NON-COALESCENCE EFFECTS IN MICROGRAVITY

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ABSTRACT

Forced non-coalescence between two bodies of the same liquid may be achieved by a variety of means, all of which provide relative tangential motion of the adjacent free-surfaces. This motion serves to provide a lubricating film of the surrounding gas to the gap which prevents the liquid surfaces from coming into contact. One means of forcing non-coalescence is to use thermocapillarity to drive the lubricating film by having the liquids at different temperatures. This paper will examine a number of scenarios of non-coalescence behavior, both qualitatively and quantitatively, and describe some envisioned applications of the phenomenon which may have relevance in both microgravity and terrestrial environments.

INTRODUCTION

Forced non-coalescence between two bodies of the same liquid was noted a century ago by Lord Rayleigh (1899), who commented on streams of water which bounce off one another. Nearly eighty years later, Walker (1978) described experiments in which droplets could be made to "float" on the surface of the same liquid using vibration. Recent investigations of this topic were motivated by difficulties experienced in re-connecting a broken liquid bridge during a laboratory experiment on thermocapillary convection; a similar experience was reported as occurring during a space-flight experiment (Napolitano, Monti & Russo 1986). A paper by Dell'Aversana, Banavar & Koplik (1996) describes the influence of relative motion and the establishment of a lubricating film as the non-coalescence mechanism.

Thermocapillarity is easily used to prevent a pair of drops of liquid from coalescing. Consider the photograph shown in Figure 1. Here, two drops of 5 cS silicone oil are attached to copper rods and subjected to a temperature difference as they are pressed together. Glass beads and smoke are used to visualize the flows both within and exterior to the droplets, respectively. The upper drop is hotter than the lower one, resulting in a region near the point of apparent contact which is either colder (upper drop) or hotter (lower drop) than the bulk liquid in the drop, and hence, the majority of the free-surface. The existence of a surface-temperature gradient and the temperature dependence of surface tension provide a liquid flow toward the contact region in the upper drop and away from it on the lower one, as illustrated in the sketch provided as Figure 2.

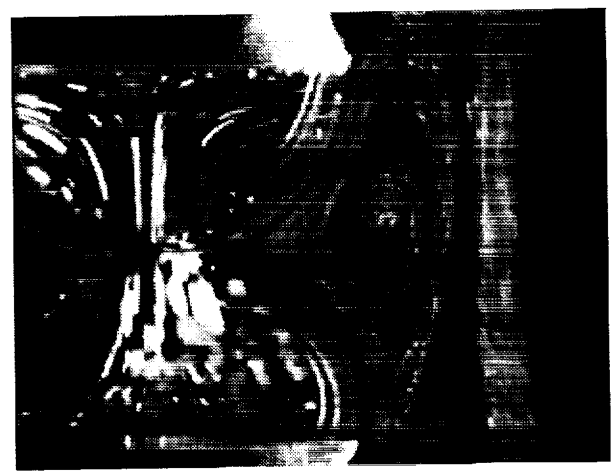

Figure 1: Two non-coalescing drops of silicone oil subjected to a temperature difference. Flows within the drops and in the air are visualized by hollow glass beads and smoke, respectively.

Since the air must migrate from the periphery of the geometry to the center and out again, the pressure

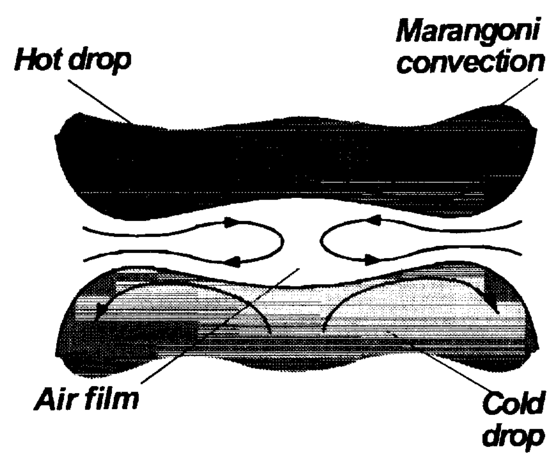

Figure 2: Expanded view of the air film separating two non-coalescing droplets.

at $r = 0$ is a maximum for the film, resulting in the dimpled appearance of the liquid surfaces, as sketched. This dimpling is confirmed through interferometry measurements made in a different, but related, geometry, as described next.

This same mechanism of using thermocapillary convection to suppress coalescence can be employed to suppress the wetting of a solid surface by a normally wetting liquid. In this case, the lower, cold drop of Figs. 1 and 2 is replaced by a cold, solid surface. In the event that this surface is a transparent one such as glass, the gap between the drop and the surface can be interrogated using interferometry from below. Dell'Aversana, Tontodonato & Carotenuto (1997), under sponsorship of this project, have used this technique to quantify the film shape and thickness. This film obviously changes in both size and shape as the droplet is pressed more firmly against the glass, the area of near-contact increasing to accommodate the increased load.

In addition to the droplet-droplet and droplet-solid examples above, a hot droplet may also be pressed against a cold bath with similar results. Such a configuration is shown in Figure 3 with a small satellite droplet nestled against the main drop. In the case of the satellite droplet, it resists coalescing with either

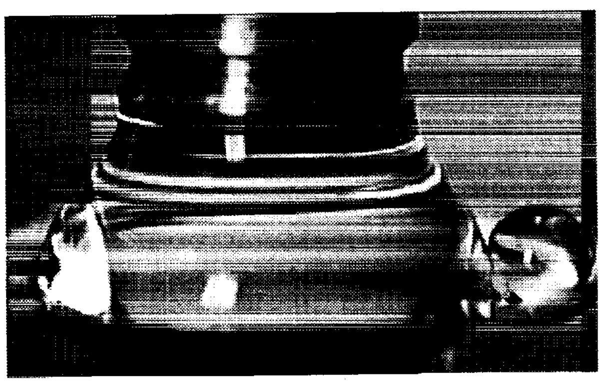

Figure 3: Non-coalescing drop, bath and satellite drop

the bulk liquid or the main drop due to surface motion driven by the rapidly moving surface of the main drop. This is determined through the use of flow visualization showing that the circulation in the satellite drop is of a single sense. Interestingly, in this drop-bath configuration, as the drop is grown larger through the addition of more liquid through the supporting heater, it reaches a size beyond which the flow within it is no longer steady (Dell'Aversana *et al.* 1997). In this case, the oscillatory flow which ensues is, not surprisingly, reminiscent of that seen for unstable thermocapillary convection within liquid bridges.

An additional discussion of the general features of the non-coalescence and non-wetting scenarios described above may be found in a paper by Dell'Aversana & Neitzel (1998). The remainder of this paper will describe some additional quantitative measurements and numerical simulations which have been undertaken and the potential application of such systems.

PRESSURE EFFECTS

Since the phenomena described in the previous section arise because of the existence of a thin, lubricating film of gas separating two free surfaces or a liquid and a solid, a natural question arises as to the minimum pressure necessary in the surrounding gas to sustain the effect. To address this question, we have installed a device for creating a pair of non-coalescing drops within a chamber capable of being evacuated to precisely controlled pressures. The lower drop remains on a fixed pedestal and the upper drop is moved toward it, its vertical position controlled to within 1 μm. The temperatures of the two heaters may be controlled to within 0.01 K and the pressure held constant to within 0.2 mbar.

For these experiments, a fixed volume of silicone oil is deposited on the flat surfaces of the 3 mm diameter copper rods using a micropipette. Allowing the volume to be continuously adjusted by injection of liquid through the top rod (as is done in the tests shown in Figure 1) creates problems with the volume changing as the pressure is decreased.

Droplets were formed using 5 cS silicone oil on each of the copper rods and these were placed in the pressure chamber. With a given temperature difference ΔT between the droplets and a fixed amount of relative displacement (beyond the point of first apparent contact), the pressure was then systematically decreased within the chamber in discrete steps, holding at each pressure level for an adequate time to assure the absence of transient behavior. The pressure at which coalescence occurred was noted and is termed

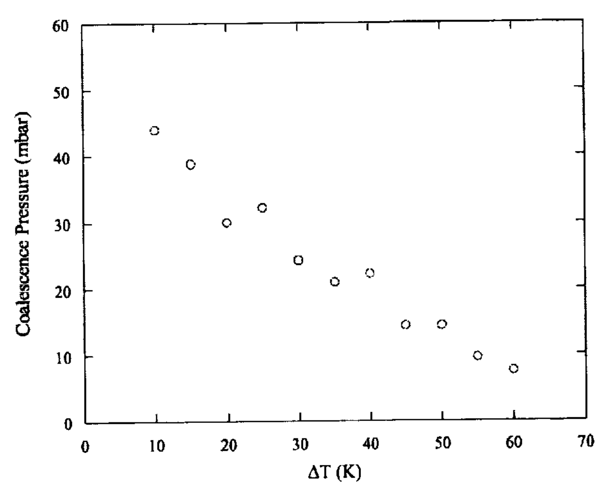

Figure 4: Coalescence pressure versus ΔT for a fixed relative displacement of 150 μm.

the coalescence pressure in the following figures.

The strength of the driving thermocapillary convection in the bulk is clearly a function of the temperature difference between the drops. Consequently, one would intuitively expect that, as ΔT is increased, less surrounding air is necessary to sustain coalescence or, in terms of the pressure, the pressure necessary to prevent coalescence decreases. This expectation is confirmed through the measurements leading to the graph in Figure 4.

Similarly, one's intuition would suggest that the greater the amount of relative displacement (i.e., squeezing) between the drops, the more difficult it would be to prevent coalescence. In terms of coalescence pressure, therefore, this should increase as the relative displacement increases. Figure 5 shows data from experiments for a fixed temperature difference between the drops of 25 K. Similar behavior is observed for other temperature differences.

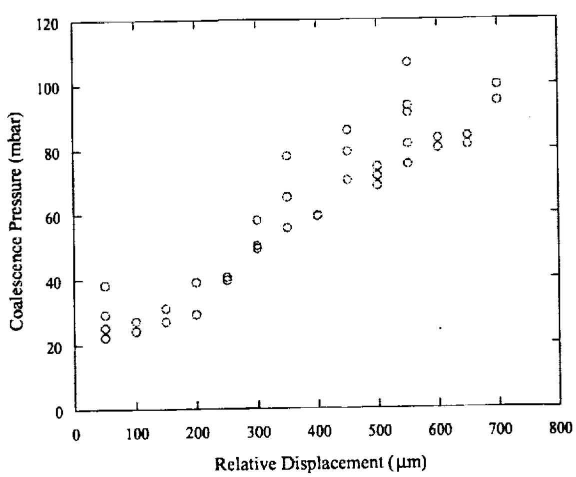

Figure 5: Dependence of coalescence pressure on droplet relative displacement for $\Delta T = 25$ K.

The results of these sealed-chamber experiments confirm the existence of the lubricating air film demonstrated convincingly by experiments employing interferometry. What is perhaps most surprising about these results is the magnitude (or lack thereof) of the ambient pressure needed to suppress coalescence. From Figure 4, we see that if the droplets are differentially heated to a rather large ΔT of 60 K, a surrounding-gas pressure of less than 10 mbar is required to keep them apart.

At these pressures, the mechanism responsible for coalescence of the droplets is no doubt related to the failure of the gas film due to rarefaction effects. While it is the pressure within the film and not in the surrounding atmosphere which supports the load placed on the system, one might begin to estimate the validity of the continuum hypothesis by examining the Knudsen number calculated on the basis of this ambient pressure and a length scale associated with the film itself. From a crude chart of a standard atmosphere, one may estimate that the mean-free path corresponding to an atmospheric pressure of 10 mbar is roughly 3 μm. From the interferometry data of Dell'Aversana *et al.* (1997), one can see that the thickness of the film at the edge of a droplet (pressed against glass) with a relative displacement of 100 μm is roughly 5 μm. Since the ratio of these yields a Knudsen number of $O(1)$, the hypothesis is indeed worthy of further investigation.

NUMERICAL SIMULATIONS

Preliminary numerical simulations of the flow in the lubricating layer between a two-dimensional droplet and a solid surface have been performed under the assumption of a specified free-surface deformation (as determined from interferometry results from the axisymmetric experiments) and an imposed velocity distribution along the free surface.

Figure 6 shows a streamline pattern and isotherms from one such simulation, indicating a maximum pressure attained at the symmetry plane as stated earlier. Current simulation efforts are directed at the solution of the coupled droplet/film problem. This problem is exacerbated by the three-order-of-magnitude (μm → mm) disparity in relevant length scales for the film and the droplet.

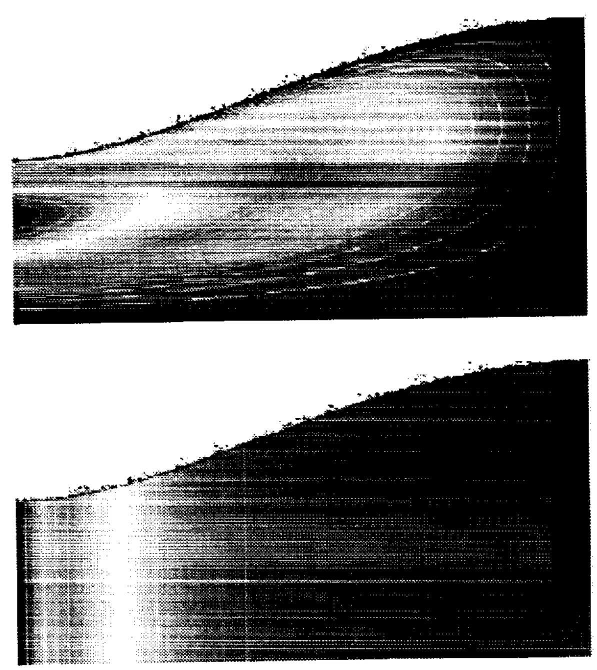

Figure 6: Streamlines (upper) and isobars (lower) for the flow within the lubricating gas film between a liquid drop and a solid wall below it. The right-hand boundary marks the symmetry plane of the calculation.

POTENTIAL APPLICATIONS

The non-coalescence and non-wetting phenomena described above offer some interesting possibilities for applications in either microgravity or terrestrial environments. First, one might think of utilizing such a system to provide a very low-friction bearing in an application in which the loads to be supported are small. We have made measurements of the load that a thermocapillary-driven film can support with a droplet attached to a 3 mm heater pressed against either glass or a cold bath) of the same liquid (roughly 30 K cooler in both cases. The measurements were performed employing a modified platinum-ring tensiometer normally used to conduct surface-tension measurements.

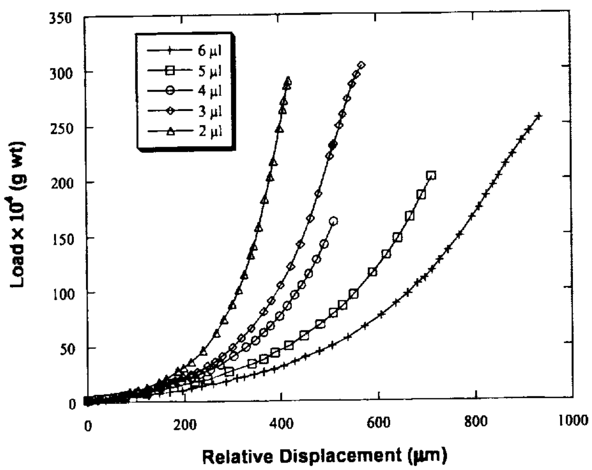

Figure 7: Load versus relative displacement for droplet/glass systems.

Figure 7 above shows some of the results measured for droplets of different volumes when pressed against glass. The results are not scaled, so that a given relative displacement represents a larger fraction of droplet size for smaller droplets. Figure 8 below compares the results for 5 µl droplets pressed against both glass and a cold bath. The load measured for the droplet-bath system is less than that for the droplet-glass with the same relative displacement due to the deformation of the bath surface.

Hence, in a microgravity environment, it may be possible to tailor a non-coalescing bearing system to support a small load or perhaps to position a rotating system precisely. With regard to the latter application, the "bearings" themselves are nearly frictionless and self-centering, so such a system is very desirable. We have also had success (Nalevanko 1997) in achieving non-coalescence with "threads" of liquid rather than discrete drops, so a large range of geometric designs is possible.

As an exercise in the use of non-coalescing liquids to support a load, a small device has been manufactured which is easily floated on a cold bath of liquid.

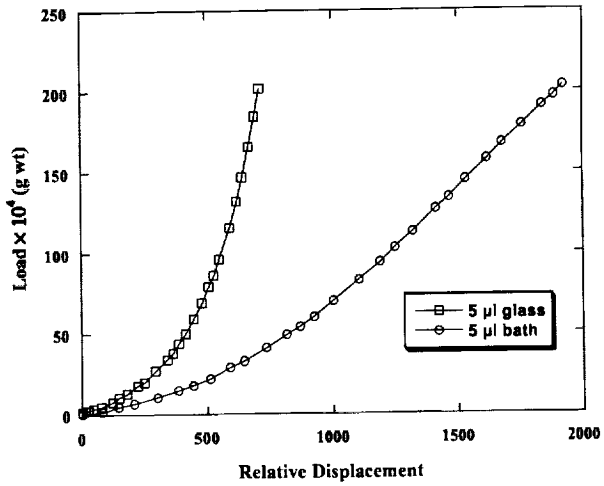

Figure 8: Comparison of loads for droplet-glass and droplet-bath systems.

The device itself is a thin metallic plate containing a number of circular discs to which droplets may be affixed. The total mass of the device with droplets included is approximately 0.2 g. Once the droplets are attached to the discs, the device is inverted, suspended above the cold bath and heated radiantly using a high-intensity light source. When lowered into position, the droplets do not coalesce with the bath but float on thin air films. Placing a magnetized needle on top of this device while it is floating results in a compass which is very sensitive to nearby magnetic fields.

As mentioned in the Introduction, Walker (1978) has made water droplets "float" on the surface of a bath of water through the use of vibration. We have succeeded in repeating these experiments using silicone oils and it is likely that the technique would also be successful with other liquids. The non-coalescence mechanism at work here is the existence of a lubricating film driven by the imposed oscillations. We shall be examining the extension of this work to the use of acoustic forcing to suppress coalescence within a cloud of droplets. The successful demonstration of this could be of benefit in applications in which it is desirable to maintain small droplet size for more efficient droplet combustion.

ACKNOWLEDGMENT

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REFERENCES

Dell'Aversana, P., Banavar, J. R. & Koplik, J. 1996 Suppression of coalescence by shear and temperature gradients. *Phys. Fluids* **8**, 15-28.

Dell'Aversana, P. & Neitzel, G. P. 1998 When liquids stay dry. *Phys. Today* **51**, 38-41.

Dell'Aversana, P., Tontodonato, V. & Carotenuto, L. 1997 Suppression of coalescence and wetting: the shape of the interstitial film. *Phys. Fluids* **9**, 2475-2485.

Nalevanko, J. C. 1997 Design of an apparatus for investigation of 2-D liquid drop non-coalescence. M.S. Thesis, Georgia Institute of Technology.

Napolitano, L., Monti, R. & Russo, G. 1986 Marangoni convection in one- and two-liquids floating zones. *Naturwissenschaft* **73**, 352.

Rayleigh, L. 1899 Investigations in capillarity. *Philos. Mag* **36**, 321.

Walker, J. 1978 Drops of liquid can be made to float on the liquid. What enables them to do so? *Sci. Amer.* **238**, 151-158.