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MIGRATION OF BUOYANT MONO- AND BI-DISPERSE SUSPENSIONS IN LOW REYNOLDS NUMBER PRESSURE-DRIVEN PIPE FLOW

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Summary: Suspensions of neutrally buoyant particles in low Reynolds number, pressure-driven flows migrate from regions of high to low shear. When the particle density does not match that of the suspending fluid, buoyancy forces, as quantified by a dimensionless buoyancy number, determines the particle distribution. We use electrical resistance tomography (ERT) to visualize and quantify particle migration in pressure-driven pipe flow of monodisperse suspensions of dense or light particles and bidisperse suspensions of heavy and almost neutrally buoyant particles. The images reveal greater particle segregation for the suspensions at higher buoyancy numbers. Experiments with bidisperse suspensions reveal enhanced resuspension of the heavier particles. In addition for some flow conditions an adverse density gradient is observed with heavy suspension above light. Additionally, ERT imaging captured the developing concentration profile, revealing a complex evolution to fully developed flow. The particle distributions are reasonably well-predicted by a suspension transport model.

INTRODUCTION

Particles in highly viscous suspension flows fall in the Stokes regime, where inertial effects are negligible. A unique property of these flows is the migration of particles away from areas of high shear [1-4]. For example, neutrally buoyant particles in pressure-driven flow in a pipe have been observed to migrate to the centre of the pipe [3,4], and this has been modelled with the so-called suspension balance model[5].

In the case of heavy or light particles, there is a competition between the buoyancy forces, which tend to segregate the particles to the top or bottom of a horizontal pipe, and the migration to the centre of the flow, as quantified by a buoyancy number. This problem for flow between parallel plates has been solved theoretically[6], but there is, however, little experimental data for low Reynolds number, pressure-driven suspension flows with buoyant particles. One exception is a study by Altobelli, Givler and Fukushima using nuclear magnetic resonance imaging [3]. Although, they were able to obtain excellent velocity profiles, the concentration profiles were only qualitative in nature, and they had difficulty resolving the concentration of particles near the surface of the pipe.

The purpose of this study is to make quantitative measurements of the concentration profiles of suspensions where buoyancy forces are important. Here, the concentration profiles of monodisperse suspensions of heavy or light particles and bidisperse suspensions of heavy and almost neutrally buoyant particles in pressure-driven pipe flow are determined using non-invasive ERT imaging. All of the experiments are performed at low pipe-Reynolds numbers, and vanishing particle-Reynolds numbers. The experimental results of this study are then compared to the predictions of the suspension balance model

ELECTRICAL RESISTANCE TOMOGRAPHY IMAGING

ERT is a non-invasive imaging technique with many applications in the medical field and industrial processes. ERT has also been applied to several industrial applications. For example, ERT has been used successfully to monitor mixing tanks at a pilot plant scale [7]. Additionally, ERT has been used to determine concentration profiles of neutrally buoyant particles in a viscous, pressure-driven pipe flow [4] and to monitor pulp consistency in paper processing [8].

ERT imaging is based on the variation in potential fields due to the applied current through a material with varying impedance. A potential field, which is determined by the conductivity distribution in the imaging plane, is produced by introducing a current through a series of electrodes surrounding the plane of interest. The resulting potentials are measured at the electrodes surrounding the image plane. A non-linear inverse algorithm is used to convert these potential measurements into the previously unknown conductivity field. Finally, the computed conductivity profiles are transformed to concentration fields of the multiphase flows using established correlations.

EXPERIMENTAL CONDITIONS

The suspending fluid consisted of UCON lubricant 75-H-90000 to which an aqueous NaI solution was added to produce the desired viscosity, density and conductivity. Silver or PMMA particles were added to the suspending fluid to the desired volume fraction and the suspension was thoroughly mixed at a moderate speed. To measure buoyancy effects in low Reynolds number, pressure-driven pipe flow, the suspensions were pumped at a controlled flow rate through a flow loop. Four ERT sensor arrays are placed at predetermined lengths, and a pressure gauge is used to obtain the average pressure gradient in each experiment.

Table 1 summarizes the volumetric flow rate, pressure gradient, particle-Reynolds number, pipe-Reynolds number and buoyancy number for all experiments. The experimental buoyancy number is defined as $N_b=2(\rho_p- \rho_f)gR^2/9\eta U$, where ρ_p is the density of the particles, ρ_f is the density of the fluid, g is gravity, R is the radius of the pipe, η is the kinematic viscosity and U is the average velocity.

Table 1. Experimental Parameters

Experiment		Q (cm^3s^{-1})	$\Delta P/L$ ($g\ cm^{-2}s^{-2}$)	$Re_{particle}$	Re_{pipe}	N_b
Heavy	1	37.1	986	6.3×10^{-3}	2.12	4.9
	2	18.9	552	3.2×10^{-3}	1.08	9.5
	3	9.7	268	1.6×10^{-3}	0.55	18.6
Light	4	10.8	613	3.7×10^{-3}	0.35	-2.1
	5	5.4	355	1.8×10^{-3}	0.18	-4.2
	6	2.6	199	8.9×10^{-4}	0.09	-8.7

Table 1. Summary of experimental conditions. The volumetric flow rate is given by *Q*, the average pressure gradient $\Delta P/L$, the particle-Reynolds number $Re_{particle}$, the pipe-Reynolds number Re_{pipe}, and the buoyancy number N_b.

RESULTS

Typical results of the experimental measurements are illustrated in Figure 1, which presents the particle distribution with increasing buoyancy number for light particles. For high flow rates (low absolute N_b) there is significant resuspension and for low flow rates (high absolute N_b) there is more particle segregation to the top of the pipe. Surprisingly, pressure gradient measurements are found to undergo a minimum before reaching a plateau at fully developed flow, which can be explained by the evolution of the concentration profile. Experiments with bidisperse suspensions (not shown here) reveal enhanced resuspension of the heavier particles. In addition for some flow conditions an adverse density gradient is observed with heavy suspension above light. All the experiments are compared to the theoretical predictions of the suspension balance model (not shown here), which is found to predict the experimental observations reasonably well.

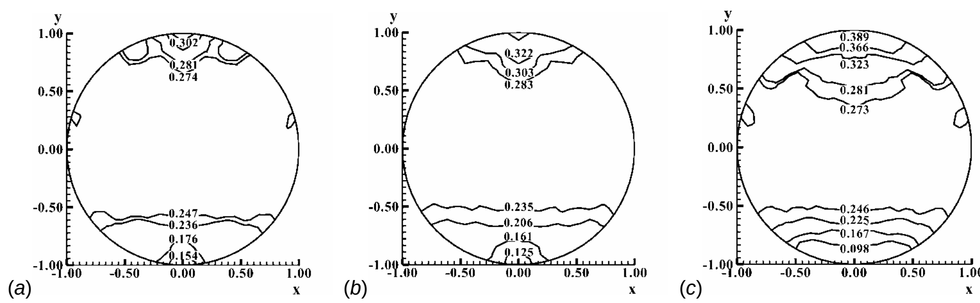

Figure 1. Contour plots of the concentration profile at 9.8 m downstream of the inline mixer for ϕ_b=0.20 and for experimental buoyancy numbers. (*a*) N_b = -2.1; (*b*) N_b = -4.2; (*c*) N_b = -8.7.

CONCLUSIONS

We have made the first quantitative measurements of the particle distribution of low Reynolds number mono- and bi-disperse buoyant suspensions in pressure-driven flow in a pipe. Viscous resuspension is shown to occur, and indeed in some cases to the extent that adverse density gradients can exist in the pipe. The suspension balance model of Nott & Brady is shown to predict the particle distribution reasonably well.

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