COMPLEX INTERFACIAL FLOWS

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Abstract

The objective of this grant was to study complex interfacial flows. Here we report on several problems considered. In particular we have investigated the motion of a liquid along a second liquid interface, we have investigated a canonical problem associated with the rupture of a viscous interface, we have investigated the dynamics of a gas bubble or drop in an inclined parallel walled channel under gravity with and without the presence of surfactants, we have studied the dynamics of a dry spot in a thin liquid film and we have developed a numerical code to study the dynamics of a liquid interface in a parallel walled channel. In addition, two students have completed their Ph.D. thesis during this grant period.

Several projects have been under investigation during the period of this grant. In the following I will be specific about the work.

A central theme of this grant is the study of microscopic interfacial phenomena. By microscopic we mean that the scale of interest of the liquid interface is small. In particular, in nano- and micro- scale devices or phenomena, interfacial forces can be the dominate forces controlling the motion. Examples of this are multiphase flows in porous media, the motion of droplets on liquid interfaces with contact lines, and the dynamics of interfaces in the neighborhood of a breaking point. We should noted that microscopic interfacial phenomena can play a big part in determining the dynamics of macroscopic multiphase flows (e.g. in a porous media). Before good predictive theories on the macroscopic scale can be derived, the microscopic dynamics needs to be well understood. During this grant period we have studied several problems of this type. All could be categorize as being a complex interfacial flow, in that the interface is dynamic, has a contact line or interacts with a solid surface.

A problem of considerable interest is how one liquid spreads along the interface of a second. This is an important problem for the analysis of liquid waste spills on bodies of water, polymer-polymer coextrusion, the formation of foams in partially saturated porous materials, aerosol delivery of bronchial medicated mists and in many other areas. Along with my graduate student James Kriegsmann, we have studied the motion of a liquid along the interface of a second liquid. By assuming that the spreading coefficient is small and negative, and by taking the lubrication limit, we have reduced this problem to a system of fourth order space, first order time partial differential equations for the liquid interfaces. These equations are coupled to a set of boundary conditions at the triple junction. The conditions at the triple junction are derived by using matched asymptotics in the neighborhood of the triple junction. Unlike the spreading of a liquid along a solid interface where a nonintegrable stress singularity exists, we have shown that the solution is regular here in the neighborhood of the triple junction. When the liquid film rests along a horizontal plane surface, we are able to evolve the coating droplet and obtain steady state solutions. When the plane is inclined to the horizontal and gravity is causing the liquid to flow along the plane, then we have discovered several interesting features. This is a canonical problem of sort since the liquid film is flowing and the droplet is flowing on top of it, i.e., the dynamics is expected to be nontrivial. We have found a family of steady state (traveling wave) solutions where two of the physical parameters are determined as part of the problem. For example, the density and viscosity ratio are determined as part of the problem while all the other parameters are specified. This implies that for this negative spreading coefficient problem, the triple junction has limited the possible steady state solutions. J. Kriegsmann completed his Ph.D. thesis in 1999 on this topic [1]. One publication has appeared and a second has been submitted [2], [3], [4].

When a gas bubble or liquid drop moves within a pore channel, it's position within the channel is influenced by gravity. If the channel is vertical, we expect the bubble to remain in the center of the channel. If the channel is at an angle to the horizontal, how the drop evolves is not known. In particular, we are not really sure if the bubble will touch the wall or if a small coating film will remain between the wall and the bubble. Experiments have shown that it is possible for a bubble to attach to the wall of the channel at certain angles of inclination. Clearly such flows can occur in many problems related to multiphase flow in

porous media and would have implications about the transport within the material. Along with my graduate student Kevin DeBisschop, we have investigated flows such as these. By considering a Stokes flow model of the problem, we have developed a boundary-integral numerical method to study these flows. Note that because of gravity, the interfaces have no symmetry. Our current results seems to compare qualitatively with the experimental work of a group headed by David Eckmann at the University of Pennsylvania. We have done a comprehensive parameter study of this problem. In particular we have been able to show that where steady state solutions are possible for low Bond numbers, they no longer exist as the Bond number increases. We find that the dynamics of the rising bubble (drop) becomes very complicated as the Bond number increases. In particular, it is possible in some cases for the bubble (drop) to implode on itself and in other cases, droplets will be detached from the surface as the main drop rises up the channel. Surfactants have been added to this study and we find that the instabilities can be enhanced by their presence. K. DeBisschop completed his Ph.D. thesis on this in 1999 [5]. A publication containing most of these results will appear shortly [6].

In any multiphase flow we find the breaking of liquid interfaces. How these interfaces break is an important question and can determine the subsequent dynamics of the macroscopic flow. Although there has been considerable work in this area in recent years, there are few exact solutions. We have been able to identify a special case which has a solution in similarity form. This occurs when initially two viscous interfaces are brought together in the form of a wedge. Then the subsequent motion is self-similar. We have solved this problem for a variety of viscosity ratios and wedge angles. This work (joint with J.-M. Vanden-Broeck) has appeared in the *Physics of Fluids* [7]. We have also studied the dynamics of a triple junction on a liquid/liquid interface. A similarity solution has been discovered for the special local geometry of a wedge. We find that the relation between the surface tensions of the interface control the dynamics of the interface and the propagation of surface waves along the interface. [8]

A study was done on the dynamics of a dry spot in a thin liquid film. Dry spots can occur in thin coating films for a number of reasons, e.g., an interfacial instability due to microscopic forces (such as vander Waals forces), heating, a surface irregularity, etc. A model was derived in the lubrication limit and compared to experimental data. Good comparison was found. Three cases were observed experimentally: opening holes, closing holes and holes asymptoting to a static shape. The theory compared well with each experimental case. The results have been submitted to the *Journal of Fluid Mechanics* [9].

The dynamics of a liquid film in a parallel walled inclined channel was also investigated. Here we developed a front tracking numerical method to solve the full Navier-Stokes equations with surface tension. Here we considered the case of two liquids in an inclined channel. The steady state consists of a constant height interface parallel to the channel walls. We find the stability of the interface as a function of the Reynolds number, the Bond number, and the density and viscosity ratio. Cases are obtained which illustrate the breaking of an interfacial wave from the interface. Comparisons are done with linear theory and we find that the full nonlinear results parallel the predictions of linear theory except in that the region of instability is increased. This work has been submitted to the *Physics of Fluids* [10].

A project initiated during this grant period is the investigation of the dynamics of a triple

junction when three liquid interfaces intersect. The liquids are governed by the Navier-Stokes equations. My graduate student, Catherine Norman, is expanding on the results of J. Kriegsmann and has developed a level set numerical method to study the dynamics of liquid coating flows. Her research is supported by a DOE Computational Sciences Graduate Fellowship. Last summer she has started working on this problem in collaboration with the staff of LBL. The problem involves solving the full Navier-Stokes equations and associated boundary conditions. For fluid mechanics problems with surface tension, the level set method is a diffuse interface method (in spirit similar to the phase field method) when the interface is defined as the zero contour of a level set function. For the problems proposed here, two (sometimes three) level set functions are introduced.

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