NON-COALESCENCE EFFECTS IN MICROGRAVITY

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Abstract

It has been observed experimentally that two drops (or a single drop and a planar surface) of the *same liquid* can be made to resist coalescence under certain conditions which lead to relative motion of the interfaces. Such relative motion may be brought about through the mechanism of thermocapillarity or forced convective motion of one of the interfaces. Such non-coalescence phenomena have been observed to persist for hours, indicative of the stability of the phenomena. This stability, in turn, implies that such non-coalescence may be put to use in a microgravity environment. One potential application is the development of easily formed, low-friction, self-centering bearings for microgravity experimentation.

A. Introduction

When two drops of liquid are brought into contact with each other, one of several things may happen. If the two liquids are *miscible*, they may quickly coalesce and form a single drop, after the fluid originally between them has drained away. A description of coalescence events can be found, for example, in the works of Marrucci (1969), Anilkumar, Lee & Wang (1991), Tambe & Sharma (1991). Coalescence is of great importance, for example, in the separation of emulsions of immiscible liquids (where the droplets of a single phase coalesce with each other) or in determining the distribution of droplet sizes in aerosols. If the two liquids are *immiscible*, when they come into contact, they may reciprocally experience adhesion forces and form a liquid-liquid interface according to their spreading coefficient. If the conditions for non-coalescence are satisfied, whether the two liquids are miscible or not, they do *not* mix and do not experience any direct adhesion over one another. Two non-coalescing drops can be pressed against one another, deformed under pressure, and then detached without any sticking. If they are pressed together strongly enough, they can even slip over one another.

Although the subject has been of interest for some time, non-coalescing systems are not yet completely understood. Rayleigh (1899) examined the behavior of water jets that bounce over one another as early as 1879. A century later, Walker (1978) still referred to matter as a "scientific curiosity." While observation of a drop of liquid floating upon the surface of the same liquid is indeed curious, being able to *control* the coalescence process is yet another matter.

Recently, Dell'Aversana, Banavar & Koplik (1996) described some experimental techniques which are able to produce systems formed by liquid bodies which behave like solid elastic objects when pressed against one another, in a surrounding medium of air. What makes this work particularly interesting, technologically and scientifically, is that *i*) coalescence can be purposely induced provided that well-defined conditions are attained, and *ii*) these systems are stable in time, even when they are subjected to noticeable mechanical stresses.

One mechanism for accomplishing noncoalescence between drops of a single liquid is to maintain a temperature difference between the two liquid bodies. Figure 1 is a photograph of two non-coalescing drops of silicone oil, differentially heated, and pressed together. The features of the contact interface are quite impressive: the interface is stable both in time and with respect to surface deformation, so that two drops of liquid can safely be squeezed together for (at least) several hours without coalescing; a time limit associated with this behavior, if one exists, is still to be determined.

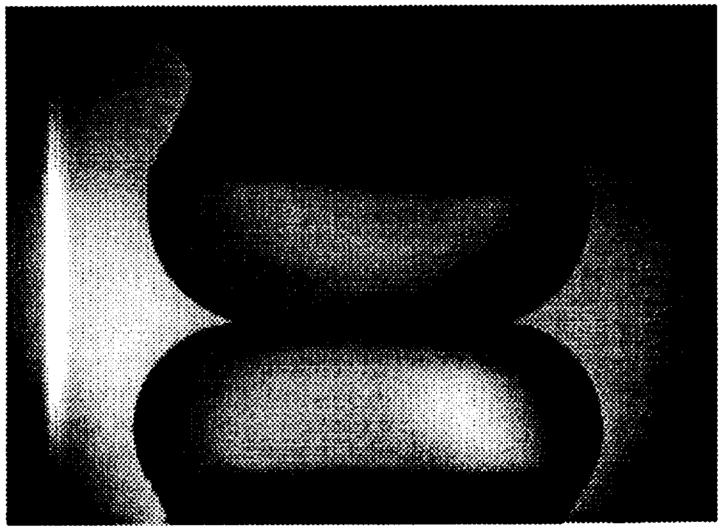

Figure 1. Non-coalescence of differentially heated drops of the same liquid (silicone oil). The rods have a diameter of 2 mm while the temperature difference between them is roughly 20 °C.

B. Physical Mechanisms

Consider again the situation depicted in Figure 1. The lower, cold drop induces a cold spot on the free surface of the upper, hot drop and vice versa. For liquids whose surface tension decreases with increasing temperature, the induced thermocapillary convection pulls the free surface of the upper drop *toward* the symmetry axis and that of the lower drop *away* from this same axis.

The motion of the interfaces induces not only motion in the bulk liquid, but also in the gas surrounding the system. It has been hypothesized that a thin film of gas exists between the two drops, serving as a lubricating layer; work by Dell'Aversana *et al.* (1996) suggests that lubrication theory is suitable to explain the phenomenon. Interfacial motion draws the surrounding gas into the thin space between the drops, forming a streamline pattern which, in a highly expanded view, might resemble the sketch in Figure 2. Furthermore, the stability of these configurations,

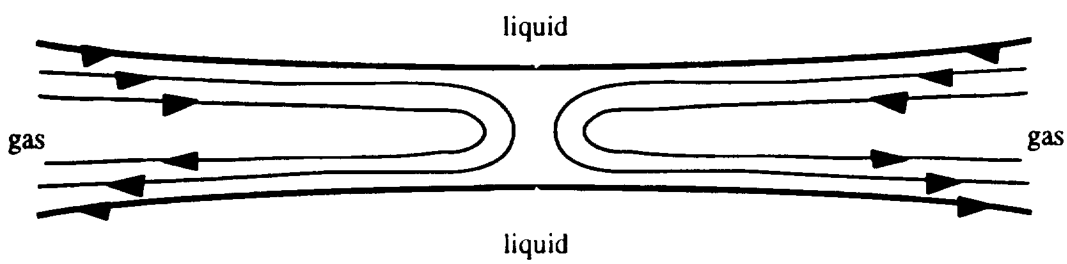

Figure 2. Expanded view of the gap between two immiscible drops showing lubrication layer.

even when purposely subjected to disturbances, suggests that this thin film maintains its integrity and does not permit the liquids to come into contact with one another. Neither would the continuum hypothesis appear to fail, since a layer thickness on the order of the mean-free path of the gas molecules would most certainly lead to coalescence. Experiments have been conducted in which one of the drops was dyed prior to pressing the two together; no dye was observed to migrate into the neighboring drop.

Additional evidence in support of this mechanism has been provided by experiments which demonstrate that differential heating is *not* necessary to prevent coalescence, but that relative motion will suffice. In these experiments, a layer of silicone oil was brought to a state of rigid-body rotation on a turntable and a drop of the same liquid *at the same temperature* was brought into contact with the rotating surface near the periphery of the apparatus. As long as the rotational speed was maintained above a particular value, coalescence was prevented, although at very high speeds, or when deformed sufficiently, the drop begins to oscillate and often breaks.

The pressure distribution established in the gas layer by the surface motion must be sufficiently large to keep the liquid surfaces apart, implying, in turn, that the free-surface motion must be sufficiently vigorous. For the rotating case described in the previous paragraph, coalescence occurs when the speed is reduced; for the differentially heated case; the drops coalesce when ΔT, the temperature difference between them, *decreases below a certain critical threshold.*

C. Proposed Research

1. Theoretical

Assuming that the mechanism preventing coalescence is accurately described in the preceding section, the most rational theoretical approach to pursue is the use of lubrication theory to describe the flow and pressure distribution in the gas layer as well as the interactions between the gas and the liquid. This has been done previously for drops *prior* to coalescence by Charles & Mason (1960). For a situation with two surfaces between which a gas flows in a *single direction*, lubrication theory may yield a complete solution. For the pair of drops at different temperatures, however, lubrication theory alone may not be able to accomplish the entire task, due to the presence of what might be termed a *stagnation region* in the middle of the gap where the two gas streams change direction. This region is depicted in the center of the sketch in Figure 2. In this region, a *numerical* solution might be necessary, since the assumptions of lubrication are violated there, while away from this region, lubrication theory continues to hold. A similar approach was used by Ruschak (1982), who analyzed a coating-flow problem in this fashion, employing a numerical matching procedure to match the numerical solution to that obtained from lubrication theory.

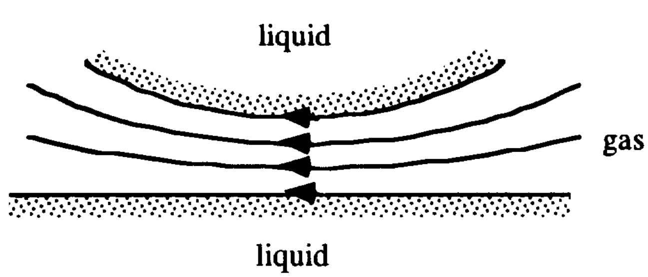

Figure 3. Two-dimensional model lubrication problem.

The first analysis to be attempted will examine the case of two, *two-dimensional* free-surfaces (one curved) with a gas film between them driven by the motion of the planar surface (see Figure 3 above). This is a more-or-less standard lubrication-theory problem with the additional complication of flexible "bearing" surfaces.

Following the treatment of this problem, the more difficult problem associated with the flow depicted in Figure 2 will be studied, first for two-dimensional flow, and then for the problem with spherical droplets. The latter case is complicated by the geometry, suggesting a formulation in terms of bispherical coordinates. The two-dimensional problem serves as more than just a model problem, however, from the standpoint of potential technological utilization of the effect. If the technology were to be developed for a microgravity-bearing application, one could easily conceive of applications for which a long, nearly two-dimensional drop would be desirable.

Although, for large relative velocities (driven by thermocapillarity in the one case), the preliminary experiments have found the situation to be very stable, there is a state of relative motion, below which, coalescence will occur. The *stability* of these flows in the vicinity of such thresholds is therefore a subject of interest, which can be examined with the aid of the lubrication (or combined lubrication/numerical) solutions.

2. Experimental Studies

A large number of experiments demonstrating the phenomenon of non-coalescence have already been performed (Dell'Aversana *et al.* 1996) but there are more questions to be answered from careful experiments. A sampling of some of these are:

- How is the coalescence threshold affected by the characteristics of the surrounding medium?
- How does the threshold change with changes in "contact" area? How large can this area be made on earth and in microgravity?
- Is there an *upper* limit to the temperature gradient that the lubricating layer can sustain?
- How long can a non-coalescing system sustain a mechanical stress of a given magnitude without occurrence of interface rupture? Is the stability of the interface a function of this stress?

Experiments to be conducted at Georgia Tech and the MARS Center in Naples, Italy will attempt to answer many of these. The apparatus to be used for spherical-droplet cases is that employed by Dell'Aversana *et al.* (1996).

Experiments will also be conducted at Georgia Tech for the case of a nearly two-dimensional droplet. Once the contact line position has been established, it is possible to either inject or withdraw liquid from the "drop" to cause the interface to either bulge or flatten. This then becomes a good experiment for examining the influence of interface curvature, and curvature mismatch, on non-coalescence.

Some possible experiments which can be conducted in either, or in some cases both, of these devices are suggested here:

Measurement of the film local thickness. This measurement can be performed by interferometric means with great precision; related measurements with interferometry have been performed at MARS.

Interface resistance as a function of the lubricating gas parameters. Important parameters which enter the functioning of non-coalescing systems are those of the surrounding medium.

Load measurements. The load the interface between non-coalescing liquids can carry can be directly measured and compared with the data obtained from the theoretical calculations based upon the film shape measured in the Experiment 1.

Measurements of friction. Together with the preceding experiment, these measurements will allow us to assess the coefficient of friction, i.e., the ratio of friction to load, for gas-lubricated liquid bearings.

Non-coalescence achieved by induced surface vibrations. It has been demonstrated (Walker 1978) that quasi-stable non-coalescence is achievable by means of vibrations of suitable frequency of the liquid surfaces. Lubrication theory seems to be able to explain this kind of phenomenon as well, in the context of squeezing films.

Interface curvature effects. Interface curvature will profoundly affect the ability of the non-coalescing system to sustain a load. Experiments to determine non-coalescence thresholds for different curvatures and curvature mismatches will be performed in the two-dimensional apparatus, as well as measurements of sustainable loads for various curvature configurations.

The actual experiments to be performed will, of course, be dictated by results obtained both from experiments and theoretical results, and the effects to be investigated. However, the existence of apparatus for both spherical and two-dimensional geometries, as well as a facility for investigating the effects of high tangential speeds will allow many of the questions posed above to be answered.

D. Summary and Outlook for Applications

The project teams at Georgia Tech and the MARS Center possess complementary and overlapping talents for the investigation of the non-coalescence phenomena described above. A possible collection of experiments was identified, to indicate the wide realm of scientific questions and possibilities present within these systems. These, in turn, suggest several potential applications of the results of this work, a couple of which have already been alluded to.

Potential space applications include the containerless confinement, shaping, and transfer of liquids. From the standpoint of scientific applications, non-coalescing systems could provide useful tools for the study of electro-chemical forces at the surface of liquids, for the study of lubricated systems, etc. As already mentioned, non-coalescing systems could be employed as liquid bearings in microgravity. In fact, because of the extremely low friction which is generated at the interface between two non-coalescing liquids, they could be employed as quasi-friction-free joints for high-precision devices in microgravity . The attractiveness of such bearings is increased by the fact that, due to the elasticity of liquid surfaces, non-coalescing bodies are self aligning and their surfaces are naturally and perfectly smooth under any conditions, eliminating the need for difficult technological efforts. Thus, liquid bearings would not present alignment, tolerance or roughness problems, would not be noisy, would not be affected by wear, would not generate heat which, in common bearings, can produce distortions, and would provide support with minimum friction and torque.

On the other hand, it must be observed that the loading capability of a liquid bearing is limited by the possibility that the liquid may spread outside its own support when the liquid surface undergoes deformation with respect to its minimum-energy shape. Therefore, one must consider coatings with outstanding anti-wetting capabilities and particular support shapes able to maximize the normal stress when determining the limits of mechanical stability of liquid bearings under load. In microgravity, however, where loads are much smaller, such bearings could find several practical applications.

Although the phenomenon is of broader scientific interest, the bulk of the proposed research will be aimed at the future exploitation of non-coalescing systems features in microgravity, since this environment seems to hold the most promise for exploitation of the effect. Due to the weak nature of surface-tension forces, these systems obtain the utmost, in terms of versatility, in a weightless environment, where a number of configurations are possible which would be unthinkable on ground.

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