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The motion of bubbles inside drops in containerless processing

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Abstract

A theoretical model of thermocapillary bubble motion inside a drop, located in a space laboratory, due to an arbitrary axisymmetric temperature distribution on the drop surface is constructed. Typical results for the stream function and temperature fields as well as the migration velocity of the bubble are obtained in the quasistatic limit.

The motion of bubbles in a rotating body of liquid is studied experimentally, and an approximate theoretical model is developed. Comparison of the experimental observations of the bubble trajectories and centering times with theoretical predictions lends qualified support to the theory.

Introduction

With the advent of the Space Shuttle, orbital processing of materials over extended periods of time will become realizable in the near future. The near free fall environment aboard orbiting spacecraft is particularly attractive for containerless operation. For instance, materials may be melted while suspended, and cooled without contacting a container. It has been suggested that certain high technology glasses which are difficult or impossible to make on earth because of container-wall-induced heterogeneous nucleation can be made in a free fall environment.[1,2] Other applications for containerless processing include the measurement of physical properties of highly reactive melts, and the preparation of ultrapure materials which are easily contaminated by containers.

In many of the above applications, it is likely that gas bubbles will be formed in the melts processed in space. For instance, in the manufacture of glasses, bubbles are formed due to the liberation of gaseous products from chemical reactions. The removal of such bubbles is essential to the preparation of a useful final product. At Clarkson, with financial support from NASA, experiments are being designed for flight aboard NASA rockets and the Space Shuttle on the subject of surface tension gradient driven motion of gas bubbles in glass melts and model fluids. The experiments will involve the photographic observation, under reduced gravity conditions, of the motion of, and the interaction among, bubbles in a liquid drop which is spot-heated. They are described in detail elsewhere.[3,4]

Another topic to be addressed, in our free fall experiments, is the centering of gas bubbles inside a liquid drop. Such centering plays an important role in the process currently employed for the production of uniform hollow glass shells (microballoons) used in inertial confinement fusion research.[5] Typically, a collection of gel particles is dropped into a vertical tube furnace. The particles melt and gas bubbles form. At some point, these bubbles coalesce into a large bubble which centers itself inside the molten glass drop. At the bottom of the furnace, fairly uniform shells are obtained.[5] In view of the conditions of operation in the production process, it is quite difficult to isolate a single particle, and follow its time-temperature history carefully. Thus, there is considerable uncertainty at this time concerning the mechanisms which might be operative in centering the bubble inside the molten liquid drop in the furnace. The sphericity and wall-thickness uniformity of the hollow glass shells obtained is crucial to the success of the fusion process wherein the shells are filled with a Deuterium-Tritium mixture and an implosion is achieved by irradiation with a laser pulse or an ion beam.[6]

In the near free fall conditions aboard the Shuttle, a bubble can be introduced into a liquid drop and various centering mechanisms such as rotation, oscillation, expansion/contraction, etc., which have been proposed to date, can be studied. Manipulation of the drop and bubble system may be achieved using acoustic fields.[7,8]

In this presentation, some of our ground-based research on the motion of bubbles inside drops will be described. Theoretical work has been performed on thermocapillary bubble migration inside a drop, and is being reported in the literature.[9,10] More details will be given in (11). Experimental work is under way on the behavior of bubbles placed inside a rotating liquid body. Some of this work is being reported in the literature[12] and details may be found in (13).

Thermocapillary motion of bubbles inside drops

A bubble placed inside a drop in the absence of gravity will move if a non-uniform temperature field is induced and maintained on the drop surface. This motion will be a direct consequence of the tangential stresses at both the drop surface and the bubble-liquid interface caused by the variation of surface tension with temperature. Such stresses will induce motion in the liquid shell due to viscous traction, and cause the movement of the bubble. In fact, a gas bubble placed in a quiescent liquid body with a non-uniform temperature field will propel itself toward the warmer regions in the liquid by causing motion of the liquid in its vicinity. The problem of the isolated bubble has been examined in the past, and both theoretical[14,15] and experimental[14,16] results are available.

In the present problem, several variations may be posed. When the prescribed temperature field is axially symmetric (as obtained perhaps by spot-heating the drop), and when the bubble is located along this symmetry axis, the velocity and temperature fields in the liquid shell will possess axial symmetry. Furthermore, we restrict attention to the quasi-static limit wherein the unsteady accumulation terms as well as the convective transport terms are ignored in comparison to the molecular transport terms in the governing conservation equations. In this case, the equations of conservation of momentum and energy are linear, and the powerful principle of superposition can be used to construct solutions.[17-19] The general solutions presented in (18,19) may be specialized to the boundary conditions applicable to our problem in a straightforward, but tedious manner. Details are presented elsewhere.[9-11]

In view of the linearity of the governing equations, the resulting motion of the bubble may be studied conveniently by decomposing the arbitrary temperature field into spherical harmonics. The scaled migration velocity (U) of the bubble has been calculated as a function of reduced bubble size κ (Bubble radius/Drop radius) and the scaled distance between the drop and bubble centers D (scaled using drop radius) for the first three Legendre modes of the surface temperature field. As expected, in all these cases, the bubble moves towards the nearest warm pole. For a P_1-mode surface temperature field, for a fixed κ, the velocity of the bubble U increases with decrease in D, and reaches a maximum when the bubble reaches the center of the drop. For higher modes, U first increases from its value of zero at $D = 0$ for increasing D, but ultimately decreases as the bubble approaches the drop surface. For all modes, for fixed D, the velocity of the bubble increases with κ, for a wide range of values of κ.

A typical set of results for the isotherms and streamlines induced by a P_1-mode surface temperature field is presented in figure 1. Here, due to the symmetry of the fluid flow, a bubble placed anywhere on the symmetry axis will move toward the warm pole along the symmetry axis. However, for the P_2 and higher modes of the surface temperature field, a bubble located at the center of the drop will not move. Any displacement of the bubble from the drop center will result in the motion of the bubble to the nearest warm pole (not shown). Detailed results on the motion of the bubble are given elsewhere.[9-11]

We also might note here that a simple approximation can be constructed for the bubble velocity for relatively small bubble size. This approximation, presented in (9,10) involves the calculation of the streaming velocity of the fluid in the drop at the location of the bubble center in the absence of the bubble using results available in the literature.[20] Then, the thermocapillary migration velocity of an isolated bubble in a quiescent liquid subjected to the temperature gradient existing in the drop at the location of the bubble center (but in the absence of the bubble) is computed from (14). The two are added to give the desired approximation. As shown in (9,10) this approximation is quite good for relative bubble radii of up to a tenth of the drop radius, and for even larger values when the bubble is close to the center of the drop.

Bubble motion in a rotating liquid

A gas bubble in a rotating liquid body will experience buoyancy toward the axis of rotation due to the radial acceleration field quite analogous to upward buoyancy due to earth's gravity.[21-24] Relatively small bubbles, introduced into highly viscous liquids rotating at small angular velocities, will migrate principally in the radial direction when viewed in a reference frame rotating with the liquid. Coriolis deflection under these conditions will be a small secondary effect.

In an effort to investigate this bubble centering mechanism, we have performed experiments using a spherical thin-walled glass shell approximately 70 mm in diameter. The shell is filled with a Dow-Corning DC-200 series silicone oil through a hole on the surface of the sphere, leaving a small air bubble (~2 mm diameter) in the liquid, and sealed using a piece of gum-tape. The bubble is initially located at the highest point in the liquid, a position dictated by gravity. The shell is then rotated about a horizontal axis with the aid of a D.C. motor. The bubble spirals in toward the rotation axis on the equatorial plane of the

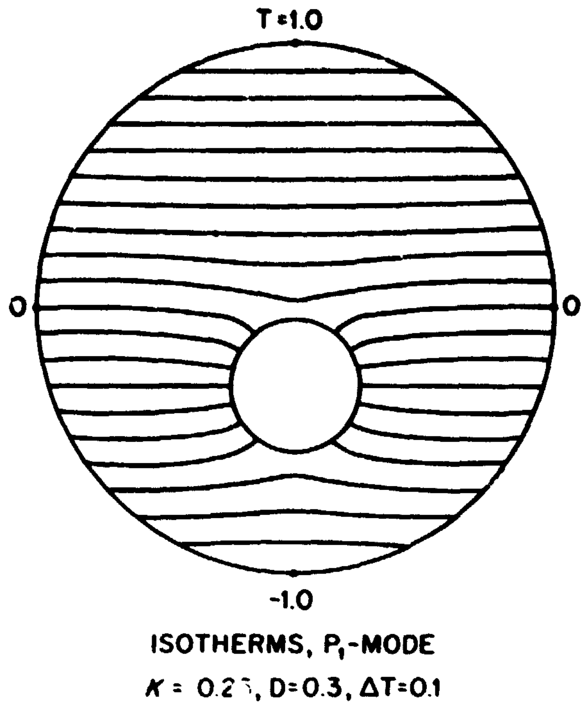

Figure 1a. Isotherms for the eccentric bubble system for a P_1-mode temperature field on the drop surface, $\kappa = 0.25$, $D = 0.3$.

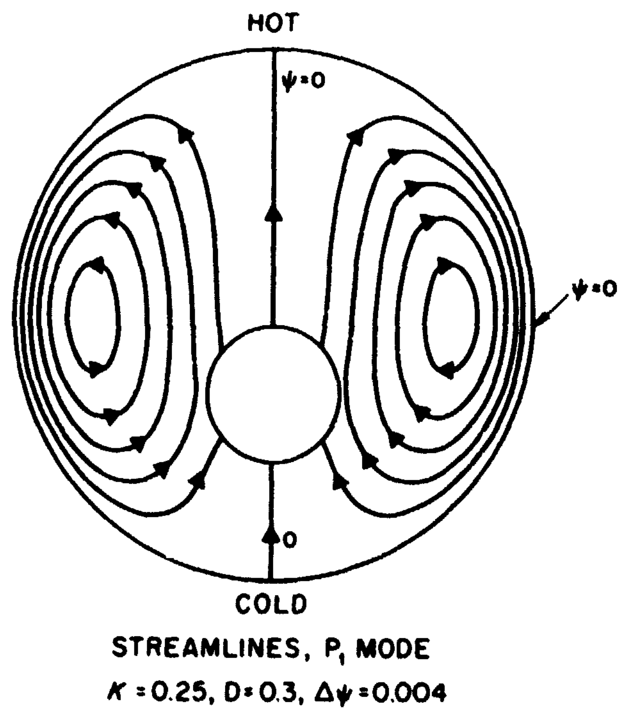

Figure 1b. Streamlines for the eccentric bubble system for a P_1-mode temperature field on the drop surface, $\kappa = 0.25$, $D = 0.3$.

shell, and the process is recorded using high speed motion picture camera, or a video camera depending on the rotation rate of the sphere for the experimental run. More details may be found in (12,13).

In Figure 2, experimental data are shown for a typical run. The radial position of the bubble, scaled by the shell radius, and corrected for optical displacement effects, is plotted against time, and the migration of the bubble to the rotation axis may be seen clearly. An approximate theoretical description of the migration process has been developed[12,13] and the prediction from theory may be seen to be in reasonable agreement with the data shown in Figure 2. The effects of secondary flows during spin-up and gravity on the bubble migration process have been discussed elsewhere.[12]

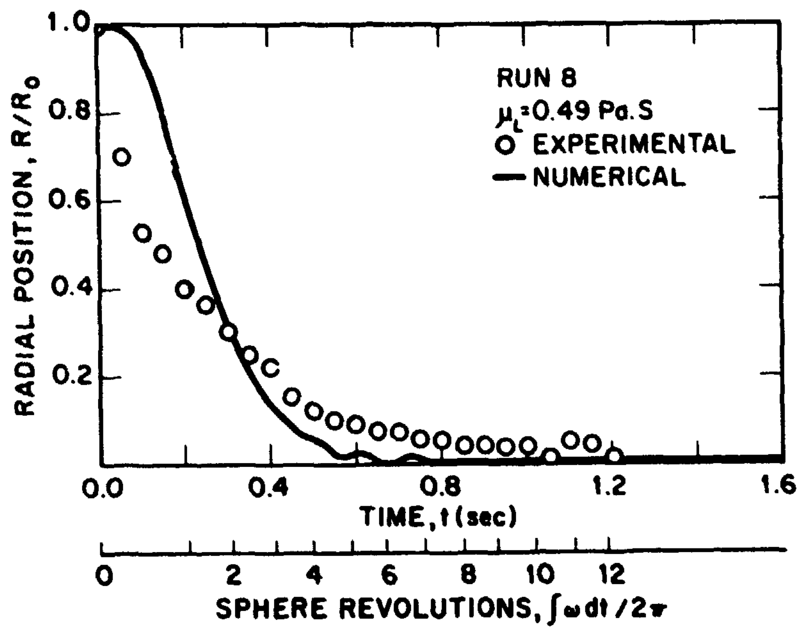

Figure 2. Bubble migration towards the rotation axis as a function of time (upper scale) and of cumulative sphere revolutions (lower scale) for Run 8.

Conclusions

Some potential mechanisms for the migration of gas bubbles in liquid bodies under reduced gravity conditions have been presented and discussed. Theoretical predictions indicate that thermocapillary migration may be used to move bubble to the surface of a liquid drop, and experimental data suggest that rotation of a drop containing bubbles is a useful mechanism for moving bubbles to the center of a drop. Both of the above mechanisms, being independent of gravity, may be effectively used to manage gas bubbles in space processing.

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