GROUND-BASED STUDIES OF THERMOCAPILLARY FLOWS IN LEVITATED LASER-HEATED DROPS

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1 Introduction

The broad objectives of this investigation are to study the fluid flow phenomena together with the thermal effects on drops levitated in acoustic and/or electrostatic fields. To a large extent, experimentation in 1-G requires a strong acoustic field and therefore, there is significant interference with other thermal-fluid effects. While most of the work has been directed towards particles in strong acoustic fields to overcome gravity, some results for microgravity have been obtained. Also included in the objectives is the analysis and experimentation of the thermocapillary flow in a spot-heated drop.

A Glovebox experiment for the MSL-1 Mission has also been tied in with this investigation. One of the primary objectives of the space experiment is to evaluate the acoustic stability criteria in microgravity. In addition, an understanding of the residual internal flows within a quasi-isothermal drop, induced by a positioning ultrasonic field at various power levels, is required.

2 Analytical Results

The analytical developments have led to several new and interesting results pertaining to fluid mechanics. For the past year, much of the analytical work has been on acoustic levitation of particles. For a particle levitated in an acoustic field, its position is determined, to some extent, by the compressibility properties of the particle phase relative to the surrounding medium. For example, liquid particles in a gas tend to position themselves at the velocity antinode, while small gas bubbles in a liquid equilibrate at the velocity node. The effect of a gravity-type body force may offset the equilibrium position to a point somewhere between the node and the antinode. Investigations have been carried out for a liquid drop at the velocity antinode, a solid particle at the velocity node, and a particle in an intermediate position.

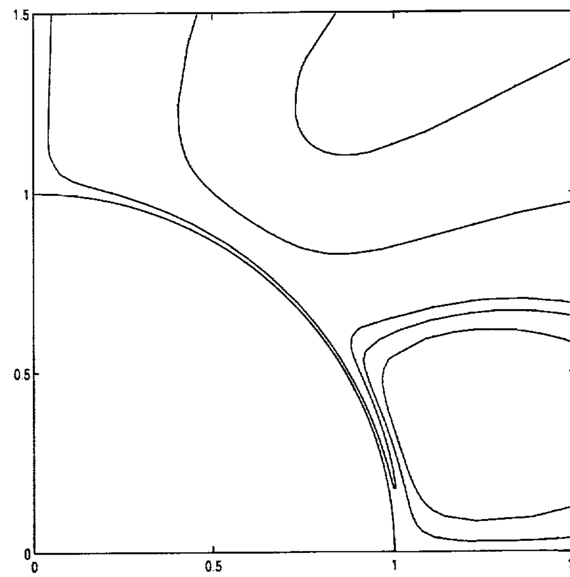

Figure 1: Flow streamlines near the surface of a solid sphere at the velocity node.

2.1 Sphere at the Velocity Node of an Acoustic Field

The flow description for the case of a particle positioned at the velocity antinode can be derived directly from Riley's [1] work which was intended for a vibrating sphere in an otherwise quiescent fluid. The flow field about the velocity node, however, has not been available and a detailed analysis for that situation has been carried out. The perturbation procedure of Riley [1] has been applied to obtain the flow field for the situation when a spherical particle is positioned at the velocity node. As in Riley's [1] solution which applies to a sphere at the velocity antinode, it is found that there is a thin shear-wave region adjacent to the spherical boundary. However, for this thin Stokes layer, the streamlines are not closed but merge with the outer flow, as shown in Figure 1. Therefore, the shear-wave layer does not cover the entire sphere as in Riley's [1] case, but lies mostly around the equatorial region of the sphere. The equatorial belt covers the region

$55^\circ < \theta < 125^\circ$, corresponding to $\cos^2\theta = \frac{1}{2}$. The details are given in a forthcoming publication [4].

Besides providing detailed knowledge about the flow field around the particle at the velocity node, the present analysis has been found to be useful for developing the solution when the particle lies between the node and the antinode.

2.2 Internal Circulation in a Drop in an Acoustic Field

An investigation of the internal flow in a drop at the antinode of a standing wave has been carried out. The main difference from the solid sphere was the inclusion of the shear stress and velocity continuity conditions at the liquid-gas interface. To the leading order of calculation, the internal flow field was found to be quite weak. Furthermore, this order being fully time-dependent has a zero mean flow. At the next higher order, steady internal flows are predicted and there is an important effect on the recirculating Stokes layer. This layer ceases to have recirculation when

$$|M| > \left(\tfrac{5}{2}\right)\sqrt{2}\,[2 + 5(\hat{\mu}/\mu)],$$

where $\hat{\mu}$ is the liquid viscosity, μ is the exterior gas-phase viscosity, and M is the dimensionless frequency parameter for the gas phase, defined by

$$M = \frac{i\omega a^2 \rho}{\mu}.$$

The detailed calculations will be presented in [3]. Experimental confirmation of this interesting new development needs to be thoroughly conducted. Although it agrees with many experiments with levitated drops where no recirculating layer has been found, a new set of experiments for specifically testing the theory need to be carried out. One possible explanation lies in the basic behavior of acoustic waves interacting with interfaces. Based on Schlichting's [2] analysis of a wave in the presence of a solid surface causes the generation of vorticity and this is manifested in the form of recirculating regions adjacent to the interface. This is also seen on a solid sphere as calculated by Riley [1]. In the case of a fluid interface, the effect of interaction is weaker in magnitude depending on the liquid viscosity. Therefore, the recirculation is weaker, and for sufficiently low viscosity there may be no recirculation at all.

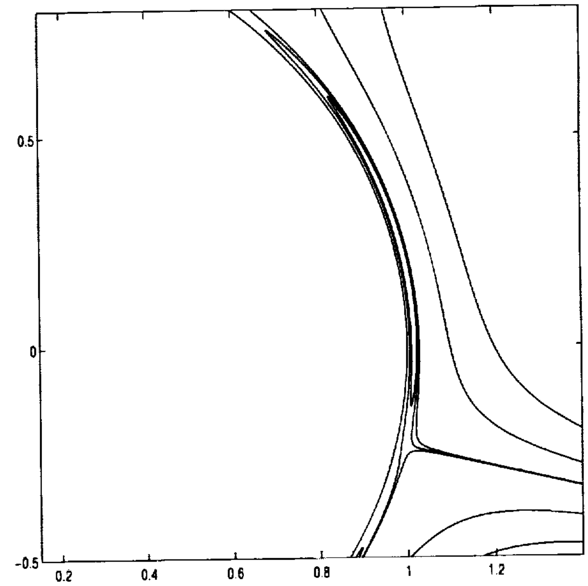

Figure 2: Flow streamlines near the particle – upper region.

2.3 Spherical Particle between the Velocity Node and the Antinode

2.3.1 Solid Particle

The previously-developed solution for a solid particle at the velocity node together with Riley's [1] solution which applies to the antinode, have been integrated to yield a complete solution. Several additional nonlinear terms have been included together with some modification of the node solution. The steady streaming part of the solution is exactly proportional to that obtained be Lee & Wang (1990) by a factor of $\frac{3}{2}$. This is a very important result, in that it verifies the extent of validity of Lee & Wang's method which allows for slip velocity to account for the Stokes layer. The present calculations have also led to the detailed flow field in the Stokes layer which exhibits some interesting patterns. The detailed flow field in the gas phase near the interface are shown in Figures 2 and 3.

In the Stokes layer, there are two axisymmetric vortices. Some of the streamlines on the outer side (gas side) of one vortex cross into the inner side, towards the interface, of the other vortex, as shown in Figure 4.

2.3.2 Liquid Drop

By allowing the continuity of tangential velocity and shear stress at the interface, the flow field for a liquid

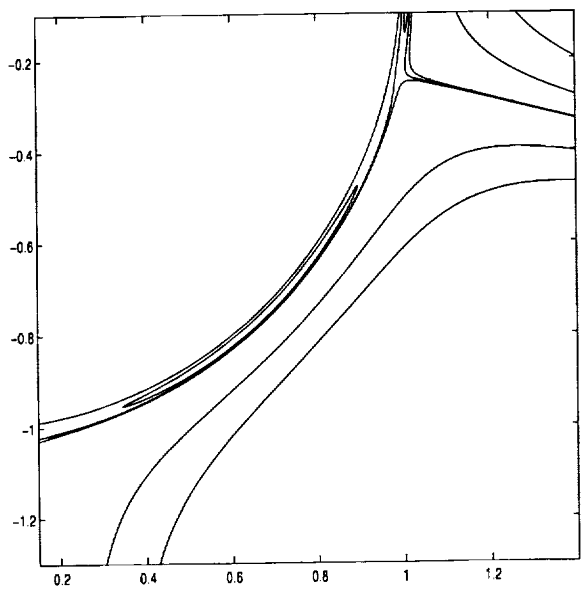

Figure 3: Flow streamlines near the particle - lower quadrant.

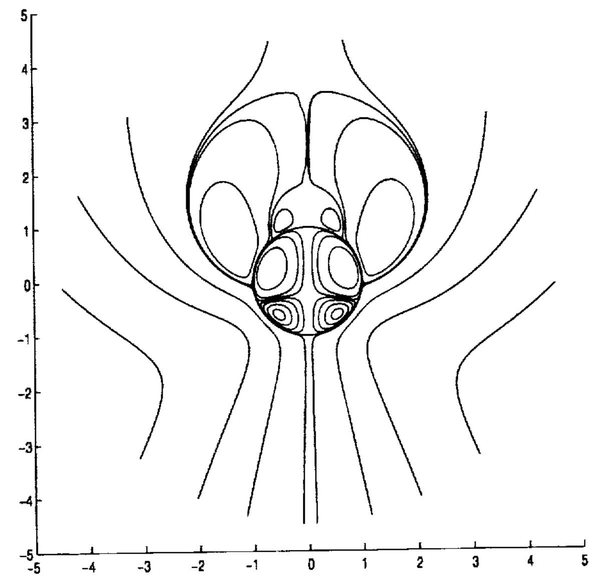

Figure 5: Theoretical prediction of streaming flow past a liquid drop between the node and the antinode. The outer streaming is in the downward direction.

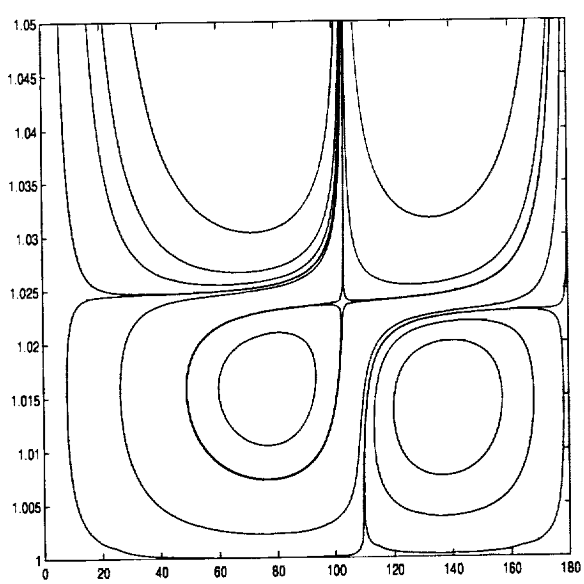

Figure 4: Detailed flow field in the Stokes layer.

drop placed between the node and the antinode has been found. As in the case of the drop at the velocity antinode, the reciculation is predicted to cease when the drop viscosity is low enough. The exact magnitudes of the parameters when this happens have not been established yet.

The exterior and interior flow fields exhibit interesting streaming-flow patterns. For the case when the recirculation in the Stokes layer does not exist (see Figure 5), there are two toroidal vortices in the drop. The exterior also has two larger vortices adjacent to the drop. The interesting feature here is that the exterior vortices are at the front of the drop with respect to the streaming flow. This is quite the opposite of what one observes for simple flow past a sphere for which the recirculating wake is at the rear. Experimental observations have exhibited the presently described phenomenon (i.e., the front-side 'wake') as shown in Figure 6. Here the striking similarity with the theoretical prediction is quite clear. A plausible physical explanation is still being sought, and detailed examination of the theoretical flow field is being conducted. Pressure calculations around the drop show the existence of a low-pressure region on the upstream side. For levitation to be possible in a gravity field, there

Figure 6: Visualization of flow around an acoustically levitated particle showing an upstream-side vortex.

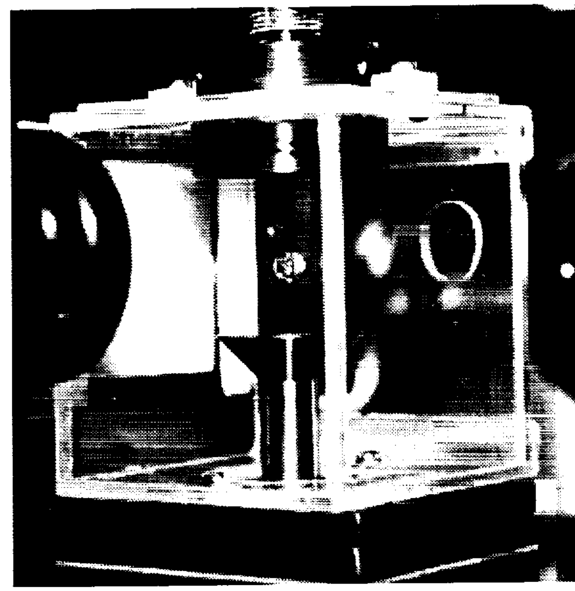

Figure 7: Photograph of an ultrasonically positioned drop during an experimental run of the Glovebox Investigation.

has to be a high-pressure region on the underside of the drop and a correspondingly low-pressure region at the top. This is consistent with the presence of the vortex at the front which can come about due to the low pressure.

3 Experimental Results

3.1 Glovebox Flight Investigation Development

An experiment for the Glovebox flight investigation took place during the MSL-1 Mission in early July 1997. This work was initiated to assess the capability for ultrasonic positioning in microgravity, and for drop internal flow measurement. A compact ultrasonic positioner (see Figure 7) was designed and integrated with laser diode illumination in order to experimentally demonstrate the rotation control of freely suspended drops in low gravity and to obtain preliminary flow field measurements for isothermal droplets. The initial goal of performing preliminary measurement on spot-heated droplets was not realized due to a combination of safety and Glovebox facility constraints.

The important findings from the flight investigations are summarized below.

1. The controlling parameters of a single axis ultrasonic system operating in air at ambient temperature which affect the ability to quiescently position a liquid drop were identified in a microgravity environment.

2. Rotation control of a drop in microgravity was investigated. The ultimate capability of the single axis levitator will be determined from the acquired information. Preliminary observations indicate a residual steady rotation of about 0.1 rps with the acoustic power required to counteract the Shuttle attitude control firings. High rotation rates necessary for drop bifurcation and fission have also been measured.

3. Tracer particles within the deployed drops have allowed the measurement of the rotation rate, and they will yield quantitative information on the dependence of acoustic torque on pressure, as well as the assessment of the internal flow within a quasi-isothermal drop in the Spacelab environment.

4. The first accurate data for drop deformation as a function of acoustic pressure were obtained for a sample located at the pressure minimum plane in the ultrasonic standing wave. All ground-based data are for a drop away from the pressure nodal plane because of gravity.

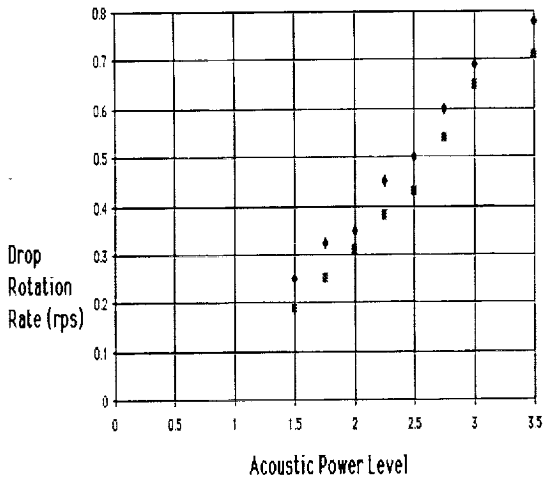

Figure 8: A plot of the measured rotation rate as a function of the acoustic power setting.

Based on these preliminary assessments, the current apparatus is deemed effective for the accurate positioning of drops in air in an actual microgravity environment. The spinning of the drop can be reduced to a very low state of residual rotation, and internal flow measurement can be achieved. Spot heating experiments, planned for a future flight, are thus deemed to be feasible.

Typical drop rotation rates as a function of the acoustic power setting are given in Figure 8. The drops were ultrasonically positioned in low gravity. As the rotation rate becomes very low, damping of residual rotation weakens and longer observation times are required to view the slowing down of residual rotation.

The development of the apparatus for the reflight of the IFFD (Internal Flow in a Free Drop) investigation is well under way. A sting heater consisting of a thermistor mounted on a stainless steel rod and held on a micropositioner stage will be used to provide local heating for a free drop with a maximum temperature rise of 20°C. The tip of the heater will be placed in the proximity of a drop in order to provide differential heating. The internal flows recorded through the motion of suspended tracer particles within the drop will be compared with those generated when the drop is in direct contact with the heater tip. Ground-based tests have shown that the heater tip can be safely moved to within 2 mm of a 4-mm diameter levitated drop without perturbing it. The effects of acoustic streaming will also be investigated for a sting-held drop by comparing the internal flows for different acoustic power levels.

3.2 Ground-Based Experimental Activities

A previously described apparatus has been used to record the motion of fluorescent tracer particles suspended in the drop liquid. The scattered light is gathered along two orthogonal views using holographic notch filters to block the elastically scattered light from the drop surface. The liquid used was an aqueous mixture of glycerin and silicone oil (Polydimethylsiloxanes) and a focused CO_2 laser was used to spot-heat the levitated drop. The results show that although it was possible to accurately measure the internal flows of isothermal drops, the combination of Earth-based ultrasonic levitation and spot heating induces an uncontrolled torque which drives a random rotational motion of the drops. The digital image processing required in the deconvolution of this rotational motion in order to extract the thermocapillary and buoyancy-driven flows requires substantial computational power, and will be pursued by this experimental effort. Control of drop evaporation has been implemented by maintaining the drop environment at a high humidity, and the Marangoni convection contribution due to evaporation can thus be neglected. Ongoing and future studies will include the measurement of flows within drastically flattened drops to constrain the flows in a two dimensional plane, the implementation of total electrostatic levitation of charged droplets, and an automated digital data reduction and analysis.

Electrostatic levitation has been useful in eliminating residual rotation of the drop. Preliminary observations have been carried out with electrostatically levitated charged drops in 1-G with focused CO_2 laser heating from the side. The quantitative characterization of the resulting complicated buoyancy and thermocapillary-induced flows require a three-dimensional analysis of the flow field. The immediate future plan is to develop the required software for the digitized video recordings of these flows using suspended tracer particles.

Thermocapillary flows coupled to natural buoyancy-driven convection have been observed for electrostatically levitated droplets using spot heating from a focused CO_2 laser directed to the right side of the drop. The current spot size is about 300 μm and the levitated drops have diameters between 3 and 5 mm. Using two overlapping views from two different video cameras, three dimensional imaging of the flow fields could be obtained and recorded on videotapes. The predicted vertical motion could be observed, although the flow pattern is very asymmetric due to the gravitational bias. Radiant input power is controlled by varying the duty cycle of the laser. Further measurements will be taken using a smaller (100 μm laser spot size).

Acknowledgements

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