Rheology of Dense Suspensions of Non-Colloidal Particles in Yield-Stress Fluids

S. Dagois-Bohy[a], S. Hormozi[b], E. Guazzelli[a], O. Pouliquen[a]

a. Aix-Marseille Université, CNRS, IUSTI UMR 7343, 13453 Marseille, France,
email : simdagbo@gmail.com
b. Department of Mechanical Engineering, Ohio University, Athens, Ohio 45701-2979, USA

Abstract :

Pressure-imposed rheometry is used to study the rheological properties of suspensions of non-colloidal spheres in yield stress fluids. Accurate measurements for both the shear stress and particle normal stress are obtained in the dense regime. The rheological measurements are favourably compared to a model based on scaling arguments and homogenisation methods.

Key words : suspensions ; particle/fluid flows ; complex fluid ; rheology ; non-newtonian flows.

Dense suspensions are materials involved in many industrial processes or natural phenomena (e.g. concrete, drilling muds, lava, debris flows, etc.). Suspensions of solid, spherical particles in a Newtonian fluid have been extensively studied over the last century [1]. In the case of particles and fluid having the same density, the scaling of the shear stress in a steady shear flow is viscous, i.e. $\tau = \eta_s(\phi)\eta_f\dot{\gamma}$, where $\dot{\gamma}$ is the shear rate, η_f the fluid viscosity. $\eta_s(\phi)$ is the effective shear viscosity, which depends only on the particle volume fraction and diverges at maximum packing fraction ϕ_m. In addition, there is a particle normal stress P, which has similar scaling properties.

There exists another approach coming from the rheology of dry granular media, and relying on a frictional description of the problem [2]. When an assembly of particles confined with a pressure P is sheared, there is only one dimensionless parameter governing the friction $\mu = \tau/P$ and the volume fraction ϕ. Boyer *et al.* [3] applied these ideas to wet suspensions, in which viscous forces are dominant, and the dimensionless number is $J = \eta_f\dot{\gamma}/P$. This alternative way of looking at suspensions allowed to circumvent the divergence observed close to ϕ_m in volume-imposed rheometry.

In many real situations though, the suspending fluid is not a perfect newtonian fluid, and can exhibit a yield stress. The understanding of these fluids themselves has not been yet fully achieved, and even the dynamics of just a few spheres in such a fluid reveals to be extremely difficult to predict, since most of the numerical and analytical methods developed for Newtonian fluids are inapplicable when the rheological law is non-linear. There is then a compelling need to capture the rheological behaviour of these complex suspensions in order to predict their flow in various practical situations.

The problem can alternatively be addressed from a continuum-level closure perspective. The aim becomes to deduce their rheological behavior from the knowledge of the pure fluid rheology and of the particle concentration. Adding particles to a yield-stress fluid usually enhances the effective yield-stress and consistency of the viscoplastic suspension, which is consistent with a nonlinear homogenization approach proposed by Chateau *et al.* [4], although the agreement is not fully satisfactory due to large experimental scatter.

In the work presented here, we used a pressure-imposed shear cell derived form Boyer *et al.* [2] to investigate the rheology of dense suspensions of rigid particles in a visco-plastic fluid. An original setup was used, consisting in an annular shear cell in a plate-plate geometry, but with a porous top plate that allows the fluid, but not the particles, to flow through it. This top plate can move vertically in the suspension and impose a pressure on the grains, which is measured and controlled throughout the experiments. Unlike in conventional suspension rheology measurements, here the solid volume fraction varies so that the particle pressure balances the imposed pressure. We carried out systematic experiments on suspensions of $d = 580\ \mu\mathrm{m}$ polystyrene grains in fluids with various yield stresses, as well as in a newtonian fluid.

In the Newtonian case, the key features found by Boyer *et al.* [3] are recovered.
In the case of a yield stress suspending fluid, an additional stress scale (i.e. the yield stress) enters the problem and the rheology can no longer be described with a single dimensional number, but needs an additional one (for example $J_y = \tau_y/P$ when P is a control parameter, with τ_y the yield stress of the pure fluid). Dimensional analysis is therefore not sufficient to describe the viscoplastic suspension. However it is possible to go further by using the hypotheses developped in Chateau *et al.* [4] : In the steady state, the fluid is supposed to be equivalent to a newtonian fluid, whose apparent viscosity would be given by the local shear rate between the grains. Close to ϕ_m, this local shear rate is supposed to be homogeneous and given by the geometry only, i.e. given only by the macroscopic shear rate and the volumic fraction ϕ.

These hypotheses are enough to fully close the problem, and we are then able to express the rheology of the viscoplastic suspension from the knowledge of the newtonian suspension and the pure fluid rheology, both in volume or pressure control formalism. This model shows excellent agreement with experimental data, and we are able to carefully test and validate these hypotheses.

Références

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