

Two Phase Flows of Rheologically-Complex Fluids,  
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Three projects were funded under this proposal number. Project one evolved into an NSF grand challenge high performance computing grant with over a million dollars of funding spread over several institutions. This work is described briefly in **I** below and in great detail at our web site ([http://www.aem.umn.edu/Solid-Liquid\\_Flows/](http://www.aem.umn.edu/Solid-Liquid_Flows/)).

Project two is to investigate a theory of diffusion which is meant to replace conventional theories all of which ignore the fact that the density of mixtures of incompressible miscible fluids is not constant when diffusion is going on. This theory and recent developments are described briefly in **II** below.

Project three on aerodynamic dissemination is of interest to several agencies of the Army and has received separate funding as

Aerodynamic Dissemination  
DA/DAAH 04-94-G-0266

Significant progress has been made on this project since our last “Red Book” report. This recent progress will be summarized in the standard “Red Book” form in **III** below.

**I. Computational studies of the motion of particles in a viscoelastic fluid.**

In Oct. 1995 I prepared a proposal for an NSF Grand Challenge HPCC grant on direct simulations of the motion of particles in fluid, including viscoelastic fluids. We formed a distinguished group of computational fluid dynamics and computer science professionals to attempt an intimate marriage of CFD and CS, an interdisciplinary team with Co PI's: Gene Golub

(Stanford), Howard Hu (Pennsylvania), Roland Glowinski (Houston) and Ahmed Sameh (Purdue). We won this grant; we were among 12/300 winners and the only team in a fluid mechanics discipline. We have developed good codes for direct simulation and we are able to move slurries of over 1000 spherical particles in two-dimensions and are working on 3D simulators. We are the only group in the world with a working code to move particles in viscoelastic fluids in direct simulation. A complete description of this effort, together with publications and animations of the direct simulation of initial problems can be found on our web page.

## **II. Non-solenoidal and viscoelastic effects in the diffusion of miscible liquids**

Non-solenoidal effects arise in binary mixtures of incompressible miscible liquids when the mixing liquids have different densities, like glycerin and water;  $\text{div} \mathbf{u} = 0$  only for equal densities.

Since density differences are the rule rather than the exception, the usual theories of diffusion are wrong in principle however good an approximation they may be in practice. This point of view which I developed in 1990 and which is expressed in D.D. Joseph, A Huang and H. Hu, "Non-solenoidal velocity effects and Korteweg Stresses in simple mixtures of incompressible liquids", *Physica D* **97**, 104-125 (1996), has been gaining acceptance and recognition in the fluid mechanics community. The most important new result is a study of diffusion at the sidewall of a vessel filled with fresh, pure miscible liquids, (see T.Y Liao and D.D. Joseph, "Sidewall Effects in the Smoothing of an Initial Discontinuity of Concentration," accepted for publication in *J. Fluid Mech*). In this paper we derive a new solution which describes the smoothing on an initial plane discontinuity in concentration across a channel bounded by side walls. The requirement that the velocity vanishes on the side wall introduces a different initial discontinuity not present in the solenoidal theory. The problem may be reduced to a partial differential equation in two similarity variables one for the smoothing of a concentration discontinuity without sidewalls and the other for the smoothing of the velocity discontinuity at the sidewall. The similarity equations are solved explicitly in a special case.

## **III . Aerodynamic Dissemination, DA/DAAH 04-94-G-0266**

This proposal was funded in 1994 for the construction and instrumentation of a shock tube to study high-speed breakup. We received \$147,000

as a first installment of a \$700,000 grant. The funding was interrupted. We built the shock tube but we had no money for instrumentation. We pirated funds from other sources to keep going. To continue without funds, we competed for an equipment grant in an NSF solicitation and won \$129,000 for a rotating drum camera and particle field holographic system. With pirated and leveraged money we were able to construct an operating system and to create movies of breakup of drops in our shock tube, in which the entire event in a time frame of  $\mu s$ , up to  $250\mu s$ , can be visualized. A movie, showing the breakup of a drop of glycerin (to be followed by others we are now creating) has been put up on a website at the following address: [http://www.aem.umn.edu/Aerodynamic\\_Breakup](http://www.aem.umn.edu/Aerodynamic_Breakup).

Funding for the rest of this project has recently become available through the ERDEC and we are told that a budget will be given to us in the next months.

## 1. Technical Objectives and Motivation

The goal of research on aerodynamic dissemination is to determine the fraction, placement and drop size distribution of agents exposed to a high-speed air stream at high altitudes.

The problem is to understand the dissemination of agents which are exposed to a high Mach number air stream, between, say,  $M = 3$  and  $M = 8$  at high altitudes. It is known that a liquid mass is reduced to a droplet cloud in hundreds of microseconds. It is believed that considerable amounts of vapor or mist are produced, but that the mechanisms of breakup, the distribution of drop sizes, the volume fractions of mist and vapor and the precise effects of thickening agents on the droplet distribution and breakup mechanism are not known. The unknowns are inputs for computer codes designed to predict how the droplet clouds are disseminated, where they will drift and the condition and size of the droplets that ultimately reach the ground.

This is a very difficult problem because there is such a great difference between the breakup of organic liquids (solvent) and thickened liquids (solvent plus polymers). Organic liquids shatter into small drops and mist at high Mach numbers, but at the highest Mach numbers tested so far (slightly supersonic), viscoelastic fluids are pulled into threads but don't shatter. From this research, (possibly the first) data for thickened agents up to Mach 8 in our shock tube will be obtained. It is vital to see if and how these threads persist in the severe conditions behind a strong shock.

The problem is significant because without more precise knowledge of

the mechanisms and consequences of breakup and the condition of the droplet cloud immediately after breakup, the dissemination of agents is unpredictable and uncontrollable.

Problems of aerodynamic dissemination have been under consideration by the Army for about 20 years. However, this work has led only to partial understanding and the databases which are available from field tests and other experimental tests are not well enough understood to be used for prediction. The field tests suffer from the fact that the variables are not controlled and the conditions of testing do not allow for precise monitoring of important breakup events and consequences. Field tests are also very expensive. Our shock tube is orders of magnitude less expensive, gives more controlled experiments and the high speed cinematography opens a window for us to see breakup events previously hidden.

## **2. Technical Approach**

Thirty-three years of experience has been applied to solving problems in the mechanics of fluids to this Army problem using math analysis, physical reasoning, numerical computation, and results from our shock tube are anticipated with excitement. These are the elements that should be applied to any problems, but the research lab partially supported with ARO grants is equipped to do them all.

## **3. Significant Accomplishments**

A history of our significant accomplishments in the years prior to 1996 is in our 1995 "Red Book" report. The main accomplishment in 1996 is described below:

### **Shock tube research for Theater Missile Defense at the University of Minnesota**

D.D. Joseph, G.S. Beavers, J. Belanger

A dedicated shock tube with a Mach 8 capability, together with instrumentation (high speed camera; particle fluid holography system) for monitoring the aerodynamic breakup of all kinds of simulants, has been constructed with Army (\$160,000) and leveraged NSF (\$130,000) funds. The shock tube and high speed camera are now operational, and the particle field holography system is being assembled.

The parameters controlling the breakup and the resulting drop size distribution in fragmented clouds arising from aerodynamic breakup of simulants at high speeds have not been identified.

The size distributions of thickened simulants of the same viscosity at the same dynamic pressure are greatly different (for example, see the works of Jim Soltisz at SAIC) but the reason why is not known. This also leaves us at risk with regard to new agents for which simulants have not been tested.

The controlling parameters are surely associated with the fluid's rheology, measures like relaxation times and solvent quality, which are outside the circle of expert knowledge of other teams. To come up with the right parameters we need good ideas and the capability of generating supporting data in reasonable times at reasonable costs.

The shock tube is dedicated to the study of aerodynamic breakup at high air speeds of all kinds of materials, organic and polymeric liquids, seeded liquids (e.g. imbibitor beads) and even compacted granular material.

The first goal of our shock tube research is to perfect methods to determine the drop size distribution, particularly the fraction in large drops and the fraction in vapor and mist, in the fragmented cloud after breakup. These data can then be used as input in the post engagement ground effect model.

Shock tube research is many orders of magnitude less expensive than reverse ballistic, sled and field tests previously used by the Army to get drop size distributions.

The entire range of conditions encountered in missile defense can be simulated in our shock tube.

The procedures of testing and data acquisition are so much easier (and cheaper) in the shock tube that it is possible to generate very extensive data bases for the interrogation of the parameters controlling the breakup of all kinds of simulants, of present interest and future unknown threats.

Scale-up effects correlating size distributions after breakup with the initial size of the liquid mass can be carried out systematically in the shock tube because the initial size of the parent drop can be systematically varied. A high speed (200,000 frames/sec), high resolution drum camera has been put in place and is being used to record the sequence of events from the initial to final breakup of a liquid mass (20 to 1000 $\mu$ s). We have used the frames from the high speed camera and an SGI computer to make a movie of the high speed breakup of a drop of glycerin in a Mach 2 airflow in a time interval from 0 to 250 $\mu$ s. The movie can be seen on our website: [http://www.aem.umn.edu/Aerodynamic\\_Breakup](http://www.aem.umn.edu/Aerodynamic_Breakup).

Of particular interest is the flattening of the drop at early times up to

about  $50\mu s$ . This is due to potential flow before boundary layers are established; high pressures at stagnation points on the front and back of the drop squash it into a pancake. Then it strips. At about  $250\mu s$  a dramatic Rayleigh-Taylor instability can be seen which leads to an explosion of the drop which we did not appreciate before. Movies of other fluids will appear soon. The different fluids breakup in different ways. Nobody has ever seen this kind of thing before. Estimates of drop size distributions will be obtained using the particle field holography system. This will also allow us to check scale effects by comparison with data from equivalent reverse ballistic tests.

#### 4. Cooperation with Army Laboratories

Collaborations with Pat Nolan at ERDEC, Tim Cowles and Marty Richardson as SSDC in Huntsville and Carl Alexander at BATTELLE have been ongoing. From time-to-time we have interactions with other Army people: Walt Holis in the Pentagon, Bill Hughes at ARL etc.

#### 5. Publications in Referred Journals

Papers on the direct numerical simulation of the motion of solid particles in liquids (Project 1) can be found on our web page, [http://www.aem.umn.edu/Solid-Liquid\\_Flows/](http://www.aem.umn.edu/Solid-Liquid_Flows/).

Two papers have been or are to be published on diffusion in binary mixtures of incompressible miscible liquids (project **II**).

Two papers were published in 1995-96 on aerodynamic dissemination.

“Vaporization of a liquid drop suddenly exposed to a high-speed air stream,” (with A. Huang and G.V. Candler), *in J. Fluid Mech.*, **318**, 223-236 (1996)

“Cavitation in a flowing liquid,” *Physical Review E*, vol. 51, no. 3 (1995).

Over the course of the last three years, five memos were written to persons in our ERDEC and SSDC group on aspects of aerodynamic dissemination, as follows:

“Shock tube for studies of drop breakup,” *Progress Report* (1995).

“Vaporization of a liquid drop suddenly exposed to a high-speed airstream,” (with A. Huang and G.V. Candler). Submitted to the ERDEC and the ARO

(October 1994).

“Discussion papers for problems of aerodynamic breakup,” submitted to the ERDEC (August 1994).

“Final report: Aerodynamic dissemination,” prepared for Joe Huerta, ERDEC, (October 1993).

“Memo on ‘Research directions in aerodynamic dissemination – Part II,’” addressed to Tim Cowles, US Army Space and Strategic Defense Command, (September 1993).

“Memo on ‘Research directions in aerodynamic dissemination,’” addressed to Bob Becker, Pat Nolan, Miles Miller, Joe Huerta, Carl Alexander, (August 1993).

“Progress report on aspects of aerodynamic dissemination,” (with A. Huang and M. Arney). Submitted to Joe Huerta, CRDEC (September 1992).

“A discussion on the aerodynamic dissemination of simulant released at high altitude,” (with A. Huang and M. Arney). (1991).

A list of all my publications in 1995 and 1996 which acknowledge ARO support appears below.

“A three-dimensional computation of the force and moment on an ellipsoid settling slowly through a viscoelastic fluid,” (with J. Feng, R. Glowsinski and T.W. Pan). *J. Fluid Mech.* vol. 283, 1-16 (1995).

“Stability of eccentric core-annular flow,” (with A. Huang). *J. Fluid Mech.* vol. 282, 233-245 (1995).

“Dynamic simulation of the motion of capsules in pipelines,” *J. Fluid Mech.* vol. 286, 201-207 (1995).

“Propogation of voidage wave in a two-dimensional liquid- fluidized bed,” (with M. Poletto and R. Bai). *Int J. Multiphase Flow* vol. 39, 323-344 (1995).

“The negative wake in a second order fluid,” (with J. Feng). *J. Non-Newtonian Fluids* vol. 57, 313-320 (1995).

“A Maxwell memory model for the delayed weather response to solar heating,” (with K.R. Sreenivasan). Submitted to *Proc. Roy. Soc. A* (1995).

“Boundary layer flow of air over water on flat plate,” (with J. Nelson and A. Alving). *J. Fluid Mech.* vol. 284, 159-169 (1995). (1995).

“Cavitation in a flowing liquid,” *Physical Review E* vol. 51, no. 3, R1649 (1995).

“Motions of particles settling in a viscoelastic fluid,” Accepted for publication in *Proceedings of the Second International Conference on Multiphase Flow*, Kyoto, Japan, April 3-7, 1995.

“Two-dimensional cusp at the trailing edge of an air bubble rising in a viscoelastic liquid,” (with Y.J. Liu and T.Y. Liao). *J. Fluid Mech.* vol. 304, 321-342 (1995).

“Cement-lined pipe for water lubricated transport of hydrocarbons,” (with M. Arney, G. Ribeiro, E. Guevarra and R. Bai). Accepted for publication in *Int. J. Multiphase Flow* (1995).

“Non-solenoidal velocity effects in the smoothing of an initial discontinuity of concentration,” Submitted to *J. Fluid Mech.* (1995).

“The effective density and viscosity of a suspension,” (with M. Poletto). *J. Rheology* vol. 39, no. 2, 323-343 (1995).

“The unsteady motion of solid particles in creeping flows,” (with J. Feng). *J. Fluid Mech.* vol. 303, 83-102 (1995).

“Vaporization of a liquid drop suddenly exposed to a high-speed air stream,” (with A. Huang and G.V. Candler). Accepted for publication in *J. Fluid Mech.* (1996).

“Direct simulation of interfacial waves in a high viscosity ratio of axisymmetric core annular flow,” (with R. Bai and K. Kellar). Submitted to *J. Fluid Mech.* (1995).

“Vaporization of a liquid drop suddenly exposed to a high-speed air stream” (with A. Huang and G.V. Candler), *J. Fluid Mech.* **318**, 223-236 (1996).

“Direct simulation of interfacial waves in a high viscosity ratio of axisymmetric core annular flow” (with R. Bai and K. Kelkar). *J. Fluid Mech.*, **327**, 1-34 (1996).

“Flow characteristics of concentrated emulsions of very viscous oil in water” (with G. Núñez, Maria Briceño, Clara Mata, and Hercilio Rivás). *J. Rheology* **40**(3), 405-423 (1996).

“A note on the forces that move particles in a second-order fluid” (with J. Feng), *J. Non-Newtonian Fluid Mech.* **64**(2-3), 299-302 (1996).

“Core-annular flows” (with R. Bai, K.P. Chen, and Y.Y. Renardy). *An-*



*nual Reviews of Fluid Mech*, **29**, Jan. 1997.

“Dynamic simulation of sedimentation of solid particles in an Oldroyd-B fluid” (with J. Feng and P.Y. Huang). *J. Non-Newtonian Fluid Mech.* **63**(1), 63-89 (1996).

“The motion of solid particles suspended in viscoelastic liquids under torsional shear” (with J. Feng), Accepted for Publication in *J. Fluid Mech.* (1996).

“The motion of a solid sphere suspended by a Newtonian or viscoelastic jet” (with J. Feng), *J. Fluid Mech.*, **315**, 367-387 (1996).

“Flow induced microstructure in Newtonian and Viscoelastic fluids”, Keynote presentation (paper no. 95a), *Proceedings of the 5th World Congress of Chemical Engineering, Particle Technology Track. Second Particle Technology Forum*, San Diego, July 14-18, 1996, AIChE New York, **6**, 3-16 (1996).

“Stability of annular flow and slugging” (with Antonio Bannwart and J. Lui), *Int. J. of Multiphase Flow*, **22**(6), 1247-1254, (1996).

“Infiltration of an initially dry, deformable porous media”, *Int. J. of Multiphase Flow*, **22**(6), 1205-1222, (1996).

“The motion and interaction of solid particles in viscoelastic liquids” (with J. Feng and P.Y. Huang), *Rheology and Fluid Mechanics of Nonlinear Materials*, **217**, 123-133 (1996).

## 6. Awards and Honors

The P.I. of this ARO-sponsored research, Daniel D. Joseph, was named the Timoshenko medalist of the ASME for 1995 and he received the Thomas Baron Fluid-Particle Systems Award of AIChE for 1996.

## 7. Students and post-docs supported by ARO grants

Peter Huang received his PhD in 1996.

Jacques Belanger is the post doc working on the shock tube.

Tim Hall is supported under an AASERT grant.