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Title: The Rheology of Concentrated Suspensions

Principal Investigator: Andreas Acrivos

Levich Institute, T-1M, City College of CUNY

Final Report

The primary purpose of the research supported by this grant was to study the flow characteristics of concentrated suspensions of non-colloidal solid particles and thereby construct a comprehensive and robust theoretical framework for modeling such systems quantitatively. At first glance, this seemed like a modest goal, not difficult to achieve, given that such suspensions were viewed simply as Newtonian fluids with an effective viscosity equal to the product of the viscosity of the suspending fluid times a function of the particle volume fraction. But thanks to the research findings of the Principal Investigator and of his Associates, made possible by the steady and continuous support which the PI received from the DOE Office of Basic Energy Sciences, the subject is now seen to be more complicated and therefore much more interesting in that concentrated suspensions have been shown to exhibit fascinating and unique rheological properties of their own that have no counterpart in flowing Newtonian or even non-Newtonian (polymeric) fluids. In fact, it is generally acknowledged that, as the result of these investigations for which the PI received the 2001 National Medal of Science, our understanding of how suspensions behave under flow is far more detailed and comprehensive than was the case even as recently as a decade ago. Thus, given that the flow of suspensions plays a crucial role in many diverse physical processes, our work has had a major and lasting impact in a subject having both fundamental as well as practical importance.

During the period 8/1/1990 – 9/30/2003 the following studies were completed and are described in the attached references:

<u>Viscous resuspension</u> This is a curious phenomenon which refers to the fact of suspensions containing heavy particles can resuspend in the presence of shear even under very viscous conditions and in the absence of secondary flows. It arises due to the action of shear-induced particle diffusion (a new mode of particle transport, first identified by the PI and his associates) which induces a flux of particles from the regions of high shear to low and from regions of high particle concentration to low. Our studies have covered flows in channels [1, 6], pipes [3], in supersettlers [5, 9] and in a Couette device [2, 4, 8, 11] and we succeeded in showing excellent agreement between theoretical predictions, using model which we had developed earlier, and the experimental results.

<u>Statistical properties of suspensions</u> Many of the novel rheological properties of suspensions are due to the random motion of the particles which are only amenable to a

statistical description. These statistical properties have been investigated experimentally [10] and in more detail via computer simulations [15, 19].

Particle Segregation A curious phenomenon was discovered in our laboratory pertaining to the fact that, where a suspension containing neutrally buoyant monosized spheres was sheared in partially filled Couette device or horizontal circular cylinder, the particles formed regularly spaced bands of high particle concentration along the horizontal axis [12, 13]. This phenomenon, which has no counterpart in pure fluids, was recently explained by a novel stability analysis which yielded predictions in close agreement with the experimental results [17, 18].

List of publications acknowledging the support from this Grant

1. Zhang, K., Acrivos, A. and Schaflinger, U. "Stability in a Two-Dimensional Hagen-Poiseuille Resuspension Flow", Int. J. Multiphase Flow 18, 51 (1992).
2. Acrivos, A., Mauri, R. and Fan, X. "Shear-Induced Resuspension in a Couette Device" Int. J. Multiphase Flow 19, 797 (1993).
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4. Acrivos, A., Fan, X. and Mauri, R. "On the Measurement of the Relative Viscosity of Suspensions" J. Rheol. 38, 1285 (1994).
5. Kapoor, B. and Acrivos, A. “Sedimentation and Sediment Flow in Settling Tanks with Inclined Walls," J. Fluid Mech. 290, 39 (1995).
6. Schaflinger, U., Acrivos, A. and Stibi, H. “An Experimental Study of Viscous Resuspension in a Pressure-Driven Plane Channel Flow” Int. J. Multiphase Flow 21, 693 (1995).
7. Acrivos, A. “Bingham Award Lecture - 1994. Shear-Induced Particle Diffusion in Concentrated Suspensions on Noncolloidal Particles” J. Rheol. 39, 813 (1995).
8. Jana, S.C., Kapoor, B. and Acrivos, A. “Apparent Wall Slip Velocity Coefficients in Concentrated Suspensions of Noncolloidal Particles” J. Rheol. 39(6), 1123 (1995).
9. Tripathi, A. and Acrivos, A. “A New Criterion for the Continuous Operation of Supersettlers in the Bottom Feeding Mode” Int. J. Multiphase Flow 22, 353 (1996).
10. Breedveld, V., Vanden Ende, D., Tripathi, A. and Acrivos, A. “The Measurement of Shear-Induced Particle and Fluid Tracer Diffusivities in Concentrated Suspensions by a Novel Method” J. Fluid Mech. 375, 297 (1998).
11. Tripathi, A. and Acrivos, A. “Viscous Resuspension in a Bidensity Suspension” Int. J. Multiphase Flow 25, 1 (1999).
12. Tirumkudulu, M., Tripathi, A. and Acrivos, A. “Particle Segregation in Mondisperse Sheared Suspensions” Phys. Fluids 11, 507 (1999). Erratum, ibid 11. 1962 (1999).

13. Tirumkudulu, M., Mileo, A. and Acrivos, A. “Particle Segregation in Monodisperse Sheared Suspensions in a Partially Filled Rotating Horizontal Cylinder” Phys. Fluids 12, 1615 (2000).
14. Tirumkudulu, M. and Acrivos, A. “Coating Flows Within a Rotating Horizontal Cylinder: Lubrication Analysis, Numerical Computations, and Experimental Measurements” Phys. Fluids 13, 14 (2001).
15. Drazer, G., Koplik, J., Khusid, B. and Acrivos, A. “Deterministic and Stochastic Behaviour of Non-Brownian Spheres in Sheared Suspensions” J. Fluid Mech. 460, 307 (2002).
16. Drazer,G.,Koplik,J., Acrivos,A., and Kusid,B., “ Adsorption Phenomena in the Transport of a Colloidal Particle Through a Nanochannel Containing a Partially Wetting Fluid “, Phys. Rev.Lett. 89, 244501-1 (2002).
17. Jin, B., and Acrivos, A. "Rimming Flows With an Axially Varying Viscosity", Phys. Fluids, 16, 633, (2004).
18. Jin, B., and Acrivos, A. "Theory of Particle Segregation in Rimming Flows of Suspensions Containing Neutrally Buoyant Particles", Phys. Fluids, 16, 641, (2004).
19. Drazer, G., Koplik, J., Khusid, B., and Acrivos, A. "Microstructure and Velocity Fluctuations in Sheared Suspensions", J. Fluid. Mech. 511, 237 (2004).