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The Stable Floating Liquid Droplet Phenomenon

D. DAVIS
Graduate Scholar, Department of Mechanical Engineering, Monash University
P. DRANSFIELD
Associate Professor, Department of Mechanical Engineering, Monash University
and
A. TAN
Engineer, Department of Mechanical Engineering, Monash University

SUMMARY Take a liquid surface which is moving at constant velocity. Let a droplet of the same liquid fall onto it from a point above the moving surface. What will happen to the liquid droplet as it hits the moving surface? It will penetrate the surface and rapidly disperse in the moving liquid, won't it? Not necessarily!

The Paper describes a situation in which the droplet forms a stable entity which is supported indefinitely in a fixed position, apparently by and on the moving surface. Some characteristics of the floating liquid droplet are investigated. Some discussion on the mechanisms of formation and sustaining of the floating liquid droplet is provided.

1 INTRODUCTION

Take a liquid surface which is moving at a constant velocity. Let a droplet of the same liquid fall onto it from a fixed point above the moving surface. What will happen to the liquid droplet as it hits the moving surface? It will penetrate the surface and rapidly disperse in the moving liquid, won't it? Not necessarily!

In 1977 one of the authors noticed that a droplet of mineral oil inadvertently dropped onto the inner surface of a rotating annulus of the same liquid did not merge with the host liquid. It formed what appeared to be a ball which rolled in a fixed position on the surface of the rotating liquid. Experiments in which a syringe was used to drop a droplet of oil onto the rotating surface quickly confirmed that the phenomenon was repeatable. The liquid ball remained in position indefinitely if the rotating annulus of liquid was maintained. It appeared initially that the droplet ran on the surface of the host liquid much as a single steel ball would run on a rotating outer ring of a ball bearing if free to do so. For this reason we initially called the phenomenon the rolling liquid ball phenomenon.

Further experiments showed that the "rolling liquid ball" was distorted from spherical, was not in contact with the liquid annulus surface, was fairly stationary in space rather than rolling, and could become unstable under some conditions.

The present paper describes the conditions, equipment, and main results of the experiments. It provides discussion on the mechanisms of formation and sustaining of the observed FLOATING LIQUID DROPLET phenomenon, including some relevant literature. The effects on the phenomenon of varying some physical parameters are described.

2 THE EXPERIMENTAL EQUIPMENT

Fig. 1 illustrates the equipment used. The drum has an internal diameter of 185 mm and is 40 mm wide. Its front end is open except for a rim 10 mm deep. The drum is driven to rotate about its axis by a variable speed drive (500-2000 rpm). In experiments originally intended for quite another purpose the liquid inside the drum was a light mineral oil (Shell Tellus 27). When the drum is rotated at sufficient speed the liquid forms an annulus (the dark annulus) rotating with the drum. The syringe used to deliberately form a droplet is shown in a position near the rotating fluid annulus. The droplet is about to be released, whereon it will "roll" to an equilibrium position.

3 RESULTS

Fig. 2 shows a photograph of a stable droplet of diameter about 2.5 mm on the surface of the moving host liquid. The dark band is the moving liquid, the light area at upper right is the inner wall of the drum. The dark shape in the host liquid is a reflection of the droplet.

The experiments highlighted various aspects of the phenomenon. These included initial formation of stable droplets, factors affecting the equilibrium position of the droplet, and limits under which the phenomenon was stable. Fluid motion within the droplet and the host liquid were also studied to help determine the support mechanism.

3.1 Droplet Formation

Droplets created with a syringe could be released from a range of heights above the moving surface, and from a variety of positions around the periphery of the liquid annulus. In each case, the droplet would apparently contact the surface and then move to its stable equilibrium position. The formation of a droplet at the surface of the moving liquid can be seen in Fig. 1.

The syringe was used as a controlled means of forming droplets of repeatable and measurable size. However, it was found that droplets were readily formed simply by disturbing the rotating liquid surface with a suitable object (such as a pencil).

Early experiments with droplet size revealed that the droplet was not spherical as first thought. A large droplet forms a more cylindrical shape with rounded ends, something like a jelly bean (Fig. 3). At higher drum speeds, there is a very noticeable distortion of shape, with flattening of the bottom, for both large and small droplets (Fig. 4).

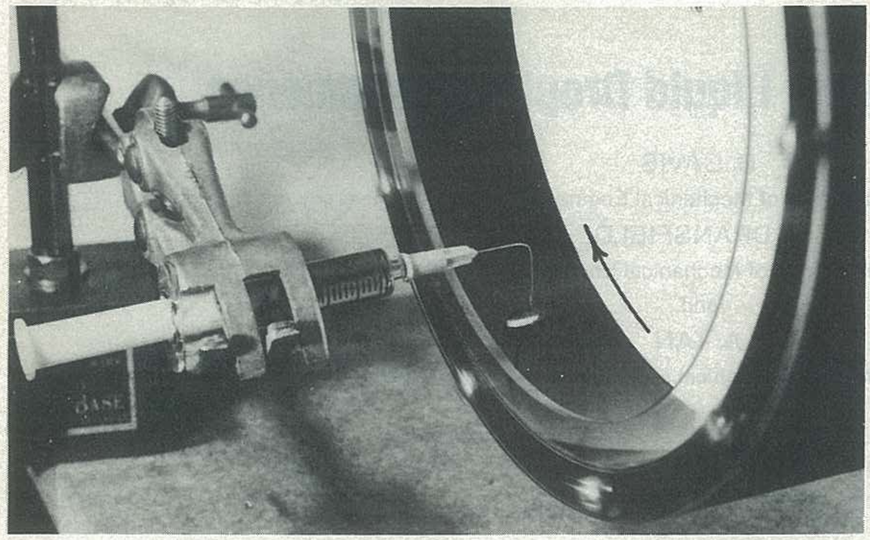

Figure 1
The Floating Liquid Droplet Rig

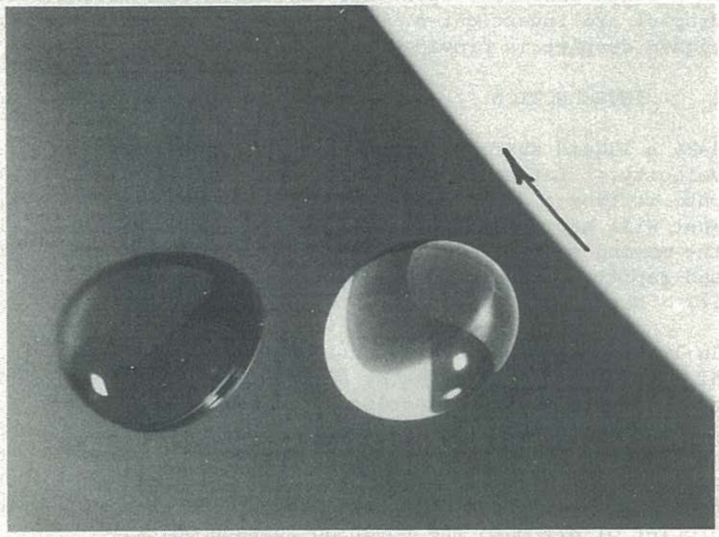

Figure 2 A Stable Floating Droplet

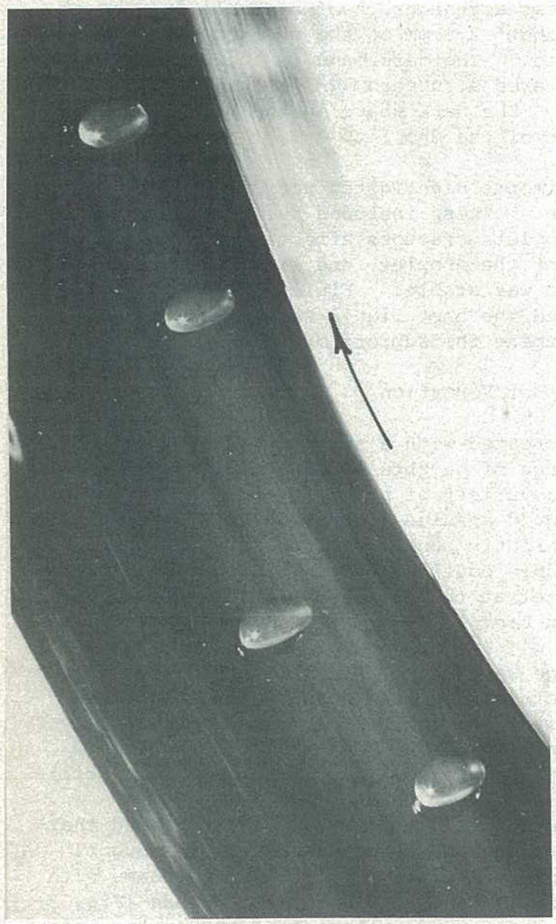

Figure 3 The Effect of Drum Speed on a Droplet's Equilibrium Position

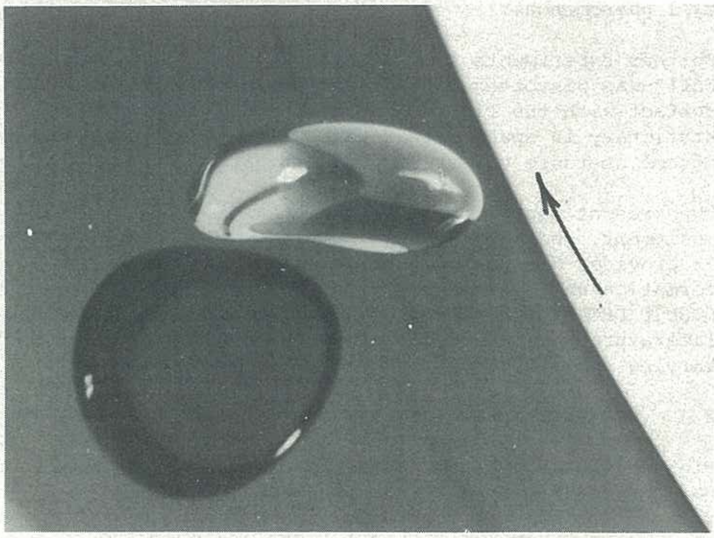

Figure 4 Distortion of the Stable Droplet at Higher Drum Speeds

Although most of the experiments were conducted with Shell Tellus 27 fluid, stable floating droplets were produced (with varying degrees of difficulty) using other mineral oils and also water. Combinations of different droplet and host fluids were also successful. Stable droplets were even produced on the dry aluminium inner surface of the rotating drum.

3.2 Droplet Equilibrium and Stability Limits

The equilibrium position of a droplet on the rotating fluid annulus was found to depend upon the surface speed of the annulus, the size of the droplet and on some physical properties of the fluid.

The effect on droplet position of changing the rotational speed of the drum is illustrated by the multiple-exposure photograph of Fig. 3. The film was exposed at each of the four drum speeds of 500, 600, 700 and 800 rpm. As speed was increased, the droplet moved further up the rotating annulus. For a particular droplet there is a stable range of drum speeds. At the low end of the speed range, the droplet will simply disperse into the host liquid. At the upper speed limit, the droplet jumps from the surface and falls to a lower position from which it re-approaches its former equilibrium position and repeats the cycle. Further increase in drum speed causes wilder jumping, and eventually the droplet falls with sufficient impact to disperse into the host fluid.

For a particular drum speed, a large droplet assumes a lower equilibrium position than does a small droplet. The speeds at which the abovementioned instabilities occur were found generally to increase as droplet size was increased. However, another form of instability was observed with very large droplets which became so elongated as drum speed increased, that they would each separate into two smaller, more stable droplets.

Experimentation with different fluids, and with different combinations of droplet and annulus fluids resulted in various ranges of equilibrium positions and drum speeds. Although it was not possible to isolate and determine the effect of each fluid property individually, tests indicated that the surface tension, density and viscosity of the fluid were significant to the phenomenon.

3.3 The Droplet-Annulus Interface

The liquid droplet does not roll upon the surface of the liquid annulus with a common surface speed as was initially thought. In fact, it may be stationary or may even rotate slowly in the opposite sense to the rotation of the host annulus. Its axis of rotation is not always parallel with the drum's axis. These characteristics were observed by separately introducing small air bubbles and aluminium flakes into the droplets.

No mass transfer appears to take place between the droplets and the host liquids. This was demonstrated in a series of experiments in which droplets treated with black dye produced no discolouration of the annulus fluid, even after extended running periods.

The floating droplet does not contact the surface of the liquid annulus, but is stably separated by a layer of air next to the surface. Figs. 2 and 4 show droplets with their reflections in the surface of the host liquid. The distance separating the droplet and the surface of the annulus is half the distance separating the droplet from its reflection. The inner surface of the drum had been treated to be non-reflective.

The importance of the air boundary layer on the stability of the phenomenon is demonstrated by deliberately introducing a disturbance to the boundary layer flow. If an object such as a pencil is placed upstream of a stable droplet so that it disturbs the air immediately in front of the droplet without disturbing the surface of the annulus, the droplet moves downwards and either adheres to the object or disperses into the host liquid. Similarly, an object introduced alongside a droplet deflects the droplet axially away from the object.

4 DISCUSSION

It is considered that when dropped onto the moving surface of the host fluid, the droplet does not penetrate the air boundary layer associated with the moving surface. The air boundary layer drags the droplet with it to a point where the forces acting on the droplet are in equilibrium, with a flow pattern something like that illustrated in Fig. 5. The gravitational force on the droplet is balanced by a combination of upward drag force and aerodynamic lift force due to quasi stagnation of air below the droplet (this induces the bottom flattening of the droplet). The droplet has moved away from the host liquid surface sufficiently that any lateral forces on it due to air flows around it sum to zero. Whether or not the droplet rotates clockwise, anti-clockwise, or is stationary depends on the net effect of the drag forces due to the boundary layer air flowing around it.

The observance of droplets of liquid "floating" on liquid surfaces is not new. Writing in the Scientific American, V. 238, N. 6, June 1978, Walker briefly traces a history of the observance and study of water-drops which float temporarily on water surfaces in certain conditions. Osborne Reynolds is noted as having written in 1881 "On the Floating of Drops on the Surface of Water Depending Only on the Purity of the Surface" in which he concluded that floating drops are rare because impurities on water surfaces somehow destroy the floating mechanism. It seems that Reynolds considered surface tension to be the main mechanism of floating.

Walker considers that though it has been discussed for nearly a century, the final word on the mechanism of transient floating has not been reached. It has been shown that the addition of detergent to the water can cause the lifetime of a floating drop to increase from about one second to "several seconds, perhaps tens of seconds". But recently, it had been observed that the lifetime could be increased to minutes by vibrating the water container in such a way that standing waves are set up on the surface of the host water.

Walker also refers to suggestions that the temporary floating mechanism might be due to electrical repulsion between the bottom of the floating drop and the host liquid beneath it. The Leidenfrost effect is also mentioned, though its basis of vapour layer support of droplets is rational only for droplets forming on superheated host liquid surfaces.

The support mechanism usually proposed for the situations studied by Walker and his predecessors (2, 3, 4) is illustrated in Fig. 6. Air trapped between the droplet and the host fluid gives temporary support of the drop.

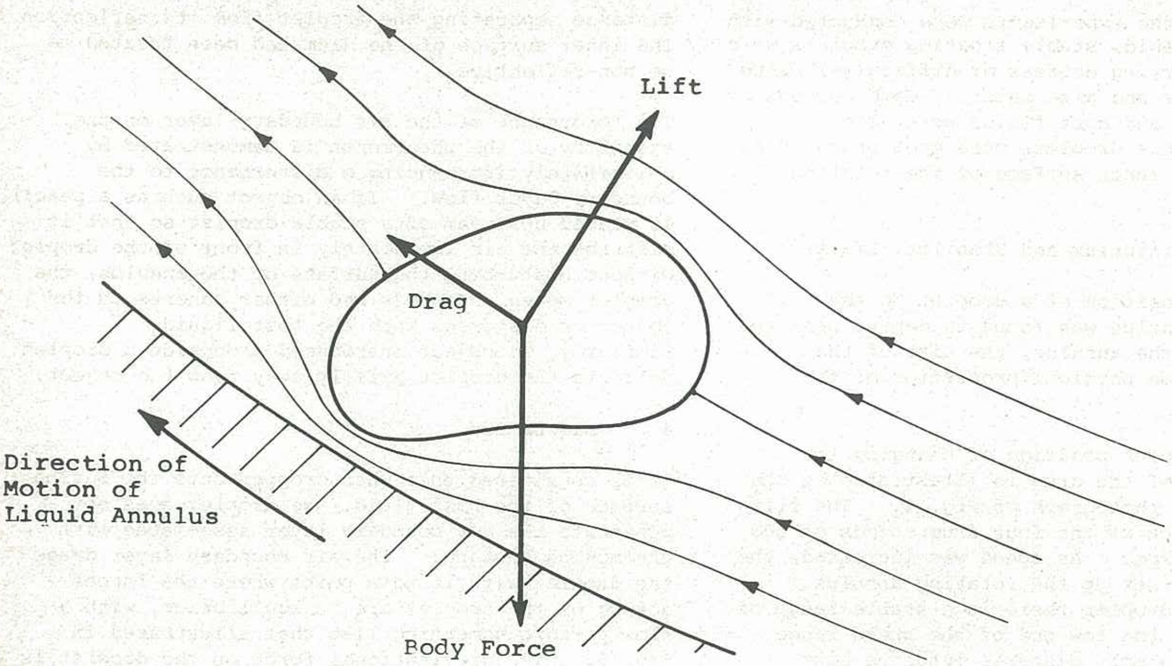

Figure 5 **Equilibrium Force System for Stable Floating Droplet**

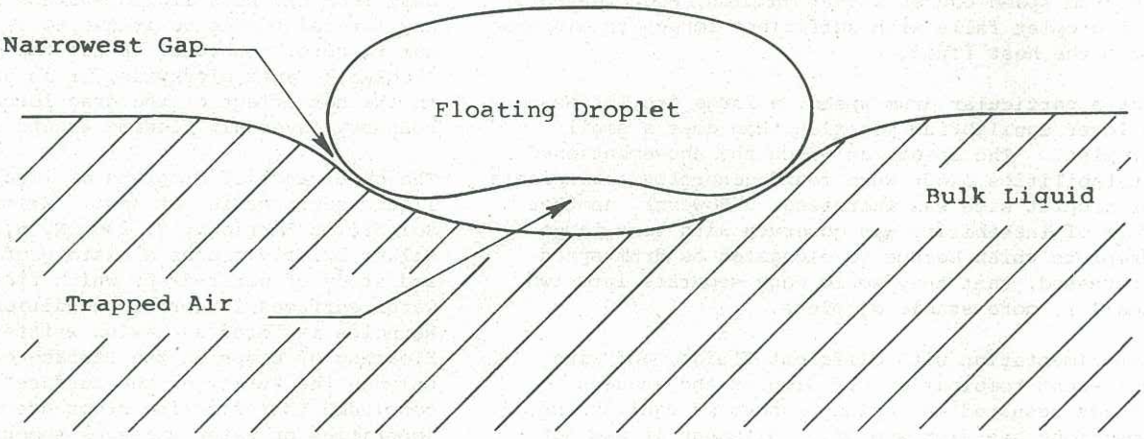

Figure 6 **Trapped-Air Mechanism for Temporarily Floating Droplet (Ref. 1)**

5 CONCLUSION

The paper describes a floating droplet situation quite distinct from references found concerning floating liquid droplets. The main physical distinction is that the droplets of the latter exist transiently, while those of the present paper can exist indefinitely.

6 ACKNOWLEDGEMENTS

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