CONSTANT FORCE AND CONSTANT VELOCITY MOMENTUM TRACERS IN CONCENTRATED SUSPENSIONS

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Summary Measurements were made of the apparent viscosity, η_r, of a suspension (relative to that of the pure fluid) using either a settling ball animated by a constant gravitational force (η_r^F) or a towed ball translating with a constant velocity (η_r^V). Over the range of suspension concentrations examined $(0.1 \le \phi \le 0.5)$, η_r^V was found to be significantly larger than η_r^F.

INTRODUCTION

Homogeneous materials are characterized by intrinsic material properties such as density and viscosity that are independent of sample size and of the state of stress of the material. In particular, viscosity is a material property of a Newtonian fluid. For example, a rheological experiment conducted with a test sphere traversing a homogeneous Newtonian fluid would yield the same viscosity whether the experiment involved measuring the force on the test sphere when towed at a constant velocity or the velocity of the test sphere when moving under the influence of a constant force. A series of experiments were performed to explore the difference between the apparent viscosity of a suspension as determined by a constant gravitational force applied to a test sphere (falling-ball rheometry) and the apparent viscosity of the same suspension measured with a test sphere towed (pulling-ball rheometry) with uniform velocity through the suspension. The relative viscosities in both the falling-ball, η_r^F, and towed-ball experiments, η_r^V, were determined by normalizing the suspension results to those obtained in identical experiments in the pure suspending fluid.

EXPERIMENTAL SETUP

The suspending fluid used for these experiments matches the density and refractive index of the particles. Suspensions made using this fluid are neutrally buoyant and transparent. This allows optical techniques to be used in experiments where there are only a limited number of particle interfaces to look through. The suspending fluid consists of a solution of 1,1,2,2, tetrabromethane (TBE, Eastman Kodak, Rochester, NY), polyethylene glycol (90,000 and 9,500 UCON oil, Union Carbide Corp., Danbury, CT), and alkylaryl polyether alcohol (Triton X-100, J.T. Baker, Phillipsburg, NJ). The suspending particles were polymethyl methacrylate (PMMA) spheres obtained from three separate manufacturers in order to obtain the wide range of sizes used in the experiments. All the particles were large enough that colloidal and Brownian forces were not expected to exert an appreciable effect on the suspension behavior [1]. Suspensions of these particles were prepared with solid fractions of $\phi = 0.1$, 0.2, 0.3, and 0.5.

In the constant force experiments, test spheres settling in the transparent suspensions were timed with stopwatches through pre-measured zones in the cylinder. The beginning of the first measurement zone was approximately one cylinder diameter from the fluid level in the cylinder, and the last zone ended at the bottom of the cylinder. The mean velocity for the falling balls at the midpoint between adjacent lines was calculated from the interval time and the known distance. In order to obtain a reproducible average, each interval velocity was then averaged over 5-10 ball drops [2]. The suspension was slowly and thoroughly stirred before each ball drop in order to randomize the microstructure and to maintain uniform concentration in each experiment.

For the constant velocity experiments, a motor with constant velocity settings was used to pull the test sphere through the suspension. After stirring the suspension, the test sphere was allowed to sink to the bottom of the cylinder (away from the centerline) pulling the line down with it. Then, the sphere was centered a small distance off the bottom of the cylinder. A scale registered the force required to pull the test sphere through the fluid system. This information was used to calculate the relative viscosities of the fluids and suspensions. The line passed through a rubber gasket fixed at the free surface to ensure that fluid dragging on the line did not leave the system. The suspensions were slowly and thoroughly stirred after each ball drop or pull.

RESULTS

The effect of ϕ on η_r^V/η_r^F was examined. Over the range of suspension concentrations examined $(0.1 \le \phi \le 0.5)$, η_r^V was found to be significantly larger than η_r^F, and the difference increases linearly as ϕ increases from 0.1 to 0.5. This is shown in Fig. 1. It is interesting that $\eta_r^V/\eta_r^F > 1$ in even the most dilute of the suspensions studied. Many non-Newtonian effects are not detectable in dilute and moderately concentrated suspensions, $\phi \le 0.2$ [2], but η_r^V/η_r^F is greater than one in all the suspensions studied $(0.1 \le \phi \le 0.5)$. Hence, the results of this investigation support the conclusion that apparent viscosities of both dilute and concentrated suspensions are non-Newtonian and are not material properties [3]. The dimensionless parameter $\lambda = a_s/a_b$ is also used in the theoretical analysis of the reduced viscosities [3]. Test spheres of several sizes were used in the falling-ball and towed-ball experiments on the suspensions. In Fig. 2, η_r^V/η_r^F is shown as a function of λ over the range of our data. There was a statistically supportable effect of λ over the experimental range of this investigation $(0.11 \le \lambda \le 1.00)$.

Figure 1

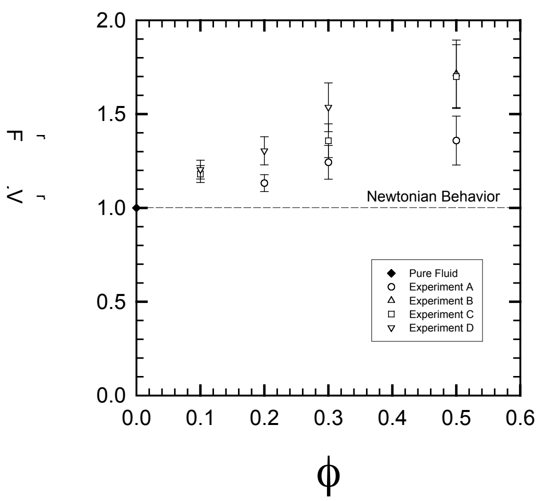
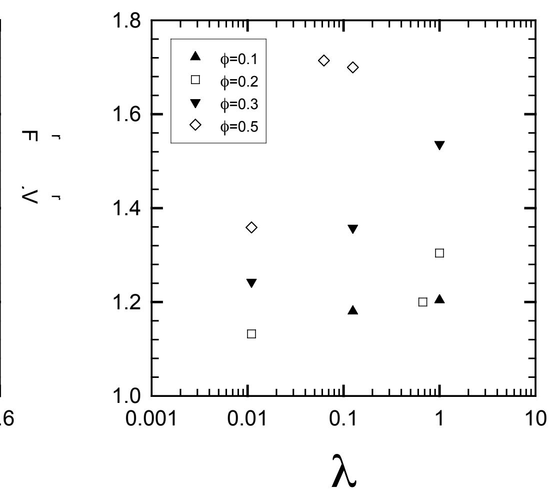


Figure 2



CONCLUSIONS

The objective of this study was to experimentally explore the difference between the apparent viscosity of a suspension as determined by a constant gravitational force applied to a test sphere (falling-ball rheometry) and the apparent viscosity of the same suspension measured with a non-rotating test sphere towed (towed-ball rheometry) with uniform velocity through the suspension. One of the primary results of this paper is the conclusion that the apparent viscosity of the suspension is always larger for the constant velocity case than for the constant force case. The experimental results of this study show a strong linear dependence of the ratio of η_r^V/η_r^F on ϕ over the entire range of our data. Past studies had indicated that dilute suspensions $(\phi \le 0.2)$ exhibited essentially Newtonian behavior, and the non-linear effects were observed at higher concentrations [2]. In this study, the towed-ball tests exhibit non-Newtonian behavior for the suspensions for the entire range $(0.1 \le \phi \le 0.5)$.

References

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