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THERMOCAPILLARY MIGRATION AND INTERACTIONS OF BUBBLES AND DROPS

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ABSTRACT

Results from experiments conducted in reduced gravity on the thermocapillary motion of bubbles and drops are discussed.

INTRODUCTION

When a drop or bubble is placed in another fluid and subjected to the action of a temperature gradient, the drop will move [1]. Such motion is a direct consequence of the variation of interfacial tension with temperature, and is termed thermocapillary migration. The literature on both experimental and theoretical research in this field up to approximately 1989 has been adequately reviewed by Wozniak *et al.* [2] and Subramanian [3].

The movement of suspended objects such as drops and bubbles is relevant to situations that are likely to arise in low gravity experiments. Liquid drops may be encountered during the formation and solidification of alloys, and in separation processes such as extraction that might be used in long duration space voyages for recycling purposes. Also, a dispersion of vapor bubbles might be encountered in heat transfer fluids used in spacecraft which undergo phase change. Gas bubbles arise in crystallization where dissolved gases are rejected at the interface and also in separation processes such as gas absorption. In most applications, it is likely that a collection of drops or bubbles would be involved in which the individual members will influence the motion of each other, and also possibly coalesce leading to changes in size distributions over time.

The speed at which a drop migrates under the action of a temperature gradient can be obtained by solving the governing Navier-Stokes and energy equations along with the associated boundary conditions. When convective transport effects become important, the problems involved 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 Péclet number is known as the Marangoni number, Ma. The Capillary

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number also is technically a parameter; however all observations to date involve no measurable deformation in shape. The relevant quantities are defined below.

$$Re = \frac{R\, v_o}{\nu}, \tag{1}$$

$$Ma = \frac{R\, v_o}{\kappa}. \tag{2}$$

Here, R is the radius of the drop or bubble, μ is the dynamic viscosity of the continuous phase, ν, its kinematic viscosity, and κ, its thermal diffusivity. The reference velocity, v_o, is defined below.

$$v_o = \frac{|\,\sigma_T\,|\,|\,\nabla T_\infty\,|\; R}{\mu}. \tag{3}$$

In the above, σ_T is the rate of change of interfacial tension with temperature, and ∇T_∞, the temperature gradient imposed in the continuous phase fluid.

In the linear limit when the Reynolds and Marangoni numbers are negligible, the contribution of thermocapillarity can be extracted from an experiment 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 the above two reviews.

To fully explore the parameter space in the Reynolds and Marangoni numbers, investigators have attempted to carry out experiments in reduced gravity conditions. The literature is discussed in Balasubramaniam *et al.* [4]. The previous studies were subject to many limitations which raise questions regarding the utility of the data. Therefore, we performed thermocapillary migration experiments in reduced gravity under conditions closer to those assumed in theoretical models. The experiments were carried out aboard the IML-2 mission of the NASA Space Shuttle in the summer of 1994. Here a brief summary of the experiments is given. For more details, the reader is referred to [4].

EXPERIMENTAL APPARATUS AND PROCEDURE

The experiments were performed in an apparatus labeled the BDPU (Bubble, Drop, Particle Unit) 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 shown schematically in Figure 1. 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 50 centistokes in both cells. 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 2.1 mm to 14.8 mm, and those of drops ranged from 2.0 to 14.4 mm. After a bubble or drop completed its traverse, it was possible to extract it from the hot wall using an extraction tube mounted at the center of a net.

The equipment provided white 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 18 frames per second.

In any given run, the procedure was first to establish the desired temperature gradient over a period of 2 hours. This was followed by the injection, traverse, and subsequent extraction of a bubble or drop. This process was repeated until the allotment of real-time video capability was exhausted. The entire procedure was performed six times permitting the use of different temperature gradients, and allowing a total of approximately 6 hours of observation time. A total of 22 bubbles and 98 drops were recorded on videotape, and 16 of the bubbles and 65 of the drops on cine film. About one-third of the data were on isolated drops or bubbles. Multiple objects were encountered in most of the remaining runs. From the latter, a few usable runs on pairs of drops were identified; data on a representative pair will be presented and discussed in the next section.

RESULTS AND DISCUSSION

Isolated Bubbles and Drops

We observed from the data that the bubbles and drops were spherical to within the uncertainty of the diameter measurements made. Only one velocity per traverse, evaluated at a suitable location, is reported. Typically, the bubble or drop achieved a quasi-steady velocity, to within the uncertainty of our velocity measurements, after moving about half a radius from the injection location. To be conservative, we report data only when the object has moved at least one radius.

In Figure 2, the velocity data on isolated air bubbles are plotted in scaled form and compared with available predictions. The velocity of a bubble is scaled using the velocity it would have in the limit of negligible values of the Reynolds number and the Marangoni number. The various physical properties are evaluated at the estimated temperature in the undisturbed fluid at the x-y plane containing the center of the bubble. Typical uncertainty estimates are shown in the figure.

Included in the drawing for comparison is a theoretical prediction originally presented by Balasubramaniam and Lavery [5] who solved the governing momentum and energy equations for the quasi-steady velocity and temperature fields and bubble velocity when the Reynolds and Marangoni numbers are not negligible. The authors also assumed a spherical bubble in an infinite extent of fluid, and Newtonian and incompressible flow with constant physical properties, except for the interfacial tension which was assumed linear with temperature. Their finite difference code was used to develop the predictions shown. The Prandtl number varied between 370 and 575 in the bubble runs because of the change in temperature. The actual curve was prepared from theoretical predictions for a Prandtl number of 370, but the predictions are not very sensitive to the Prandtl number in the above range. Also included is the prediction of Balasubramaniam and Subramanian in the asymptotic limit of large Marangoni number for negligible Reynolds number.

It is evident from Figure 2 that the data support the qualitative trend predicted from the quasi-steady theory with the following discrepancies noted. First, for small values of Ma in the approximate range 5 to 10, the observed velocities are significantly larger than those predicted. Second, while the four data points at values of Marangoni number between 250 and 800 are distributed around the asymptote for large values of Ma, it is not evident that the overall trend of the data is to achieve this asymptotic behavior; clearly we need to extend the observations to larger values of the Marangoni number for making a definitive statement. The discrepancies may be attributed to a variety of reasons which are discussed in [4]. The most plausible explanation appears to be that interactions of the walls with the migrating bubbles via the temperature fields can account for the observation.

In Figure 3, we show a drawing similar to Figure 2, but for Fluorinert FC-75 drops. These data display a trend very similar to that shown by bubbles in Figure 2. The reference velocity is once again the predicted velocity at negligible values of Reynolds and Marangoni number from Young *et al.*. Note the asymptotic trend displayed by the scaled velocity at values of Ma $\geq$ 100. We do not have a theoretical prediction in this case so that no statements can be made with respect to agreement with predictions or lack thereof. The behavior of the scaled velocity as Ma approaches small values is similar to that observed in the case of bubbles. The curve shown in the figure is a fitted result and does not represent a prediction.

Interacting Drops

A few usable runs were performed on pairs of Fluorinert drops. In these, the leading drop was smaller than the trailing drop. It was observed that the leading drop moved at approximately the velocity it would have if isolated, but the trailing drop was found to move at a reduced velocity compared to the value it would have if isolated. This remarkable observation can be explained qualitatively by recognizing the existence of a thermal wake behind the leading drop in which temperature gradients are weakened. The trailing drop moves into this region and therefore experiences a reduction in the driving force for its motion. We intend to explore this phenomenon in more detail and also extend the range of parameters obtained in IML-2 in follow-on flight experiments scheduled for conduct on the LMS mission of the Space Shuttle in summer 1996.

CONCLUDING REMARKS

Results from observations made on isolated bubbles and drops moving in a temperature gradient in a space laboratory are reported. The results for the migration velocity of air bubbles qualitatively confirm the trend predicted by a theoretical model, but there are quantitative discrepancies. Some tentative explanations are offered to account for these discrepancies. The data for drops display similar trends. Experiments on pairs of drops revealed the remarkable feature that a small leading drop, which itself appears unaffected in its motion, can significantly influence the motion of a larger trailing drop almost twice its diameter. It is conjectured that this is a consequence of the thermal wake behind the leading drop.

ACKNOWLEDGMENTS

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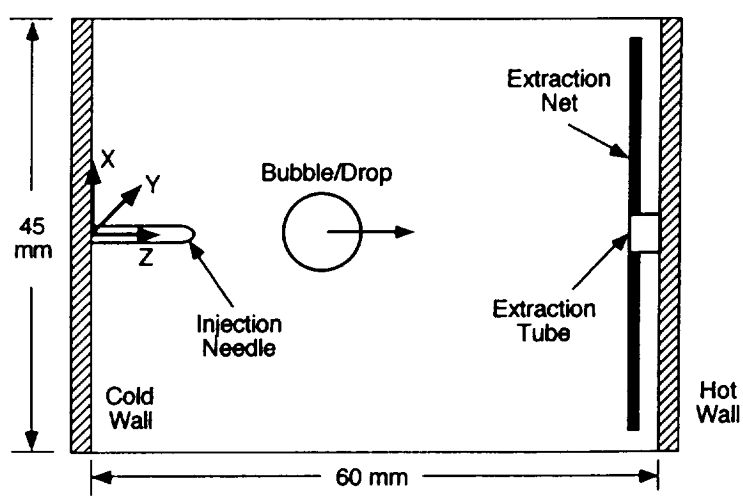

Figure 1. Sketch of test cell

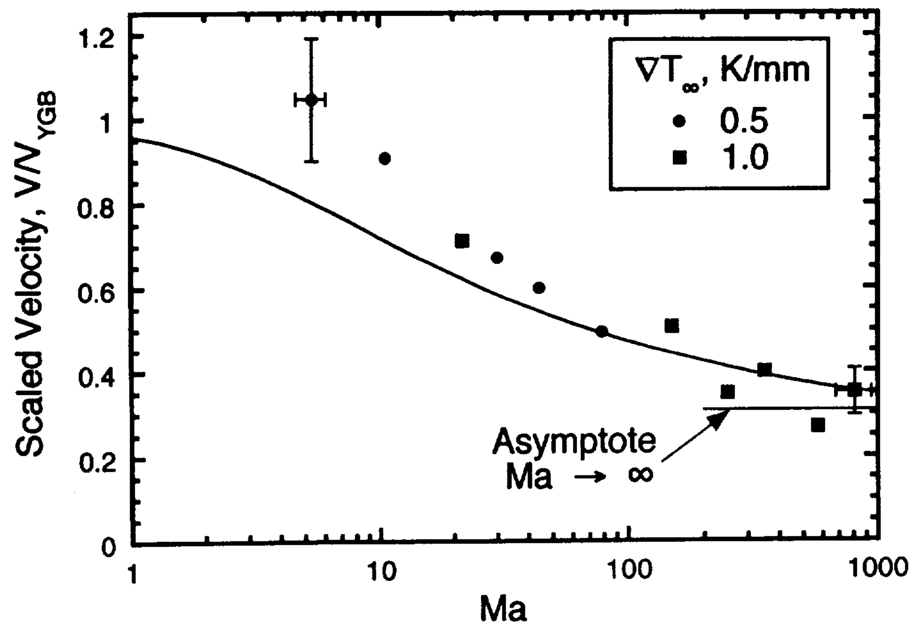

Figure 2. Scaled velocity of the bubbles versus the Marangoni number. The solid curve represents predictions from a numerical solution. The horizontal solid line is from a prediction for negligible Reynolds number and Ma → ∞ based on asymptotic analysis.

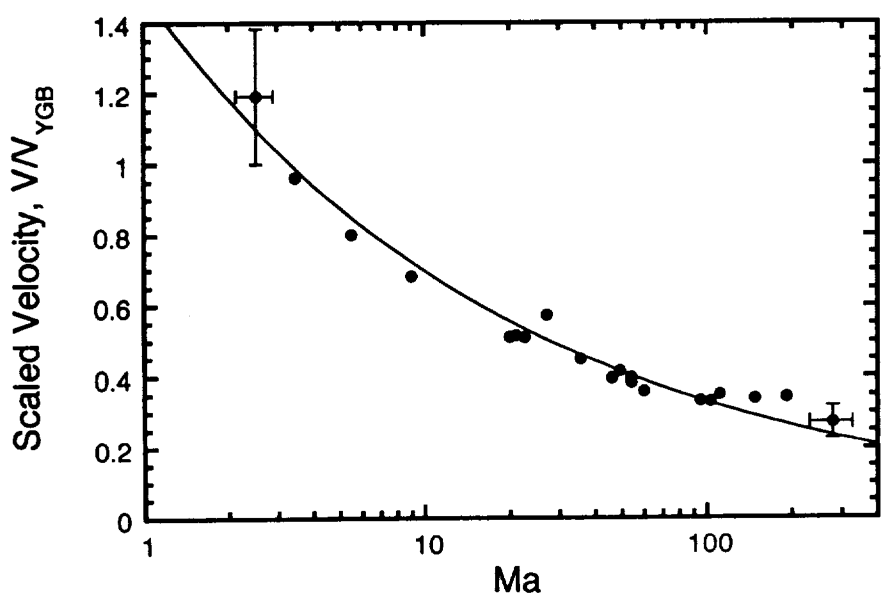

Figure 3. Scaled velocity of the Fluorinert FC-75 drops versus the Marangoni number. The solid curve represents an empirical curve fit of the data.