THERMOCAPILLARY MIGRATION AND INTERACTIONS OF BUBBLES AND DROPS

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1. INTRODUCTION

When a drop or bubble is introduced into a second fluid in which there exists a temperature gradient, the drop (or bubble is implied from hereon) will move (1). Such motion is a consequence of the variation of the interfacial tension along the interface between the drop and the continuous phase. Reviews of the literature on this subject may be found in Wozniak *et al.* (2) and Subramanian (3). This movement is termed thermocapillary migration, and can be important in materials processing in space, and in separation processes used in long duration space excursions for recycling and on the surface of the moon.

The speed at which a drop migrates can be obtained by solving the governing continuity, Navier-Stokes, and energy equations along with the associated boundary conditions. When convective transport effects are important, the problems are nonlinear. The relative importance of convective transport of energy when compared to conduction can be judged from the magnitude of the Péclet number whereas a similar ratio for momentum transport is described by the Reynolds number, Re. When a velocity scale characteristic of thermocapillary migration is used, the Pèclet number is known as the Marangoni number, Ma. The Capillary number also is another parameter that influences the shape of the drop. Definitions of these quantities may be found in (4).

In the linear limit when the Reynolds and Marangoni numbers are negligible, the contribution of thermocapillarity can be extracted from experiments on the ground. Therefore, experiments designed to explore thermocapillary migration on the ground are subject to this important limitation; some of this experimental work is discussed in references (2,3). To better explore the parameter space in the Reynolds and Marangoni numbers than is possible on the ground, investigators have attempted to carry out experiments in reduced gravity conditions. The previous studies, as discussed by us in Balasubramaniam *et al.* (4), were subject to many limitations which raise questions regarding the utility of the data. Therefore, in summer 1994, we performed thermocapillary migration experiments in reduced gravity under conditions closer to those assumed in theoretical models. We used air bubbles and Fluorinert FC-75 drops migrating in a Dow-Corning DC-200 series silicone oil of nominal viscosity 50 centistokes. The apparatus in which the experiments were performed was the Bubble, Drop, and Particle Unit (BDPU) built under the auspices of the European Space Agency. Our experiments, carried out aboard the IML-2 mission of the Space Shuttle, yielded good data on isolated drops up to a Reynolds number of 0.85 and a Marangoni number of 280, and on isolated bubbles up to a Reynolds number of 2.2 and a Marangoni number of 810. In the case of air bubbles, the data were found to be generally consistent with our predictions from a numerical solution of the governing equations as well as an asymptotic theoretical result obtained by Balasubramaniam and Subramanian (5). Also, some preliminary results on interacting drops were obtained and reported in (4).

In an attempt to explore further the interactions between pairs of drops and pairs of bubbles and to extend the range of values of Marangoni and Reynolds numbers, we performed follow-on flight experiments aboard the LMS mission of the Space Shuttle in summer 1996. The same fluids, air and Fluorinert FC-75, were used for the bubble and drop phases, respectively, and a silicone oil of nominal viscosity 10 centistokes was employed for the continuous phase. This choice was made so as to be able to extend the maximum Marangoni number by approximately a factor of 6, and the corresponding maximum Reynolds number by a factor of approximately 30. Also, tracer particles dispersed in the silicone oil were used in the air bubble migration experiments in order to track the flow in the continuous phase during the migration process. In addition, the Point Diffraction Interferometry (PDI) system used in IML-2 was refined by the European Space Agency to incorporate a Wollaston Prism with a divergence angle of 10 degrees, so that interferometry was able to provide quantitative information on temperature fields in the LMS experiments involving gentle temperature gradients. Except for these modifications, the procedures and the experiments were similar to those in IML-2.

2. EXPERIMENTAL APPARATUS AND PROCEDURE

The experiments were performed in the BDPU which was provided by the European Space Agency through a cooperative arrangement with the National Aeronautics and Space Administration. The apparatus consists of a "facility" which provided power, optical diagnostics and illumination, imaging facilities including a video camera and a motion picture camera, and other sundry support services. Within this facility, a test cell that was specific to the experiment was inserted by the payload specialist on the Shuttle when needed.

Conceptually, the experiments were simple. Within a test cell mounted in the facility and filled with a suitable liquid, a temperature gradient was established, followed by the introduction of a bubble or a drop as desired. The subsequent motion of the object, in the direction of the applied temperature gradient, was recorded for later analysis on videotape on the ground as well as on cine film on board the Shuttle in selected experiments. When a bubble or drop reached the hot wall, it was extracted and another was introduced after a small waiting period.

The heart of the experimental apparatus is the test cell. Two rectangular test cells were available. Both were of identical dimensions, measuring 60 x 45 x 45 mm in the interior. This cavity was filled with a Dow-Corning DC-200 series silicone oil of nominal viscosity 10 centistokes in both cells. As mentioned earlier, the silicone oil in the bubble cell contained a small concentration of tracer particles provided by Dornier GmbH from Germany. It was possible to maintain the two end walls (made of aluminum) in the long dimension of the cell at fixed known temperatures so that a temperature gradient could be established in the z-direction. Within the cavity, an injection needle was available when needed. When not in use, the tip was flush with the cold aluminum surface at its center. It was possible to introduce air bubbles in one test cell, and Fluorinert FC-75 drops in the other cell. The diameters of the bubbles varied from approximately 1.3 to 14.4 mm, and those of drops ranged from 2.1 to 14.3 mm. After a bubble or drop completed its traverse, it was extracted from the hot wall using an extraction tube mounted at the center of a net.

The equipment provided red background illumination and the opportunity to capture images of the interior of the test cell on videotape on the ground. Also, a limited amount of cine film was available, and was used to capture images during selected runs at suitable framing rates.

In any given run, the procedure was first to establish the desired temperature gradient over a period of 2 hours. This period included approximately 30 minutes in which the liquid in the cell was stirred by back and forth movement of the net, followed by a quiescent period lasting approximately 90 minutes. This was followed by the injection, traverse, and subsequent extraction of bubbles or drops. At low temperature gradients, interferometry images received on the ground were used as a diagnostic tool to determine when the temperature field became steady.

At the end of the heating period, when real time TV and commanding capability were available, the experiment was initiated by sending a command to inject a bubble or drop of a specified size at a specified position along the long axis of the cell. The traverse of the object was followed on the ground while recording it. When the bubble reached the opposite wall, it was usually extracted using a small tube at the center of that wall. After the passage of a sufficient amount of time, judged from interferometry images where available, the next injection was initiated. This waiting period was usually of the order of 3 minutes. For a pair of bubbles or a pair of drops, suitable commands were packaged and sent up to the apparatus to perform the sequential double injection automatically. When a sufficient number of runs were made with one temperature gradient, another gradient was employed. The bubble cell and the drop cell were each used twice. Temperature gradients of 0.33 and 1 K/mm were used with bubbles, and 0.25 and 1 K/mm with the drops. A run with a temperature gradient of 0.067 K/mm with the bubble cell yielded no usable data due to poor communications between the orbiter and ground caused by the "safe" attitude of the orbiter.

A total of 64 bubble runs and 74 drop runs were recorded on videotape, and 35 bubble runs and 38 drop runs on cine film. Of these, 53 bubble runs and 67 drop runs were analyzed. The rest either contained objects too small to be measured precisely or presented other problems that precluded analysis. A sufficient number of runs were made on isolated drops and bubbles to extend the range of Reynolds and Marangoni numbers beyond those encountered in the IML-2 experiments. The remaining experiments focused on interacting drops and bubbles. While we introduced pairs of bubbles and pairs of drops deliberately in selected runs, sometimes a collection of two or more objects was introduced by the injection system even when the objective was to inject a single object.

3. RESULTS AND DISCUSSION

Isolated Bubbles and Drops

The video and cine images were analyzed using an automated computerized system developed by NASA Lewis Research Center. This worked by selecting single frames and tracking the boundary of the object involved. It was found that even the largest drops displayed no detectable deformation in shape while the largest bubbles in the temperature gradient of 1 K/mm were slightly oblate.

Since the position of the objects was followed throughout the traverse it was possible to calculate the velocity at various locations in the cell. The velocity changed during the traverse because of the initial acceleration of the bubble or drop upon release from the injector as well as due to the change of physical properties (principally viscosity) with temperature. Therefore, the velocity was never truly steady for any given bubble or drop. In the isolated bubble runs, the Reynolds number varied from 0.8 to 87 while the corresponding Marangoni number ranged from 51 to 5800. In the case of the drops, the range of Reynolds number was 0.14 to approximately 10 and the corresponding range of Marangoni number was 14.6 to approximately 600.

We have reported the results pertaining to isolated bubbles and drops in Hadland et al. (6). A detailed presentation and discussion can be found there. The main points are briefly summarized here. It was found that the data from LMS were generally consistent with those obtained in the earlier IML-2 experiments where there was overlap. However, as mentioned earlier, the range of Marangoni numbers was extended both in the case of bubbles and in the case of drops. Data on air bubbles were in agreement with predictions from a numerical solution except at very large values of the Marangoni number where the observed velocities were not as large as those predicted. However, at large values of the Marangoni number, the data from bubbles appeared to approach an asymptotic result good in this limit which is reported in (5). The scaled velocity of Fluorinert drops was consistent with predictions from a numerical solution reported by Ma (7) at low to moderate values of the Marangoni number. However, at large values of the Marangoni number, both an asymptotic analysis and the numerical solution predict that the scaled velocity should increase with increasing Marangoni numbers while the data did not display this behavior. The motion of the drops was unsteady due to the variation of viscosity with temperature and due to the significant amount of time it would take to achieve a steady temperature gradient distribution within a drop. This may explain the observed discrepancies at large values of the Marangoni number.

Interacting Bubbles and Drops

In some experiments on pairs of drops involving a small leading drop and a large trailing drop, the trailing drop moved slower than it would if it were isolated. This was consistent with similar behavior noted in IML-2 experiments. However, some other interesting patterns of behavior were noted in LMS experiments. In several runs a leading bubble or drop moved straight along the axis of the cell while a trailing object released a small distance behind the leader moved away from the axis in a transverse direction. This movement was typically only by a few mm in that direction but was clearly measurable. We observed the same behavior on the part of bubbles as well as drops. In some cases the trailing drop passed the leading drop when its transverse movement brought it sufficiently away from the axis. Finally, in a few experiments involving multiple drops, the drops were seen to execute three-dimensional trajectories across the cell.

Explaining the behavior of interacting drops is not trivial. It is likely that the wake of the first object plays a role in causing the observed behavior. One can envision a thermal wake behind the leading object in the case of both the bubble and drop experiments. This is a relatively thin region in which the temperature field is presumably axisymmetric and the temperature gradient is weaker than that in the undisturbed fluid. Whereas in IML-2, the trailing drop moved straight along the axis when influenced by this wake, in some LMS experiments, it appears that slight asymmetries in the positioning of the second object with respect to the wake caused the fluid in the wake to wrap around this object asymmetrically; in turn, this must have led to an asymmetry in the temperature gradient distribution on its surface which may have caused the resulting movement away from the axis of the cell.

4. CONCLUSIONS

The results for the migration velocity of isolated air bubbles extend the range of values of the Marangoni number investigated in earlier IML-2 flight experiments. The data are consistent with those from IML-2 and with theoretical predictions. The data on isolated drops display similar trends even though agreement with predictions from a numerical solution is only noted at small to moderate values of the Marangoni number. Experiments on multiple drops and bubbles show evidence of wake effects from a leading object. In some cases, the trailing bubble or drop moves off the axis of the cell; large trailing drops pass the leading drop in this way. In other experiments, trailing drops exhibit a three-dimensional trajectory. The shapes of even the largest drops in the largest temperature gradient used were spherical to within the uncertainty of the measurements while large bubbles moving in the same temperature gradient were found to be slightly oblate.

5. ACKNOWLEDGMENTS

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