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# MACROSTATISTICAL HYDRODYNAMICS

Progress Report for the Period April 15, 1991-September 14, 1992

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Submitted by:

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# MACROSTATISTICAL HYDRODYNAMICS

*Progress*

This work has been supported for the past four years by the U.S. Department of Energy, Division of Engineering and Geosciences, Office of Basic Energy Sciences. This research is being performed in collaboration with Dr. Alan L. Graham of Los Alamos National Laboratory and Lisa A. Mondy of Sandia National Laboratory. During the course of these efforts we have been studying suspension of particles in Newtonian and non-Newtonian liquids, embodying a combination of analysis, experiments, and numerical simulations. Experiments primarily involved tracking small balls as they fall slowly through otherwise quiescent suspensions of neutrally buoyant particles. Detailed trajectories of the balls, obtained either with new experimental techniques or by numerical simulation, were statistically interpreted in terms of the mean settling velocity and the dispersion about the mean. We showed that falling-ball rheometry, using small balls relative to the suspended particles, could be a means of measuring the macroscopic zero-shear-rate viscosity without significantly disturbing the original microstructure; therefore, falling-ball rheometry can be a powerful tool for use in studying the effects of microstructures on the macroscopic properties of suspensions. We plan to extend this work to the study of more complex, structured fluids, and to use other tools (e.g., rolling-ball rheometry) to study boundary effects. We also propose to study flowing suspensions to obtain non-zero-shear-rate viscosities. The intent is to develop an understanding of the basic principles needed to treat generic multiphase flow problems, through a detailed study of model systems.

*Continuation of experimental dispersivity studies*

Detailed paths taken by balls falling through several suspensions of various suspended particle size and concentrations were analyzed as a Fickian-like dispersion process. A Fickian-like dispersivity, arising strictly from hydrodynamic interactions between the ball and the suspended particles, was used to quantify the data. After a characteristic time interval (usually equivalent to the time needed for a ball to settle four to six suspended-sphere diameters), the experimental data could be interpreted via an analogy to the long-time root-mean-square statistical behavior of a colloidal particle undergoing Brownian motion, namely the mean-squared displacement equals twice the dispersivity times the time. To permit comparisons to be made between suspensions composed of different suspending fluids and suspending-sphere sizes, the measured dispersivities ($D$) were rendered dimensionless by using the diameter ($d_3$) of the suspended spheres and the mean falling-ball velocity ($U$) as characteristic scaling parameters $\left(D^* = D/[Ud_3]\right)$. In general, this dispersivity need not be isotropic. The dispersivity in the settling direction $\left(D_{\parallel}\right)$, parallel to gravity, may differ from that in the horizontal direction $\left(D_{\perp}\right)$, resulting in a transversely isotropic dispersivity dyadic characterized by these two scalar dispersivities. In fact, we found that over the range of our data (volume fraction of solids, $\phi$, between 0.15 and .50), the vertical mean-square displacements are approximately 20 times larger than the horizontal displacements.

The vertical dispersivity component can, alternatively, be estimated by using mean settling velocity measurements gleaned from a series of experiments conducted over known settling distances. Use of the data from many previous experiments, together with information learned from the more complete tracking experiments above, enabled estimations of the dispersivity coefficients to be made over a wide range of solid volume fractions (.05 to .55) for both suspensions of spheres and of rods.

In the dilute particle limit, the effect of particle concentration on the falling-ball's settling velocity would be expected to be small, whereas the number of collisions per unit length is expected to be proportional to the concentration. This suggests that the dimensionless dispersivity, like the macroscopic viscosity, should be proportional to the particle concentration in the dilute limit. At higher concentrations, an increase in the dispersivity would be caused by the increased number of interactions (all other things being equal). A functional relationship was found to exist between the dimensionless dispersivity and the specific viscosity $(\mu_r - 1)$ of suspensions of spheres, over two orders of magnitude in the specific viscosity: $D_{\parallel}^* = 0.579(\mu_r - 1)^{0.95}$ (spheres). This near linear relation between the dispersivity and specific viscosity suggests that multibody (suspended) particle effects contribute equally to the observed increase in specific viscosity and dimensionless dispersivity.

A similar functional dependence was found for suspensions of randomly oriented rods. Here: $D_{\parallel}^* = 0.0349(\mu_r - 1)^{0.87}$ (rods). Again it appears that the concentration dependence of the dispersivity is governed by the same mechanism as that which governs the viscosity of the suspension

*Numerical simulations of falling-ball rheometry*

We have used a boundary element method to simulate the hydrodynamic interaction among suspended particles in a falling-ball experiment (Mondy, Ingber, and Dingman, 1991). The method couples the quasi-static Stokes equations for the fluid with the equilibrium equations for the particles. We modeled suspensions ($0.01 \leq \phi \leq 0.05$) of neutrally buoyant spheres subjected to the flow caused by the fall of a heavier, but otherwise identical, sphere. The instantaneous drag on the falling ball, due to 40 suspended spheres and the containing walls, was calculated for many different initial configurations by the suspended spheres. The results showed the expected sensitivity of the heavy sphere's velocity to the position of the suspended spheres. By calculating the resistance to the fall of the heavy ball, as neutrally buoyant spheres were added one at a time, we demonstrated that only the suspended balls in the neighborhood of one cylinder diameter above and below the heavy ball significantly affect the heavy ball's fall velocity. Significant computational time could be saved by modeling this "near field" only. As in our experiments, an apparent viscosity of the suspension could be calculated from the heavy sphere's average velocity. This viscosity of suspensions of uniformly sized spheres was very close to that predicted by Einstein's relationship. Bimodal suspensions exhibited a slightly lower viscosity.

Similar falling-ball rheometers for suspensions of neutrally buoyant rods ($\phi = 0.01$) and particle aspect ratios of 5 and 10) were modeled. Twenty-five suspended rods can be initially oriented randomly, or aligned either parallel or perpendicular to gravity. Good agreement with experimental measurements for the randomly oriented rods was obtained. As expected from the experiments described earlier, suspension of aligned rods are predicted to have an effective viscosity parallel to the rods' axes that is distinctly different from that perpendicular to the axes. However, no data currently exist for rods of this aspect ratio when aligned parallel with gravity, and no data exist for any aspect-ratio rods when aligned perpendicular to gravity.

Studies on the effects of the rod orientations are expected to be much easier to this "numerical rheometer" than in the laboratory. In addition, dynamic simulations may lead to more understanding of the relationship among fluctuations in the falling-ball velocity and the microstructure of the suspensions. Such dynamic simulations have been shown to be possible, but only preliminary testing has been done to date (Mondy, Ingber, and Dingman, 1991).

*Numerical modeling of periodic arrays of particles*

To date, the boundary element method has also been used to solve the Stokes equations for more concentrated suspensions of periodic arrays of force- and torque-free rigid particles (Phan-Thien, Tran-Cong, and Graham, 1991). Simple cubic arrays of spheres, spheroids, cubes, and clusters of spheres were subjected to a bulk simple shearing flow. The effective volume-averaged stress tensor for the suspension and the detailed velocity and stress fields throughout the Newtonian suspending fluid were calculated. Even coarse meshes gave very good volume-averaged results, but fine meshes were required to track local minima and maxima in the stress field.

For simple cubic arrays of spheres, the boundary element results were in excellent agreement with the analytical viscosity predictions of Nunan and Keller (1984). Even at the highest concentration of solids studied ($\phi = 0.50$), no significant normal stress differences were observed, in agreement with Nunan and Keller's results.

Up to moderate concentrations of particles, the volume-averaged properties of a suspension display only a weak dependence on the particle geometry. Suspensions of spheroids and cubes behave approximately as suspensions of spheres on average, despite large differences in the local micromechanics of stress and velocity fields.

Simple cubic arrays of *clusters* of spheres tend to behave on a macroscopic level as a cubic array of spheres whose effective volume fraction is about 150% of the total volume fraction of the spheres in the clusters. At the macroscopic level, this lends some credibility to the "immobilized" liquid concept of Vand (1948). However, the microscopic stress field reveals moderately high stress regions in the interior of the clusters. These studies (Phan-Thien, Tran-Cong, and Graham, 1991) show that valuable information about the relationship between the microstructure and the macroscopic properties can be learned through numerical or analytical modeling of periodic systems and through numerical modeling of more complex systems.

*Analysis of the collision-induced dispersion coefficient*

In this period, a generalized Newtonian, one-dimensional, constitutive model and a "diffusion" equation for the particle concentration (Phillips, Armstrong, Brown, Graham, and Abbott, 1991) was tested against our data and shown to predict particle concentration and velocity fields in concentrated, monomodal suspensions quite well. In this model, the diffusion equation accounts for shear-induced particle migration through particle flux expressions derived by scaling arguments. The viscosity of the suspension is modeled as an increasing function of the volume fraction of particles. Particle concentrations for neutrally buoyant, monomodal suspensions of spheres undergoing flow between rotating concentric cylinders were measured using nuclear magnetic resonance imaging (Abbott, Tetlow, Graham, Altobelli, Fukushima, Mondy, and Stephens, 1991). The predictions agree very well with the measurements, thereby verifying the scaling analysis and the basic mechanics incorporated into the constitutive description.

The above model of the collision-induced, phenomenological, dispersion coefficient governing the shear-induced lateral migration of suspended spheres furnishes a value for the dispersion coefficient of about $2.4\phi$. For a solids volume fraction of $\phi = 0.50$, this predicts that the dimensionless Fickian dispersion coefficient for such shear flows will be about unity. This is the same order of magnitude as the dimensionless dispersivity seen in the falling-ball experiments described earlier, in which a ball (of the same size as the suspended spheres) settles through a quiescent suspension. This suggests that the same basic physics governs both phenomena.

*Continuation of experimental dispersivity studies*

Additional dispersivity data was taken this period, concentrating on the detailed path taken by balls of various sizes falling through suspensions with a suspended-sphere volume fraction of 0.15. Several sizes of suspended spheres were used in order to vary the ratio of the falling-ball size to the suspended sphere size from 1 to 21. The purpose of this study was to elucidate the functional dependence of the dispersivity coefficient on the sizes of both the falling ball and suspended spheres. Results were compared to theory by Davis and Hill (1992) and to scaling arguments developed in conjunction with the model discussed above. We found that Davis and Hill overpredict the sensitivity of the dispersivity coefficient to the size of the suspended particles. For example, Davis and Hill predict that the dimensionless dispersivity in a suspension of 0.32 cm spheres should be four times that measured in a suspension of 1.27 cm spheres. Our scaling arguments indicate that the dispersivity coefficient should be the same in both suspensions. The latest data (for relative size ratios of the settling spheres to suspended particle sizes of 5 and 21) imply that, indeed, the dimensionless dispersivity is the same.

*New experimental techniques*

We proposed to concentrate on extending the technique of falling-ball rheometry to more complex suspensions. To this end we recently developed a non-Newtonian liquid which can either match the index of refraction or the density of our PMMA particles, thereby creating the capability to study suspensions with a non-Newtonian suspending fluid. We also perfected methods to align particles with aspect ratio greater than 1.0 (rods), thus preparing to study the dispersion in suspensions with transversely isotropic properties.

We also plan to further study the appropriate slip/stick boundary condition for materials with microstructure through laboratory examination of a technique similar to falling-ball rheometry -- rolling-ball viscometry. In rolling-ball viscometry, a dense ball is allowed to roll/slide down an inclined surface (in this case, the inside of a cylinder containing suspension), and its rate of travel is compared to that in a fluid of known viscosity. In a suspension, we can ratio the time it takes for the ball to travel a known distance in the suspension to that in the suspending liquid alone and, from this ratio, estimate the apparent relative viscosity. This procedure is similar to estimating the apparent viscosity with falling-ball viscometry; however, the immediate region of the suspension seen by the moving ball is not uniform, but has structure determined by the proximity of the bounding wall.

Preliminary rolling-ball data was taken for a suspension with volume fraction solids equal to 0.30. Three sizes of rolling balls were used such that the ratio of the size of the rolling ball to the size of the suspended spheres ranged from 0.75 to 6.0. As in falling-ball rheometry, the instantaneous velocity of the moving ball is not steady; however, a statistical analysis reveals that the *average* velocity of the ball, measured over a distance usually equivalent to 100 to 1000 suspended particle diameters, is reproducible. The *average* velocities of the three sizes of balls then translate into three measured relative viscosities. These viscosities all agreed within the 95% confidence limits of the data, indicating that the measured viscosity was independent of the size of the falling ball. Furthermore, the viscosity measured with rolling-ball viscometry was statistically indistinguishable from that measured with falling-ball rheometry. This is surprising in light of the fact that the suspended particles cannot be distributed near the wall in the same manner that they are distributed in the bulk of the suspension, simply due to geometric constraints. Further data may allow differences now obscured by the statistical nature of the system to be distinguished. It appears that rolling-ball viscometry will allow more insight into the behavior of concentrated suspensions and is a technique worth further study.

This period, we also created an apparatus necessary to study falling-ball rheometry in flowing suspensions. A homogeneous flow apparatus (HFA) (Graham and Bird, 1984) was built, consisting of two moving, flat, parallel belts and a containing vessel made from polymethyl methacrylate and aluminum bracing plates. A motor drives the belts in a smooth, steady motion. The belts are coupled with a gear drive so that their motion is parallel, but opposite, in the center section of the HFA. Initially, we plan to drop balls in the center of the flow field where the velocity is close to zero. The average velocity is likely to reflect the different bulk environment seen in the flowing suspension, in contrast to a quiescent one. We hope to learn more about the connection between the microscopic structure and the macroscopic rheology through this experiment.

*Boundary element modeling of suspensions*

The ability to perform dynamic simulations of a ball falling through suspensions of dozens of particles has been enhanced by decreasing the computational effort required at each time step. This was accomplished by using a variable-order-Gauss quadrature routine. The number of quadrature points is *locally* increased where needed to obtain an accurate solution, but in most elements the number of quadrature points is reduced without affecting the accuracy of the solution. The resulting number of equations is reduced from our original method, and the accuracy is enhanced. Furthermore, we obtained a six-fold speed-up in obtaining most solutions.

*Plans for the year beginning September 15, 1992*

In this year, we plan to continue the analytical studies developing a constitutive description of flowing, concentrated suspensions, accounting for shear-induced migration of the suspended particles. Our hope is to develop the capability to describe two-dimensional flows and to gather the appropriate data with which to test the model.

We expect to complete the dispersion studies in suspensions of uniform spheres and to continue these studies in the laboratory on more complex materials (e.g., suspensions of aligned, rod-like particles). We plan to expand the slip/stick boundary study using rolling-ball viscometry to suspensions of various concentrations.

We plan on studying, analytically and numerically, falling-ball rheometry in suspensions of particles in periodic arrangements and other layered media. These materials are representative of multiphase materials with nonisotropic and transversely isotropic material properties.

We will also continue our numerical studies using boundary element methods. One goal for the numerical studies would be to add periodic boundary conditions which would allow the dynamic simulation of flowing suspensions. We also hope to improve the speed of the computations, as well as to increase the number of suspended particles possible to simulate, by exploring the possibilitiy of solving these problems on computers using parallel architectures. We plan to complete an initial series of experiments combining falling-ball rheometry and the HFA. We also envision the need to create new tools such as a spinning-ball or -wire rheometer to further explore the slip/stick issue. The appropriate equipment will be built and initial studies of suspensions of uniform spheres will be performed. The spinning wire (Couette) rheometer could later also be used to study falling-ball rheometry in a flowing suspension. We also plan to study the pressure drop created by a ball falling through a suspension or other multiphase material. In a single-phase, Newtonian fluid at this pressure is constant, independent of viscosity (at low Reynolds number), and can be described analytically (Pliskin and Brenner, 1963). In a suspension, the pressure drop may be dependent upon the microstructure and, like the viscosity, may vary due to the discrete, noncontinuum nature of the material. This may prove to be another measure of the microstructure of the suspension.

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Phillips, R.J., Armstrong, R.C., Brown, R.A., Graham, A.L., and Abbott, J.R., "A Constitutive Equation for Concentrated Suspensions that Accounts for Shear-Induced Particle Migration," *Phys. Fluids A*, **4** (1), 30-40 (1992).

Vand, V.J., *Phys. Colloid. Chem.*, **52**, 277 (1948).

# Appendix A

## PUBLICATIONS ACKNOWLEDGING DOE SUPPORT (BY THE "MACROSTATISTICAL HYDRODYNAMICS" GROUP) (April 15, 1991-April 14, 1992)

### I. Publications by H. Brenner, *et al.*

#### Journal Articles

Brenner, H., "Macrotransport processes: Brownian tracers as stochastic averagers in effective-medium theories of heterogeneous media," *J. Stat. Physics* **62** ( 1991).

Frankel, I., and Brenner, H., "Generalized Taylor dispersion phenomena in unbounded homogeneous shear flows," *J. Fluid Mech.*, **230**,147-181 (1991).

Frankel, I., Mancini, F., and Brenner, H., "Sedimentation, diffusion and Taylor dispersion of a flexible fluctuating macromolecule. The Debye-Bueche equation revisited," *J. Chem. Phys.*, **95**, 8636-8646 (1991).

Dingman, S., Ingber, M.S., Mondy, L., Abbott, J., and Brenner, H., "Particle tracking in three-dimensional Stokes flow, *J. Rheology* **36**, 413-440 (1992).

Iosilevskii, G., Mendoza-Blanco, A.E., and Brenner, H., "The slow axisymmetric rotation of a sphere in a transversely-isotropic fluid," *Quart. J. Mech. Appl. Math.* (in press, 1992).

Iosilevskii, G., and Brenner, H., "Taylor dispersion in systems containing a continuous distribution of reactive species," *Int. J. Non-Linear Mech.* (in press, 1992).

Iosilevskii, G., and Brenner, H., "Stokes law for a sphere in a transversely-isotropic fluid. The axisymmetric case," *Int. J. Eng. Sci.* (submitted, 1991).

Iosilevskii, G., Brenner, H., Moore, C.M.V., and Cooney, C.L., "Mass transport and chemical reaction in Taylor-vortex flows with entrained catalytic particles: Applications to a novel class of immobilized enzyme biochemical reactors," *Proc. Roy Soc. Lond.* (submitted, 1991).

Iosilevskii, G., and Brenner, H., "Taylor dispersion in discrete reactive mixtures," *Int. J. Non-Linear Mech.* (in press, 1992).

Mavrovouniotis, G.M., and Brenner, H., "A micromechanical investigation of interfacial transport processes: I. Interfacial conservation equations, *Proc. Roy. Soc. Lond.* (submitted, 1991).

Mavrovouniotis, G.M., Brenner, H., Edwards, D.A., and Ting, L., "A micromechanical investigation of interfacial transport processes: II. Interfacial constitutive equations," *Proc. Roy. Soc. Lond.* (submitted, 1991).

Mauri, R., and Brenner, H., "Rheological properties of neutrally buoyant suspensions determined by momentum tracer methods," *Phys. Fluids A* (submitted, 1991).

Frankel, I., and Brenner, H., "Taylor dispersion of orientable Brownian particles in unbounded homogeneous shear flows," *J. Fluid Mech.* (submitted 1991).

Edwards, D.A., Shapiro, M., and Brenner, H., "Flow, dispersion and reaction in two-dimensional model porous media," *Phys. Fluids A* (submitted 1992).

Haber, S., and Brenner, H., "Effect of entrained colloidal particles in enhancing the transport of adsorbable chemical contaminants during groundwater flow in porous media," *J. Colloid Interface Sci.* (submitted 1992).

**Book**

Edwards, David A., Brenner, Howard and Wasan, Darsh T., *Interfacial Transport Processes and Rheology*, Butterworth-Heinemann, 558 pp. + xix, Boston, Massachusetts (1991).

**Conference Proceedings**

Abbott, J.R., Brenner, H., Graham, A.L. and Mondy, L.A., "Techniques for analyzing the behavior of concentrated suspensions," *FED* (Fluids Engineering Division) **118**, 1-11 (1991); *Liquid-Solid Flows-1991*- Proceedings of the First ASME•JSME Fluids Engineering Conference, Portland, Oregon (June 23-27, 1991) (M.C. Roco and T. Masuyama, Eds.), Amer. Soc. Mech. Engrs., New York, NY.

Brenner, H., Altobelli, S.A., Graham, A.L., Abbott, J.R. and Mondy, L.A., "Hydrodynamic particle migration in small-amplitude, oscillatory circular Couette flow: The limits of reversibility," (accepted for publication in the *Proc. XIth International Congress on Rheology*, Brussels, Belgium (August 17-21, 1992).

Abbott, J.R., Mondy, L.A., Graham, A.L. and Brenner, H., "Techniques for Analyzing the Behavior of Concentrated Suspensions, "in *Particulate Two-Phase Flow* (M.C. Roco, Ed.), Chapt. 1, pp. 1-31, Butterworth-Heinemann, Boston, MA (1992).

### Thesis

M.T. Kezirian, "Hydrodynamics with a Wall-Slip Boundary Condition for a Particle Moving Near a Plane Wall Bounding a Semi-Infinite Viscous Fluid," for the degree of Master of Science in Chemical Engineering, MIT (1992).

## II. Publications by A.L. Graham and L.A. Mondy *et al.*

Mondy, L.A., Ingber, M.S., and Dingman, S.E., "Boundary element method simulations of a ball falling through quiescent suspensions," *J. Rheology* **35**, 825 (1991).

*Abbott, J.R., Brenner, H., Graham, A.L., and Mondy, L.A., "Techniques for analyzing the behavior of concentrated suspensions," *Proceedings of the 4th International Symposium on Liquid-Solid Flows*, Portland, Oregon (June 24-26, 1991).

Phan-Thein, N. and Graham, A.L., "A new constitutive model for fibre suspensions: Flow past a sphere," *Rheol. Acta* **30**, 44-57 (1991).

Phan-Thein, N., Zheng, R., and Graham, A.L., "The flow of a model suspension fluid past a sphere," *J. Stat. Physics* **62** (5/6), 1173-1196 (1991).

Graham, A.L., Gottlieb, M., and Dowell, F., "Dynamics of concentrated systems," *J. Stat. Physics* **62** (5/6), 887-889 (1991).

Abbott, J.R., Tetlow, N., Graham, A.L., Altobelli, S.A., Fukushima, E., and Mondy, L.A., "Experimental observations of particle migration in concentrated suspensions: Couette flow," *J. Rheology* **35** (5), 773-795 (1991).

Phan-Thein, N., Tran-Cong, T., and Graham, A.L., "Shear flow of periodic arrays of particle clusters: A boundary element method," *J. Fluid Mech.* **228** (5), 275-293 (1991).

Phillips, R.J., Armstrong, R.C., Brown, R.A., Graham, A.L., and Abbott, J.R., "A constitutive equation for concentrated suspensions that accounts for shear-induced particle migration," *Physics of Fluids A* **4**(1), 30-40 (1992).

Abbott, J.R., Mondy, L.A., Graham, A.L., and Brenner, H., "Techniques for analyzing the behavior of concentrated suspensions," in *Particulate Two-Phase Flow* (M.C. Roco, Ed.), Chapt. 1, Butterworth-Heinemann, Stoneham, MA (1992).

Dingman, S., Ingber, M.S., Mondy, L.A., and Abbott, J.R., "Particle tracking in three-dimensional Stokes flow," *J. Rheology* (in press, 1992).

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* Also included in preceding H. Brenner/DOE Publication List.

Ingber, M.S. and Mondy, L.A., "Direct second kind boundary integral formulation for Stokes flow problems," *Computational Mech.* (submitted, 1992).

Tullock, D.L., Phan-Thein, N., and Graham, A.L., "Boundary element simulations of spheres settling in circular, square and triangular conduits," *Rheol. Acta* (in press, 1992).

Schwartz, D.F., Surovec, R.D., Stephens, T.S., and Graham, A.L., "Effects of propellant shear in small test motors," *Proc. JANNAF Propulsion Meeting*, Indianapolis, IN (February 24-27, 1992).

Mondy, L.A. and Ingber, M.S., "Direct second kind boundary integral formulation for Stokes flow problems," accepted for publication in *Proc. of XIth International Congress on Rheology*, Brussels, Belgium (August 17-21, 1992).

* Brenner, H., Altobelli, S.A., Graham, A.L., Abbott, J.R., and Mondy, L.A., "Hydrodynamic particle migration in small-amplitude, oscillatory, circular Couette flow: The limits of reversibility," accepted for publication in *Proc. of XIth International Congress on Rheology*, Brussels, Belgium (August 17-21, 1992).

Papathanasiou, T., Ingber, M.S., Mondy, L.A., and Graham, A.L., "Boundary element modeling of three-dimensional multiparticle composites," accepted for publication in *Proc. of XIth International Congress on Rheology*, Brussels, Belgium (August 17-21, 1992).

Guell, D.C., Mondy, L.A., and Graham, A.L., "Aligned Short-Fiber-Reinforced Composite Materials," accepted for publication in *Proc. of XIth International Congress on Rheology*, Brussels, Belgium (August 17-21, 1992).

* Also included in preceding H. Brenner/DOE Publication List.

## Appendix B

## SEMINARS AND TECHNICAL PRESENTATIONS OF THE "MACROSTATISTICAL HYDRODYNAMICS" GROUP ACKNOWLEDGING DOE SUPPORT (April 15, 1991- September 14, 1992)

### Presentations by H. Brenner *et al.*

### 1991

(with J.R. Abbott, A.L. Graham, L.A. Mondy and S.A. Altobelli) Fourth International Symposium on Liquid-Solid Flows, American Society of Mechanical Engineers/Japanese Society of Mechanical Engineers Meeting, Portland, Oregon (June).

[1] Department of Chemical Engineering, Carnegie Mellon University, Pittsburgh, Pennsylvania (4 lectures) (July/August).

(with M. Kezirian) 1991 AIChE Summer Meeting, Pittsburgh, Pennsylvania (August).

(with M. Shapiro and I.J. Kettner) American Association for Aerosol Research, 10th Annual Meeting, Traverse City, Michigan (October).

Department of Chemical Engineering, City College of the City University of New York, New York City, New York (November).

(with M. Shapiro and I.J. Kettner) American Institute of Chemical Engineers Annual Meeting, Los Angeles, California (November).

(with J.R. Abbott, A.L. Graham, S.A. Altobelli and L.A. Mondy) American Institute of Chemical Engineers Annual Meeting, Los Angeles, California (November).

Department of Chemical Engineering, Tufts University, Medford, Massachusetts (December).

Department of Biomedical Engineering, Respiratory Research Laboratory Seminar, Transport and Mechanics Series, Boston University, Boston, Massachusetts (December).

### 1992

Department of Mechanical Engineering, University of Toronto, Toronto, Canada (March).

Boston Aerosol Study Group, Harvard School of Public Health, Department of Environmental Science and Physiology, Respiratory Biology Program, Boston, Massachusetts (April).

[2] 10th Canadian Symposium on Fluid Dynamics, The University of New Brunswick, Saint John, New Brunswick, Canada (June).

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[1] Gulf Visiting Professor Lectures.

[2] Invited Lecturer.

(with A.L. Graham and L.A. Mondy) 3rd International Workshop on Two-Phase Fundamentals, Imperial College of Science, Technology and Medicine, London, England (June).

[2](with A.L. Graham and L.A. Mondy) Symposium on Basic Research Needs in Fluid Mechanics, Fluids Engineering Division, American Society of Mechanical Engineers, Los Angeles, CA (June).

[2](with M. Shapiro and I.J. Kettner) 23rd Annual Meeting of the Fine Particle Society, Session on Flow Through Porous Media and Multiphase Flow, Las Vegas, NV (July).

(with S.A. Altobelli, A.L. Graham, J.R. Abbott and L.A. Mondy) 11th International Congress on Rheology, Brussels, Belgium (August).

(with Itzchak Frankel) 18th International Congress of Theoretical and Applied Mechanics, Haifa, Israel (August).

(with J.R. Abbott, A.L. Graham, L.A. Mondy) 18th International Congress of Theoretical and Applied Mechanics, Haifa, Israel (August).

[2](with A.M.J. Davis and M.T. Kezirian) 3rd International Symposium on Current Problems in Rheology, Biorheology and Biomechanics, Russian Academy of Sciences, Moscow, Russia (September).

(with S. Haber and T. Thuraisingham), Colloids in the Aquatic Environment (poster session), University College London, London, England (September).

## Appendix C

### HONORS, AWARDS AND SIGNIFICANT PROFESSIONAL ACTIVITIES BY H. BRENNER (April 15, 1991-September 14, 1991)

- Consulting Editor, Chairman of the Advisory Board, The Butterworth-Heinemann Series on Chemical Engineering.
- Member, Editorial Advisory Boards: *International Journal of Multiphase Flow*, Pergamon Press; *Transport in Porous Media*, Kluwer Academic Publishers.
- Member, International Advisory Committee, The Caribbean Congress of Fluid Dynamics.
- Co-Chairman and Organizer, Session on "Anomalies in the Motion of Particles Near a Wall," AIChE Pittsburgh National Meeting (August, 1991).
- Gulf Visiting Professor of Chemical Engineering, Carnegie-Mellon University (Summer, 1991).
- Chairman, External Review Committee for the Evaluation of Graduate Programs in the Department of Chemical and Petroleum Engineering, University of Pittsburgh, Pittsburgh, Pennsylvania.

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