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On-Line Slurry Viscosity and Concentration Measurement as a Real-Time Waste Stream Characterization Tool

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Research Objective

This project seeks to develop an on-line sensor to measure the viscosity of dense slurries.

Research Progress and Implications

This report summarizes work after two years of a three year project.

The flow behavior of slurries is important for many of the proposed unit operations to be used in the conveying and processing of tank wastes. One alternative for determining the rheological properties of such materials is to obtain samples and test them off-line using conventional rheometers. Such a protocol is not practical for a wide variety of wastes. Rather, it is the goal of this work to find on-line, in - process techniques for measurement. There are two systems that we have propose examining: (1) Nuclear magnetic resonance imaging (NMRI), and, (2) Ultrasonic Doppler Velocimetry. Central to both of these techniques is the measurement of velocity profiles in pipe flows.

For the NMRI measurements, the presence of particles has two principal effects on the NMRI velocity profiles: a decrease in signal intensity and image blurring. Similar effects are observed in turbulent flows due to the local random fluctuations in the flow. This similarity has led us to turbulent flow using NMRI. The governing equations for the signal obtained by NMRI are the Bloch-Torrey equations. Previously, we showed a relationship between turbulent fluctuations and spatial signal intensity variations, assuming isotropic turbulence. However, this assumption does not reflect the true nature of turbulence in a pipe flow where the turbulence is not isotropic. In our new work the Bloch-Torrey equations will be solved by first, time averaging and then employing a turbulence model for pipe flow. The purpose of the time averaging is to smooth the fluctuations of time scale smaller than that of NMRI data acquisition.

After this work with single phase fluids, we shall undertake NMRI experiments of slurry flow. Various operational parameters will be optimized during the experiments to obtain velocity profile of the flow. Pressure drops will also be recorded to obtain shear stress distribution. Plot of shear stress versus the shear rate, obtained from the velocity profile, will yield the shear viscosity over a wide range of shear rate. The velocity images will also be analyzed to compare the effects of fluctuations with those of turbulent flow experiments

For single phase fluids, the NMRI and the UDV work will be compared with measurements using LAV. In our LAV. flow apparatus, the working fluid, water, is gravity fed from a reservoir into a horizontal one inch Pyrex tube, 180 diameters in length. The system enables traverses of the optical probe in the horizontal and vertical directions, with a resolution of 200 micrometers.

Radial distributions of the axial component of velocity were obtained at a location 150 diameters from the tube entrance. Measurements in the laminar regime indicate a precision of within one percent, as indicated by the root mean square fluctuations. In the turbulent regime, radial profiles of the mean and fluctuation velocities agree with literature values. In the laminar regime, symmetry of the radial velocity distribution was observed in the horizontal plane passing through the axis, but was not in general observed in the vertical plane passing through the axis. Further investigation revealed that the asymmetry was a result of buoyancy due to heat transfer between the working fluid and the surroundings, even though the pipe was not actively heated or cooled. Temperature differences as little as 1 degree Celsius were found to result in significant asymmetry. To have a reproducible result in the laminar regime, it was necessary to control the reservoir temperature to within 0.1 degree Celsius.

Modeling efforts are underway to predict the asymmetric velocity profiles using a commercially available finite element code, FIDAP, which solves the Navier Stokes equations with the energy equation. Also, possible effects of this heat transfer phenomena on the transition to turbulence are being investigated.

The UDV work is aimed at the development and demonstration of a new approach for measurement of the velocity profile and local viscosity in a heterogeneous slurry pipe flow. This technique is based on simultaneous tomographic pulse-echo ultrasonic flow velocity and time-of-flight speed of sound measurements. Reconstruction of the velocity distribution is based on the measured local speed of sound, which depends on the local slurry concentration. To show the feasibility in applying this technique, we have carried out controlled experiments in the laboratory with known fluids and flow conditions. The two fluids tested were a viscous Newtonian fluid, propylene glycol, and a non-Newtonian fluid, Carbopol 980. The flow conditions tested were fully developed laminar pipe flow. The velocity measurements were validated against both LAV. measurements and theoretical predictions. The speed of sound results were shown to produce reproducible measurements and consistent with existing data. Obtaining an accurate velocity profile is our first milestone for developing an on line, real-time rheometer for measurements in dense slurries flowing within pipelines.

The experimental work with slurries is coupled with simulations of particle suspensions. Here, we have extended our previous studies of the mechanics of hydrodynamically interacting spherical particles having different sizes to suspensions of many sizes. Stokesian Dynamics is used to study the microrheology of suspensions having particles of two or more different sizes. The simulation is carried out by calculating the many body far-field hydrodynamic interactions, the near-field hydrodynamic lubrication resistances and the interparticle forces. Velocity and stress are then determined from these calculations, from which the position is integrated in time and the bulk suspension viscosity is found. Our work to date has shown that at fixed solids loading of particles, the relative viscosity of concentrated suspensions is lower when particles of different sizes are used than particles of the same size. This is illustrated by the case of suspensions including two sizes; the viscosity reduction increases as the ratio of the particle radii increases and it has a maximum reduction when about 25% of the particles (by volume) are of the smaller size. Our new studies include the effects of colloidal forces, particularly, DLVO forces and the effect of multiple sizes. The DLVO forces are electrostatic repulsion and van der Waals attraction. We have extended the scope of simulation to three dimensions involving Ewald summed periodic boundary conditions for polydisperse systems. The initial results show that the inclusion of the DLVO forces modifies the relative viscosity, with the effect increasing with ionic strength. For example, a bimodal suspension with size ratio of four to one and a relative volume fraction of 0.25 small spheres to large spheres demonstrates this behavior. The purely hydrodynamically induced relative viscosity, at 61.7% solids loading, is calculated to be 12.0, while the relative viscosity of a suspension of particles interacting electrostatically and via van der Waals forces (i.e. with a Debye length of 9.63nm) is calculated to be 18.6 (where the relative viscosity is the ratio of the viscosity of the suspension to that of the suspending medium). These calculations agree with literature data. Current work is aimed at quantifying these effects and understanding the role of the colloidal forces on the microstructure in concentrated suspensions of polydisperse particles.

Planned Activities

1. NMRI measurements in turbulent flow.
2. NMRI measuremnts with slurries.
3. UDV mesurments with slurries.
4. Simulations of polydisperse suspensions.