Particle simulation and continuum modeling for dense suspension flows

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Viscoelastic fluids are non-Newtonian fluids characterized by their elastic structures and relaxation processes. However, what type of non-Newtonian fluid behavior emerges when solid particles are dispersed in a viscous liquid? Suspensions of fine solid particles, despite having much simpler components compared to polymer systems, have seen slow progress in the study of their rheology and constitutive modeling. This presentation aims to provide an overview of the current state of research on particle suspensions.

Particle suspensions have traditionally been studied within the framework of fluid mechanics. In dilute limits, a solid theoretical foundation exists based on hydrodynamics, making it a well-defined problem based on the Stokes equation—a comfortable starting point for applied mathematicians. However, when the volume fraction becomes finite, a crucial decision arises: should the particles be modeled as smooth spheres, which is a natural assumption? Typically, a no-slip boundary condition is applied at the particle surface. Under such idealization, the resistance coefficient diverges as particles approach each other, creating a singularity that has long hindered progress. Particularly for colloidal particles, it was once believed that the Brownian motion, considering the increasing viscous resistance in the limit of close particle approach, would prevent contact. The higher the Péclet number, the closer the system approaches this singularity, leading to an increase in the apparent viscosity—a phenomenon considered the mechanism behind shear thickening.

In reality, experimental evidence suggests that contact occurs even at finite Péclet numbers. Since real particle surfaces are not perfectly smooth, surface contact leads to interlocking, restricting tangential relative motion [1]. Even in systems without attractive forces that induce gelation, frictional contacts can create transient "bonds" during flow. This emergence of elastic structures from an otherwise freely moving particle system is the essence of the physics governing the flow behavior of dense suspensions.

Capturing the emergence of such elastic structures in a constitutive model is not straightforward. Existing models [2] for suspensions are rooted in the historical context mentioned above, involving components like affine deformations, hydrodynamic interactions, and closures that assume isotropy—all based on the fluid mechanical perspective. It is suggested that these models must explicitly address the emergence of elastic structures rather than the mere divergence of viscosity. Additionally, the volume fraction field acts as an internal degree of freedom within particle suspensions, and uniform dispersion cannot always be assumed under non-uniform flow.

Thus, there are still challenges to be addressed in the study of dense suspensions, which are of significant industrial relevance.

References

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