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HYDRODYNAMIC PARTICLE MIGRATION IN SMALL-AMPLITUDE, OSCILLATORY, CIRCULAR COUETTE FLOW: THE LIMITS OF REVERSIBILITY

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1. INTRODUCTION

Initially well-mixed suspensions of large spherical particles in viscous Newtonian fluids subjected to continuous nonhomogeneous shear flows demix and establish large concentration gradients. A number of experimental studies have determined that the particles migrate to the low shear-rate region in one-dimensional flow fields (Refs. 1-7). Other investigators have proposed mechanisms to model the migration caused by the presence of nonuniform shear gradients (Refs. 8-10). Here, we report on the shear-induced migration of particles in the annular space between two coaxial cylinders (a wide-gap Couette), with the inner cylinder oscillating and the outer cylinder fixed. In these experiments, the conditions are such that colloidal and inertial forces do not exert an appreciable effect on the suspensions of neutrally buoyant spherical particles in Newtonian liquids. Nuclear magnetic resonance (NMR) imaging is used to measure the concentration profile during the demixing of the initially well-mixed suspensions.

In a previous paper, the particles were found to migrate from the higher shear-rate regions near the rotating inner cylinder to the lower shear-rate regions near the stationary outer wall, which established large concentration gradients after only a short time (Ref. 11). The particle migration rate was determined to be directly proportional to the shear rate, all other things being equal. Therefore, the total extent of the migration depends only on the total amount of strain applied to the suspension, independent of the rate. Furthermore, if the inner rod was rotated 100 turns clockwise, followed by 100 turns counterclockwise, the extent of the migration would be comparable to 200 turns in

either direction, even though in creeping flow the particle motions should be reversible. An interesting question is, "if the shear is applied by oscillating the inner rod, does the suspension ever display reversible flow (i.e. no particle migration)?" By comparing the concentration profile from an oscillatory case with one in which the rod is turned continuously in one direction, we found that below a certain critical amplitude oscillation, the flow is reversible. At greater amplitudes of oscillation, migration occurred only in the high shear-rate region of the profile. Preliminary observations indicate that the critical oscillation amplitude appears to be independent of particle size.

2. EXPERIMENTAL

The techniques used in this experiment remain essentially the same as those described in Ref. 11. The suspensions consisted of polymethyl methacrylate (PMMA) particles suspended in a density-matched liquid. This liquid has been tested up to a shear rates of 100 s^{-1} and displays no non-Newtonian behavior. Its viscosity μ_0 is 4.95 Pa·s at 23.15°C. Both monodisperse 3.175 mm-diameter spheres and polydisperse, 6.3–1200 μm particles were used. Although the temperature of each suspension was controlled only by the room air conditioner, no settling of the suspended particles was detected over the duration of a typical experiment. However, during one of the oscillatory experiments, the suspension did settle over a 24 hour period.

Wide gap Couettes were used to produce inhomogeneous shear flow fields in the gaps. Each apparatus consisted of a rotating solid PMMA cylinder concentric in a fixed outer PMMA tube capped with solid PMMA disks. In the Couette, the outer

radius of the inner rod (R_i) was 0.64 cm, the inner radius of the outer tube (R_o) was 2.38 cm, and the length of the suspension-filled cavity was 25 cm.

In this set of experiments, the effective rotation rate of the inner cylinder varied between 6 and 60 rpm and was constant during any one experiment. This gives shear rates from about 0.04 to 4 s⁻¹ (assuming a Newtonian fluid response) across the gap of the Couettes. The motor was stopped after predetermined number of oscillations and NMR images of the Couette were taken.

After taking an initial image, the procedure was to start with a smallest amplitude oscillation θ_m of interest. Then, from results of the continuously turned Couette, we chose a total number of revolutions such that a significant amount of migration could occur if the Couette was turned continuously in one direction. The equivalent number of full revolutions N is related to the number of oscillations N_o by $N = \frac{\theta_m}{\pi} N_o$. If no migration is observed then, a second, or third, set of oscillations could be tried. If no migration was observed for the subsequent sets of oscillations, then a larger amplitude oscillation would be tried. Using this method, the experiment would proceed until migration was observed.

Images were taken of a cross-sectional slice, 2.4-in thick, perpendicular to the Couette axis, about midway along the apparatus. The time required for each image was ~ 8 min. Back-to-back repeated images indicate no significant settling or particle redistribution during this interval. In these experiments, the intensity values in the part of the slice corresponding to the Couette were normalized such that the average intensity of the image matched the mid fraction, which was known to a high degree of accuracy. The centroid of each image was computed, corresponding to the Couette axis, allowing the average fluid concentration to be determined as a function of radial position measured from the imputed centroid. From a prior set of experiments (Ref. 11), it has been determined that the overall accuracy, including suspension preparation, sample loading, and NMR measurement, is $< 5\%$.

RESULTS

Three principle results came from this investigation. The first shows that there is a critical amplitude oscillation below which migration will not occur (which is probably because of the critical amount of strain necessary to make the particle

Figure 1: The concentration profiles of a 50 vol % suspension of polydisperse 670 μm particles both for continuous turns and oscillations. The transient responses are for an oscillation amplitude of 1.57 radians. Note that the continuous turning caused migration throughout the gap, while the oscillatory response only caused migration in the high shear rate part of the gap. The solid line represents the initial location of the critical strain, assuming a Newtonian response.

particle interactions irreversible). The second is that the critical oscillation appears to be independent (or, at most weakly dependent) of particle size. The third is that an estimate of the critical strain was determined, based on the Newtonian fluid response at the beginning of each experiment.

In the first two experiments 50 vol% suspensions of 3.175 mm spheres and 670 μm particles were used. Using amplitudes of 0.29, 0.35, and 0.52 radians, neither of the suspensions showed any migration for several hundreds or thousands of oscillations (the larger amount of oscillations for the smaller particles). However, at an oscillation amplitude of 1.11 radians, the 3.175 mm spheres showed some particle migration. Because of the small amount of migration, the smaller particle Couette was oscillated for 600 oscillations. The resulting profile was the steady state profile suggesting that the effect upon the rate of migration may depend on either particle size or polydispersity.

A second experiment with the small particles was performed with $\theta_m = 1.57$ radians to determine approximately the migration rate. Several interesting things occurred in this experiment. First, we were able to determine the transient response in

the small particle suspension as shown in Figure 1. Second, we observed that when the suspension was allowed to oscillate overnight, it rose, leaving a small layer of pure fluid along the bottom of the Couette. Interestingly, upon continuously rotating the inner rod, we found that the pure fluid layer had been "mixed" back into the suspensions by 60 revolutions. Third, the suspension developed a two-dimensional profile, resembling a two arm spiral galaxy, in which there were gradients in the θ direction. This instability is the subject of another investigation. However, because the Taylor number for these experiments is small ($< 10^{-2}$), this instability is not believed to be caused by inertial effects.

If the mechanism for particle migration is related to the total amount of strain a particle undergoes during one oscillation, then we can determine a minimum value for critical strain from the maximum strain value when $\theta_m = 0.52$ radians (the largest amplitude oscillation for which there was no migration,) which is 0.29 ± 0.02 . If we then determine the radial position at which this amount of strain would be present in a Newtonian fluid, then the position at which we find this strain value is marked on Figures 1 by a vertical line. Since this point is near the minimum fluid (maximum solids) concentration in the suspension, this suggests that the minimum value is probably close to the actual critical strain value.

4. SUMMARY

NMR imaging allows the study of flow-induced particle migration in concentrated suspensions. Concentration profiles are easily determined, and good spatial resolution can be obtained. When subjected to flow between rotating concentric cylinders, neutrally buoyant, suspended particles migrate away from the rotating inner rod only if the amplitude of oscillation exceeds a critical value. We have shown that for small oscillations, the suspension flow appears to be fully reversible (no particle migration). Above a critical oscillation amplitude, however, migration does occur, but only in the high strain flow region. This leads to the concept of a critical amount of strain, which is necessary for particle migration to occur. We have bounded the critical amount of strain between 0.25 and 0.50, which corresponds roughly to the maximum strain near the inner rod for oscillation amplitudes of 0.5 and 1.0 radians (assuming a New-

tonian response), respectively. This critical strain value appears to be independent of particle size, although the effect upon the migration rate might be quite different. This phenomena can not currently be explained by any particle migration model.

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