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# Editorial: Dynamics of complex fluids

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Editorial on the Research Topic
Dynamics of complex fluids

This timely Research Topic delves into the dynamics of complex fluid systems, a topic of fundamental importance in science and technology. Complex fluids have been studied for decades in various contexts; yet, they are still to be understood fully and remain subjects of intense exploration. Rheologically complex and typically microstructured, the non-equilibrium response of these systems to external forcing and stress is usually scale-dependent. Features of fundamental importance include transport properties, phase separation, flow-induced fluctuations, hydrodynamic stability, and memory effects. In technological settings, complex fluids interact with their environment via fluid-boundary interactions and geometric confinement with these external effects combining with the complex rheological properties to provide avenues for interesting and non-trivial properties to arise. Furthermore, connecting effects that occur due to mechanisms operating at the microscale with larger system size effects driven by boundaries remains very challenging.

The papers in this Research Topic highlight and explore intricate and non-trivial behaviors seen in complex fluids and structured systems. These include understanding shear flows of soft cohesive particles with a view toward elucidating shear strength, structure, and avalanches; flow fluctuations and particle speeds in rapidly flowing suspensions; nanofluid dynamics in confined systems and near surfaces; rapid flows in dense suspensions; the impact of bubble distributions on internal flow characteristics of multiphase pumps, stochastic non-Newtonian flows in porous media, and applications of AI and neural network models to probe transport properties of hybrid fluid flows. By integrating theoretical, experimental, and computational methodologies, the authors address important scientific questions across various materials ranging from granular matter, particle suspensions, nanofluids, and multiphase systems. Some of these papers also go beyond traditional continuum fluid mechanical approaches and incorporate mechanisms operating at the particle scale, such as particle-shear effects, particle-particle interactions, and stochastic effects. In general, in terms of approaches, methodologies, and results, the investigations presented here reveal nuanced insights into important and timely research topics.

Here, we summarize each contribution briefly and highlight novel aspects of each. The manuscript on dense suspensions by Moghimi et al. describes a novel method for precisely measuring particle speeds in fast-flowing dense suspensions using laser line scanning. A comparison of results obtained from line scanning in the flow direction with results of line scanning in the vorticity direction suggests that scanning along the vorticity direction overestimates the speed by 15%–25% due to the anisotropic structure of the suspension. Furthermore, in the shear-thickening regime, line scanning in the flow direction revealed complex flow behaviors, including backflows and stagnation effects which were not easily or accurately detected with scanning in the vorticity direction. Thus, the experimental methodology presented here provides a more accurate way to measure particle velocities in challenging flow conditions, particularly in rapidly flowing dense suspensions experiencing strong non-affine flows. Combining the two scanning modes together has the potential to identify dynamic behavior of suspensions across multi-scale multi-flow regimes. This paper also highlights the need to critically evaluate current techniques for precise speed measurements in complex flows.

The theoretical contribution by Saitoh on soft cohesive particle systems provides an excellent illustration of how small scale particle-particle interactions may fundamentally affect the mechanical behavior in soft particulate systems. Specifically, the role of cohesive interactions on the mechanical response is investigated using molecular dynamics simulations. Using a cohesive contact model where particles are coated with sticky layers of controlled thickness, the study demonstrates that even minimal cohesive interactions (via thicknesses as low as 1% of particle diameter) dramatically change not only shear strength and shear stress effects, but also structural features including force-chain networks and particle rearrangements. In particular, the study reveals that cohesive forces cause localization of particle rearrangements to become more localized, particularly in less dense systems. Interestingly, scaling laws governing avalanches in these complex materials exhibited power-law exponents that differed from mean-field theory predictions. Together, the simulations clearly show that cohesive interactions profoundly influence the mechanical responses of granular materials, especially in systems with low particle density.

In their paper, Arif et al. study a different out-of-equilibrium and rheologically complex system using computational methods. Specifically, they present a novel two-stage computational approach for solving stochastic Darcy-Forchheimer non-Newtonian fluid flows, focusing on a Williamson fluid over a stationary sheet. The computational scheme integrates elements of classical solution schemes for partial-different equations with elements of stochastic solution schemes. Specifically, the approach integrates a modified time integrator with a second-stage Runge-Kutta scheme, achieving second-order temporal accuracy and sixth-order spatial discretization. In parallel and as a component of the model, the Euler-Maruyama approach is used to handle stochasticity to effectively capture complex interactions between deterministic and stochastic effects in fluid dynamics. Comprehensive numerical experiments examine key effects including elastic effects, magnetic effects, and inertial effects. Numerical experiments demonstrate the method's superior accuracy compared to existing second-order Runge-Kutta schemes, particularly in solving Stokes' first problem. The article thus provides a efficient and practical framework for modeling stochastic non-Newtonian fluid flows in porous media with important potential applications in engineering, geophysics, and industrial systems.

Bubbly suspensions and gas-liquid-based multiphase materials offer a means to investigate critical interfacial phenomena at the fundamental level. In their computational investigation of the effect of bubbles in multiphase pumps, Guo et al. tackle technologically and industrially relevant problems that arise in the handling of these complex soft systems. Here, the impact of bubble dynamics, specifically bubble coalescence and breakup, on flow patterns in multiphase pumps of bubble dynamics is considered using a CFD model. A systematic study reveals that the bubble distribution characteristics and the bubble volume fraction vary spatially within the pump and are also strongly impacted by the operating speed. The authors performed a careful analysis of vortical flow patterns in the diffuser and impeller domains and correlated the flow characteristics with bubble patterns and bubble breakup zones. The results presented provide useful guidelines for predicting and optimizing the design of multiphase pumps.

Novel computational approaches such as artificial neural networks and fuzzy models have fundamentally transformed the way science and technology problems are approached. These approaches are versatile and offer novel means to tackle high-dimensional problems such as those naturally emergent in complex fluid flows under non-equilibrium conditions. Nanofluids are a particularly important type of complex fluids; the flow of these typically involves electromagnetic fields and occurs in intricate geometries. This Research Topic features three papers that address the dynamics in these novel systems.

The article by Ullah et al. presents an investigation of an idealized, yet important, canonical flow problem, the two-dimensional flow of a nanofluid past an exponentially stretched sheet. In the study, the effects of the magnetic field, heat transfer, and convective flow are also considered. A reduced ODE model is first obtained and solved. The novelty here is the parallel analysis of these equations using Artificial Neural Networks (ANNs), trained with the Levenberg-Marquardt algorithm. Analysis of the residual error and the minimum absolute error enable the authors to calculate metrics quantifying the accuracy and the overall performance of the ANN model. This study is an example of how ANN models offer advantages in detailed investigation of complex multi-dimensional problems. The article also illustrates the importance of validating ANN models. The article by Ullah et al. on insights into thermal transport in hybrid nanofluid flows also uses ANN methods to guide the investigation of complex fluid flows. Here, the authors investigate the impact of magnetic fields, thermal radiation, thermophoresis, and Brownian effects on hybrid nanofluid flow past a porous spinning disk. Finally, the paper by Zulqarnain et al. is a similarly themed numerical contribution that studies the role of hydromagnetic effects, heat transfer, and viscous dissipation on the flow of a fuzzy hybrid nanofluid over an permeable exponentially stretching/shrinking surface. First, a set of similarity transforms is used to convert the underlying partial differential equations (PDEs) into an ODE system. Homotopy methods are then applied to tackle the ODE system under conditions where there is fuzziness in the nanofluid and hybrid nanofluid volume fractions. The methodology employs fuzzy differential equations (FDEs); typically, these are rarely encountered in studies of complex fluids. In terms of practical applications, the paper suggests means to enhance hear transfer by using hybrid nanofluids with applications in the processing and manufacturing sectors. At the theoretical level, the use of fuzzy differential equations combined with homotopy techniques is novel and illuminating.

Collectively, these investigations demonstrate the profound complexity inherent in soft matter systems. They reveal how seemingly minor variations in particle interactions, boundary conditions, and external forces can generate dramatically different material behaviors. Overall, the papers demonstrate that new methods and sophisticated, interdisciplinary approaches are needed to understand complex fluid systems, a critical component of these being the bridging theoretical modeling, precise experimental techniques, and machine learning and network based novel solution methods.

In conclusion, the experimental techniques, advanced computations, and theory described in the featured articles of this topical Research Topic represent a significant advancement in our understanding of complex fluid dynamics. By presenting a diverse array of cutting-edge research, the Research Topic of research articles offers a nuanced perspective on the fundamental properties of these fascinating materials, while simultaneously highlighting promising avenues for future scientific and technological innovation.

## Author contributions

AG: Project administration, Resources, Writing – original draft, Validation, Supervision, Conceptualization, Writing – review and editing. AS: Writing – original draft, Validation, Resources, Project administration, Writing – review and editing, Conceptualization, Supervision. FV: Resources, Supervision, Writing – original draft, Project administration, Conceptualization, Validation, Writing – review and editing.

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## Conflict of interest

The author(s) declared that this work was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

## Generative AI statement

The author(s) declared that generative AI was not used in the creation of this manuscript.

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