Abstract

This thesis presents experimental measurements of the rheological behavior of liquid-solid mixtures at moderate Reynolds (defined by the shear rate and particle diameter) and Stokes numbers, ranging from $3 \leq Re \leq 1.6 \times 10^3$ and $0.4 \leq St \leq 195$. The experiments use a specifically designed Couette cylindrical rheometer that allows for probing the transition from transporting a pure liquid to transporting a dense suspension of particles. Measurements of the shear stress are presented for a wide range of particle concentration (10 to 60% in volume) and for particle to fluid density ratio (ρ_p/ρ) between 1 and 1.05. The effective relative viscosity exhibits a strong dependence on the solid fraction for all density ratios tested. For $\rho_p/\rho = 1$ the effective viscosity increases with Stokes number (St) for volume fractions (ϕ) lower than 40% and becomes constant for higher ϕ. When the particles are denser than the liquid, the effective viscosity shows a stronger dependance on St. An analysis of the particle resuspension for the case with $\rho_p/\rho = 1.05$ is presented and used to predict the local volume fraction where the shear stress measurements take place. When the local volume fraction is considered, the effective viscosity for settling and no settling particles is consistent, indicating that the effective viscosity is independent of differences in density between the solid and liquid phase. Shear stress measurements of pure fluids (no particles) were performed using the same rheometer, and a deviation from laminar behavior is observed for gap Reynolds numbers above 4000, indicating the presence of hydrodynamic instabilities associated with the rotation of the outer cylinder. The increase on the effective viscosity with Stokes numbers observed for mixtures with $\phi \leq 30\%$ appears to be affected by such hydrodynamic instabilities. The effective viscosity for the current experiments is considerably higher than the one reported in non-inertial suspensions.

Experiment - where theory comes to die

-Sidney R. Nagel

Contents

[1] Some of the material that is summarized in this section is taken from a paper by Koos, Linares-Guerrero, Hunt, and Brennen (2012)

List of Tables

List of Figures

List of Symbols

$\bar{\phi}$	Loading volume fraction
δ	Depletion layer thickness
$\dot{\gamma}$	Shear rate
μ_{app}	Apparent suspension viscosity from smooth wall measurements
μ	Suspending liquid viscosity
μ'	Suspension effective viscosity
μ'^{*}_{min}	Lowest effective viscosity for each volume fraction $\rho_p/\rho = 1.05$
μ'_{min}	Lowest effective viscosity for each volume fraction and $\rho_p/\rho = 1$
ω	Rotational speed
ϕ	Volume fraction
ϕ_m	Maximum volume fraction
ϕ_{RCP}	Random close packing
ϕ_{RLP}	Random loose packing
ψ	Sphericity
ρ	Suspending liquid density
ρ_p	Particle density
τ	Shear stress
b	Shear gap width
d	Particle diameter
H	Height of test cylinder

h	Height reached by particles
h_s	Height of settled particles
h_T	Total annulus height
h_{tm}	Height measured from porous medium surface to annulus top
M	Measured torque
$M_{eff,\, laminar}$	Effective laminar torque based on effective viscosity, $M_{eff,\, laminar} = 2\pi r_i^2 H\dot{\gamma}\mu'_{min}$
$M_{laminar}$	Torque from laminar theory, $M_{laminar} = 4\pi\mu H\omega r_i^2 r_o^2/(r_o^2 - r_i^2)$
Pe	Péclet number, $Pe = 6\pi\mu d^3\dot{\gamma}/kT$
r_i	Inner cylinder radius
r_o	Outer cylinder radius
Re	Reynolds number based on shear rate and particle diameter, $Re = \rho\dot{\gamma}d^2/\mu$
$Re^*_{b,\, eff}$	Modified effective Reynolds, $Re^*_{b,\, eff} = \rho\omega b/\mu'^*_{min}$
Re^*_b	Modified gap Reynolds number based on rotational speed, $Re^*_b = \rho r_o\omega b/\mu$
Re_b	Gap Reynolds number based on shear rate, $Re_b = \rho\dot{\gamma}b^2/\mu$
$Re_{b,\, eff}$	Effective Reynolds number, $Re_{b,\, eff} = \rho\omega r_o b/\mu'$
Sc	Schmidt number, $Sc = Pe/Re$
St	Stokes number, $St = \rho_p Re/9\rho$
V_p	Volume of particles