Two Phase Flow Measurements

by Nuclear Magnetic Resonance (NMR)

DE-FG02-98ER14844

Final Report – Accomplishments, Students Supported, Publications

The objectives this grant were:

a) Development of NMR imaging techniques for multi-phase flows,
b) Application of the techniques to concentrated suspensions,
c) Technological development of a low-field NMR/MRI system,
d) Direct detection of solid components in multiphase flow,
e) Microscopic studies of sedimentation and flotation,
f) Combination of d) and e) to measure a 3-phase flow, and
g) Develop and use NMR imaging for gas flowing in porous media.

In concentrated suspensions, there is a tendency for the solid phase to migrate from regions of high shear rate to regions of low shear (Leighton & Acrivos, 1987). In the early years that our effort was funded by the DOE Division of Basic Energy Science, quantitative measurement of this process in neutrally buoyant suspensions was a major focus (Abbott, et al., 1991; Altobelli, et al., 1991). Much of this work was used to improve multi-phase numerical models at Sandia National Laboratories. Later, our collaborators at Sandia and the University of New Mexico incorporated body forces into their numerical models of suspension flow (Rao, Mondy, Sun, et al., 2002). We developed experiments that allow us to study flows driven by buoyancy, to characterize these flows in well-known and useful engineering terms (Altobelli and Mondy, 2002) and to begin to explore the less well-understood area of flows with multiple solid phases (Beyea, Altobelli, et al., 2003). We also studied flows that combine the effects of shear and buoyancy, and flows of suspensions made from non-Newtonian liquids (Rao, Mondy, Baer, et al, 2002). We were able to demonstrate the usefulness of proton NMR imaging of liquid phase concentration and velocity and produced quantitative data not obtainable by other methods.

Fluids flowing through porous solids are important in geophysics and in chemical processing. NMR techniques have been widely used to study liquid flow in porous media. We pioneered the extension of these studies to gas flows (Koptyug, et al, 2000, 2000, 2001, 2002). This extension allows us to investigate a wider range of Peclet numbers, and to gather data on problems of interest in catalysis.

We devised two kinds of NMR experiments for three-phase systems. Both experiments employ two NMR visible phases and one phase that gives no NMR signal. The earlier method depends on the two visible phases differing in a NMR relaxation property. The second method (Beyea, Altobelli, et al., 2003) uses two different nuclei, protons and ^{19}F. It also uses two different types of NMR image formation, a conventional spin-echo and a single-point method. The single-point method is notable for being useful for imaging materials which are much more rigid than can usually be studied by NMR imaging. We use it to image "low density" polyethylene (LDPE) plastic in this application. We have reduced the imaging time for this three-phase imaging method to less than 10 s per pair of profiles by using new hardware. Directly measuring the solid LDPE signal was a novel feature for multi-phase flow studies.

We also used thermally polarized gas NMR (as opposed to hyper-polarized gas) which produces low signal to noise ratios because gas densities are on the order of 1000 times smaller than liquid densities. However since we used multi-atom molecules that have short T_1's and operated at elevated pressures we could overcome some of the losses. Thermally polarized gases have advantages over hyperpolarized gases in the ease of preparation, and in maintaining a well-defined polarization. In these studies (Codd and Altobelli, 2003), we used stimulated echo sequences to successfully obtain propagators of gas in bead packs out to observation times of 300 ms.

Zarraga, et al. (2000) used laser-sheet profilometry to investigate normal stress differences in concentrated suspensions. Recently we developed an NMR imaging analog for comparison with numerical work that is being performed by Rekha Rao at Sandia National Laboratories (Rao, Mondy, Sun, et al, 2002). A neutrally buoyant suspension of 100 μm PMMA spheres in a Newtonian liquid was sheared in a vertical Couette apparatus inside the magnet. The outer cylinder rotates and the inner cylinder is fixed. At these low rotation rates, the free-surface of the Newtonian liquid shows no measurable deformation, but the suspension clearly shows its non-Newtonian character.

Students and Post-Docs

Since we are not a degree granting institution, it's very uncommon for us to have graduate students and none were supported by this grant. Several outstanding post-doctoral students were partially supported by this grant.

Steven Beyea, Ph. D. Currently at the NRC-CNRC, Halifax, Canada.

Sarah Codd, Ph. D. Currently at the Department of Mechanical Engineering, Montana State University.

Eun-Kee Jeong, Ph. D. Currently at Department of Radiology, University of Utah.

Joseph Seymour, Ph.D. Currently at the Department of Chemical Engineering, Montana State University.

Lee Z. Wang, Ph.D. Currently at DSP in Taiwan.

Summary

This is a culmination of research on multiphase flows that was supported by this series of grants (DE-FG04-90ER14087, DE-FG02-98ER14844), initially through Oscar Manley, then Bob Price, and finally with Tim Fitzsimmons. We made the first confirmation of shear-induced migration in concentrated suspension in tube flow and Couette geometry. We also pioneered measuring spatially resolved sedimentation with one and two solid components so the concentration-dependent hindered floatation function could be measured in a single experiment. Finally, we made the first measurement of steady gas flow profile in a tube as well as in porous bead packs, goals that were discussed with Oscar so many years ago that he did not get to see. NMR and MRI are now well established as reliable tools to measure such fluid dynamic parameters that are otherwise difficult or impossible to measure. A significant fraction of this work was performed in collaboration with Sandia National Laboratories in which we provided experimental data that were essential to their applications as well as numerical modeling.

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