Evolution of the flow of a concentrated suspension through an annular expansion measured by NMRI

Tracey Moraczewski and Nina C. Shapley
Department of Chemical Engineering, Columbia University, New York, NY

Introduction

We investigate the flow of a concentrated suspension through an abrupt, axisymmetric expansion, which can be encountered in such applications as materials processing or flow in the circulatory system. To date, few experimental data and modeling calculations are available for concentrated suspensions in expansion flow. In this study, suspensions of neutrally buoyant, noncolloidal spheres in Newtonian liquids undergo pressure-driven flow at low to moderate Reynolds numbers in an abrupt, axisymmetric 1:4 expansion. Particle concentration and velocity profiles are obtained by nuclear magnetic resonance imaging (NMRI). We aim to determine the influence of particle and flow properties (e.g. particle volume fraction ϕ, particle and flow Reynolds number Re and Re_p, tube-particle radius ratio R/a) on the interaction between particles and recirculating flow regions such as the corner vortex.

In two studies carried out under distinct flow regimes, both Altobelli *et al*. (1997) and Karino and Goldsmith (1977) found that particle accumulation or depletion in expansion flow vortices depended on particle size, but reported opposite trends of particle separation by size. The apparently conflicting findings motivated the investigation here of particle behavior over a range of volume fractions and Reynolds numbers. Also, flow through an abrupt expansion is a familiar test problem for comparing theory and experiment in Newtonian (Macagno and Hung, 1967) and non-Newtonian fluids (Townsend and Walters, 1994). As reviewed in an article by Arola et al. (1998), the influence of several non-Newtonian flow properties on the length of recirculating regions in laminar expansion flows has been examined. Hence, the comparison can be extended here to concentrated suspensions.

Materials and Experimental Methods

A Plexiglas flow cell (see Figure 1) consisting of an abrupt, axisymmetric expansion was placed through the bore of a 9.4 Tesla vertical bore magnet (Bruker), and a bi-directional, computer-controlled, tubing pump circulated the suspension in a closed loop from a reservoir through the flow cell. Velocities ranging from 0.2 to 7.6 cm/s in the downstream tube were used in this study. An expansion size ratio of 1:4 was used, and concentrated suspensions of three different particle sizes were investigated. Each of the suspensions consisted of neutrally buoyant, rigid spheres in a Newtonian fluid. The suspending fluid was a mixture of glycerin and water with a composition to match the density of the particles to ± 0.001 g/cm^3. Three particle sizes were studied at particle volume fractions ranging from 0.2 to 0.5. In all cases, the particles were large enough to neglect Brownian and colloidal effects.

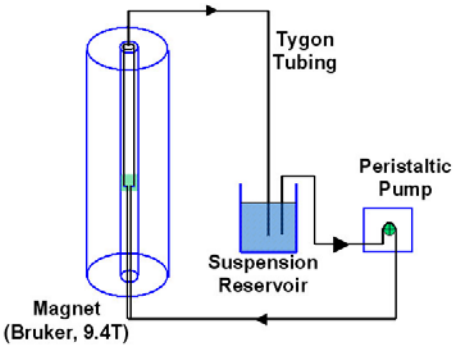

Figure 1. Experimental setup for NMR imaging.

One suspension contained poly(methyl methacrylate) (PMMA) spheres with a broad size distribution and a mean diameter of 85 ± 20 μm with a density of 1.18 g/cm^3. The second suspension contained polystyrene spheres with a mean diameter of 255 ± 105 μm. A third suspension of larger polystyrene particles with a mean diameter of 485 ± 105 μm was also used. The density of the polystyrene suspensions was 1.045 g/cm^3. Carboxymethyl cellulose of either 0.5 or 0.75 wt% (depending on the desired viscosity) was dissolved in the suspending fluid to increase the viscosity of the polystyrene particle suspensions.

Spin-echo axial and longitudinal images were obtained with nuclear magnetic resonance imaging (NMRI) to monitor concentration and flow patterns in both the radial and flow directions. Due to the short spin-spin relaxation time of the protons in the particles, each image pixel provides concentration or motion information due to the fluid only. The typical image size was 128 x 128 pixels with a 3 cm field of view and a slice thickness of 1 mm, producing a voxel size of 0.2 x 0.2 x 1 mm^3. Concentration profiles were calculated from normalized intensity images. Velocity analysis was performed using time-of-flight (TOF) tagging and phase encoding methods. Flow field properties such as volumetric flow rates and recirculation lengths were obtained from velocity images.

Results

Figure 2 shows representative longitudinal concentration images through the center of the tube for the 85 μm particle (*R/a* = 224) suspensions. The images were obtained after the flow reached steady state. Similar general features were observed in the concentration images for all particle sizes and bulk volume fractions. A more concentrated region was seen in the center of the tube with a less concentrated region near the walls and in the corners of the expansion, indicating particle depletion from recirculating regions. From Figure 2, it can be seen that the bulk particle fraction had a distinct effect on the shape of the concentration profiles. At bulk particle concentrations of 0.4 and higher, the images exhibited a bright border of high fluid volume fraction between the center and outer regions in the downstream tube for all particle sizes.

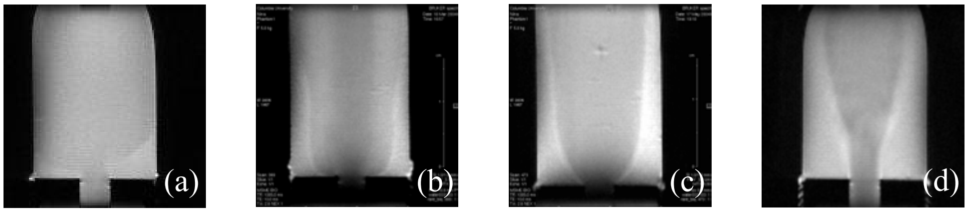

Figure 2. Spin-echo concentration images (longitudinal cross-sections) of initially homogeneous, monodisperse suspensions in an abrupt, 1:4 expansion. Images were obtained after the flow reached steady state. (a-d) 85 μm PMMA particles a) ϕ_{bulk} = 0.2, *Re* = 0.6, Re_p = 0.005; b) ϕ_{bulk} = 0.4, *Re* = 0.7, Re_p = 0.023; c) ϕ_{bulk} = 0.48, *Re* = 0.01, Re_p = 0.006; d) ϕ_{bulk} = 0.5, *Re* = 0.01, Re_p = 0.016.

Discussion

The suspensions investigated here clearly deviated from behavior seen for Newtonian fluids in expansions. Oliveira and Pinho (1997) reported that the normalized recirculation length (x_R/h) was 0.45 for a Newtonian liquid at a Reynolds number of 0.5 in a 1:4 expansion. The recirculation length for a suspension was significantly larger than the Newtonian recirculation length and clearly increased with increasing particle volume fraction, as is demonstrated in Figure 3. Maximum values of the recirculation length in steady flow were observed at particle volume fractions ranging from 0.45 to 0.5. In comparison, the particle size has only a minor impact on the recirculation length.

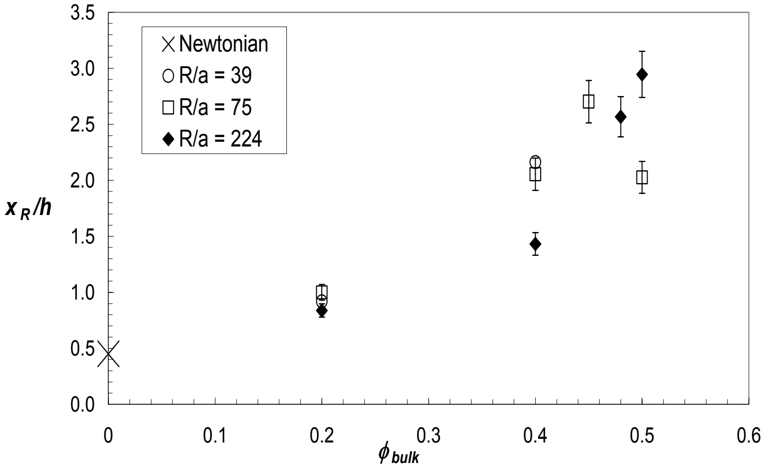

Figure 3. Effect of particle size and bulk particle volume fraction on normalized recirculation length. Reynolds numbers range from 0.01 to 0.7.

Conclusions

In steady flows of concentrated suspensions in a 1:4 abrupt, axisymmetric expansion, concentration profiles were found to have a strong dependence on bulk particle volume fraction. Also, particle depletion was observed in recirculation regions under all the conditions examined in this study. Further results concerning the evolution of particle concentration and flow fields can be acquired by fast imaging methods.

References

Altobelli, S. A., E. Fukushima and L. A. Mondy, "Nuclear magnetic resonance imaging of particle migration in suspensions undergoing extrusion," J. Rheol. **41** (5), 1105-1115 (1997).

Arola, D. F., R. L. Powell, M. J. McCarthy, T. Q. Li and L. Odberg, “NMR imaging of pulp suspension flowing through an abrupt pipe expansion,” AICHE J. **44**, 2597-2606 (1998).

Karino, T. and H. L. Goldsmith, "Flow behavior of blood-cells and rigid spheres in an annular vortex," Phil. Trans. of the Royal Society of London Series B-Biological Sciences **279**, 413-445 (1977).

Macagno, E. O. and T. K. Hung, “Computational and experimental study of a captive annular eddy,” J. Fluid Mech. **28**, 43-64 (1967).

Oliveira, P. J. and F. T. Pinho, “Pressure drop coefficient of laminar Newtonian flow in axisymmetric sudden expansions,” International Journal of Heat and Fluid Flow **18**, 518-529 (1997).

Townsend, P. and K. Walters, “Expansion flows of non-Newtonian liquids,” Chem. Eng. Sci. **49**, 749-763 (1994).