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TWO-PHASE FLOW MEASUREMENTS BY
NUCLEAR MAGNETIC RESONANCE (NMR)

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We pioneered NMR studies of concentrated suspensions starting in the late 1980's (Majors, et al., 1989; Altobelli, et al., 1991; Abbott, et al., 1991). In those studies, we measured concentration and velocity of the liquid component in either in pipe or Couette flow. If we compare these early studies of suspensions with more recent ones (Hampton, et al., 1997), imaging time has gone from 40 minutes to 8 minutes and the imaging matrix has increased from 32 x 32 to 128 x 128. In the interim, we have performed many concentrated suspension flows in both pipe and Couette geometries, with different particle sizes and shapes, and different kinds of liquids. We summarize the main results here and list the publications that emanated from this grant.

Suspension flow in a pipe. After a gap of a number of years from the initial studies [Majors, et al., 1989; Altobelli, et al., 1991], we have remeasured concentrated suspension flows in a circular pipe [Hampton, et al., 1997]. In order to make careful measurements of small effects, we scaled up the experiment in order to study the evolution of the suspension as a function of distance traveled by the suspension starting at an output of a commercial flow mixer. The flow loop consisted of 70 m lengths of tubing either 2.54 cm or 5.08 cm id with total volumes of 70 and 170 liters, respectively. Particles with diameter 650 μm were used in the smaller tube to achieve the ratio of particle to tube diameter, a/R , of 0.0256 with solids concentration ϕ ranging from 20 to 45%. The larger diameter tube contained suspensions with particle diameter of 3.175 mm (giving a/R of 0.0625) with ϕ ranging from 10 to 50%. For ϕ exceeding 20%, the particles rapidly migrate to the low-shear-rate region in the center of the pipe, resulting in the blunting of the velocity profile compared to that for pure Newtonian liquid. This effect depends strongly on both a/R and ϕ , as expected. An interesting feature is the very sharp maximum in the solids concentration at the center of the pipe for $a/R=0.0256$ and ϕ of 20 to 30%.

In another experiment (Altobelli, et al., 1997), suspensions of 50% by volume of particles in a Newtonian liquid were forced to flow through a four-to-one contraction, then an abrupt expansion back to the original round pipe, by a plunger. Two sizes of suspended particles were studied: 100 and 675 μm diameter. The unconstricted section of pipe had a diameter of 5.08 cm. Little change in particle concentration was seen in the region of the contraction until the plunger was within about one pipe diameter of the contraction. The particles in the small diameter pipe migrated towards the center, as

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expected, and the resulting high fluids-fraction shell convects to the outer wall, once the mixture emerges past the step-expansion.

Suspension in a couette. A horizontal Couette is much easier to set up than a pipe flow experiment because the system is much more compact and requires much less sample. We have performed many multiphase flow experiments in Couette geometry over the years, starting in 1991 with spherical particles in a symmetric Couette. Later studies include Mondy, et al. (1994) on rods, Phan-Thien, et al. (1995) in an eccentric Couette, i.e., the journal bearing geometry, and Tetlow, et al. (1998) in a much more detailed experiment than in the past.

Liquid-liquid, porous media, and diffusional flows. Jeong, et al. (1994) found that a 50-50 mixture of density-segregated immiscible liquids flowing in a horizontal rotating cylinder yielded a surprising result, namely, that the flow pattern in one the fluids always separate into two counter-rotating cells. Givler and Altobelli (1994) performed a detailed measurement of the flow velocity profile in a high porosity foam and determined the effective viscosity. Feinauer, et al. (1997) measured the velocity profile in a coarse packed-bead bed and took into account partial volume effects. Finally, basic questions on NMR measurements of diffusion were addressed in several papers. Wang, et al. (1995) derived the conditions under which the traditional treatment assuming short PGSE gradient pulses is valid. Caprihan, et al. (1996) formulated a new and improved way to mathematically treat the problem of PGSE pulses that cannot be approximated as instantaneous. Kenkre, et al. (1997) found a new method to treat arbitrary time dependence of the magnetic field gradient pulses in PGSE experiments.

Instrumental improvements. Major modifications to the instrument made in the past three-year period include the construction of a Faraday shield to electrically isolate the sample volume from the rest of the lab. It consists of two copper screen "rooms" that electrically seal against each end of the horizontal magnet. Electrical filters were designed and built for all lines that go through the shield; the major task being for the high current lines for the gradient coils. The rooms have sleeved openings that allow passage of pipes, rods for rotating Couettes, and pistons for pushing mixtures through high impedance flow systems.

The new shield has led to a measurable but only moderately significant improvement in S/N. However, the true worth of the shield has come in the vastly improved decoupling of the gradient, shim, and rf circuits. Heretofore, the unwanted interactions were unpredictable and lead to component failures due to transient spikes, for example, from the rf to the gradient/shim circuit.

PUBLICATIONS EMANATING FROM THIS GRANT

- Altobelli SA, Fukushima E, Mondy LA. 1997. Nuclear magnetic resonance imaging of particle migration in suspension undergoing extrusion. *J. Rheol.* 41:1105-15
- Caprihan A, Wang LZ, Fukushima E. 1996. A multiple narrow pulse approximation for restricted diffusion in a time varying field-gradient. *J. Magn. Reson. A* 118: 94-102
- Feinauer A, Altobelli SA, Fukushima E. 1997. NMR measurements of 3-D flow profiles in a coarse bed of randomly packed spheres. *Magnetic Resonance Imaging* 15:479-87
- Givler RC, Altobelli SA. 1994. A determination of the effective viscosity for the Brinkman-Forchheimer flow model. *J. Fluid Mech.* 258:355-70
- Hampton RE, Mammoli A, Graham A, Tetlow N, Altobelli S. 1997. Migration of Particles undergoing pressure driven flow in a circular conduit. Submitted to *J. Rheol.*
- Jeong EK, Altobelli SA, Fukushima E. 1994. NMR Imaging studies of stratified flows in a horizontal rotating cylinder. *Phys. Fluids.* 6:2901-6
- Kenkre VM, Fukushima E, Sheltraw D. 1997. Simple solutions of the Torrey-Bloch equations in the NMR study of molecular diffusion. *J. Magn. Reson.* 128: 62-69
- Mondy LA, Brenner H, Altobelli SA, Abbott JR, Graham AL. 1994. Shear Induced Particle Migration in Suspensions of Rods. *J. Rheol.* 38:444-52
- Phan-Thien N, Graham A, Altobelli S, Abbott J, Mondy L. 1995. Hydrodynamic Particle Migration in a Concentrated Suspension undergoing Flow between Rotating Eccentric Cylinders. *Ind. Eng. Chem. Res.* 34:3187-94
- Tetlow N, Graham AL, Ingber MS, Subia SR, Altobelli SA. 1998. Particle migration in a Couette apparatus: Experiment and modeling. *J. Rheol.* 42:307-27
- Wang LZ, Caprihan A, Fukushima E. 1995. The narrow pulse criterion for pulsed gradient spin echo diffusion measurements. *J. Magn. Reson. A* 117: 209-219

Submitted July 29, 1998 by Eiichi Fukushima, PI.

A handwritten signature in black ink, appearing to read 'Eiichi Fukushima', with a long horizontal flourish extending to the right.