attractive interactions lead to both yield stress and shear thinning behavior in rigid fiber suspensions. This discovery holds significance as it contributes to the ongoing debate on the source of yield stress in fiber suspensions. The proposed model is used to quantify normal stresses in addition to shear thinning and yield stress.

Thursday 9:45 Sweeney Ballroom A CS52

Cracking of films and buckling of shells in drying colloidal dispersions

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Chemical Engineering, Indian Institute of Technology Bombay, Mumbai, Maharashtra 400076, India

Drying films of colloidal dispersion containing hard particles crack while fast drying drops of similar dispersion buckle, both caused by the capillary pressure exerted by the liquid menisci between particles. For drying films on substrates, there exists a maximum crack-free thickness, while for fast drying drops, there is a maximum buckle-free shell size, with both quantities depending on particle size, elastic modulus of the particles and nature of particle packing. Here, we measure the critical cracking thickness for a drying colloidal film made of a mixture of hard and soft elastic particles to extract the effective modulus of the film for various ratios of hard and soft particles. Scanning electron images of the cross-section of the film reveal the spatial distribution of the hard and soft particles. The measured effective modulus exhibits a trend that is identical to that obtained using the nanoindentation technique, indicating that measurement of the critical cracking thickness gives a quantitative measure of the effective modulus of the packing. The values of effective modulus from the two techniques fall between the two limits obtained from the simple rule of mixtures for composite materials. The deviation from either limit is attributed to particle segregation caused by the sedimentation of the heavier particles.

Thursday 10:55 Sweeney Ballroom A CS54

How does slip affect Thixotropy-Elasto-Visco-Plastic (TEVP) predictions in simple and oscillatory shear?

Jourdain H. Piette and Savvas G. Hatzikiriakos
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The dynamics of slip and thixotropy are investigated in simple and oscillatory shear for an elasto-viscoplastic (EVP) model. The Saramito EVP model is modified to include a thixotropic structural parameter term that contributes to the yield stress and elastic material properties. For slip, a hydrodynamic lubrication condition is used to describe the development of a depleted layer at the wall. This depleted layer has a relatively smaller viscosity than the bulk and contributes to a reduction in shear stress across the gap. The proposed model is evaluated against experimental data from a suspension of 5 wt.% cellulose nanocrystal (CNC) with 20 mM NaCl. A suite of simple and oscillatory shear tests is conducted in a cone-plate geometry with cone angles of 1° and 4°, and parallel plate geometry with and without sandpaper. The system exhibited thixotropic behaviour as well as apparent slip, which could not be suppressed even with the application of sandpaper of grit 80 (200 ?m) and 220 (68 ?m) at the wall of the parallel-plate geometry. The model is fitted to steady-shear results, accounting for both slip and thixotropic behaviours. The yielding point of strain amplitude sweeps are shown to have both geometry and surface finish dependence. A trend is found where the strain amplitude at yield is shifted to lower strain amplitudes for smoother surfaces. This trend is validated by the proposed model which predicts a lower yielding point when slip is present. Thus, it is important to account for slip behaviour when analysing strain amplitude sweeps for yielding properties.

Thursday 11:15 Sweeney Ballroom A CS55

Dominant agglomerate scales for cohesive grains a rotating drum

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In the presence of inter-particle cohesion, granular flows readily break up into agglomerates of a range of sizes depending on the flow and magnitude of stickiness. In this study, we report experiments for the dominant agglomerate size observed when such sticky grains are made to tumble in a rotating drum. A phase diagram is provided for the range of the observed phenomenon in this geometry, before special attention is paid to the regime where successive individual failure events are observed. In this case, a primary agglomerate is observed to detach and slide off the bulk of the rotating grains. The size and frequency of the failure events is determined by the driven rotation of the drum and the cohesion among grains. To this end, we show how cohesion can be measured using a Mohr-Coulomb analysis of these failure events. Independent yield stress measurements are conducted for each grain species in a shear cell, and are shown to corroborate the presented argument. Inter-particle cohesion is induced using capillary bridges, or by applying a thin polymer coating on grains, and are described altogether. The observed structures on the free surface of the tumbling grains are a consequence of the dominant agglomerates undergoing further fragmentation as they advect over the flowing layer.

Thursday 11:35 Sweeney Ballroom A CS56

Surface-modified microfibrillated cellulose to enable hydration and dehydration

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Rheological modifiers adjust flow behavior, control rheology and induce phase transitions in formulations. Our research aims to repurpose microfibrillated cellulose (MFC) from paper waste as a rheological modifier in consumer product formulations. MFC fibers have high aspect ratios, which alters rheology with minimal added material but can associate even at low concentrations. To maintain fiber dimensions and stability, MFC is produced and stored as an aqueous dispersion. This high water content presents challenges for large-scale use by increasing transportation costs and environmental impact. Designing formulations that allow water removal before shipping and rehydration at the destination is a more efficient and sustainable solution. Drying bare MFC leads to irreversible aggregation due to strong hydrogen bonding, causing loss of nanoscale structure and mechanical properties. Once fibers irreversibly aggregate, redispersion is difficult and negates the benefits of the nanoscale dimensions and high elastic moduli of a well-dispersed fiber network. To overcome these limitations, we modify MFC surface chemistry by synthesizing surface-oxidized MFC (OMFC) and grafting a thermoresponsive polymer, Jeffamine M2005 polyetheramine, onto the surface to enable dehydration and rehydration while retaining material properties. Both OMFC and thermoresponsive MFC are dried using freeze, vacuum and oven drying. We measure equilibrated rheological properties before and after a dehydration-redispersion cycle using amplitude and frequency sweeps and measure temperature-dependent rheology of thermoresponsive MFC. By modifying MFC surface chemistry and partially blocking hydroxyl groups, we can successfully redisperse MFC. We measure similar equilibrated material properties and thermal responsiveness in thermoresponsive MFC. This work provides a strategy to design MFC for efficient shipping while preserving structure and properties through dehydration, transport and rehydration.

Symposium SE
Rheology and Sustainability for Energy and Production

Organizers: Rekha Rao, Joseph Samaniuk and Phillip Irace

Thursday 8:45 Sweeney Ballroom B SE6

Examining the impact of polypropylene contamination on film blowing polyethylenes via extensional rheology

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Despite growing interest in sustainable materials, reducing virgin polymer usage in favor of recycled alternatives remains technically challenging. One major limitation in plastics recycling is feedstock variability and contamination. Contamination can come in many forms, but one of the most detrimental is a secondary incompatible polymer which is introduced via mis sorting. The secondary polymer will create microscopic zones that heavily impact macroscopic behavior such as processing and final product performance. The impact of polypropylene (PP) contamination on film-blowing high density polyethylene (HDPE) will be examined through shear and extensional rheology and extrusion. Model HDPE/PP blends with defined PP concentrations will be prepared from virgin materials via mechanical compounding and compared to three post-consumer recycled PE samples with variable, unknown PP contamination. Preliminary extensional rheology of the post-consumer recycled HDPEs showed minimal strain hardening, failing through ductile snapping rather than controlled necking. Adequate strain hardening is essential to prevent film breakage or sagging, the model HDPE/PP blends will be used to determine the critical amount of PP contamination that compromises processing. Shear and extensional rheology are powerful quality control tools for determining polymer processing and product performance with minimal sample usage. This work aims to increase the recyclability of post-consumer HDPE so that it can effectively displace some of the virgin polymers in circulation. Acknowledgements: The research is supported by a grant from DoE.

Thursday 9:05 Sweeney Ballroom B SE7

Thermodynamic insights into shear flow-mediated crystallization

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During scalable perovskite solar cell processing, many of the roll-to-roll manufacturing techniques, such as blade-coating or slot-die coating, rely on understanding many simultaneous phenomena: fluid dynamics, crystal nucleation and growth, evaporation, and resulting film morphology. To optimize the process and consistently produce high-quality films, the synergy of these concurrent phenomena must be further investigated. To address the limited knowledge in how the fluid dynamics during processing could impact crystallization, we utilize a novel simulation technique to probe the early stages of crystal nucleation and growth in the presence of a flowing Newtonian fluid. The technique, known as the Hydrodynamic Structural Phase Field Crystal (HXPFC) method, is a grid-based method that represents crystallizing colloidal particles interacting via attractive hard-sphere potentials. Direct access to thermodynamic quantities, such as the chemical potential and free energy, is one of the greatest strengths of the method. By extending the free energy functional, other thermodynamic potentials, such as the entropy, can also be probed. Fundamental

nucleation behavior is first recovered to connect the mesoscopic level crystallization behaviors to the atomic level encountered during perovskite crystallization. Then, various scenarios, governed by the HXPFC dimensionless parameters, are analyzed to draw conclusions that are applicable to full-scale processing. In addition, the energetic and entropic contributions to early-stage crystallization are probed as the velocity is increased.

Thursday 9:25 Sweeney Ballroom B SE8

Rheological characterization of CO_2 hydrate suspensions

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Climate change is increasingly present in all localities, and reducing greenhouse gas emissions is an issue to be addressed. However, the energy transition requires a complete overhaul of the energy production and consumption system, which is a slow and complex process. Some studies suggest alternative solutions for mitigating CO_2 emissions. The current research focuses on one of these alternatives: capturing CO_2 using hydrate formation. Hydrates are crystalline solids formed when water and CO_2 come into contact under low temperatures and high pressures. When these thermodynamic conditions are met, a crystalline structure creates cages trapping CO_2 through hydrogen bonds. Although the hydrate formation process has been extensively studied, this work aims to evaluate the rheological properties of CO_2 suspensions with a view to the transport through pipelines. The rheological behavior of this suspension was assessed using a rotational rheometer with an attached pressure cell. Hydrates were formed using only water and CO_2 at varying shear rates and temperatures. The rheometric test results revealed the shear rate's impact on induction time. Additionally, this material was characterized by identifying a shear-thinning behavior dependent on time. The main contribution of this work was to highlight the effects of agglomeration on the rheological behavior of this material, which possesses a fractal structure that influences the viscosity of the suspension.

Thursday 9:45 Sweeney Ballroom B SE9

Rheological and gelation study of silica-based nanofluid for flow control in enhanced geothermal systems

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Fractures and fracture networks are critical to the operation of enhanced geothermal systems (EGSs), serving as conduits for the migration of geothermal working fluids. However, the non-uniform conductivity of these fractures presents a significant challenge to the optimization of heat extraction. Highly conductive fractures can lead to undesirable fluid losses into the surrounding formation and cause thermal short-circuiting, both of which reduce energy recovery and economic performance. Thus, it is important to control the losses of working fluid and thermal short-circuiting in EGS reservoirs. This study investigates the potential of silica-based nanofluids to mitigate these issues by selectively controlling flow within highly conductive fractures, thereby redirecting fluid into less permeable, higher-temperature zones. The rheological behavior and gelation kinetics of the nanofluid are systematically evaluated as functions of silica concentration (2-6 wt%), pH, salt content, and temperature (100?°C, 120?°C, and 150?°C). Polyethylene glycol (PEG) aqueous solution is used as the base fluid. Results demonstrate that both rheology and gelation behavior of the nanofluids are significantly influenced by the studied parameters. Increased silica concentration and temperature are found to enhance shear-thickening and gelation, while pH and salt content further modulated performance. These findings highlight the feasibility of using silica-based nanofluids as stimuli-responsive flow control agents to mitigate thermal short-circuiting and improve heat sweep efficiency in EGS applications.

Thursday 10:35 Sweeney Ballroom B SE10

Understanding structure-property relationships of ionic liquids for biofuel production

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Understanding structure-property relationships of ionic liquids for biofuel production Ionic liquids, salts that are molten at room temperature, are increasingly being used as novel solvents. The variety of ions that can be mixed and matched, tunable properties of these ions, as well as interesting properties such as low toxicity and low volatility, make these ideal as a new generation of "designer solvents". In green fuel applications, ionic liquids have been shown to efficiently dissolve biomass with recycling potential, promising important savings in processing steps for biofuel production. However, the choices of liquids in these works are often guided by trial and error, with studies either sticking to liquids for which there is already established literature, or just testing a small range of different ion combinations. The problem is further complicated by the presence of water in samples. Wet algae lipid extraction is preferred for its cost benefits in downstream processing, but has a nontrivial effect on the properties of the solution and the extraction efficiency. In this paper, we first present our experimental characterization of rheological properties of a few ionic liquids and discuss how they relate to the lipid extraction efficiency from microalgae as biofuels. We discovered ionic liquids that outperform existing ones. We discovered a strong influence of anion structures across a wide range of water concentrations. Later we present our simulation work aiming to bridge molecular and mesoscopic properties.

Thursday 10:55 Sweeney Ballroom B SE11

Melt rheology of bio-based polymer composites: Effects of wood filler loadings, polymer blend ratio, and crosslinking

Aditi Khatiwada[1], Kathryn E. Slavny[2], Amber M. Hubbard[2], and Ria D. Corder[1]
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An emergent manufacturing method for multi-functional composites is the use of reactive extrusion, in which neat resins and reactive agents are shear mixed at elevated temperatures in a compounder or extruder to promote a necessary reaction. While bio-based composites have found industrial applications ranging from vehicle lightweighting to construction materials, understanding how composition affects melt rheology is crucial to the development of processable, bio-based composites with enhanced functionalities. In this work, we investigate the effects of polymer blend ratio and wood filler type and loading on the rheological behavior of bio-based polymer composites. Our samples contain polylactic acid (PLA), polyhydroxybutyrate (PHB), and either wood flour or wood fibers. We demonstrate that increasing PHB content decreases the complex viscosity and elastic/viscous moduli in composites containing 0 and 10 wt% wood flour. However, for 20 and 30 wt% wood flour, complex viscosity increases with higher PHB content due to effects of wetting, phase separation, and strong filler interactions. The viscous modulus dominates over the storage modulus in most samples; the exceptions being PLA/PHB- 80/20 and 70/30 composites containing 30 wt% wood flour, in which the elastic modulus dominates due to formation of filler networks. Additionally, the linear viscoelastic region shifts to lower values at increased wood flour loadings, suggesting that fillers increase sensitivity to deformation. We also examine the role of particle size and aspect ratio through analysis of composites containing wood fiber in place of wood flour. Finally, we begin to explore how the melt rheology evolves with crosslinking during reactive extrusion. By relating melt rheology data to that obtained from complementary techniques such as DSC, TGA, and tensile testing, we can better design bio-based polymer composites for enhanced properties and processability.

Thursday 11:15 Sweeney Ballroom B SE12

Rheological and morphological investigation corn stover undergoing enzymatic hydrolysis

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Lignocellulosic biomass is a plant-derived material that can be processed into a variety of products such as fuels, pharmaceutical precursors, and additives for materials science applications. Corn stover is one source of lignocellulosic biomass, and it can be processed into liquid fuels with a multi-step process that includes enzymatic hydrolysis to produce fermentable sugars. Prior to enzymatic hydrolysis a pretreatment step is typically employed to increase the surface area of lignocellulosic material available to enzymes. A pretreatment step developed at the National Renewable Energy Laboratory (NREL) called deacetylation and mechanical refining (DMR) combines chemical and mechanical action to break down the lignocellulosic material into an aqueous suspension of fibers. The enzymatic hydrolysis reaction that follows occurs over approximately 48 hr, and it leads to gradual changes in the morphology of the fiber suspension, as well as changes to the rheological properties. Understanding and characterizing those changes is important for designing processing equipment to effectively and efficiently pump, mix, or pour the suspension at various times through the duration of the reaction. In this work we have investigated the changes in suspension morphology and rheology that occur over time with enzymatic hydrolysis of corn stover following DMR pretreatment. The main finding is that reduction in fiber length rather than the breakdown of a fiber network is the driver for changes in the rheology. We will discuss the implications for pressure loss calculations in piping at an industrial level, and the consequences of modeling the rheological data with either yield-stress models such as the Bingham Model and Herschel-Bulkley Model, or with a simpler power-law model.

Thursday 11:35 Sweeney Ballroom B SE13

Engineering clay-zwitterion membrane supercapacitors using rheology as a tool

Roxy Islam[1], Pritha Sarkar[1], Suvash Ghimire[1], Gernot Rother[2], and Kausik Mukhopadhyay[1]
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Clays are among the most affordable, sustainable, and environmentally friendly materials widely available for biomedical, petrochemical, pharmaceutical, cosmetic, coating, geopolymers, and energy applications. They are dielectric materials with exchangeable ions that allow for tuning the chemical and mechanical properties by functionalizing with organic molecules within their layers. When functionalized with zwitterions, clay slurries demonstrate unique rheological properties influenced by the organic and inorganic substituents, as well as the concentration, particle size, and CEC of the clays. Our recent studies revealed that, by adjusting the carbon-chain length, zwitterion-functionalized clays introduce ion conductivity, superior storage moduli, and thixotropic behavior compared to pristine clays. However, the rheological behavior of clay slurries remains poorly understood due to their distinctive non-spherical shapes and anisotropic surface charge properties. Herein, we present an analysis of the effects of functionalizing bentonite clay with betaines of varying carbon-chain lengths on the rheological properties of clay slurries, particularly focusing on their viscoelastic and conductivity characteristics. The results indicate that the betaine-bentonite clays exhibit higher viscosity, storage moduli, and flow stress due to the formation of pH-dependent three-dimensional networks and increased aggregation resulting from intercalation. Using Rheo-SAXS, Rheo-EIS, Zeta potential, and SEM analyses, we also investigated the interactions between the clay and zwitterions, and how they impact the structure, durability, and properties of bentonite-betaine clays, thereby providing insight into predicting the stability, strength, and ionic conductivities of the bentonite-betaine clay membranes comparable to other porous systems. The

findings suggest the influence of rheology on the viscoelasticity and conductivity of such materials to engineer sustainable clay-based supercapacitors that we have developed.

Symposium SR
Rheology for Soft Robotics and Use of Field-Responsive Materials

Organizers: Laurel Kroo, Ryan Poling-Skutvik and Bhuvnesh Bharti

Thursday 8:45 Coronado + DeVargas SR6

Shear-induced structural transitions of cholesteric liquid crystals

Abhishek Shetty[1] and Christina Tang[2]

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Cholesteryl ester liquid crystals (LCs) self-assemble into periodic helical structures, imparting unique and responsive optical properties. These characteristics have inspired applications in thermal mapping, crack detection, and flow visualization [1]. However, hysteresis in structural color transitions-triggered by temperature or shear-can limit practical use and may stem from changes in LC texture. In this work, we investigate texture evolution using a shear-induced polarized light imaging (SIPLI) coupled with an air-bearing rheometer [2]. Temperature sweeps (25°C-75°C) were performed across a range of shear rates to study phase behavior during both heating and cooling cycles. Discontinuities in viscosity aligned with phase transition temperatures identified by DSC. While transition temperatures were consistent across shear rates, a dependence on the direction of the temperature ramp (heating vs. cooling) was observed [3]. During cooling, low shear rates (0.1-1 s?¹) produced radial textures with central point defects, dynamically shifting in color from red to blue as temperature decreased. Higher shear rates (10-500 s?¹) induced twisted radial textures. Conversely, during heating, twisted configurations appeared even at low shear rates. These findings highlight the sensitivity of cholesteryl ester self-assembly to thermal and mechanical conditions, offering critical insight into the design and processing of functional LC materials.

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[2] Mykhaylyk, Oleksandr O., et al. Applications of shear-induced polarized light imaging (SIPLI) technique for mechano-optical rheology of polymers and soft matter materials. J. Polym. Sci. Part B: Polym. Phys. 54 (2016): 2151-2170.
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Thursday 9:05 Coronado + DeVargas *Keynote* SR7

Knotting semi-flexible filaments in strong fields with hydrodynamics

Lucas H P Cunha[1], Luca Tubiana[2], Sibani Lisa Biswal[3], and Fred C. MacKintosh[3]

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Knots appear spontaneously across length scales, from headphone cords and Christmas lights at the macroscale to polymers, proteins, and DNA filaments inside bacteriophages or in microfluidic setups. The probability with which different knots emerge provides insight into the forces and constraints governing their formation. Here, we uncover how hydrodynamic interactions and body forces cooperate to induce and stabilize knots in semi-flexible filaments. Using Brownian dynamics simulations with hydrodynamics, we show that field-driven sedimentation generates toroidal flows that guide the filament into knotted configurations. The resulting hydrodynamic tension between the leading knotted head and the trailing tail tightens the structure, producing a hierarchy of metastable knots whose stability increases with topological complexity. Consequently, the filament undergoes an annealing-like sequence of transitions between simple and complex knots, ultimately reaching stabilization.

Thursday 9:25 Coronado + DeVargas SR8

Coordinated motion of magnetic Janus particle microroller swarms

James F. Gilchrist[1], John Riffle[2], Genevieve Powell[2], Tyler Richardson[1], Olivia Percaccio[3], Noah Tobin[1], Katie Weis[1], Erlind Kore[1], and Aidan Donnelly[4]

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This work investigates the granular-like behavior of dense systems of microrollers that are responding to rotating magnetic fields. Microrollers also flow, segregate, and fluidize with kinematics similar to those found in granular systems. In this work, a granular system of 50 micron ferromagnetic Janus particles is prepared. These responsive Janus particles are rotated through the application of magnetic torque by an external rotating magnetic field resulting in swarming behavior that allows determination of their kinematics for more transport through complex geometries. In the geometry explored, their swarming behavior follows Archimedes spirals and their local kinematics follows granular behavior. Swarming to one location and then directed to swarming to another location allows further control and determination of their coordinated motion.

These swarms are also directed through 3D printed mazes to demonstrate how they move along walls and together to deliver a cargo. A simple model using granular $\mu(I)$ rheology captures the behavior of these systems to predict behavior in various geometries.

Thursday 9:45 Coronado + DeVargas SR9

Magnetically rotated Janus particles near solid boundaries

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Colloidal particles with anisotropic structure or composition can be actuated using external fields to produce sustained motion in viscous fluids, thus providing a framework for engineering microrobots and model active matter systems. Here, we study the dynamics of polystyrene Janus microspheres coated with a thin iron patch and driven by a time-varying uniform magnetic field. The particles show three distinct modes of motion depending on their position relative to a solid boundary: steady rolling at the surface, trochoidal trajectories in an intermediate zone, and in-place rotation at larger separations. The transition between these regimes is governed by the interplay between magnetic torque and the viscous resistance imposed by the surrounding fluid. Using high-speed microscale imaging, and particle image velocimetry, we show that the observed curvilinear motion at intermediate heights arises from rapid switching between rolling, tumbling, and spinning states. The results highlight how substrate proximity and patch-induced asymmetry control particle trajectories, with implications for engineering surface-guided active colloids.

Symposium ML
AI and ML in Rheology

Organizers: Vikram Jadhao, Shamsheer Mahammad and Hassan Pouraria

Thursday 8:45 Sweeney Ballroom C ML16

Obtaining rheological constitutive equations for geopolymer systems from scarce data

Donya Dabiri[1], Ted Egnaczyk[2], Norman Wagner[2], and Safa Jamali[1]
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Understanding the behavior of complex fluids through their constitutive dynamics has long been a subject of considerable interest. Traditionally, this involved phenomenological or empirical formulations of material functions. In recent years, the Sparse Identification of Nonlinear Dynamical Systems (SINDy) technique has demonstrated strong potential in extracting compact yet accurate models from noisy datasets. Recently, Rheo-SINDy has been developed with specific applications of model discovery in rheology as well. In this work, we use a hybrid framework that combines Rheology-informed Neural Networks (RhINNs) with SINDy to uncover constitutive relations in geopolymer systems using experimental data, where classical rheological models fall short or are absent. Our dataset includes time sweeps of the viscoelastic moduli. This integrated approach leverages machine learning and experimental data-capitalizing on SINDy's ability to infer governing equations with limited information, and RhINNs' strength in learning and solving such equations. We validate our method by constructing simplified yet expressive models that accurately capture the behavior of geopolymers across different flow protocols.

Thursday 9:05 Sweeney Ballroom C ML17

From microstructure to rheology: Discovering tunable design rules with neural latent spaces

Babak Valipour Goodarzi and Reza Foudazi
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Unique properties of nanoemulsions, such as their extensive surface area and enhanced stability, have made them applicable across various industries, including food, cosmetics, oil and gas, pharmaceuticals, and vaccine production. The rheological properties of nanoemulsions are closely linked to their droplet size, the effective volume fraction of the dispersed phase, and interdroplet interactions. However, the collective effects of these factors are so complex that a theoretical model cannot accurately predict rheological properties only based on these microstructural parameters. In addition, existing models are limited to the linear elastic behavior and fail to predict the non-linear regime. In this research, we aim to predict the coefficients of the Saramito model, which serves as a reference mechanical model for nanoemulsions, based on tunable microstructural parameters. To avoid the need for a significant number of experiments for neural network learning for this purpose, we utilize encoder-decoder neural networks to generatively map the relationships between nanoemulsion microstructure and rheology using latent neural encoding.

Thursday 9:25 Sweeney Ballroom C ML18

Rheometric signal denoising using latent space modelling

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In rheometry, precise evaluation of the viscoelastic properties of materials depends on accurately capturing undistorted response signals, such as strain (or angular displacement) and stress (or torque). However, these signals are frequently affected by substantial noise originating from the

rheometer hardware itself or from external sources. Unlike many traditional filtering problems, in rheometry it is essential to accurately determine both the phase information and the amplitude of the measured signal. Conventional signal denoising methods, including moving average filters, Savitzky-Golay filters, Wiener filters, and wavelet-based techniques, often require manual parameter tuning for each signal. This not only makes the process labor-intensive and time-consuming but can also result in the loss of important signal features, especially in the frequency domain. To address these limitations, we introduce a novel data-driven denoising framework based on latent space modeling techniques. By learning a compact representation of the underlying noise-free or 'undistorted' signal, the model effectively separates noise from meaningful content while preserving critical features across both time and frequency domains. The architecture leverages contemporary deep learning techniques-such as encoder-decoder structures and generative models-to learn mappings from noisy inputs to clean outputs using paired training data. Preliminary results demonstrate that the proposed approach outperforms traditional denoising techniques, effectively reducing noise while preserving signal integrity in both time and frequency domains. Moreover, the method offers a significant advantage over classical techniques by automatically adapting to the specific characteristics of the measured signal and requires minimal manual tuning. This scalable, automated approach offers a robust solution for processing noisy rheometric datasets, facilitating more precise determination of complex material behavior.

Thursday 9:45 Sweeney Ballroom C ML19

High-throughput viscometry via machine-learning using videos of inverted vials: The effects of process parameters on the inference accuracy

Ignacio Arretche[1], Mohammad Tanver Hossain[2], Ramdas Tiwari[2], Mya G. Mills[3], Abbie J. Kim[3], Connor D. Armstrong[1], Jacob J. Lessard[4], Sameh H. Tawfick[2], and Randy H. Ewoldt[2]

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Here, we explore the complex uncontrolled flow of the inverted vial-driven by gravity, surface tension, inertia, and initial conditions-to achieve scalable, simultaneous viscosity inference. To do this, we introduce the computer vision (CV) viscometer, a system that automates the test by inverting multiple vials at once and recording their flow with a simple camera. Given the flow's complexity, and the lack of approximate solutions, we approximate its inverse function for inference with a neural network. Rather than relying on velocity fields, we train the network to learn the inverse function directly from raw video footage, using the visual appearance of the flow as input. Surprisingly, from raw videos alone, we quantitatively infer the viscosity of Newtonian fluids across nearly five orders of magnitude (0.01-1000 Pa·s), achieving relative errors below 25%-improving to 15% above 0.1 Pa·s. By varying inversion speed and observation time, we delineate how inertial and capillary effects define the method's accuracy limits. We show how high Deborah numbers and dimensionless stress amplitudes can also increase inference variability, outlining the method's practical boundaries when it comes to non-Newtonian behavior. Instead of depending on carefully controlled flows like traditional methods, we show that complex, uncontrolled flows can be used to infer viscosity. The CV viscometer represents this new approach, providing a simple, low-cost way to collect viscosity data at scale. It can easily fit into both automated and manual lab workflows, helping speed up material research and support robotic laboratories.

Poster Session

Symposium PO
Poster Session

Organizers: Reza Foudazi, Joe Peterson and Travis Thornell

Wednesday 6:30 Sweeney Ballroom E+F PO1

Polymer gels for superior infrastructure materials: Internally cured cement and clay-based additive manufacturing

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Global development needs and sustainability concerns have pushed for an increase in polymer science within the world of infrastructure materials. Specifically, research and development on polymeric admixtures has been pivotal in improving the utility and durability of concrete and other building materials in recent years. Here, we present two research areas where polymer gels are leveraged as beneficial additives for construction materials through chemical and structural methods. 1) Covalently crosslinked polymer hydrogels have been investigated for two decades for their ability to release water and internally cure concrete. In this work, alkoxysilane-functionalized hydrogels were synthesized and investigated for their ability to participate in the nucleation and growth of cement-strengthening hydrates. Silane containing hydrogels dissolved in alkaline cementitious mixtures, diffused into cement paste, and nucleated various morphologies of cement hydrates. Uniquely, Cryogenic Scanning Electron Microscopy (CryoSEM) was utilized study the interface between fresh cement paste and hydrogels of varying chemistry. Silane-functionalized gels showed the ability to promote nucleation dominated hydrate formation as opposed to the growth dominated mechanism seen in conventional gels. 2) Synergistic gelation of two polysaccharides was leveraged to improve the buildability of 3D printable earthen construction materials. Synergistic gelation of locust bean gum (LBG) and xanthan gum (XG) blends in solution was investigated through rheological methods. Subsequently, gelation of the biopolymer solutions were utilized to improve the structuration of a kaolinite clay suspension. Synergistic gels improved the yield stress and storage modulus of the clay suspension without significantly increasing viscosity displaying promising attributes for a 3D printable material. Moreover, gels with the highest storage modulus also produced clay suspensions with the best 3D printing properties.

Wednesday 6:30 Sweeney Ballroom E+F PO2

Rheology and printability of earth-based materials for sustainable construction

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With the growing emphasis on sustainable construction, Earth-based materials such as clay and sawdust-often considered waste-are gaining renewed relevance. Additive manufacturing enables their use in printable slurries for environmentally friendly building components. The rheological properties of these slurries directly influence print behavior, including extrudability and shape fidelity.

This study investigates the relationship between rheological characteristics and 3D print performance of clay-based composites with varying solid contents and additives. Using rotational and oscillatory rheological techniques, we evaluate how various formulations influence flow behavior, material structure, and thixotropic recovery. The rheological results are correlated with outcomes such as print height and post-print stability.

Notably, the formulation containing 0.5 wt. % xanthan gum (with respect to the mass of clay) as the sole additive and the lowest water content exhibits higher stiffness-as indicated by its storage and loss moduli. When printed, this formulation achieves the greatest print height before collapse amongst the formulations studied in this work.

In contrast, the formulation containing 1.2 wt. % xanthan gum, 2 wt. % glycerol, and 0.5 % cellulose nanocrystal solution exhibits lower stiffness, and the lowest print height before collapsing.

The findings of this study provide guidance for formulation and processing to enhance performance during and after 3D printing.

Wednesday 6:30 Sweeney Ballroom E+F PO3

3D printing epoxy thermosets: Additive manufacturing of polymerization-induced phase separating materials

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Epoxies are widely used across various technical industries due to their exceptional physical and chemical stability, as well as their tunable thermomechanical properties. We have developed heterogenous epoxies that feature hard and soft domains with phase-separated length scales which are systemically tuned from the macroscale to nanoscale. We employ polymerization-induced phase separation (PIPS) to adjust the phase composition and scale, enabling the selection of specific thermomechanical properties and morphologies. 3D printing of these materials would

allow for the creation of hierarchical structures, with tailored properties for specific applications. However, there are significant challenges in printing step-growth epoxies due to their slow reaction kinetics. In this work, we focus on the development of printable phase-separated epoxies. Direct ink write printing (DIW) was used to print formulations primarily consisting of epoxy resin and amine curing agents, with a secondary UV curable acrylate component and rheological modifiers. Rheological measurements of these formulations were used to tailor inks for printability, both through in-situ UV cure measurements and thixotropic testing. The dual-cure formulation allows for printed structures to be partially cured via UV exposure during the print, providing green strength, follow by a final thermal polymerization step resulting in phase separation of the epoxy system. This method enables the control of mesoscale structure through phase separation and macroscale structure through printing. Dynamic mechanical analysis of printed materials reveals distinct phase separation of these materials along with the high tunability of glass transition profiles and other properties. This approach not only enhances the performance of epoxy materials but also paves the way for advanced applications in additive manufacturing, ultimately contributing to the development of more efficient and versatile materials in various industries.

Wednesday 6:30 Sweeney Ballroom E+F PO4

Rheological characterization of cement pastes with alternative cementitious materials during early hydration

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Understanding the rheological behavior of cement paste containing alternative cementitious materials (ACMs) is important for developing sustainable concrete, particularly in the context of extrusion-based additive manufacturing. ACMs such as fly ash (FA) partially replace cement in paste mixtures, improving workability and reducing water demand and CO2 emissions associated with cement production. However, the evolution of rheological properties, especially in the linear viscoelastic region, during early-stage cement hydration is not yet very well understood. In this study, we first demonstrate the development of disposable vane in cup geometries that allow us to follow cement hydration over arbitrarily long hydration times. With these geometries, we study the solidification behavior of cement pastes composed of both pure Ordinary Portland Cement (OPC) and OPC-FA mixtures. With a fixed water-to-cementitious material ratio of 40%, we replace up to 30% of the cementitious material with FA. We measure particle sizes for OPC and FA using laser diffraction and scanning electron microscopy to assess morphology and distribution before rheological characterization. OPC features a broad particle size range and angular morphology, while FA shows spherical particles and a narrower size distribution. Using Optimally Windowed Chirp (OWCh) waveforms we follow the evolution of the viscoelastic spectrum during solidification, revealing a process very different from classical gelation. Our findings provide insights on the connection between particle-scale properties and macroscopic rheology, presenting a new perspective on solidification of dense suspensions and paving the way for sustainable concrete design.

Wednesday 6:30 Sweeney Ballroom E+F PO5

Bubble-fiber interactions in multiphase flow: A pathway to sustainable paper manufacturing

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In a 2014 report, the DOE recognized the paper industry as the third largest consumer of energy in the United States, accounting for 13% of the manufacturing energy consumed nationally. Because water is the predominate carrier fluid for paper manufacturing, evaporative drying at the end of the process can account for 2/3 of paper making energy consumption. Accordingly, fiber foams, where the carrier fluid is a bubbly foam, present a path for a predicted 10%-40% energy savings, without sacrificing product quality. To inform industrial processes, a pressure driven pipe flow apparatus is designed and used to simulate the paper making process. A representative fiber foam made of aqueous sodium dodecyl sulfate is examined as a function of gas volume fractions (20% to 80%) and fiber content (0% to 2%). Constitutive models for fiber-laden foam will subsequently inform computational models for designing nozzles and processes that will demonstrate the utility of this carrier fluid for the paper making industry.

Wednesday 6:30 Sweeney Ballroom E+F PO6

Time-resolved mechanical properties of ordinary Portland cement during early-stage hydration

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Cementitious materials are widely used in construction applications. While the long-term mechanical properties of these materials are well understood, placement and finishing procedures require additional information about the short-time, pre-hardened properties of the cementitious pastes in order to properly tune the processing and formulation of the binder and/or composite. When cement powder is mixed with water, it forms a deformable paste which shows elastoviscoplastic properties, but as the paste hydrates it undergoes a reaction which produces Calcium Silicate Hydrate (C-S-H) gel, the main structural component of the cement which provides its long-term properties. In the early stages of the hydration reaction, the material is still highly deformable allowing the material to be flowed and shaped. Understanding the development of these mechanical properties in time is critical to the improvement of processes using the cement while it is in this regime. In this study, we utilize multiple time-resolved methods to characterize the time-dependent viscoelastic properties of simple Ordinary Portland Cement (OPC) pastes during the early stages of the hydration reaction. Specifically, we characterize the kinetics of the reaction via isothermal calorimetry, the evolution of the viscoelastic moduli via strain-controlled small-amplitude oscillatory shear (SAOS) rheology, and the formation of structure via ultrasonic pulse velocimetry (UPV). Through continuous data collection over the course of several hours, we are able to identify the transitions between the first three phases of the cement hydration reaction (initial mixing, dormant, and acceleration), and provide a clearer picture of the progression of

mechanical changes in these pastes during each of these stages. We also look at the impact that adjusting the water/cement ratio has on these timescales and properties.

Wednesday 6:30 Sweeney Ballroom E+F PO7

Interfacial rheology of lanthanide binding peptide surfactants

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The rare earth elements (REEs), which include the lanthanides (Lns), yttrium, and scandium, are crucial for many modern technologies. These elements, particularly the Lns, are notoriously difficult to separate since the ionic radii of Ln cations decrease only slightly with increasing atomic number and the REEs are predominantly in the 3+ oxidation state. We are developing a bio-inspired, foam-based REE separation method that employs peptide surfactants (PEPS), which specifically bind REEs in solution and transport them to the air-water interface. In the separation scheme, bubbles sparged through the solution will capture the REE:PEPS complexes, which will be collected in foams. As PEPS, we exploit lanthanide binding tags which selectively coordinate the Ln in a multidentate binding loop. The selectivity relies on the structure of the binding loop, so binding loop integrity is paramount in the selective separation process. To probe the PEPS structure in the highly anisotropic interface, we characterize the interfacial rheology of PEPS-laden interfaces with particle tracking microrheology. We find that PEPS with excess negative charge and exposed chelating residues are elastic in the presence of excess cations, indicating crosslinking of PEPS at the interface. Such crosslinking is detrimental to the selectivity of the process. We hypothesize that as Ln is added to the solution, gelation occurs gradually among clusters of PEPS until enough Ln is present to form a PEPS gel that spans the entire interface. At even higher concentrations of Ln, we hypothesize that the interface becomes jammed with many small clusters of PEPS gel. These results are corroborated by surface tensiometry and simulation. Lastly, we show that the non-specific crosslinking can be resolved by mutating PEPS so that no ligating residues are present outside the binding loop. This result, among others, indicates that the PEPS binding loop remains intact at the highly anisotropic air-water interface, which bodes well for our envisioned process.

Wednesday 6:30 Sweeney Ballroom E+F PO8

Heterogeneity in red blood cell mechanics drives altered blood rheology in sickle cell disease

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In sickle cell disease (SCD), polymerization of hemoglobin under deoxygenated conditions causes red blood cells (RBCs) to stiffen, resulting in aberrant blood flow. At the continuum level, deoxygenated blood in SCD exhibits increased shear-thinning and wall friction, but it is not understood how the distribution of RBC properties contributes to whole-blood rheology. Therefore, we developed a novel microfluidic platform to probe the effect of oxygen-dependent RBC stiffness and volume fraction on the rheological properties of blood from patients with SCD. Using high-throughput single-cell measurements, we established that oxygen-dependent changes in red blood cell mechanics are highly heterogeneous. In parallel, we measured the effective rheology of the blood from spatially resolved flow fields and found that increases in effective resistances in heterogeneous suspensions were driven by increases in the proportion of stiff cells, similar macroscopically to the behavior of rigid-particle suspensions. To explore mechanisms leading to the emergent rheology, we developed a computational model to simulate confined flow of heterogeneous mixtures of cells. This allowed us to probe the dynamics of the cells and measure the impact on rheology, which we confirmed experimentally. In the presence of deformable cells, the stiffened cells marginate towards channel walls, increasing effective wall friction. In fully deoxygenated conditions in which all cells are stiffened, significant heterogeneity in cell volume fraction along the direction of flow caused localized jamming, drastically increasing effective viscous flow resistance. Overall, our study directly links single cell properties to blood dynamics in microchannels across individual donors and establishes mechanisms for the apparent rheology of heterogeneous mixtures.

Wednesday 6:30 Sweeney Ballroom E+F PO9

Deposits from drying blood droplets - an alternative technique to differentiate healthy and unhealthy blood cells

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Drying drops is a fascinating subdomain in the science of drying. Blood is one of the most important and complex biological components of a living organism. Among the tests that differentiate healthy blood cells from unhealthy ones is the test known as erythrocyte sedimentation rate, also known as ESR. Though an ESR test is a reliable one, a better alternative is being demanded to meet the ever-growing need for developing more affordable scientific testing kits. Keeping the socio-economic reasons in mind, we have started to explore the drying of blood droplets. The resulting deposition patterns showed a clear distinction between healthy and unhealthy blood droplets. We have identified the difference in the deposit patterns via various visual and height profile measurements. The difference is somewhat expected, as an unhealthy blood droplet contains active matters (we have introduced microorganisms into the healthy blood droplets), which should leave a different deposition pattern. This feature of drying blood droplets can be exploited to develop an alternative technique to identify unhealthy blood cells, as the required amount in this method is in microliters compared to its counterpart, ESR, where at least a milliliter of blood is needed. Thus, the outcome of our studies can be exploited to develop an alternative that is more affordable than the existing ESR technique.

Wednesday 6:30 Sweeney Ballroom E+F PO10

Natural additive based biopolymer film for medical applications

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Wounds are vulnerable to several germs while they are healing. For some time, several antimicrobial agents, including carbon-based and nano-sized heavy metal particles, have been used to inhibit the activity of these bacteria. These non-bio-based materials can occasionally harm a person's health. On the other hand, due to their bio-based origins, PVA and almond oil are compatible with each other up to a defined percentage. When used as a film, Almond oil resists microorganisms, while PVA maintains moisture due to its hydrophilic nature and provides strength. This project shows the fabrication of PVA films with traces of Sweet and Bitter Almond oil using the solution casting technique. The film was analyzed through various characterization techniques. The rheological behavior showed the interaction between PVA and Almond oil, while FTIR confirmed the presence of functional groups. Optical microscopy revealed the film's morphology, while the Agar test confirmed its antimicrobial activity against Staphylococcus Aureus, and Antioxidant activity was confirmed using the DPPH assay. The optimized sample, which exhibits excellent antibacterial and antioxidant properties, was P12A2 (PVA-12 wt%/SAO-2 wt%). This study demonstrated the differences between SAO and BAO in terms of their antibacterial, antioxidant and rheological properties. Moreover, it has been proven that SAO has potential for use in wound healing applications. Keywords: PVA, Sweet almond oil, Bitter almond oil, Films, Solution casting.

Wednesday 6:30 Sweeney Ballroom E+F PO11

More slippery than most: Rheological insights into fish skin mucus hydrodynamics

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Have you ever wondered why certain fish are more slippery than others? The answer is not solely the skin and scales but is also influenced by a thin mucus coating. This mucus, a weak biological hydrogel predominantly composed of the glycoprotein mucin and large amounts of water, is believed to act as both a hydrodynamic drag reduction agent and a barrier against pathogens. Understanding the rheological behavior of the hydrogel is critical to understanding fish evolution and informing the development of biomimetic, nonsloughing, nonfouling lubricants. In this study, the rheological properties of mucus coats from Actinopterygii (ray-finned fish) species spanning a wide evolutionary distance were characterized. Viscosity and viscoelasticity were measured under biologically relevant shear rates using steady shear and oscillatory rheometry. The mucus exhibited shear-thinning, power-law behavior with a gel state at low shear strains, consistent with current literature. However, we observed substantial differences between freshly collected mucus and frozen-thawed samples-a common practice in prior studies. The freeze-thaw process reduced the viscosity, dynamic moduli, and degree of shear thinning, likely due to phase separation of mucin from water. Fresh mucus displayed the greatest interspecies variation, with viscosity and viscoelastic moduli differing by orders of magnitude between species. These findings highlight the importance of sample handling and provide new insights into how fish species have adapted. This enhanced knowledge of fish skin mucus and its rheological properties can offer a deeper understanding into fish health, fishery management, biomimetic lubricants, evolution, and climate change.

Wednesday 6:30 Sweeney Ballroom E+F PO12

Controlling slip-flow onset of hydrated soy protein melts as a basis for selecting cooling die temperature profiles in high-moisture extrusion

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High-moisture meat analogs (HMMA) develop their characteristic fibrous structure during cooling in the extrusion die, yet the industry lacks practical guidelines for designing die temperature profiles. This work proposes a novel rheological approach adapted from the study of polymer melt fracture to identify critical cooling temperatures where hydrated soy protein melts transition from non-slip to slip flow behavior, the latter serving as a limit to further shear-induced structuring in the melt. Using a pressurized parallel plate rheometer under constant shear rate, distinct shear stress plateaus were observed during controlled cooling (2.5 °C/min) between 145 and 100 °C, with moisture content influencing plateau onset. Guided by the rheological results, extrusion trials with the heat-transfer media in the initial section of a segmented cooling die were set to 145, 130, 115, and 100 °C, followed by rapid cooling in the remaining sections . Products extruded at the intermediate (115-130 °C) initial die temperatures tested exhibited visually enhanced fibrous alignment and significantly higher anisotropy indices ($p < 0.05$) at 60% moisture, without altering mechanical hardness, consistent with chemical crosslinking being governed by fixed barrel melt temperature (144-146 °C). This study demonstrates that controlling the initial cooling die section temperature may prolong melt residence within a "texturization zone", which can measurably improve HMMA structure, providing a foundation for engineering-based optimization of plant-based meat extrusion processes.

Wednesday 6:30 Sweeney Ballroom E+F PO13

Training rheological properties of biological tissues under mechanical cues

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Cells in multicellular organisms maintain homeostasis in dynamic environments by sensing mechanical cues and adapting their internal processes. Such adaptive responses-modifying behavior to optimize function-parallel emerging concepts of physical learning. We present a minimal model

for mechanical learning in epithelial tissues using a vertex model extended to include dynamic tension remodeling, mimicking active cellular contractility. In our model, tensions evolve in response to local strains exceeding a threshold, capturing key learning features such as habituation under repeated pulsatile activation, non-local memory and cooperative learning. After the system remodels under mechanical signals, we quantify changes in shear modulus, bulk modulus, and Poisson's ratio. We find that tissues can soften, stiffen or behave as auxetic materials based on the model parameters. Our results reveal how simple local rules can encode adaptive mechanical responses in tissues, offering a mechanistic link between cellular contractility dynamics and emergent rheological properties.

Wednesday 6:30 Sweeney Ballroom E+F PO14

Viscosity modified resin for morphogenic growth 3D printing

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Growth printing (GP) is a morphogenesis-inspired 3D printing paradigm based on exothermic frontal ring-opening metathesis polymerization (FROMP) of dicyclopentadiene (DCPD). Once triggered locally, the reaction front self-propagates without external energy, curing liquid monomers into poly-DCPD. Unlike voxel-based methods such as FDM or SLA, GP grows continuously from an initiation nucleus, producing large, complex geometries. Here, we demonstrate that tailoring fluid properties expands the accessible design space: adding 15 wt% polybutadiene (PBD) to DCPD increases resin viscosity, enabling stable growth fronts and the formation of intricate 3D structures. Thus, viscosity-modified resins extend the versatility of growth-based manufacturing beyond neat DCPD.

Wednesday 6:30 Sweeney Ballroom E+F PO15

Rheological characterization of fungal mycelium gels for use in soft electronics

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Historically, electronic systems have been developed from rigid materials, limiting their use in certain applications, like healthcare and wearables which require soft materials that can more comfortably interact with biological organisms. Fungal mycelium shows promise as a soft electronic material, forming a soft gel-like mat of filamentous cells. However, to our knowledge, the mechanics of these materials remain to be studied. In this work, a method is developed to accurately test the mechanical properties of mycelium mats of the species Pleurotus ostreatus, accounting for poroelastic, viscoelastic, and sample-loading effects. A combined compression, torsion experiment is used to determine the optimal loading force at which full contact with samples is achieved but compression is minimized. As a result, dynamic moduli and the extent of the linear-viscoelastic regime are measured accurately, minimizing the effect of strain-stiffening. With a method to reliably characterize the mechanical properties of mycelium mats, the development of structure, processing, and property relationships will be possible, allowing for the further advancement of these novel soft materials.

Wednesday 6:30 Sweeney Ballroom E+F PO16

Investigating injectability of high concentration mAb formulations with microfluidic viscometry

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This poster explores the critical role of viscosity in developing high-concentration monoclonal antibody (mAb) formulations (= 100 mg/mL) for subcutaneous injection. To improve patient experience and compliance, these biotherapeutics must be suitable for injectability, which must further be explored by measuring their non-Newtonian behavior at representative shear rates during injection. We demonstrate the use of VROC (Viscometer-Rheometer-on-a-Chip) technology for the accurate screening of formulation candidates using small sample volumes (< 200 µL). By generating comprehensive viscosity profiles over a wide shear rate range, this method allows for the effective identification and selection of viable candidates with optimal viscosity for subcutaneous delivery, ensuring proper therapeutic development.

Wednesday 6:30 Sweeney Ballroom E+F PO17

Flow dynamics of active living entangled systems

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We investigate how active, entangled networks of California blackworms (Lumbriculus variegatus) behave as flowing, living materials. These long, slender organisms spontaneously form dynamic entanglements, giving rise to bulk viscoelastic properties that are sensitive to individual motility. Inspired by the pitch drop experiment (1984), we examine the gravity-driven flow of worm masses through cylindrical channels and characterize the pinch-off dynamics at the outlet. By quantifying motility through activity, a (measured from the mean square displacement of individual worms), and relaxation time, t (calculated from end-to-end distance fluctuations), we connect individual locomotion to macroscopic rheology. Motility is tuned by immersing worms in alcohol to reduce a and by applying an electric potential across the bulk during flow to decrease t. These changes significantly alter the bulk viscosity, revealing a direct coupling between individual motility and emergent fluidity in living entangled matter. Our findings offer a framework for engineering and controlling the collective behavior of active biological systems.

Wednesday 6:30 Sweeney Ballroom E+F PO18

From sedimentation to suspension: Critical strain as a predictor of particle resuspension thresholds

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Resuspension of solid particles in fluids is a fundamental transport process with implications for sediment and contaminant mobilization in rivers, erosion control, biogeochemical cycling, mixing in chemical and food processing. While turbulent resuspension is well studied, far less is known about dense particle beds under oscillatory, time-dependent shear flows, where particle interactions are highly dynamic and nonlinear. Here, we investigate the resuspension of non-Brownian spherical particles in a Newtonian fluid under both steady and oscillatory shear across particle volume fractions ? = 0.30-0.55. Rheology and in situ rheo-microscopy reveal that strain, rather than shear rate, is the primary parameter governing the onset and completion of resuspension. This strain-driven transition from a quiescent sediment bed to a fully suspended state arises from enhanced particle-particle collisions and collective motion. A particle-collision-based theoretical model quantitatively predicts critical resuspension strains as a function of volume fraction, enabling the construction of universal state diagrams for both steady and oscillatory flows. These findings establish a predictive framework for controlling suspension dynamics in environmental, industrial, and biomedical systems.

Wednesday 6:30 Sweeney Ballroom E+F PO19

Motion correlation for rigid particles in dense suspensions

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Dense suspensions under shear can jam at a critical solid volume fraction. We study systems where lubrication, repulsion, and contact forces are present. Under shear, particles form rigid clusters, which are groups of particles with highly correlated motion that continually undergo growth and destruction. Shear jamming occurs when the combined effects of repulsion, and contact forces are balanced by the applied shear stress. We observe that there is a finite probability of jamming when a rigid cluster spans the entire system, causing complete flow arrest. Particles within these clusters show strong correlations in the angular velocities of their nearest neighbors, whereas particles outside the clusters exhibit weak or even negative correlations at lower packing fractions. We simulate dense suspension flows using the well-established LF-DEM model.

Wednesday 6:30 Sweeney Ballroom E+F PO20

A finite-element formulation of the suspension balance model applied to complex geometry flows

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We present a finite element framework for simulating the flow of dense, non-Brownian suspensions in geometries containing sharp corners. The formulation employs a two-phase description that incorporates particle stress contributions, including anisotropic normal stresses, within the Stokes flow regime. The coupled velocity--pressure--particle volume fraction fields are advanced using a fully variational approach, enabling stable resolution of steep concentration gradients that develop near constrictions. The framework is applied to contraction and expansion flows over a range of inlet particle concentrations, corner angles, and normal-stress anisotropy tensors. The simulations reveal that particle migration patterns are strongly modulated by normal stresses: higher anisotropy ratios promote wall depletion and core focusing, while suppression of normal stresses leads to more diffuse particle distributions. Variation of contraction angle alters the balance between advective focusing and shear-induced diffusion, with sharper angles producing stronger axial gradients and localized concentration peaks. These results highlight the central role of normal stresses in determining steady-state particle distributions in dense suspensions, and demonstrate the capability of the present formulation for exploring suspension rheology in complex geometries.

Wednesday 6:30 Sweeney Ballroom E+F PO21

Microcapsule suspension rheology for geothermal short-circuiting prevention

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Polymer-based injectates delivered by microcapsules have been proposed to mitigate thermal short-circuiting in geothermal reservoirs by reducing fracture permeability [1]. Although the chemical mechanisms for microcapsule rupture and interaction with surrounding resin have been developed, the rheological properties of the suspension have not been examined, which are key to understanding the transport of the microcapsules through the borehole to target fracture networks. In this work, we study the relevant rheological properties for effective transport (viscosity and yield stress) of a dilute diutan biopolymer solution with various microsphere concentrations at multiple temperatures. Hysteresis flow sweeps were performed over microsphere concentrations from 10-50 wt% and temperatures from 25-70 degrees C, providing a rich dataset from which the suspension's rheological properties were extracted. Experimental results indicate that diutan is an associating polymer which thickens below a critical shear rate of 0.01 s^{-1} and whose critical stress increases with temperature. The addition of microcapsule concentrations above 20 wt% is shown to erase the low shear rate Newtonian plateau of the carrier fluid, and with increasing concentration, the suspension approaches true yield stress behavior. Using typical volumetric flowrates for geothermal wells in production, the wall stresses common for borehole and fracture flow were estimated and compared with the critical stresses of the material. While the viscosity of the carrier fluid is highly tunable, these results

highlight the importance of also considering the yield stress of the bulk material, especially at extreme particle concentrations which may occur at unknown locations in the downhole flow path.

[1] Tetteh, P. et al., "Microcapsule transport in transparent rough fractures for EGS fracture modification," Proceedings, 48th Workshop on Geothermal Reservoir Engineering, Stanford.

Wednesday 6:30 Sweeney Ballroom E+F PO22

Viscous heating limit lines for experimental prediction and qualification

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Viscous heating is a nonlinear phenomenon caused by fluid friction, resulting in the apparent shear rate dependence of viscosity of even Newtonian fluids in steady shear. Although the Nahme-Griffith number [1] has been used to neglect viscous heating [2], or with certain assumptions, has itself been plotted as a limit line [3], the bulk dimensionless number does not account for spatial variations in temperature and viscosity and therefore cannot be directly used to predict viscous heating effects in experiments. In this work, we derive a viscous heating limit line to be co-plotted with viscosity vs shear rate data which accurately predicts a prescribed deviation in viscosity during a flow sweep, with only prior knowledge of geometry and fluid properties. Through an approximate analytical solution to the coupled heat and momentum equations - as began by Rudolf Nahme in the 1940s [4] - we determine an expression for the apparent viscosity measured by parallel plate non-isothermal Couette flow of a Newtonian fluid. Experimental results show good agreement between model-predicted viscosity and that which is measured by a parallel plate rotational rheometer, especially concerning the sooner onset of viscous heating with a larger gap. The proposed limit line may be used to predict viscous heating in experiments and qualify existing data, as well as give insight into viscous heating effects in industrial flows.

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Wednesday 6:30 Sweeney Ballroom E+F PO23

On the dynamics of yield stress fluids

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Polydispersity in particle size is a defining feature of many suspensions and has a significant role in governing the microscopic dynamics and macroscopic rheology of yield stress fluids. These materials, composed of soft deformable particles, behave as weak elastic solids at rest and exhibit shear-thinning flow at high stresses when the particle volume fraction exceeds the jamming transition threshold. Here, we investigate the influence of particle size distribution on the rheology and dynamics of amorphous soft particle glasses using particle dynamics simulations. Suspensions at a fixed volume fraction of $(φ = 0.80)$, which is beyond the jamming fraction, and varying polydispersity $(0.2 \leq δ \leq 0.8)$ are subjected to shear flow at a broad range of rates. At high shear rates, the nonlinear rheological responses approximately converge across all size distributions due to the strength of the flow, whereas at the quasi-static regime of flow, a broader size distribution in particle size reduces the dynamic yield stress and promotes fluidization. Our results indicate that increasing δ enhances non-affine motion and shear-induced diffusion coefficient. Suspensions with a narrow size distribution show distinct size-dependent mobility with small particles diffusing faster than larger ones. On the other hand, a high degree of polydispersity in the size distribution of particle radii disrupts local cages, homogenizes mobility, and broadens free volume distributions, thereby facilitating cooperative rearrangements.

Wednesday 6:30 Sweeney Ballroom E+F PO24

Rheological behavior and shear stability of graphene-based nanofluids using Carbopol as base fluid

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Graphene has been extensively studied in recent years; however, understanding the stability of graphene dispersions remains a key challenge in nanofluid systems. Investigating its rheological behavior in various fluid matrices is essential-particularly its effects on viscosity, shear response, and viscoelasticity, especially in non-Newtonian systems. This work proposes a systematic approach for formulating graphene nanofluids using carbopol as a non-Newtonian base fluid. Carbopol dispersions (0.15 wt%) were prepared with graphene nanoparticle concentrations from 0.25 to 2.5 wt%. The dispersions were analyzed through oscillatory stress amplitude tests and flow curves. Complementary characterizations, such as scanning electron microscopy (SEM) and Zeta Potential (ZP), were performed. SEM images revealed flake-like structures with morphologies consistent with carbon-based nanomaterials. The rheological results showed that incorporating graphene significantly reduces the viscosity of the carbopol matrix. This reduction becomes more pronounced with increasing nanoparticle concentration, suggesting a disruption of the carbopol network-commonly referred to as the flake-flake effect. This phenomenon intensifies at higher concentrations, indicating a concentration-

dependent behavior. All flow curves exhibited typical Herschel-Bulkley behavior with yield stress. In oscillatory tests, increasing graphene concentrations caused a progressive decrease in the viscoelastic moduli, particularly G'. However, despite this reduction, dispersions maintained viscoelastic solid behavior, with G' consistently greater than G". Frequency sweeps confirmed this trend. ZP measurements indicated high dispersion stability, with values near -2000 mV, and high electrical conductivity. These results confirm the excellent shear stability of graphene-based nanofluids, even at high nanoparticle concentrations.

Wednesday 6:30 Sweeney Ballroom E+F PO25

Powder rheology of alternative grain free flour substitutes

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Biodiversification is increasingly relevant in agricultural practices, due to shifts in consumer practices and pressure to offer sustainable options. Flours like almond, coconut, cassava, and chickpea are made from readily available sources and can reduce reliance on traditional grains, thus increasing biodiversity and offering consumers alternatives. A key aspect of implementing these granular materials at scale is the rigorous characterization of how the powders tendency to resist flow changes under consolidation, and how more specifically the flow function changes as a function of upper consolidation stress and temperature. Furthermore, the relationship between the powder shear characteristics and the compressibility is explored, elucidating how the storage and handling characteristics of the materials change with increased industrial scale. Here, Powder rheology plays a vital role in mechanically characterizing these alternative flours, providing insights into their flow behavior and the relationships between these properties.

Wednesday 6:30 Sweeney Ballroom E+F PO26

Designing mercury-free photoelastic polyurethane particles

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Photoelastic polymer particles have been widely used to study the internal stress distributions in phenomena involving granular materials such as landslides, avalanches, hopper flow. Polyurethane remains a popular choice of material for fabricating photoelastic particles owing to its cost, tunability, optical and mechanical properties, and ease in particle molding. However, the state-of-the-art grade of polyurethane used to mold photoelastic particles contains a not-insignificant amount of toxic organomercury. This poses a risk to both users and the environment. In our work, we fabricated photoelastic particles from numerous commercially available polyurethane resins that are purportedly mercury-free. We tested the rheological and stress-optical properties of each and found an optimal candidate as a viable replacement for the state-of-the-art material. To explore whether this new polyurethane resin can be tuned to improve its requisite stress-optical properties beyond what is currently possible, we studied its photoelastic dependence on its polymer microstructure and morphology using shear rheology, dynamic mechanical analysis (DMA) and differential scanning calorimetry (DSC). We altered the microstructure by creating blends of polyurethane and ethylene glycol fillers, which altered the crystalline domains of their networks. We then studied the consequent change in the photoelastic properties of these blends. These mercury-free polyurethane particles serve as a a viable replacement for the state-of-the-art materials, owing to being free of organomercury, and having similar rheological and stress-optical characteristics as the latter.

Wednesday 6:30 Sweeney Ballroom E+F PO27

Comparative rheological characterization of nanofluids containing fumed silica: Insights from mineral oil and Carbopol-based systems

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This study presents a comparative rheological characterization of nanofluids containing pyrogenic silica nanoparticles dispersed in two distinct media: mineral oil and Carbopol-based hydrogels. In the oil-based system, silica concentration governs key transitions, including the emergence of viscoelasticity, yield stress, and a shift from thixotropic to antithixotropic behavior. At concentrations =?1.0 wt% SiO2, time-dependent tests revealed rheopexy, while shear thickening appeared only at high concentrations and shear rates (>?2.0 wt%, >?500?s?¹). These effects are attributed to shear-induced structuring, supported by FTIR analysis showing hydrogen bonding and partial siloxane bridging between particles. In contrast, the Carbopol-based nanofluid exhibited a reverse response. Increasing silica content caused a systematic reduction in elasticity and yield-like behavior. Steady shear data showed that up to 1.0 wt% SiO2, the Power Law model offered better fits (R²?>?0.99), suggesting fluid-like viscoelasticity without a true yield stress. Oscillatory strain sweeps at 1?Hz showed decreasing G' and the dominance of G? at low strain, corroborated by frequency sweep tests where G? > G' at low frequencies. These findings indicate a soft viscoelastic fluid behavior rather than a solid-like gel. No signs of thixotropy or antithixotropy were detected, and weak shear thickening was observed only for =?2.0 wt% SiO2. SEM revealed disruption of the gel network by silica, suggesting competition for water and interference with hydrogen bonding. These contrasting behaviors underscore the key role of the dispersing medium in modulating fluid-particle interactions. While oil promotes shear-induced structuring and nonlinear responses, Carbopol suppresses such effects, yielding a more viscous and less structured system.

Wednesday 6:30 Sweeney Ballroom E+F PO28

Study of silica-based nanofluids for flow control in enhanced geothermal systems: A rheological perspective

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As geothermal energy gains prominence in the global energy mix due to its low carbon emissions, high power output, and widespread availability, enhanced geothermal systems (EGSs) present significant potential for large-scale electricity generation. However, the efficiency and development of EGSs remain constrained by thermal short-circuiting, a phenomenon in which the working fluid preferentially flows through highly conductive fractures, bypassing lower-conductivity fractures that could yield higher-temperature output. This imbalance reduces both the thermal recovery and the economic performance of EGS reservoirs, making flow control a critical factor in optimizing energy production. This study investigates the use of silica-based nanofluids for flow control in EGS reservoirs by examining their rheological properties and gelation kinetics. The rheological behavior and gelation kinetics were systematically evaluated for nanofluids formulated using silica content ranging from 2 to 6 wt%. Aqueous solution of polyethylene glycol (PEG) with a molecular weight of 6,000 g/mol was used as the base fluid. Results show that both rheology and gelation behavior are strongly influenced by silica content, temperature, and confining pressure. These findings demonstrate the potential of silica-based nanofluids as stimuli-responsive flow control agents to mitigate thermal short-circuiting and enhance heat sweep efficiency in EGS applications.

Wednesday 6:30 Sweeney Ballroom E+F PO29

The degeneracy of particles with purely area-dependent potential energy

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It has long been known that a dilute suspension of linear polymers can be modelled reasonably successfully using a dumbbell consisting of two spheres connected by a spring. If the spring is linear, the resulting fluid follows the Oldroyd-B constitutive relation. However, Oldroyd introduced two models, and until recently, there was no microscopic derivation of the other, Oldroyd-A, which has been thought more appropriate for flat particles rather than linear ones. The recent microscopic derivation for flat elastic particles led to exactly the lower-convected derivative associated with Oldroyd-A. We use molecular dynamics simulation to implement this model and observe a fundamental degeneracy where the particle collapses to a line. We then use phase plane analysis to prove that the degeneracy is inherent in the formulation of the forces. This degeneracy is expected to apply to any physical model that reproduces Oldroyd-A, thereby explaining why Oldroyd-A rheology is not commonly observed in real physical systems.

Wednesday 6:30 Sweeney Ballroom E+F PO30

Thermodynamically consistent rate-type constitutive relations for modelling shear banding in complex fluids

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Shear banding is observed in a wide range of complex fluids, including colloidal suspensions, wormlike micellar solutions, polymeric fluids, foams, and emulsions. These materials often exhibit a non-monotonic steady-state relationship between shear stress and shear rate in viscometric flows. In fluids where this non-monotonic response is observed with respect to shear rate, shear bands typically develop in the flow-gradient direction, and such fluids tend to exhibit "spurt" phenomena in pressure-driven flows. Conversely, in fluids where the non-monotonicity is observed with respect to shear stress, banding tends to occur in the vorticity direction. To model these phenomena, thermodynamically consistent rate-type constitutive relations have been developed by specifying two scalar potentials: a non-convex rate of dissipation potential and a convex free energy potential. From the class of admissible constitutive relations, a choice has been made by requiring that the rate of entropy production be non-negative and maximal. The resulting constitutive relations have been studied under simple flows and show good agreement with experimental observations reported in the literature.

Wednesday 6:30 Sweeney Ballroom E+F PO31

The influence of fluid elasticity on the flow-induced response of a flexibly-mounted square prism

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We numerically investigate how fluid elasticity can affect a canonical fluid-structure interaction (FSI) system. The system of choice is a flexibly mounted rigid square prism placed in viscoelastic fluid flow, with one degree-of-freedom in the cross-flow direction. The FENE-P (Finitely-Extensible Nonlinear Elastic) constitutive model is applied to solve for the polymeric stress field, while a two-way coupling scheme is implemented to accurately simulate the interaction between the fluid flow and the spring-mass system. We test square prisms with two very distinct mass ratios $m^* = 2$ & 20, under various reduced velocities U^* in [3, 45], at a Reynolds number of $Re = 200$. For viscoelastic cases, we set our fluid to have a viscous ratio $\beta = 0.9$, and the Weissenberg number is controlled to be $Wi = 2$, which then yields an elastic number of $El = 0.01$. We show that even a small amount of fluid elasticity can affect the flow-induced instabilities significantly. Through the simulations, we observe an enhancement of galloping response on the prism in viscoelastic fluid compared to Newtonian fluid, especially for the small mass ratio case, where the critical reduced velocity for galloping decreases dramatically and the oscillation amplitude increases. Our results also show a suppression in vortex

induced vibration (VIV) in viscoelastic fluid versus Newtonian fluid. We propose some potential mechanisms that lead to these phenomena based on visualizations of the flow field and analysis of flow forces.

Wednesday 6:30 Sweeney Ballroom E+F PO32

Extensional rheology and spinnability of polyvinylpyrrolidone solutions

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Centrifugal Force Spinning (CFS) provides an alternative fiber spinning method from other well-developed fiber spinning methods, and allows for quick and efficient manufacture of continuously spun fibers. In this contribution we investigate how polymer solution properties such as the presence of polymer entanglements, extensional relaxation time, and evaporation rate affect the fiber spinning process. These parameters are compiled through torsional rheometry, Dripping-onto-Substrate (DoS) protocols, and thermogravimetric analysis (TGA). Paired together with fiber spinning process parameters, these properties are used to provide an optimized processability map, predicting fiber formation and morphology. The fibers produced are analyzed through SEM imaging and the mechanical fiber mat properties are measured.

Wednesday 6:30 Sweeney Ballroom E+F PO33

Coupling of hydrodynamic slip behaviour to a simple thixotropic elasto-viscoplastic model

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The dynamics of slip and thixotropy are investigated in simple and oscillatory shear for an elasto-viscoplastic (EVP) model. The Saramito EVP model is modified to include a thixotropic structural parameter term that contributes to the yield stress and elastic material properties. For slip, a hydrodynamic lubrication condition is used to describe the development of a depleted layer at the wall (apparent slip). This depleted layer has a relatively smaller viscosity than the bulk and contributes to a reduction in shear stress across the gap. The proposed model is evaluated against experimental data from a suspension of 5 wt.% cellulose nanocrystal (CNC) with 20 mM NaCl. A suite of simple and oscillatory shear tests is conducted in a cone-plate geometry with cone angles of 1° and 4°, and parallel plate geometry with and without sandpaper. The system exhibited thixotropic behaviour as well as apparent slip, which could not be suppressed even with the application of sandpaper of grit 80 (200 mm) and 220 (68 mm) at the wall of the parallel-plate geometry. The model is fitted to steady-shear results, accounting for both slip and thixotropic behaviours. The yielding point of strain amplitude sweeps are shown to have both geometry and surface finish dependence. A trend is found where the strain amplitude at yield is shifted to lower strain amplitudes for smoother surfaces. This trend is validated by the proposed model which predicts a lower yielding point when slip is present. Thus, it is important to account for slip behaviour when analyzing strain amplitude sweeps test for identifying yielding properties.

Wednesday 6:30 Sweeney Ballroom E+F PO34

Structural characterization of flow-aligned cellulose nanocrystals using in situ scattering methods

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Cellulose nanocrystals (CNCs), rod-like, chiral nanoparticles derived from biomass via strong acid hydrolysis, have gained significant interest for the development of sustainable materials with high mechanical strength, thermal stability, and tunable optical properties. In suspension, CNCs exhibit concentration-dependent self-assembly: showing isotropic assembly in the dilute regime, followed by a biphasic regime with a mixture of liquid crystal domains and isotropic particles, then completely liquid crystalline at higher concentrations. CNC assembly is also a function of medium composition and properties, such as counterion species and concentration, pH, and the addition of dissolved polymers or polyelectrolytes. Under flow, CNCs undergo shear-induced alignment, and it has been shown that coated films of CNCs after drying retain some degree of the alignment which was induced during the coating process. In this work, we utilize newly established Rheo-SAXS capabilities through a collaboration at Argonne National Laboratory to study the alignment behavior of CNCs in aqueous suspensions containing poly(ethylene glycol) (PEG). We observe a molecular weight dependence on how the alignment is affected. For low molecular weight PEG, we found agreement in the alignment as a function of PEG concentration when normalized by the rotational Peclet number. This agreement is not observed for high molecular weight PEG. Finally, while in situ Rheo-SAXS and Rheo-SANS capabilities have enabled the study of structure-property relationships to link applied shear rates to the extent of alignment in colloidal suspensions, the final properties of coated films are governed by more complex flows. To investigate the microstructure induced by coating flows, we have developed a slot-die coater sample environment capable of continuously coating liquid films for simultaneous SANS measurements in collaboration with Oak Ridge National Laboratory.

Wednesday 6:30 Sweeney Ballroom E+F PO35

Not all recoverable strain is elastic

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The phenomenon of strain recovery is well established as relating to elastic behaviors: when a stress is abruptly removed from a deformed material, it will recoil by an amount referred to as the recoverable strain or the elastic strain. The amount of deformation that remains unrecovered a long time after stress has been removed is associated with plasticity and has also been called 'the permanent set'. In every rheological protocol, some strain can be said to have been acquired recoverably and some will be acquired unrecoverably. The rheology of yield stress fluids is important in numerous industrial, environmental, and biomedical applications owing to their ability to act as a solid or a liquid, or deform recoverably or unrecoverably, depending on the stress. The common conception of yield stress fluid rheology is that no unrecoverable strain is acquired below the yield stress. Here we study the process of recovery in brittle yield stress fluids via the KDR model with brittility [PNAS 121, 22 (2024) e2401409121]. While previous studies have assumed that all the strain recovered in a zero-stress step is elastic, we show that the process of recovery can induce plasticity that means more strain is recovered than would be expected by elasticity alone. That is, we show that yield stress fluids can transiently deform plastically even when the stress is zero. This extra amount of strain that is recovered has implications for experimental studies using recovery rheology principles. It is also qualitatively consistent with Lockwood and Fielding's recent study of the Soft Glassy Rheology model [J. Rheol. 69, 329-341 (2025)], showing that both continuum and mesoscopic models predict the same phenomenon.

Wednesday 6:30 Sweeney Ballroom E+F PO36

Kitchen pot thickens, drop by drop

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Many food formulations contain sugars and polysaccharides as thickeners that influence flow behavior, stability, processability, texture, and mouthfeel. Interfacial and rheological properties of key ingredients including polysaccharides influence production and processing of various foods, as well as the consumer perception and bioprocessing that begin withe every bite. Typically, chefs, formulators and regular cooks in kitchens judge stickiness, stringiness, spinnability, ropiness, and flowability by dripping a sauce or a mixture from a ladle, stretching a liquid bridge between finger and thumb, or by dispensing from a nozzle/bottle onto a substrate. Stream-wise velocity gradients associated with extensional flows spontaneously arise during these operations associated with dripping, dispensing or stretching liquid bridges. In spite of great advances in quantitative characterization of shear rheology response, elucidating ...

Wednesday 6:30 Sweeney Ballroom E+F PO37

Quantifying and predicting human behavior during interactions with viscoelastic materials

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Human/material interactions are ubiquitous in everyday life and materials with which humans interact are often designed with this interaction in mind. Humans perceive feedback during material deformation, e.g., dynamic resistance to force; however, it is unclear how measurable properties map to perceptual judgements and decision-making.

Over 100 subjects completed discrimination tasks where the objective was to determine which of two viscoelastic stimuli (silly putty) were "more firm" by pressing with the index finger. Tasks varied in difficulty from easy (putty vs. rubber ball) to difficult (identical putties) to variable (putties of differing "hardness") and were performed with a bare finger and with a rigid finger cover to reduce cutaneous feedback.

Pressing behavior varied significantly across subjects. Variations in behavior with trial specifics like task difficulty, stimulus firmness, and lack of cutaneous feedback will be discussed. Subjects were clustered based on their pressing behavior and several behavioral outliers are present throughout all tasks. Subjects clustered into two large groups of roughly equal size regardless of task difficulty when cutaneous feedback is present, while they clustered into one larger, dominant group and a smaller group regardless of task difficulty when cutaneous feedback is not present.

Several features are evaluated by AUROC as potential predictors of subjects' "more firm" choice. Simple features such as applied cumulative force-time, max force, and force gradient are sufficient predictors of "more firm" choice, but only when judgments are easy. Basic recovery rheology parameters with clear physical meaning are shown to be excellent predictors of "more firm" choice for all viscoelastic stimuli in a maximum difficulty scenario, suggesting that humans can infer these parameters from material feedback and then use them to judge "firmness" of complex, viscoelastic materials irrespective of individual pressing behavior.

Wednesday 6:30 Sweeney Ballroom E+F PO38

Rheo4Kids: Bringing rheology to children and teenagers

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Although rheology plays a key role in daily life - from the way we squeeze toothpaste in the morning to how we spread jam on toast - it remains largely invisible in basic science education. In Brazil, where access to hands-on science is uneven and student interest in STEM is declining, Rheo4Kids aims to transform rheology into a fun, inclusive, and inspiring experience. This project has 3 main objectives: i) To introduce fundamental rheological concepts to children and teenagers through hands-on, playful experiments; ii) To stimulate curiosity and reduce fear or distance from science, particularly among students who have little contact with research environments; iii) To create lasting connections between schools and university, opening doors to future engagement with STEM and rheology. The project is operating on two fronts: visiting schools to bring rheology directly into classrooms, and inviting students to visit the university for immersive experiences in real research spaces. Activities include interactive experiments with non-Newtonian fluids, games and storytelling to illustrate concepts such as viscosity, elasticity, and yield stress, and informal talks that connect rheology to students' everyday lives. One of the most innovative aspects of Rheo4Kids is the strong involvement of undergraduate and graduate students as facilitators. These students participate in planning and conducting the activities, serving as near-peer mentors and role models. This promotes not only outreach and engagement but also the development of science communication skills within the academic community. Methodologically, the project adopts an experiential learning approach, in which knowledge is constructed through doing, touching, and observing. It uses low-cost, everyday materials (e.g., cornstarch, glue, gelatin) to simulate complex rheological behaviors in ways that are accessible and engaging. We thank the Society of Rheology for helping us to make a difference and try to spread rheology throughout our children!

Wednesday 6:30 Sweeney Ballroom E+F PO39

A shared struggle: Impostor phenomenon within The Society of Rheology

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Members of The Society of Rheology (SoR) - from students to fellows - have often uttered the phrase, "I'm not a rheologist, but..." While such comments are frequently lighthearted, self-deprecating, or expressions of humility among scientific peers, they may also reflect our collective experiences related to Impostor Phenomenon (IP). First described by Clance and Imes in 1978, IP refers to persistent feelings of inadequacy and the fear of being exposed as a "fraud," despite evident success or competence. These feelings are especially common among high-achieving individuals and are associated with heightened anxiety, social isolation, and reduced risk-taking. In 2023, we received a Rheology Venture Fund award to raise awareness of IP and investigate its prevalence within the SoR community. A voluntary survey (IRB: 2024-1571) was distributed to all SOR members digitally in Winter 2024. The 151 unique responses were analyzed using a modified Clance Impostor Phenomenon Scale (CIPS). Results showed that all respondents experienced IP to some degree, with an overall average indicating a "moderate" level of IP and a substantial proportion of respondents reporting "frequent" or "intense" IP feelings. Age emerged as a major influencing factor: respondents under 35 reported frequent or intense IP significantly more often than those 35 or older. Higher IP levels were observed amongst students, non-PhD, non-male responders, and those outside of the chemical engineering field compared to their respective counterparts. By recognizing and quantifying IP within our professional community, we hope to open a dialogue among students, mentors, and colleagues in order to foster a more supportive, inclusive environment.

Wednesday 6:30 Sweeney Ballroom E+F PO40

Flowing between disciplines: Integrating art and rheology into undergraduate education

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Rheology and the arts share a surprising number of touchpoints, from the yield-stress of oil paints in van Gogh's impasto to the viscoelastic foams in Piero Gilardi's sculptures, the settling of pigments in traditional ink-making, the flowing choreography of Pina Bausch, and the cinematic imagery (time-pressure concept) of Andrei Tarkovsky's films. Building on the RheoLit initiative, which explores such connections across painting, sculpture, literature, dance, music, and film, we present Engineering Art, a multidisciplinary challenge-based learning (CBL) project at Eindhoven University of Technology. In this course, undergraduate teams design and create an "art object" (e.g., painting, sculpture, short film) using engineering principles connected to rheology and fluid dynamics. The projects integrate diversity, equity, and inclusion by bringing together students from different academic and cultural backgrounds, engaging external stakeholders such as artists, curators, and industry partners, and encouraging creative expression alongside technical problem-solving. Digital tools enable collaboration, formative assessment, and dissemination, while public exhibitions connect the work to the broader community. By linking the aesthetic language of art with the analytical tools of rheology, this initiative shows how CBL can broaden STE(A)M education, foster interdisciplinary thinking, and make complex scientific ideas, such as rheology, tangible, relatable, and inspiring.

Wednesday 6:30 Sweeney Ballroom E+F PO41

Protein/surfactant interface formation and properties by interfacial shear rheology

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Protein solutions are used in a variety of industries including BioPharma, cosmetics, and food where they play roles such as functional moieties, emulsifiers and foaming agents. Of particular interest is the interfacial activity of these large biomolecules between immiscible phases. Many proteins are known to be surface active where they migrate and adsorb to interfaces forming viscoelastic film layers. This interfacial layer can significantly impact formulation properties and performance. Due to its importance, research efforts have focused on understanding and tuning this interfacial activity. One strategy to control the interfacial behavior of proteins is to add small molecule surfactants to the system. These amphiphiles can interact with the protein and compete for position at the interface which enables control over the protein behavior. This study examined the interfacial activity of a globular Serum Albumin protein in the presence of an anionic Sodium Dodecyl Sulfate (SDS) or cationic Cetyltrimethylammonium Bromide (CTAB) surfactant. Specifically, the early-stage interfacial film formation and properties are examined by interfacial shear rheology. A double wall ring (DWR) interfacial accessory was utilized to determine how surfactant ionicity influences interfacial film formation rate and time-dependent viscoelasticity and viscosity. The results identify how the differing surfactant ionicity impacts the interface formation rate and rheological properties. In addition, altering the surfactant concentration was shown to be an effective strategy in tuning the viscoelasticity of the interface.

Wednesday 6:30 Sweeney Ballroom E+F PO42

Linear and non-linear rheology of titanium dioxide Pickering emulsions

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Pickering emulsions are used in many products, including foods, cosmetics, and paints, as well as in industrially relevant applications (e.g., oil recovery and agrochemicals) thanks to their improved stability to Ostwald ripening and coalescence. Among the many possible nanoparticles (NPs) that can be used as stabilizers, Titanium dioxide (TiO2) NPs have emerged as a promising avenue for 3D printing of macroporous ceramic scaffolds for energy and biomedical applications. Understanding the rheology of TiO2 Pickering emulsions is therefore very important both to be able to process the emulsions and to design the final products with desirable properties. Working with hydrophilic fumed TiO2 Pickering emulsions in the presence of polystyrenesulfonate (PSS), a negatively charged polyelectrolyte, we investigate the role of NP concentration (up to 30 wt.%), pH (3-9) and oil volume fraction (0.5-0.8 vol.%) on the linear and non-linear rheological properties of the emulsions. By carefully characterizing the emulsions microstructure at the nano-, micro- and macro-scale we provide new insights on the mechanical behavior of these complex systems, with the aim of developing a general framework for the rheological characterization and modeling of Pickering emulsions.

Wednesday 6:30 Sweeney Ballroom E+F PO43

Automated Lagrangian droplet analysis framework to investigate individual droplets in capillary jets

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Control of droplet breakup, from aqueous sprays to injected fuels, has a rich history in experimental methods for characterizing the process, and the impact it and the additives used to modify it. Instead of generalized 3-dimensional Lagrangian Particle Tracking (LPT) methods used to observe the behavior of a large number of individual droplets for long times (Schröder & Schanz, 2022), in this work, we develop an LPT framework to track individual droplets from birth to death in a 1D or quasi-1D flow. We track the features of each droplet, such as mechanism of birth (primary pinch-off, secondary breakup, or coalescence), center of mass, velocity, kinetic and potential energy, shape, etc., for all frames in which it is observed. Motivated to improve fire safety of lubricants, we apply our method to observe the effects of "megasupramolecules" formed by end association of long telechelic polymers (Wei et al, 2015) on the breakup of a polyalphaolefin capillary jet, particularly in regard to the suppression of small satellite droplets.

Wednesday 6:30 Sweeney Ballroom E+F PO44

Influence of surfactants, polymers and proteins on foam film drainage

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Foams can be described as colloidal dispersions containing large gas cells separated by thin liquid films, whose junctions are called Plateau borders. Drainage of individual ultrathin foam films (thickness < 100 nm) into Plateau borders is governed by the interplay of capillarity, disjoining pressure, viscosity, and interfacial rheology. It is well-established that confinement-induced structuring and layering of supramolecular structures like micelles, liquid crystals, colloidal particles, or polyelectrolytes within foam films results in drainage via stratification. Only few examples show the possibility of stratification in foam films containing polymers or proteins. In this contribution, we visualize and analyze drainage in foam formulated with surfactants, proteins, polymers and their mixtures, and describe the specific connection to foam stability and applications in diverse areas in foods, cosmetics, environmental remediation, oil recovery, and healthcare.

Wednesday 6:30 Sweeney Ballroom E+F PO45

Molecular modeling of star block copolymers at immiscible polymer interfaces

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Star block copolymers (star-BCPs) undergo dramatic changes in chain conformation when immersed in homopolymer melts, and have recently attracted attention as compatibilizers at immiscible homopolymer interfaces. By collapsing either their cores or shells, star-BCPs can diffuse more rapidly through homopolymers and find their way to interfaces. However, the details of these molecular dynamics and how star-BCPs contribute to interfacial reinforcement remain unexplored. Here, we apply coarse-grained molecular dynamics simulations to predict the structure and dynamics of star-BCPs in linear homopolymers of either the core or shell phases, and at their immiscible interfaces. We vary the molecular structure and miscibility of the two polymer species and measure their impact on chain conformation and diffusion. We then relate the aggregation of star-BCPs at the interface to the interfacial strength and toughness in the solid state.

Wednesday 6:30 Sweeney Ballroom E+F PO46

Eggless vegan food emulsions

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Food emulsions like mayonnaise, hollandaise, aioli, etc. that are used as dressing, dips, or sauce bases are often egg-based. In this poster, we present the challenges and opportunities in emulating such dense emulsions using plant-based proteins. We focus primarily on consistency, shelf-life, dispensing, emulsification, processability, and consumer experience or preferences set by the flow behavior. We characterize the shear and extensional rheology response of animal and plant-based emulsions and study the interfacial and bulk rheology of protein-polysaccharide mixtures utilized in making such emulsions.

Wednesday 6:30 Sweeney Ballroom E+F PO47

Rethinking elastoviscoplastic models for large amplitude oscillatory shear data

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The Saramito-type models for elastoviscoplastic (EVP) liquids offer an interpretable framework for describing the flow behavior of yield stress materials. Although the model captures key features of yielding and post-yield flow, parameter sets for fitting a single strain amplitude in large-amplitude oscillatory shear (LAOS) often fail to predict responses under different conditions. Particularly, for many EVPs, Saramito-type models with fixed parameters can hardly be fitted across multiple strain amplitudes, indicating limited generalizability. To address this limitation, we propose nonlinear definitions for the dashpot and spring in the models. This modification preserves the models' logic while capturing amplitude-dependent responses, thereby improving predictive performance.

Wednesday 6:30 Sweeney Ballroom E+F PO48

Rheology of concentrated mixtures of non-ionic and ionic surfactants

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The rheology of surfactant mixtures is inherently complex, particularly when triblock copolymers interact with ionic surfactants. These mixtures are commonly used in formulations ranging from cosmetics and creams to more advanced functional materials, yet the relationship between their microstructure and macroscopic rheology require further studies in concentrated regimes. In this work, we investigate how sodium dodecyl sulfate (SDS) concentration influences the bulk rheology and nanoscale structure of Pluronic F68. SDS was incorporated at concentrations from below to far above its critical micelle concentration (CMC) to probe the effects of both dilute and highly concentrated surfactant regimes. Bulk oscillatory shear measurements showed that increasing SDS decreased the storage modulus while increasing the yield strain, suggesting micellar restructuring and modifications to the polymer network. These results provide insight into how surfactant-induced changes at the nanoscale translate to bulk rheological behaviors.

Wednesday 6:30 Sweeney Ballroom E+F PO49

Flow-history-dependent morphologies in particle-filled drops

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We study the deformation and relaxation dynamics of particle-filled drops under controlled planar extensional flow using a Stokes trap-an automated flow control technique enabling precise manipulation of freely suspended drops. The suspending phase is polydimethylsiloxane (PDMS, viscosity = 30 Pa·s), while the drop phase is polyisobutene (PIB-24, viscosity = 19 Pa·s) containing polyethylene (PE) spheres (2-4 μm diameter) as solid inclusions. Experiments show that particle addition slows relaxation after flow cessation, and at high loadings (~35 % v/v),

relaxation arrests at a stable, elongated shape rather than returning to sphericity. This arrest suggests that particles impart a yield stress to the drop phase exceeding the restoring interfacial stress. Applying flow in a perpendicular direction can partially overcome this arrest and reinitiate deformation; however, the resulting shapes are asymmetric and history-dependent, indicating rearrangement of the internal particle network. Complementary OpenFOAM simulations incorporating Carreau-Yasuda rheology capture this arrest through pronounced shear-thinning behavior. These findings provide quantitative insights into the flow-history-dependent morphologies of particle-filled drops.

Wednesday 6:30 Sweeney Ballroom E+F PO50

Bio-based additives as rheology modifiers for Hevea and guayule rubber latexes

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Colloidal rubber suspensions must flow through pumps and spray heads yet rapidly solidify after deposition, so tailoring their viscoelastic response with sustainable additives is a growing priority. Cellulose nanomaterials, sourced from agricultural residues and forestry side streams, offer renewability, low density, and a rich surface chemistry that can tune colloidal interactions without petroleum surfactants. Although many solid rubber composites show strength gains from cellulose reinforcements, the suspension-stage rheology that governs dipping, spraying, and printing remains underexplored, particularly for high-aspect-ratio cellulose nanofibrils (CNF) and shorter cellulose nanocrystals (CNC) in latexes. This study will build systematic rheological maps for commercial Hevea brasiliensis latex and centrifuge-purified Parthenium argentatum (guayule) latex formulated with CNF or CNC at solids levels used in production. Small-amplitude frequency sweeps will track shifts in storage modulus G', loss modulus, and relaxation spectra across processing temperatures. Steady-shear tests will determine zero-shear viscosity, shear-thinning index, and yield stress, establishing how each nanomaterial widens or narrows the workable window. Confocal laser scanning microscopy on shear-arrested droplets will visualize the spatial distribution of CNF and CNC inside the latex matrix, linking microstructure to rheological behavior and providing insight into depletion softening, reversible particle bridging, or percolated fiber networks. Comparing the complete data sets for CNF-filled and CNC-filled systems will reveal whether depletion softening, reversible bridging, or percolated fiber networks dominate, and whether guayule latex requires different modifier strategies from Hevea. The resulting charts will guide greener, allergen-reduced latex formulations and extend fundamental understanding of bio-particle suspensions as rheology modifiers.

Wednesday 6:30 Sweeney Ballroom E+F PO51

Influence of supercritical CO_2 and N_2 on the viscosity and solidification behavior of polymer melts

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The high viscosity of polymer melts poses a challenge for efficient processing, often necessitating increased energy input. Supercritical carbon dioxide (scCO2) presents a promising alternative to conventional solvent-based plasticizers by effectively reducing melt viscosity [1]. This study investigates the rheological behavior of various polyethylene (PE) types under elevated pressure using an unique plate-plate pressure cell integrated with a modular compact rheometer capable of rotational and oscillatory modes. Rheological tests-including flow curves, frequency sweeps, and temperature ramps-were conducted at ambient pressure, 120 bar nitrogen (N2), and 120 bar scCO2. While N2 had minimal effect on melt viscosity, it increased the solidification temperature in a PE-type-dependent manner. In contrast, scCO2 acted as a reversible plasticizer, significantly reducing melt viscosity and slightly delaying crystallization. Oscillatory measurements proved especially effective for high-viscosity samples, allowing reliable data acquisition near melting temperatures when strain and frequency were appropriately optimized. These findings underscore the potential of scCO2 for enhancing energy efficiency in polymer processing and foaming, and highlight the utility of high-pressure rheometry in studying pressure-sensitive polymer properties in polymer melts.

References [1] Wan, C., Lu, Y., Liu, T., Zhao, L., & Yuan, W. Foaming of low density polyethylene with carbon dioxide based on its in situ crystallization behavior characterized by high-pressure rheometer. Industrial & Engineering Chemistry Research 2017, 61(16), 5334-5345.

Wednesday 6:30 Sweeney Ballroom E+F PO52

Linking rheology and spinnability of alginate solutions enriched with probiotics

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Electrospinning of biopolymer solutions into fibers enables the fabrication of materials with desirable mechanical and biophysical properties. Sodium alginate, known for its biocompatibility and biodegradability, has recently emerged as a promising material for bacterial therapy, in which live bacteria embedded in an alginate fiber mesh are used to treat infections. In order to be electrospun, alginate can be combined with a high molecular weight carrier polymer that enhances the shear and extensional viscosity of the solution. These rheological properties influence the ability of the solution to form fibers-a property also known as spinnability-by controlling the dynamics of filament formation, thinning, and breakup, which ultimately dictate the morphology of the resulting fibers. Here, we investigate the shear and extensional rheology of solutions composed of sodium alginate, a high MW poly(ethylene oxide) (PEO) carrier polymer, and commercial probiotics. We find that the concentrations and molecular weights of the alginate and the carrier polymer significantly influence the solution rheology, as well as the distribution of fiber

diameters after electrospinning. By linking the composition and rheology of biopolymer solutions to the morphology of the electrospun fibers, we seek to enable the rational design and optimization of fiber-based, probiotic-loaded materials for bacterial therapy.

Wednesday 6:30 Sweeney Ballroom E+F PO53

Understanding the combined role of chemistry and topology on dilute polymer rheology using high-shear capillary rheometry

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The theoretical understanding of dilute polymer rheology is hindered by the typically large shear rates, sometimes exceeding 10^6 s^{-1}, required to experimentally study their nonlinear deformations, hindering the ability to engineer their rheology and mechanical stability. In particular, existing rheological theories are mostly limited to linear, ideal homopolymers, and thus fail to account for common molecular variables including polymer chemistry and topology used in the design of rheological modifiers for high shear rate applications. Extending these theories to nonlinear topologies and complex polymer-polymer or polymer-solvent interactions will require experimental studies that combine well-controlled synthesis with the ability to characterize their dynamics and rheology at shear rates well beyond those accessible in conventional rheometry. To achieve this, we synthesize and characterize the thermochemical-dependent properties of a series of topology-controlled linear and star poly(methyl methacrylate-co-stearyl methacrylate) polymers with a range of molecular weights and comonomer ratios representing varying degrees of polymer-solvent interactions. We use a combination of equilibrium and high shear-rate rheology measurements using a high-pressure capillary rheometer to determine the dynamics and rheology of these polymers at shear rates corresponding to Weissenberg numbers well into the nonlinear (shear thinning) regime. We compare these results to test existing theories of dilute polymers. In particular, we test whether existing descriptions of relaxation dynamics and finite extensibility are sufficient to describe polymers under a range of solvent qualities. The results will provide insights into the effects of nonideal polymer designs on their high shear rate rheology, providing guidance for their engineered applications and the refinement of molecular-level theories.

Wednesday 6:30 Sweeney Ballroom E+F PO54

Role of the energy conversion factor in flow birefringence and polymer crystallization

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Shearing a high-density polyethylene (HDPE) melt stretches chains in the high molecular weight tail of the molecular weight distribution. Size exclusion chromatography data in that tail are fit to $\exp(-M/M_{max})$ to estimate the volume fraction of chains E that get stretched at a given shear rate, that exceeds the reciprocal of their Rouse time. Hence, a sheared polymer melt undergoes de Gennes' first-order coil-stretch transition; the longest chains are stretched and coexist with shorter chains that are only partially oriented. We find that E is proportional to the measured birefringence at each shear rate. While the applied specific work (W) seems to be the control variable for acceleration of nucleation kinetics over a limited range of shear rates, that is not the case for strong variations in shear rate. Shear rates from 1 - 70 s^{-1} were applied below the equilibrium melting temperature to form a network of crystal precursors that stabilize the melt, resulting in W levels of up to 60 MPa by varying the shearing time. A flow-induced nucleation model is applied based on Flory's entropy reduction model and Hoffman and Lauritzen's isothermal heterogeneous nucleation model. We find that the acceleration in crystallization after shear plotted as a function of EW collapses all data to the same curve, making the volume fraction of chains E that get stretched the effective energy conversion factor. The critical crystal nucleus volume V* is quantified using the model and found to increase with temperature in the range of 122°C = T_C = 126°C. We find the quiescent V* = 7.5 - 10.4 nm^3, containing 23 - 37 Kuhn monomers of HDPE. The sheared V* is 2/3 of the quiescent V* at all temperatures and shearing conditions thus far explored.

Wednesday 6:30 Sweeney Ballroom E+F PO55

Effect of dialysis on the osmotic pressure, conductivity, and rheology of aqueous polyelectrolyte solutions

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The presence of salts in polyelectrolyte solutions leads to electrostatic screening, which directly alters chain conformation and rheological properties. Commercial polyelectrolytes often contain considerable residual salts. Poly(diallyldimethylammonium chloride) (PDADMAC) samples, for example, can contain substantial amounts of salt along with residual monomers from the manufacturing process. PDADMAC is a fully cationic, water-soluble polyelectrolyte with high charge density, a stable quaternary ammonium structure, and broad pH tolerance. The presence of residual salts modifies the ionic strength and can significantly influence measured solution properties. In this work, we compare the viscosity, osmotic pressure measured by freezing point depression, and conductivity of dialyzed PDADMAC and its copolymer with acrylamide, poly(acrylamide-co-diallyldimethylammonium chloride) (PAAcDMAC), with those of their as-received, not-dialyzed counterparts to assess the influence of residual salts and impurities on both the homopolymer and the copolymer. As expected by simple models, residual salt lowers the

viscosity, while maintaining the same power law dependence on concentration as the salt-free solutions. For all not-dialyzed samples, the ratio of salt ions to monomers (cs/cp) was calculated to be in the range of 0.1 to 0.25 based on osmolality measurements. For the copolymers, the increase in specific viscosity upon dialysis was larger for samples with a higher cs/cp ratio in the not dialyzed state. However, for PDADMAC homopolymers, the lower molecular weight sample (150 kDa), which had a lower cs/cp value compared to the higher molecular weight sample, exhibited a greater increase in specific viscosity after dialysis.

Wednesday 6:30 Sweeney Ballroom E+F PO56

Molecular scale modeling of mechanical degradation in molten polymers

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Strong flows can drive molten polymers to degrade through chain scission. Controlling this mechanical degradation is critical for designing effective polymer processing, reprocessing, and recycling. Each common flow type, uniaxial and biaxial elongation, and shear, imposes distinct deformation patterns that lead to different stress distributions, chain orientations, and degrees of elongation. We use molecular dynamics simulations to systematically study how different flow conditions govern mechanical degradation in polymer melts. Because scission during flow produces geometry-specific instabilities, it also changes the kinetics of further breakage. Extensional flows drive significantly higher chain stretching and scission than shear. Most scission occurs during the initial unraveling, with limited additional breakage once chains are fully extended. While both uniaxial and biaxial elongational flows exhibit saturation in chain extension and scission, biaxial flows achieve greater degradation at lower stress levels by promoting more homogeneous deformation and suppressing the melt inhomogeneities observed in uniaxial flows.

Wednesday 6:30 Sweeney Ballroom E+F PO57

Tuning supramolecular weight distributions and nonlinear rheology in blends of linear telechelic polymer

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Self-assembling telechelic polymers exhibit dynamic topological rearrangements in response to external stimuli, enabling recyclable materials with resilience to harsh processing conditions. Their rheological behavior is governed by the underlying self-assembled structure, which arises from associative group cohesion and temperature. In this study, we explore a strategy to tune the distribution of self-assembled clusters by introducing terminating chains, which are telechelic polymers containing one associative and one nonassociative end, into self-assembling systems. Using coarse-grained molecular dynamics simulations, we investigate the effects of varying terminating chain concentrations on supramolecular structure and flow response. We find that even low concentrations (=5%) of terminating chains significantly narrow the equilibrium supramolecular chain size distribution, enhance chain mobility, and reduce viscoelastic relaxation times. Under uniaxial extensional flow, terminating chain addition can decrease the steady-state viscosity over multiple orders of magnitude without changing temperature or associative bond strength. These results reveal a new mode of nonlinear rheological control that does not require changes to chemical functionality or processing conditions.

Wednesday 6:30 Sweeney Ballroom E+F PO58

Simulation of particulate flows in viscoelastic fluid using immersed boundary Lattice Boltzmann Method

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Lattice Boltzmann Method (LBM) is a technique for simulating continuum fluids by discretizing time and space using particle distribution function, which normalize the probability that microscopic coarse-grained particles exist between lattices. Originated from physical theory of gases, such as Lattice Gas Automata (LGA), this method combines Newtonian dynamics of solid particles with a discretized Boltzmann equation for fluid phase. LBM has its advantages of simplicity in their formulation and versatility. For simplicity, LBM can simulate the motion of fluid particles with only two successive procedures: particle propagation and collision. And for versatility, LBM can apply to turbulent flow, multiphase flow, but LBM specializes in simulation of colloid/suspension fluids. Complex fluid represent fluid which co-exist multi - phase state. For example, Anode slurry that are used for manufacturing battery electrode are consist of solvent, carboxymethyl cellulose (CMC) polymer, carbon black (CB), graphite and so on. In battery electrode manufacturing process, there are representative five - steps, mixing, transportation, coating, drying and calendaring. In each step, various process conditions can influence flow effects on slurry - for example, in transportation step, there can be unstable flow and in coating step, due to viscoelastic and thixotropic property of the slurry. These phenomena can be interpreted as not only material property but also flow condition. These can be attributed to microstructure formation / decomposition process due to varying flow conditions. So, visualization and interpretation about microstructure of battery slurry can be a good milestone for control flow conditions in battery coating process.

Wednesday 6:30 Sweeney Ballroom E+F PO59

Melt rheology of bio-based polymer composites: Effects of polymer blend ratio and wood filler loading

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The increasing demand for sustainable materials has driven industry to seek alternatives to fossil fuel-derived plastics with comparable physical properties. A major challenge in this transition lies in understanding melt rheology and predicting processability of these materials, which directly influences large-scale manufacturing. Integrating wood fillers with bio-based polymers like polylactic acid (PLA) and polyhydroxybutyrate (PHB) offers a promising solution, providing both structural integrity and flexibility across a suitable range of compositions. This study investigates the effects of polymer blend ratio and wood filler loading on the rheological behavior of bio-based polymer composites.

We demonstrate that increasing PHB content decreases the complex viscosity and elastic/viscous moduli in composites containing 0 and 10 wt% wood flour. However, for 20 and 30 wt% wood flour, complex viscosity increases with higher PHB content due to effects of wetting, phase separation and strong filler interactions. The viscous modulus dominates over the storage modulus in most samples; the exceptions being PLA/PHB- 80/20 and 70/30 composites containing 30 wt% wood flour, in which the elastic modulus dominates due to formation of filler networks. Additionally, the linear viscoelastic region shifts to lower values at increased wood flour loadings, suggesting that fillers increase sensitivity to deformation. Finally, we examine the role of particle size and aspect ratio through analysis of composites containing wood fiber in place of wood flour. Flow-induced alignment of wood fibers and potentially weaker interfacial interactions reduce the rheological properties of the composites, despite the inherent rigidity of the fibers. By relating melt rheology data to that obtained from DSC, TGA, and tensile testing experiments, we can better design bio-based composites for enhanced properties and processability.

Wednesday 6:30 Sweeney Ballroom E+F PO60

Thermo-rheological behavior of biopolymer blends

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Biopolymers are an environmentally sustainable substitute for conventional materials, derived from renewable biomass and exhibiting biodegradability in controlled environments. The rising demand for eco-friendly materials has generated considerable interest in biopolymer blends, as they offer tunable properties suitable for consumer goods, packaging, and fibrous nonwovens. This study investigates the rheological properties of polylactic acid (PLA) blended in with polybutylene succinate (PBS). In particular, we examine how blend composition affects properties and whether blending can be exploited to obtain synergistic properties. The viscoelastic properties of the blends will be examined as a function of temperature and composition; such measurements will also be utilized to determine conditions and types of phase separation. The Cole-Cole plot is one approach that reveals such information, and these results will be correlated with that observed via morphological SEM and thermal (DSC) analysis. Results from this work would enhance the understanding of structure-property relationships in biopolymer blends, offering practical insights for sustainable material development. The findings will be valuable for researchers and industries striving to replace conventional plastics with eco-friendly alternatives.

Wednesday 6:30 Sweeney Ballroom E+F PO61

Microstructured polymer electrolytes with high Li-ion conductivity by tuning structural uniformity

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The pending demand by the automotive sector to cut off the emissions caused by the use of fossil fuel has generated a subset of motors which use electric energy as the main source of propulsion. This electric energy is stored in Li-ions rechargeable batteries: previous studies have pointed out the problem associated with the use of this kind of batteries, as well as the risks and hazards of their application for cars. To overcome these problems, alternatives based on polymer electrolytes and their gels have arisen. More specifically, the possibility of finely tuning the properties of the liquid electrolytes and solid polyelectrolytes by the addition of salts opens up various possibilities. This study wants to tailor the properties of gel polymer electrolytes with ethylene oxide units in the side chains, with the aim of enhancing the mobility of Li-ions without decreasing the mechanical properties. The mechanical and thermal properties of self-synthesized PEGMA and PEGA samples with different molecular weights and polydispersity, with Li or without, have been measured. Thermal measurements showed that the addition of Li and an increase in molecular weight act synergistically to increase the values of glass transition temperatures and the heterogeneity of the structure. In the investigated temperature range, moreover, the salt addition completely suppresses the melting and crystallization phenomena. Rheological measurements have been performed on the polymers in linear regime, and revealed that their microstructure exhibits mostly a liquid-like behavior at room temperature. The addition of Li increases the viscoelasticity of the polymers. Regardless the degree of chains' dispersity, PEGA samples exhibit the lowest viscoelasticity, whereas PEGMA samples, especially with the addition of salt, show viscosity enhancements of almost three order of magnitude.

Wednesday 6:30 Sweeney Ballroom E+F PO62

Interplay of conductivity and rheology of polymer electrolytes containing Li^+ and Mg^{2+}

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Challenges related to the cost and limited availability of lithium-based electrolytes have prompted the exploration of electrolytes for multivalent cations. Polymer electrolytes offer advantages over conventional liquid electrolytes, including enhanced safety, stability, and the mitigation of leakage and flammability issues. This study investigates the electrochemical and rheological behavior of polymer electrolytes composed of short-chain block copolymers combined with ionic liquids (ILs), in the presence of lithium bis(trifluoromethanesulfonyl)imide, LiTFSI, or magnesuim bis(trifluoromethanesulfonyl)imide, $Mg(TFSI)_2$, salt. The produced electrolytes have microphase separated domains, forming nanostructures with PEO domains that facilitate ion transport. Due to differences in coordination behavior of O with Li^+ and Mg^{2+}, the ionic conductivity varies depending on the nature of the salt. Adding IL and salts increases the viscosity of the polymer electrolyte, which can slow down the ion transport. Additionally, the higher concentration of cations increase the relaxation time of the PEO backbone. In this work, we investigate the correlations between ion conductivity, viscosity, and O coordination number with cations from simulation. These findings highlight the interplay between ion-polymer interactions, rheology and conductivity in tuning the performance of PEO-based electrolytes.

Wednesday 6:30 Sweeney Ballroom E+F PO63

Shape memory microparticles for tailoring the flow behavior and aging of suspensions

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Particle suspensions are crucial in various natural and industrial processes, from maintaining healthy ecosystems and forming part of bodily fluids in living organisms to engineering daily-life products. Understanding the flow behavior of particle suspensions is an essential area of research with both fundamental and practical applications. The rheological properties of particle suspensions can be complex and may change with time, temperature, and imposed strain or shear rate. This complexity can make it challenging to predict and tailor the behavior of the suspension and design or optimize processes that consider these properties. Temperature-responsive polymers offer a way to engineer materials with reversible changes in their chemical and mechanical properties. However, most applications of temperature-responsive polymers focus on the tunability of bulk mechanical properties, with only a few examples of their use as polymeric particles to tune the flow behavior of suspensions. We designed stimuli-responsive particles to regulate the rheological properties of suspensions. We expand the use of temperature-responsive polymer materials to synthesize anisotropic, temperature-responsive particles with tunable shape and shape memory effects. We investigate the equilibrium and non-equilibrium properties and effect of temperature on the rheological properties of semidilute and dense suspensions. The stimuli-responsive particle suspensions' linear and non-linear shear rheology and time effects are studied using torsional rheometry to elucidate concentration-dependence variation and temperature effects. We show that shape memory and the strength of attractive interactions modify the flow behavior and promote tunable suspension aging and thixotropy. Using stimuli-responsive materials that change the single-particle physicochemical properties provides an alternative route to modify the flow behavior of suspensions.

Wednesday 6:30 Sweeney Ballroom E+F PO64

Optical tribo-rheoscope for 4D spatiotemporal characterization of model Soft Earth analogs

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The soil beneath our feet is a class of non-equilibrium material. This re-classification of earth-based materials as Soft Earth systems enable us to generate universal mechanical frameworks. Additionally, this allows material deformation and failure to be explained in terms of: (a) rearrangement timescales of constituent building blocks, and (b) multiscale physics of amorphous solids. Here, we present a new, unique design for a tribo-rheometer coupled with optical imaging capability to characterize the spatiotemporal rearrangement dynamics of complex particulate systems under pressure-imposed shear, thereby characterizing rheology and tribology simultaneously. The design consists of the complex fluid system sandwiched between the concentric cylinders, with outer transparent acrylic wall. The lower plate is rotated to tune the applied shear rate or strain, and the top plate maintains the desired normal load. We use two Soft Earth analogs: (i) a granular suspension and (ii) a model ice-soil slurry. We use index-matched mixture of PMMA particles in viscous oil for the former, while the latter is prepared by replacing the solvent using carbopol. We extract particle positions and characterize the rearrangement dynamics of these materials under pressure-imposed shear. Our unique instrumentation enables us to simultaneously estimate the shear stress, macroscopic friction coefficient, and characterize the particle-scale dynamics towards precise prediction of flow and failure in different types of Soft Earth materials.

Wednesday 6:30 Sweeney Ballroom E+F PO65

Time-resolved rheology of dental molding elastomers during gelation

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Silicone-based elastomers are widely used as duplicating materials in many important applications such as dental molding. In such operations, the material transitions from a viscoelastic liquid into a viscoelastic solid throughout a curing process also known as gelation. In this work we focus on two-part dental molding products and study the temporal evolution of their viscoelastic properties throughout the gelation process via time-resolved mechanical spectroscopy. We first characterize the linear viscoelastic properties of the two individual components by performing small-amplitude oscillatory shear (SAOS) measurements on each non-gelling fluid. Measurements at different working temperatures allow us to examine the possibility of time-temperature superposition for these viscoelastic liquids. We then perform time-resolved oscillatory measurements for the curing mixture of the two components at different instants of gelation. Each measured spectrum spans an order of magnitude in the frequency domain and is collected at a rate that is faster than the mutation of the gelling material, providing quasi-instantaneous snapshots of the viscoelastic state. By utilizing principles such as time-temperature and time-connectivity superposition, we accurately track the temporal evolution of the dynamic properties in these model gelling systems under different temperature and flow conditions. Our results provide a magnified view to the mechanical fingerprints of the underlying gelling network in curing elastomers and duplicating materials.

Wednesday 6:30 Sweeney Ballroom E+F PO66

Interpenetrated hydrogel with tunable stiffness and strength

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Hydrogels have become a key focus in soft materials research because of their high water content, biocompatibility, and tunable viscoelastic properties. However, despite extensive studies, many traditional hydrogels still fall short of mimicking the complex mechanical performance needed for real-world applications. Most are naturally brittle, have poor toughness, and struggle to keep their structure under dynamic or prolonged loading. These mechanical limitations slow their broader use in areas like load-bearing scaffolds, organoid models, controlled drug delivery, and emerging fields such as soft robotics and bioelectronics. To address this, we developed a double-network hydrogel that creates an interpenetrated structure with both permanent covalent crosslinks and reversible temporary interactions. This approach has shown promise for increasing strength, enabling self-healing, and better mimicking the mechanical resilience of biological tissues. By combining the biomimetic structure of GelMA with the self-healing properties of PVA crosslinked with a borax solution, we created a gel that maintains its strength without sacrificing flexibility or structural integrity. Mechanical testing revealed a 600% increase in strength and toughness after repeated folding, indicative of tanglemer-like behavior. The presence of reversible bonds also suggests potential for tunable stiffness and water-soluble drug delivery. Rheological assessments were used to probe the origins of this behavior. RheoEIS measurements showed that, with increasing strain, the gel's conductivity also increased, suggesting that polymer chains were aligning in response to the applied strain. Rheo-PI birefringence analysis further illuminated the topological changes occurring under varying strains, providing insight into the degree of entanglement within the gel network. These findings, combined with biocompatibility and additional mechanical assessments, provide a comprehensive understanding of the gel's structural and functional behavior.

Wednesday 6:30 Sweeney Ballroom E+F PO67

Stress relaxation in dense suspensions of sticky particles

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Mechanical aging in soft, jammed attractive suspensions arises from the slow relaxation of internal stresses generated by particle jamming, deformation, and sticky contacts. These stresses drive spontaneous microstructural rearrangements even in the absence of flow, directly impacting start-up flow rheological and microstructural properties. We investigate how pre-shear directionality and relaxation time influence transient start-up flow using a two-step protocol: pre-shear in forward or backward direction, followed by a stress relaxation for a waiting time, tw, and re-shear in either the same (forward-forward) or opposite (backward-forward) direction. Our simulation results show that stress relaxation exhibits a two-step decay which is an initial rapid drop followed by a slow, long-time relaxation following flow cessation. Increasing attraction strength resists stress relaxation, shortening the duration of the initial rapid decay phase. This trend is corroborated by the mean squared displacement, which reveals reduced particle mobility with increasing attraction strength during relaxation. With an increasing degree of interparticle attraction, the start-up flow shows reduced memory effects. The stress strain behavior in the elastic region and the static yield stress value are independent of tw as the attraction between particles becomes stronger. Microstructural analysis shows that the backward-forward protocol flips the depletion and accumulation axes in the two-dimensional pair distribution function, indicating substantial particle reorganization during start-up flow. These results establish a direct link between the mechanical memory of the dense suspensions of sticky particles with their dynamics in shear flow.

Wednesday 6:30 Sweeney Ballroom E+F PO68

Effects of solvent polarity on the burst of a natural rubber balloon

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An inflated balloon readily pops when an orange peel is squeezed next to it. This phenomenon can be attributed to the interaction of limonene, a compound found in orange peel oil, with the natural rubber of the inflated balloon. Upon contact with limonene, the strained rubber in the balloon swells to the point of rupture. The effect of both polar and nonpolar solvents on the bursting of a balloon can undergo was quantified through a custom film pressurization setup. Films of a crosslinked natural rubber were swollen in different solvents and inflated to failure. Additionally, drops of various solvents were applied to inflated rubber films, with a solvent's polarity being found to be inversely correlated with the burst time. Highly non-polar solvents such as cyclohexane and p-xylene mimicked the behavior of limonene whereas more polar solvents such as THF, acetone, and ethanol did not. Modeling of this burst phenomenon is ongoing.

Wednesday 6:30 Sweeney Ballroom E+F PO69

Synthesis, hydrogelation, and adhesion of bioinspired block copolymers

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Marine organisms such as mussels and sandcastle worms secrete glue proteins that enable robust wet adhesion on diverse substrates. The adhesive attributes of these proteins have been ascribed to catecholic 3,4-dihydroxy-L-phenylalanine (DOPA) moieties. Correspondingly, numerous attempts have sought to imbue synthetic and bioderived polymers with wet adhesion characteristics by incorporating catechol groups. However, current catechol-containing wet adhesive technologies suffer from poor adhesion due to their lack of control over the content and location of catechol groups in the polymer backbones. In this work, we address these limitations by designing and synthesizing block polycatechols with a controlled, high-density placement of catechol groups by leveraging a two-step synthetic strategy. Aqueous solutions of these block polycatechols exhibit strong bonding with diverse organic and inorganic surfaces - strong adhesion was achieved with failure strengths exceeding 1 MPa on collagen, 3 MPa on glass, and >10 MPa on metals such as aluminum, steel, and zinc, far outperforming typical medical and industrial adhesives. Moreover, using a library of block copolymers, we establish that the adhesive performance of these block polycatechols can be systematically tuned by varying the catechol block length, bridging polymer length, and the catechol oxidation state by modulating the extent and strength of the cohesive and the interfacial bonds. Our block copolymer adhesive design platform has a robust performance, ease of preparation, and environmental compatibility compared to state-of-the-art aqueous adhesives.

Wednesday 6:30 Sweeney Ballroom E+F PO70

How gel architecture controls ductility and dissipation in single and double network gels

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Controlling viscoelasticity, ductility and viscous dissipation is important to promote adhesive contact and prevent cohesive failure in soft gels. Generally these properties have been controlled by altering the gels chemically. However, our work takes a different approach by modifying the architecture through the incorporation of multiple components, inspired by multi-component protein gels in the biological context. For us, this warrants investigation on the role played by inter-species interactions in shaping gel architecture and rheology. We use a computational model to study the effect of changing the interaction strength of the interaction between two species forming a fibrous double network [1]. We explore two classes of double network architectures: one where the two species demix and another one where the species are intertwined with each other. We study yielding and hysteresis in single and double network gel models. To this end, we perform mechanical tests and analyze the hysteresis in these gels under large shear deformation, strain localization, and subsequent failure or yielding. In our simulations, the microscopic underpinnings can be identified in the different degrees of non-affine motion and local stresses, which can have significant implications for the formation of adhesive contacts, ductility and brittleness of the gels. We find that the hysteretic behavior qualitatively changes from a single network gel to a double network one, even when all is kept the same and only interspecies interactions are changed. We also find that the specific double network architecture also dramatically affects the ductility and brittleness. We discuss the possible implications for constitutive models and in the light of recent experiments.

Wednesday 6:30 Sweeney Ballroom E+F PO71

Rheology of semiflexible filament gels with polymer-mediated attractive interactions

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Weakly charged semiflexible filaments can form gels that display rheological properties reflecting the balance of filament-filament electrostatic repulsion and physical association that results in network formation. Polymeric additives can alter the nature of these interactions and modify the rheology of the system. Here, we study how the addition of oppositely charged polymers affects the rheology of a suspension of semiflexible colloidal filaments. We examine mixtures of weakly negatively charged semiflexible filaments, cellulose nanofibrils (CNFs), with weakly positively charged polymers, branched polyethyleneimine (b-PEI). The linear rheology reveals a striking nonmonotonic response of the storage

modulus (G') to polymer concentration: an initial rapid increase from polymer-mediated bridging, a peak (G'_{Max}) marking optimal network connectivity, and a subsequent decline upon oversaturation and network disruption. This behavior is robust across CNF concentrations and collapses onto a single curve when normalized by the neat CNF modulus (G'_0) or the critical concentration ratio $(c_P/c_{CNF})^*$. Increasing the ionic strength of the system by salt addition results in a nonmonotonic response in the network modulus as both attractive and repulsive electrostatic interactions are screened. These results highlight a potential strategy for realizing electrostatically interacting colloidal systems with a reduced susceptibility to salt effects, and provide new insight for engineering CNF-based colloidal gels.

Wednesday 6:30 Sweeney Ballroom E+F PO72

Viscoelasticity and extensional rheology of polystyrene vitrimers

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A formidable challenge in soft matter is to develop materials that combine the reprocessing capabilities of thermoplastics with the shape stability and mechanical strength of thermosets. Most approaches aim to create crosslinked networks with dynamic covalent bonds, which can reversibly form and break in response to changes in external conditions. Materials containing these dynamic covalent bonds are referred to as Covalent Adaptable Networks (CANs). A specific subset of CANs, known as vitrimers, was introduced by Leibler and colleagues in 2011. Vitrimers exhibit two key characteristics: they maintain stable network connectivity across a range of temperatures and can relieve mechanical stresses through bond exchange reactions. In this work, we present our current results on the linear and extensional rheology of a series of polystyrene vitrimers, where dynamic exchange reactions are facilitated by dioxaborolane metathesis. We show how crosslink density and dynamic bond exchange influence the flow and deformation behavior under both linear and nonlinear deformations, which are particularly relevant for processing operations. In particular, a systematic investigation of the uniaxial extensional response of vitrimer systems is presented, detailing how the presence of dynamic crosslinkers affects strain hardening behavior. We also provide preliminary data on biaxial extension. These insights contribute to a deeper understanding of the fundamental rheological behavior of polystyrene-based vitrimers and their potential for use in advanced material design.

Wednesday 6:30 Sweeney Ballroom E+F PO73

Evolution of nonmonotonic viscous moduli during the formation of polymer hydrogels

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Hydrogels, defined as polymer networks swollen with water, are versatile materials used in consumer products, biomedical materials, and sustainable agriculture. Hydrogels are formed through gelation, which occurs when polymers in solution form chemical or physical crosslinks, resulting in a polymer network. This transition is monitored using in situ small-amplitude oscillatory shear rheology, which measures the dynamic elastic (G') and viscous (G") moduli. Typically, both moduli increase monotonically during gelation: G" initially exceeds G', then a crossover leads to G' surpassing G", and both moduli reach a final plateau as the system approaches maximum crosslinking. In some gelation processes, the viscous modulus overshoots its final plateau value shortly after the crossover, before decreasing to its plateau value. We hypothesize that the G" overshoot signals simultaneous polymer cluster growth and percolated network formation, followed by cluster incorporation into the network. Using star polymers terminated with photo-crosslinking functional groups, we observe that more polymer arms and higher polymer concentrations enhance the G" overshoot. During in situ photo-rheology, frequency sweeps collected between periodic irradiation reveal the G" overshoot is enhanced at high frequencies, consistent with faster relaxation of clusters in the sol than the overall polymer gel. Recoverable strain analysis provides additional insight into hydrogel microstructure during gelation. This work improves understanding of polymer network formation, providing valuable insights to guide material development for numerous applications.

Wednesday 6:30 Sweeney Ballroom E+F PO74

Investigating viscoelastic properties of vacuum distillation residue oils

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Crude oil is often processed using a pair of distillation steps to separate lower molecular weight species from higher molecular weight components. Following these distillation steps, the remaining high-molecular weight components leaving the distillation column are referred to as a 'residue oil' or 'resid' and, if the distillation is conducted at pressures below ambient, a 'vacuum residue oil'. These oils contain complex mixtures of aggregating molecules and exhibit viscoelastic behavior at temperatures below ~100°C. The primary driver of viscoelasticity in these fluids is the formation of weak colloidal gels due to the temperature-induced aggregation of asphaltene molecules. Most residue oils undergo testing to determine the mass fraction of asphaltene molecules present, but standard testing does not provide any information regarding the asphaltene aggregation behavior. This work uses temperature ramps and oscillatory shear measurements to quantify the viscoelastic properties of a variety of industrially-provided vacuum residue oils to quantify their gelation behavior and link their viscoelastic properties to commonly used thermochemical characteristics used to describe these fluids. In particular, we attempt to develop a relationship between gel strength and the asphaltene interactions present in the fluid.

Wednesday 6:30 Sweeney Ballroom E+F PO75

Tuning the microstructure and particulate network in attractive colloidal gels through oscillatory shear flows

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Attractive colloidal gels find applications across a wide range of fields, including pharmaceuticals, food, consumer products, and constructions. Generally, colloidal gels form through percolation of a particulate network from individual particle-level physical bonds. As such, the overall mechanics of colloidal gels are directly governed by this network's characteristics. It has been shown that mechanical disturbance in the form of small amplitude oscillatory flows offers an effective means of tuning gel mechanics. In this study, we employ Brownian dynamics simulations incorporating the Rotne-Prager-Yamakawa tensor to investigate attractive colloidal gels under oscillatory shear. We study the microstructural consequences of mechanical tuning in colloidal gels. Our analysis focuses on how the structural features and network connectivity of colloidal gels evolve with different flow conditions, attractive strengths, and volume fractions.

Wednesday 6:30 Sweeney Ballroom E+F PO76

Solvent mixture effect on the rheological behavior of amphiphilic block copolymer self-assemblies

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Self-assembly of amphiphilic block copolymers in selective solvent(s) results in lyotropic liquid crystals (LLCs), forming mesophases with domain size ranging from 2 to 50 nm. Water has been conventionally used as a solvent for self-assembly of Pluronic surfactants. Ionic liquids (ILs) have been proposed as a replacement for water to produce mesophases with higher moduli in order to retain the structure in templating applications. Self-assembly of Pluronic F127 has been extensively studied in water and ethylammonium nitrate (EAN), a hydrophilic protic IL. Our preliminary results show that synergistic hydrogen bonding between EAN and water changes the self-assembly behavior of the mesophases. This study investigates the effect of solvent mixture (i.e., EAN:water ratio) on the rheological behavior of Pluronic F127 self-assemblies. Studying sol-gel transition of this system by both rheology and calorimetric methods show that the sol-gel transition temperature shows a negative deviation from the mixing rule when water and IL mixtures are used. All samples show Newtonian behavior at sol state and Type III nonlinear behavior at gel state accompanied by yield stress.

Wednesday 6:30 Sweeney Ballroom E+F PO77

Convenient updates for lab viscosity and rheology measurements

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Busy laboratories search for ways to boost efficiency and productivity. Developments in instrumentation, such as adding convenient features through electronics, firmware and software improvements, help make the job easier, overall. Providing users the option of either USB or simple Bluetooth connectivity, for example, allows a choice to help optimize the workflow. This poster presents and discusses various updates, to help viscometry and rheological testing of a range of products - most of which are often highly non-Newtonian. This benefits operators within both the QC/QA and R&D realms.

Wednesday 6:30 Sweeney Ballroom E+F PO78

Characterization of gas-solid multiphase flows using a powder flow cell coupled to an air-bearing rheometer with a toroidal-flow distributor

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Understanding the jet decay and wall friction effects in toroidal flow fluidized beds is foundational to the control and optimization of fluidized bed operations such as granulation and coating. The effect of toroidal flow on wall friction and its contribution to the fluidization pressure drop was studied using the Anton Paar Rheometer MCR 502. This study also focuses on understanding how the higher velocity jets emerging from an inclined slots distributor plate decay as a function of distance from the plate and their interaction with solid particles under fluidization conditions. An Anton Paar MCR 502 Rheometer with a fluidized bed attachment was used to test jet decay and wall friction behavior in gas-solid multiphase flows (MCC Cellets 175 and Cellets 200, Glatt, Ramsay NJ). The MCR was equipped with a slotted air distributor plate that induced toroidal flow via 45-degree inclined slots; it was compared to a control experiment having vertical slots. Fluidization tests were performed to determine the minimum fluidizing air velocity using pressure-drop measurements. Torque measurements were performed at varying bed heights and air flow rates. In toroidal flows, torque was measured in both co-flow and counter-flow direction to understand the jet decay effect. Wall friction effects were deduced from pressure drop/airflow measurements above minimum fluidization. Fluidization curves suggests that wall friction contributes to the pressure drop in toroidal flows, as shown by a marginal increase in pressure with increasing air flowrate, in contrast to the straight slots air distributor. Torque varied with height at air flow rates near incipient fluidization, with higher values at the bottom of the bed compared to the top. This suggests greater resistance to the stirrer's movement at the bottom of the bed. At higher flow rates, torque values were minimized across different bed heights.

Wednesday 6:30 Sweeney Ballroom E+F PO79

Extracting molecular-level insights into wormlike micelle systems in complex flows using a fluidic four-roll mill

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Engineering flow processes to control the microstructure and properties of semiflexible polymers and molecular assemblies is critical for a wide range of industrial applications. A major challenge to this aim lies in understanding the intricate relationship between flow history, microstructure, and rheology in the complex deformation histories typical of processing applications. To address this, we have developed a fluidic four-roll mill (FFoRM) coupled with scanning small-angle X-ray scattering (sSAXS) to generate large Lagrangian flow-history datasets of microstructural evolution in well-defined complex flows. Here, we demonstrate the capabilities of this technique by analyzing a wormlike micelle (WLM) solution using a recently-developed connected-rod scattering model. This model has been validated for WLMs in simple, steady shear flows, but not yet in flows featuring strong extensional or rotational components relevant in industrial processes. The analysis will yield the evolution of key structural and dynamic parameters that describe micellar orientation, stretch, and inter-micellar interactions along Lagrangian trajectories. These insights provide a direct means to test and refine rheological theories and quantify the history-dependent responses of the molecules. By quantitatively characterizing history-dependent material behavior in complex flows, we aim to accelerate the development of predictive constitutive models for complex fluids and enable inverse model-driven design of flow protocols for soft materials processing.

Wednesday 6:30 Sweeney Ballroom E+F PO80

Coupling rheology and microstructure in real time: Advances in rheo-polarized imaging

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Rheo-polarized imaging (RPI) is a rheo-optical technique that couples a rheometer with polarized light imaging to visualize flow-induced anisotropy in complex fluids. We present an advanced RPI system capable of operating from -20 °C to 200 °C while performing real-time calculations of retardation (birefringence) and orientation axis. The setup integrates a stress-controlled air-bearing rheometer with a high-speed polarization camera, enabling simultaneous acquisition of rheological data and two-dimensional microstructural information. Temperature control is achieved via a Peltier glass plate and hood assembly directly mounted on the rheometer.

To demonstrate its capabilities, we performed startup shear experiments on surfactant solutions. The system successfully captured rapid, large-scale changes in microstructure immediately after the onset of flow, providing time-resolved correlations between structural evolution and rheological response. This real-time coupling allowed direct visualization of the formation and break-down of anisotropic structure during transient shear.

By combining rheometry with quantitative polarized imaging, this technique offers a powerful platform for advancing our understanding of soft matter dynamics under complex flow conditions.

Wednesday 6:30 Sweeney Ballroom E+F PO81

4D Rheo-SANS investigation of the structure-property relationships of nanoparticle gels

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Designing soft materials for specific functionalities under flow conditions is critical for many industrial and scientific communities. Effective measurement of the shear deformation of a soft material's structure using scattering techniques paired with accurate mechanical measurements can improve the understanding of fundamental material structure-property relationships. In this work, a 4D Rheo-SANS sample environment measures the paired structure and rheological properties of a model thermoreversible gel following a series of thermal and shear conditions. The 4D Rheo-SANS device enables the measurement of the simultaneous rheology and microstructure in all three planes of flow (flow-vorticity, flow-velocity gradient, and velocity gradient-vorticity planes) in addition to kinetic effects measured as a function of time. A model system of adhesive hard spheres comprised of octadecyl-coated silica particles undergoes gelation upon cooling from 40 °C to under 21 °C. The dispersion is rapidly quenched from the sol state to below the gel temperature and the time evolution of the dynamic moduli (G' and G") are measured. The resulting shear rheology displays a complex path dependence on the quench rate, quench depth, and application of shear. The competition between gel formation, phase separation, and flow influences the rheology-structure behavior of this model colloidal gel, which we characterize using a sticky hard sphere model to determine a measure of attraction in the system. Results from this study help to unify disparate findings in the field between model depletion gels, which gel as arrested phase separation, and thermoreversible gels with rigidity percolation.

Wednesday 6:30 Sweeney Ballroom E+F PO82

On making rheological measurements using a minimum amount of sample

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Rheology is a very useful tool to characterize complex materials like polymers, soft gels, dispersions etc. However, it remains a batch process where a user must manually load the sample in the rheometer and run the experiments. Our aim is to get to a state where performing rheology

experiments can be automated. In order to automate, one step is to find out the minimum amount of sample that is needed to get "good" data. In this work, we attempt to determine the minimum quantity of samples that can give reproducible and accurate results. We tested different materials on two different rheometers and showed that one can get good data at gaps as low as 0.02 mm. We also looked at various errors, like alignment at low gaps and edge effects, that can negatively impact the results.

Wednesday 6:30 Sweeney Ballroom E+F PO83

Developing an optical microscopy method for identifying microplastics in environmental samples

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Microplastic contamination in coastal environments poses a growing threat to ecosystems and human health, yet current detection methods for these microscopic particles are often limited by long processing times, high cost, limited availability, and low signal detection for complex samples. This project aims to develop an optical microscopy technique using Differential Dynamic Microscopy (DDM) to identify and characterize microplastics in environmental water samples. A DDM-based approach would provide valuable information to help track microplastics. To test the approach, PMMA and polystyrene microplastic samples were prepared in water and imaged with brightfield microscopy. Videos of particles were recorded for measurement with DDM. Results verify that the diffusivity increases from the substrate bottom upwards toward the center of the specimen, demonstrating the particles are in genuine Brownian motion. Additionally, the amplitude extracted with DDM is a function of the wavevector (q), and the local minima in amplitude can define the effective length scale of the particles.

Wednesday 6:30 Sweeney Ballroom E+F PO84

Challenges in rheometric signal denoising: Limitations of traditional filters and the potential of latent space modelling

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Accurate rheometric analysis relies on capturing clean time-domain response signals-such as strain (or angular displacement) and stress (or torque)-while preserving their amplitude and phase characteristics. However, in practice, these signals are often contaminated by substantial noise originating from instrumentation or environmental sources, especially when measuring very soft solids or mobile liquids. Traditional denoising methods, including moving average, Savitzky-Golay, Wiener, and wavelet filters, all require extensive parameter tuning and risk altering critical signal features, which can undermine the fidelity of subsequent frequency-domain analysis. These challenges motivate the exploration of data-driven denoising alternatives that can remove artifacts while preserving both temporal and spectral signal integrity. In this poster, we will demonstrate that latent space modeling outperforms traditional denoising methods for rheometric signal denoising. By comparing reconstructed signals from our framework with those produced by conventional filters, we show that this new approach not only reduces noise effectively but also preserves critical signal characteristics in both the time and frequency domains. It delivers good performance in frequency-domain analysis, improving the accuracy of material property evaluations while eliminating the need for manual parameter tuning. This robust approach provides a scalable and efficient solution for establishing a unique signal baseline for any rheometer, as well as for subsequent denoising and processing large rheometric datasets, enabling accurate, high-throughput automated material characterization.

Wednesday 6:30 Sweeney Ballroom E+F PO85

Some useful methods for gathering and analyzing rheological data

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The purpose of this presentation is to summarize in a convenient package some unusual methods for gathering and handling typical rheological data. Included will be such topics as time-temperature superposition, finding the zero-shear-rate viscosity, and locating kink points in steady-flow data. As an example for this abstract, consider the oft-used frequency sweep. The most used method to gather data is to "sweep" from high frequencies to low, while another uses a randomized order of frequencies to eliminate the time-dependence of the measurements. While the data from the latter may look "rougher," it is more realistic in that it has removed the time dependence and converted it to random error, which a model can handle. In addition, the time dependence can be removed.

Wednesday 6:30 Sweeney Ballroom E+F PO86

From chains to networks: Viscoelastic behavior of Vibrio cholerae polysaccharide (VPS)

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Bacterial exopolysaccharides (EPS) are crucial for biofilm mechanics and stability. Here, we investigate the Vibrio polysaccharide (VPS), produced by *Vibrio cholerae* (*Vc*), the causal agent of pandemic cholera. We focus on its rheological behavior in aqueous solutions across varying concentrations. By recording the amplitude/frequency sweeps in linear rheology and large-amplitude oscillatory shear (LAOS) responses, we

quantify the concentration-dependent viscoelastic properties of VPS in aqueous solutions. Our results reveal a transition from dilute to semi-dilute regimes, with chain entanglements emerging at a critical concentration (C_e). We complemented the rheological measurement with characterization of single chain dynamics by small angle X-ray scattering (SAXS), molecular weight measurement with size exclusion column, and molecular dynamics simulations. This work provides mechanistic insight into VPS solution behavior and establishes VPS as a model system linking polysaccharides characteristics to macroscopic rheological properties in bacterial biofilm.

Wednesday 6:30 Sweeney Ballroom E+F PO87

Patterns of viscous intrusion in visco-elasto-plasto media

Benjamin Allen and Nicholas W. Hayman
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Fracturing from plastic failure and viscous fingering can occur simultaneously in many geological and engineering systems, but no model describes the possible transitions and feedbacks between the two. In order to explore fingering and fracturing we access the visco-plastic-elastic transition with injections in a weak transparent gel. We create a tunable reaction in Carbopol 934 gel, a well-known Hershel-Bulkely fluid, by changing the pH to control the cross-linking in the gel, and hence the stiffness and yield-stress. We then inject the gel in a Hele-Shaw cell and inject a glycerine solution creating a fingering instability. The gel has a yield stress and shear-thinning behavior, and therefore the plastic instabilities, viscous stresses, surface tension and elastic response of the gel work to create a phase space with a rich and complex interplay of fingering and fracture like dynamics. Our experiments have applications in geosciences by illuminating geometric patterns in rock veining and producing escape-type structures that might impact carbon sequestration efforts in the field. Such failure phenomena may therefore undergo a more viscous type intrusion rather than sharp fracture singularities.

Wednesday 6:30 Sweeney Ballroom E+F PO88

Optical visualization of plastron stability and wetting transitions on superhydrophobic surfaces

Estefanía Solano-Calderón and Shabnam Mohammadshahi
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We experimentally investigated the plastron (trapped gas layer) stability on superhydrophobic surfaces (SHSs) consisting of spanwise micro-grooves under hydrostatic loading and turbulent flows. 12 SHSs were fabricated via 3D printing and hydrophobic nanoparticle coating; scanning electron microscopy verified nanoparticle coverage. Texture parameters were systematically varied across samples: groove gap (g) from 220 to 600 μm, ridge width (d) from 100 to 500 μm, and groove height (h) from 200 to 400 μm (printing uncertainty ˜ 20 μm). For each sample, the solid fraction fs=d/(d+g) (the percentage of surface area covered by solid) was calculated, and the static water contact angle $\theta 0$ was measured optically by placing a small water droplet (~1 μl). $\theta 0$ was higher than 150° and generally increased with decreasing fs, consistent with Cassie-Baxter behavior. The laminar slip length b was estimated from a standard SHS model (b=(g+d) ln[sec(πfg/2)]/2π, where gas fraction fg=1-fs); larger gaps and lower solid fractions imply larger slip. Plastron stability was first studied in a pressurized chamber using reflected-light microscopy and side-view bright-field imaging. Initially flat interfaces deflected concave as liquid pressure increased; the local contact angle grew to a limiting value, and the interface de-pinned from ridge tips at a critical pressure difference. This critical pressure decreased with increasing groove gap, expecting to fail in shear flows at lower Reynolds numbers. The same SHSs were then tested in a fully developed turbulent channel with Reynolds number (based on channel height and mean velocity) up to 29,000. At the lowest Reynolds number, interfaces were nearly flat and pinned slightly below groove tips. With increasing the Reynolds number, the interface remained pinned but exhibited vibrations; beyond a critical value, a wetting transition occurred, and the entire grooves filled with water. No metastable, partially wetted state was observed in the tested ran

Wednesday 6:30 Sweeney Ballroom E+F PO89

Starch granules offer programmable reinforcement and dynamicity to polymer composites

Shirlaine Juliano[1], Jasmine Samaniego[2], Ian Lillie[1], Peter Iovine[3], and Rae M. Robertson-Anderson[1]
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Composites of particles and polymers are widely used in industry due to the increased mechanical tunability afforded by varying particle-polymer interactions and concentrations of the two components. Biological tissues are exemplary particle-polymer composites that exhibit both strength and reconfigurability. Here, we seek to understand the design rules underlying the mechanical properties of tissue-like composites which we engineer by embedding chemically modified starch granules in a gelatin matrix. We measure the bulk linear viscoelastic properties of composites with varying granule concentration and surface chemistry (neutral, waxy, cationic, anionic). We find that increasing granule concentration increases the modulus of all composite types, suggesting reinforcement. However, surprisingly, we also observe increased dissipation likely due to increased transient hydrogen bonding. Finally, examining composites of multiple starch types reveals emergent mechanical properties that are not a simple sum of the constituent composite properties. These results show that tailoring starch chemistry enables more fine-tuned control over the viscoelastic response of particle-polymer composites, suggesting new design strategies for industrial and biomedical applications.

Gallery of Rheology

Symposium GI
Gallery of Rheology - Images

Organizers: Lilian Hsiao, Kendra Erk and Seth Lindberg

Wednesday 6:30 Sweeney Ballroom E+F GI1

Cutting edge: Fracture of viscoelastic liquids

Maxwell C. Marsh and Randy H. Ewoldt
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Present theories into the onset of the edge fracture instability are well established and accepted by the rheological community. However, prior studies often lack compelling visual evidence of a critical shear rate or a characteristic length consistent with these theories. Here we provide a detailed, high-resolution image of the edge fracture instability in a sheared viscoelastic fluid, complemented by rigorous rheometric data and our newly derived criteria. This result can be used to reinforce the theories behind edge fracture and inspire new mitigation strategies.

Wednesday 6:30 Sweeney Ballroom E+F GI2

Resuspension tree: Shaped by flow and gravity

Mohammadreza Mahmoudian[1], Simon A. Rogers[2], and Parisa Mirbod[1]
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This image reveals a tree-like pattern formed during the resuspension of particles under oscillatory shear flow. As the dense suspension is sheared, particles begin to detach from the sedimented bed and rise to interact with the upper plate. When the shear stops, gravity drives some particles to resettle, while others remain adhered to the plate's surface. These adhered particles, shaped by the transient flow structures during the resuspension process, leave behind a striking branching pattern resembling a tree. This visual captures the moment when flow, adhesion, and sedimentation dynamics intersect, offering a unique window into the interplay between shear forces and particle behavior in dense suspensions.

Wednesday 6:30 Sweeney Ballroom E+F GI3

Twist the rainbow

Abhishek Shetty[1] and Christina Tang[2]
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Cholesteryl ester liquid crystals (LC) self-assemble into periodic helical structures which give rise to their unique, responsive optical properties. We visualize changes in the optical textures with temperature and shear using polarized light microscopy. The observed texture depends on composition, temperature, and shear rate and is path dependent. The colorful textures provide insight into process and material structure. A collection of birefringence patterns are presented.

Wednesday 6:30 Sweeney Ballroom E+F GI4

Luminous webs

Mohammad Tanver Hossain and Randy H. Ewoldt
Mechanical Science and Engineering, University Of Illinois Urbana-champaign, Urbana, IL 61801, United States

Embedded 3D printing enables the fabrication of soft, intricate biological structures by extruding a liquid filament into a yield stress support matrix. This approach enables the creation of features that exceed the resolution limits of conventional 3D printing. Here, a soft fiber structure approximately 100 μm in diameter, illuminated under ultraviolet light, demonstrates the technique's precision and stability. The aqueous microgel suspension supports both immobilizing the printed filament and permits in situ polymerization, producing mechanically stable architectures. This method facilitates the replication of complex biological forms such as spider webs and hagfish slime threads and informs the design of advanced biomimetic materials with improved structural fidelity and functional performance.

Wednesday 6:30 Sweeney Ballroom E+F GI5

Helix of growth

Mohammad Tanver Hossain, Yun Seong Kim, Sameh H. Tawfick, and Randy H. Ewoldt
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Emerging from the earthy foundation, the twisting helix in this image represents our research journey from potential to realization. Fabricated via 'growth printing', a novel additive manufacturing process we developed, the helix mimics the principles of natural growth seen in plants and organisms - where chemical reactions interact with the environment to drive development. Utilizing chemistry that converts liquid resin to solid plastic, we 'grew' this helix into its shape using a motion stage. This sprouting helix showcases the potential of merging nature's wisdom with scientific innovation, opening a doorway to a more sustainable future for manufacturing. For those interested in the technical aspects of materials science: the growth printing is driven by frontal ring-opening metathesis polymerization (FROMP) chemistry, carefully coordinated with printer motion and heat transfer. The self-sustaining exothermic FROMP reaction cures a resin mixture of dicyclopentadiene (DCPD) and polybutadiene (PBD) into a thermoset polymer at a curing at speed approximately 1 mm/s. This process does not require any continuous input of energy to the system to sustain the chemical reaction, making growth printing remarkably energy-efficient and faster compared to conventional additive manufacturing methods.

Wednesday 6:30 Sweeney Ballroom E+F GI6

The art of flow in 3D

Mohammad Tanver Hossain and Randy H. Ewoldt
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Soft matter fabrication merges the science of flow with the creativity of design. Using techniques such as embedded 3D printing and growth printing, fluids are shaped into intricate three-dimensional structures. Rheological control enables the formation of stable, precise, and often biologically inspired architectures, revealing both the functional potential and aesthetic beauty of materials in motion.

Wednesday 6:30 Sweeney Ballroom E+F GI7

Unraveling hagfish skeins

Mohammad Tanver Hossain[1], Douglas S. Fudge[2], and Randy H. Ewoldt[1]
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Time-lapse sequence showing hagfish skein unraveling as a thread peels under tension between a fixed skein and a calibrated glass rod submerged in buffer solution.

Wednesday 6:30 Sweeney Ballroom E+F GI8

Predicting complex structure

Robert Campbell[1], Calvin Zhuang[2], Paniz Haghighi[1], Ali Mohraz[2], and Safa Jamali[1]
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Microstructure affects the rheology of many materials. In colloidal gels, we can predict structure from just three pieces of information, but this model has limits. It assumes that colloidal interactions are dominated by "central forces" - long range interactions like gravity and electromagnetism. Many real colloidal particles also experience "non-central forces" like friction. This composite image combines confocal images of real colloidal gels made with both high and low non-central forces. Each experiment is paired with a computer simulation that predicts the structure. The images are stitched together with generative AI to create a continuous gradient, showing how structure changes under both conditions as the total central forces become stronger. Building model systems like these is important for discovering new ways to design the structure and rheology of real products.

Wednesday 6:30 Sweeney Ballroom E+F GI9

The AI revelation: Using machine learning tools to accelerate micrograph analysis

Matthew Kaboolian and Kendra A. Erk
School of Materials Engineering, Purdue Univeristy, West Lafayette, IN 47907, United States

Getting quantitative analysis from micrographs can often be challenging. Trying to segment features from grey-on-grey images can be extremely tedious or even impossible, given the image. But what about using systems that try to think and see like a human? Into this niche are Vision Foundation Models (VFMs) such as Segment Anything for Microscopy (µSAM). These artificial intelligence (AI) tools train models on extremely large external image sets in order to achieve quick, high-accuracy segmentation. Here, thermal stress-induced parabolic focal conic defects (pFCDs) formed in surfactant liquid crystals were readily segmented using µSAM. Within a few minutes, a series of high-resolution micrographs were segmented and the respective defect sizes measured. We hope to convey that the application of AI image processing tools, such as VFMs, opens the door to characterizing structures that were once deemed impossible to analyze.

Wednesday 6:30 Sweeney Ballroom E+F GI10

The treachery of modeling

Javen S. Weston and Kathryn Weston
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This illustration is not a pipe, it does not contain a fluid, be it Newtonian or shear-thinning; it does not exhibit shear banding, nor do we have to worry about boundary layer slip at the solid-fluid interface. The purpose of this poster is to remind us all that representations and models are not reality. They are a necessary and invaluable part of how we understand the world around us, but they are not the thing they are depicting. By pairing an illustration of pipe flow similar to those seen in every fluid mechanics textbook with the textual statement that 'this is not pipe flow' you are invited to reflect on the idea that images are symbols and representations not the things that they represent. In our work, we must resist the instinct to believe in the illusion that they are identical. (This work is a direct homage to the 1929 painting 'The Treachery of Images' by artist Rene Magritte)

Wednesday 6:30 Sweeney Ballroom E+F GI11

Event-based capillarity-driven extensional rheometry

Lucas N. Warwaruk and Gareth H. McKinley
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Capillarity-driven extensional rheometry is a widely used technique for measuring the extensional viscosity of low-viscosity liquids. It leverages the Rayleigh-Plateau instability and surface tension to induce uniaxial deformation in a thinning liquid filament. By tracking the filament radius over time, key rheological properties-including extensional viscosity-can be inferred. While effective, this method typically requires high-speed imaging, making it costly in terms of both equipment and data storage. To address these limitations, we introduce a novel approach using an event-based imaging system to perform capillarity-driven extensional rheometry. Event-based cameras detect changes in light intensity rather than capturing full frames, enabling adaptive sampling rates based on scene activity. This eliminates the need for user-defined frame rates and dramatically reduces data requirements. Our method achieves comparable accuracy in measuring filament radius and extensional viscosity at roughly 20 % of the cost of a conventional high-speed camera. Moreover, data storage is reduced by two orders of magnitude: a typical 12-bit, 1 MPixel high-speed recording may require ~1 GB, whereas an event-based recording uses only ~10 MB. This event-driven imaging paradigm offers a transformative alternative for capturing high-speed free-surface flows, making capillarity-driven extensional rheometry significantly more accessible and cost-effective for a broader range of researchers and applications.

Wednesday 6:30 Sweeney Ballroom E+F GI12

Mineralization

Akul N. Seshadri, John A. Howarter, and Kendra A. Erk
School of Materials Engineering, Purdue Univeristy, West Lafayette, IN 47907, United States

Cement a seemingly humble material upholds our built environment. An unassuming view of cured cement at the macroscale veils the complex and alien world fresh cement hydration at the microscale. Polymer hydrogels internally cure cement by releasing water, fueling hydration reactions, and affecting the nucleation and growth of cement-strengthening hydrates. Cryogenic and low-vacuum electron microscopy allows this dynamic process to be viewed directly. These images showcase the kaleidoscope of early-age cement hydrate morphologies in cement paste and mineralizing on polyacrylamide-based hydrogels.

Wednesday 6:30 Sweeney Ballroom E+F GI13

Jellyfish: Oil drainage from porous hydrogels

Babak Valipour Goodarzi and Reza Foudazi
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Porous hydrogel can be synthesized from oil-in-water emulsion templates. In this work, as-synthesized hydrogels based on poly(ethylene glycol)-diacrylate and chitosan are immersed in water for washing the oil in pores. Consequently, the process of water uptake by pore network expels residual oil and surfactants from porous network of hydrogel. The expelled oils form plumes that visualize the flow profile of the drainage within the water bath, resembling the shape of a jellyfish. These dynamics play a crucial role in solvent exchange, which is particularly important for drug delivery in pharmaceutical industry.

Wednesday 6:30 Sweeney Ballroom E+F GI15

Echoes of a vortex in soft-gel

Mousavi Seyed Pedram[1], Hassanzadeh Hossein[1], Masoud Daneshi[2], Claus-Dieter Ohl[3], and Taghavi Seyed Mohammad[1]
[1]Laval University, Québec, Quebec, Canada; [2]NETZSCH, Burlington, MA 01803, United States; [3]Faculty of Natural Sciences, Institute for Physics, Otto-von-Guericke-University Magdeburg, Magdeburg, Germany

Understanding how liquids move through materials is crucial for advancing technologies such as liquid-in-liquid printing and drug delivery. Our research investigates how the flow and dispersion of fluids are influenced by the properties of gel-like materials. In our experiment, dyed water was injected into a polymer gel using a micro-nozzle. The image captures the formation of a stable vortex ring, expanding symmetrically around a central axis and forming a striking anchor-shaped structure. Remarkably, this configuration remained intact for hours after the injection stopped.

The gel's high viscosity and yield stress played a key role in preserving the mixing vortex structures by preventing its early dissipation. By studying how these material properties affect fluid motion, we aim to better control jet behavior.

Symposium GV
Gallery of Rheology - Videos

Organizers: Randy Ewoldt, Michelle Calabrese and Ryan Murphy

Wednesday 6:30 Sweeney Ballroom E+F GV1

Pinching cytoskeleton composites

Aysan Razzaghi[1], Megan T. Valentine[2], Ryan J. McGorty[1], and Rae M. Robertson-Anderson[1]
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Active cytoskeletal composites (ACCs) - in vitro reconstitution of actin filaments, microtubules, and motor proteins - are structurally and mechanically heterogeneous. In this video, we use holographic optical tweezers to trap multiple micron-sized beads within an ACC and periodically move them to locally "pinch" the network. This multiplexed shearing allows us to simultaneously probe locations with different connectivity and stiffness, mapping spatiotemporal stress propagates through this complex medium. The multiplexed shear-induced deformation reveals time evolving correlations, and space-dependent responses.

Wednesday 6:30 Sweeney Ballroom E+F GV2

Jamming in sickle blood flow

Hannah M. Szafraniec[1], Freya Bull[2], Philip Pearce[2], and Dave K. Wood[3]
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The rheology of suspensions is driven by the volume fraction of particles where discrete effects, such as near-wall lubrication and non-uniform cross-sectional particle distributions, govern local flow dynamics at small scales. This video demonstrates striking flow dynamics of deoxygenated sickle blood where significant axial variations in local red blood cell volume fractions develop along the length of the channel. Flow fields in these high-volume-fraction regions exhibit extreme profile blunting indicative of jamming, despite average volume fractions remaining well below the theoretical jamming limit. These variations reveal a critical microscopic mechanism responsible for the drastic increases in flow resistance observed in microchannels containing deoxygenated sickle blood not predicted by continuum approaches. In sickle cell disease, such hyper viscosity is linked to microvascular complications and increased disease severity, highlighting the need for accurate descriptions of biofluids that also capture the particle-level dynamics in physiologically relevant systems.

Wednesday 6:30 Sweeney Ballroom E+F GV3

Photoelastic microparticles glow as they flow

Krishnaroop Chaudhuri, Brandon Hayes, and Nathalie M. Vriend
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Photoelastic disks have been widely used to study granular flows. Interactions between disks have been studied to understand the deformations and stress distribution during natural occurrences like avalanches, landslides, and hopper flows. However, the length scales of these studies are of the macroscopic order, i.e., in centimeters and meters. It is not well understood how the scaling and dynamics of photoelastic collisions change as we reduce the size scale, and proceed to the micrometer and nanometer order. We study the interactions inside a suspension of photoelastic gelatin microparticles in water. We introduce stresses inside the chamber and observe the resultant stress-optic behavior using a high speed camera and a microscope.

Wednesday 6:30 Sweeney Ballroom E+F GV4

When bubbles fall in love: A cavitation tale

Hassanzadeh Hossein[1], Seyed Pedram Mousavi[1], Claus-Dieter Ohl[2], and Seyed Mohammad Taghavi[1]
[1]Laval University, Québec, Quebec, Canada; [2]Faculty of Natural Sciences, Institute for Physics, Otto-von-Guericke-University Magdeburg, Magdeburg, Germany

We investigate laser-induced cavitation bubble dynamics near the free surface of a viscoplastic fluid. Through controlled experiments, we explore how the stand-off distance and fluid rheology influence the formation and evolution of bubble-driven flows. Four distinct regimes emerge depending on these parameters: swelling, trapped, bullet jet, and vapor jet. At close proximity to the surface, the bubble remains anchored, producing a gentle surface deformation. At intermediate distances, the competition between inertial and yield stress forces gives rise to either confined jets or more forceful bullet-like penetrations. At larger separations, vigorous bubble collapse leads to narrow vapor jets that pierce the fluid. To rationalize the observed behaviors, we develop a simplified force-balance model that captures the penetration dynamics in the trapped and bullet jet regimes, showing strong agreement with experimental observations.

Wednesday 6:30 Sweeney Ballroom E+F GV5

Brownian dynamics simulations of chains in shear and extensional flow

Isaac M. Pincus

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The coil-stretch transition and end-over-end tumbling are key features of polymer dynamics in extensional and shear flow respectively. Although we might understand how a changing Weissenberg number affects the rheology of a polymer solution in each flow, it can be helpful to also have a clear picture of the individual polymer dynamics. Here we display Brownian dynamics simulations of polymer chains in shear and extensional flows, with the flow fields included to aid visualization. We hope that they will be useful in better understanding the dynamics of polymer solutions in a variety of flows.

Wednesday 6:30 Sweeney Ballroom E+F GV6

Windmills of your polymer

Arshiya Bhadu[1], Alicyn M. Rhoades[2], and Ralph H. Colby[1]

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A polymer melt (HDPE here) under steady shear in parallel plates geometry undergoes a liquid crystalline phase transition that resembles a spinning windmill. This makes me wonder what the windmill would look like for the polymer that you work with?

Wednesday 6:30 Sweeney Ballroom E+F GV7

Waves, spirals, and chaos in soft matter!

Taisuke Sato[1] and Abhishek Shetty[2]

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We present real-time visualization of flow-induced microstructural changes in a surfactant solution using rheo-polarized imaging (RPI). Combining a stress-controlled rheometer with a high-speed polarization camera, RPI simultaneously measures rheology and birefringence. In a constant-shear startup, a high-birefringence wave propagated inward, followed by a spiral pattern toward the center. Irregular patterns later revealed spatiotemporal microstructural fluctuations. These results show that micellar structures evolve dynamically from flow onset, with RPI capturing transient mesoscale features-waves, spirals, and instabilities-offering new insight into soft matter startup dynamics.

Wednesday 6:30 Sweeney Ballroom E+F GV8

Milk splash!

Louie Edano and Vivek Sharma

Chemical Engineering, University of Illinois Chicago, Chicago, IL 60607, United States

We revisit the milk splash experiment using a plant-based alternative: sheet happens, things fall apart, revealing splashy differences!

Wednesday 6:30 Sweeney Ballroom E+F GV9

Defects, defects everywhere

Matthew Kaboolian and Kendra A. Erk

School of Materials Engineering, Purdue Univeristy, West Lafayette, IN 47907, United States

Concentrated surfactant lamellar phases can form parabolic focal conic defects (pFCDs) when heated. In this video, SLES lamellar paste was heated from 25 °C to 85 °C, clearly showing the transition from isotropic, aligned bilayers into the birefringent, flower-shaped, anisotropic pFCD texture. Deformation within the microstructure can be seen, with oily streaks shifting in concert with the defects' appearance. Based on the defect formation temperatures and their shapes, the nanoscale mechanical properties of the lamellae can be probed. This approach allows for improved formulation development as well as providing a method to produce microlenses and nanotemplates.

Wednesday 6:30 Sweeney Ballroom E+F GV10

Formulation dynamics and shear stability of graphene–Carbopol nanofluids: From preparation to rheological performance

Yane H. Santos[1], Cecillia Tanner[1], Géssica Palaoro[1], Diogo E. V. Andrade[2], and Admilson T. Franco[3]

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The preparation process of graphene-carbopol nanofluids is crucial to achieving uniform dispersion and long-term stability, which directly impact their rheological properties. This work presents a visual and experimental investigation of the formulation dynamics of Carbopol 0.15 wt% gels loaded with graphene nanoparticles (0.25-2.5 wt%). The sequence of images captures the dispersion stage, highlighting nanoparticle wetting, vortex-induced mixing, and the gradual integration of graphene into the polymeric network. Rheological analyses, including steady shear and

oscillatory tests, revealed a pronounced viscosity reduction and viscoelastic modulus decrease with increasing graphene content, consistent with a flake-flake network disruption effect. Despite these changes, all samples maintained Herschel-Bulkley behavior with measurable yield stress and stable viscoelastic solid response (G' > G"). Zeta potential measurements confirmed high electrostatic stability (˜ -2000 mV), and the nanofluids exhibited excellent shear resistance during extended mixing. The combination of visual documentation and rheological characterization offers a comprehensive perspective on the interplay between formulation conditions and the final performance of graphene-based non-Newtonian nanofluids.

Wednesday 6:30 Sweeney Ballroom E+F GV11

Fluid intrusion and fingering across the viscous to solid transition

Benjamin Allen[1] and Nicholas W. Hayman[2]

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Fracturing from plastic failure and viscous fingering can occur simultaneously in many geological and engineering systems, but no model describes the possible transitions and feedbacks between the two. In order to explore fingering and fracturing we access the visco-plastic-elastic transition with injections in a weak transparent gel. We create a tunable reaction in Carbopol 934 gel, a well known Herschel-Bulkley fluid, by changing the pH to control the cross-linking in the gel, and hence the stiffness and yield-stress. The gel has a yield stress and shear-thinning behavior, and therefore the plastic instabilities, viscous stresses, surface tension and elastic response of the gel work to create a phase space with a rich and complex interplay of fingering and fracture like dynamics. Our experiments show blunted tips and elastic like fracture that might be seen in rock veining, which suggest a more viscous type intrusion rather than sharp fracture singularities. Examining the surrounding matrix of rock we can compare the strain history around the edges of rock veins with the strain of the bulk measured in our experiments.

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Social Program and Special Events

Sunday, October 19

Rheology Research Symposium (continued from Saturday, Oct 18)

Welcoming Reception
6:00 PM – 8:00 PM Santa Fe Convention Center Outdoor Plaza
Sponsored by Anton Paar USA

Monday, October 20

Exhibits
8:30 AM – 4:00 PM Santa Fe Convention Center Lobby

Geosciences Lunch, by invitation only
12:00 noon – 1:30 PM Pojoaque/Nambe/Ohkay Owingeh

Gallery of Rheology Preview
1:30 PM – Wed 4:00 PM Sweeney Ballroom E+F

Gallery of Rheology Online Voting
1:30 PM – Wed 8:00 PM Meeting Web App

Monday Evening Reception
7:00 PM – 9:00 PM New Mexico History Museum
Sponsored by TA Instruments

Tuesday, October 21

Exhibits
8:30 AM – 4:00 PM Santa Fe Convention Center Lobby

Society Business Meeting
12:00 noon – 1:30 PM Sweeney Ballroom E+F

Student Night
6:30 PM – 9:00 PM Tumbleroot Pottery Pub

Awards Banquet
8:00 PM Santa Fe Farmers' Market Pavilion
Bus to Pavilion leaves 6:30 – 8:00 PM from Grant St in front of Convention Center.

Wednesday, October 22

Exhibits
8:30 AM – 4:00 PM Santa Fe Convention Center Lobby

Student-Industry Forum
12:00 noon – 1:30 PM Pojoaque/Nambe/Ohkay Owingeh
Sponsored by Dow and American Institute of Physics

Poster Session and Reception
6:30 PM – 8:30 PM Sweeney Ballroom E+F
Reception sponsored by Anton-Paar USA

Gallery of Rheology Sessions
6:30 PM – 8:30 PM Sweeney Ballroom E+F
Equipment sponsored by Los Alamos National Laboratory
Online voting ends at 8:00 PM.

Thursday, October 23

Exhibits
8:00 AM – 10:35 AM Santa Fe Convention Center Lobby

The Society of Rheology gratefully acknowledges the generous support of Anton-Paar USA, TA Instruments, Dow, American Institute of Physics, Sandia National Laboratories and Los Alamos National Laboratory.