J. Fluid Mech. (1999), *vol.* 380, *pp.* 297–307. Printed in the United Kingdom

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Levitation of a drop over a film flow

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(Received 15 July 1996 and in revised form 2 September 1998)

A vertical jet of water impinging on a horizontal surface produces a radial film flow followed by a circular hydraulic jump. We report a phenomenon where fairly large (1 ml) drops of liquid levitate just upstream of the jump on a thin air layer between the drop and the film flow. We explain the phenomenon using lubrication theory. Bearing action both in the air film and the water film seems to be necessary to support large drops. Horizontal support is given to the drop by the hydraulic jump. A variety of drop shapes is observed depending on the volume of the drop and liquid properties. We show that interaction of the forces due to gravity, surface tension, viscosity and inertia produces these various shapes.

1. Introduction

When a vertical jet of water impinges on a horizontal surface a thin radially spreading film flow is produced. At some radius a circular hydraulic jump occurs, accompanied by a sudden increase in the thickness of the film. To visualize the flow we tried to inject dye with a syringe upstream of the jump; to our surprise, we found that a drop of the dye would just ‘float’ on the thin film just upstream of the jump. We found drops of glycerol, engine oil, soap solution can also be similarly supported. In this paper we present experimental observations of and a theory for this phenomenon. Some preliminary results have been presented in Sreenivas, De & Arakeri (1995).

2. Experiments

In one set of experiments we had water issuing out of a vertical glass tube (internal diameter 5 mm) and impinging on a 40 cm diameter horizontal glass plate. The lower edge of the glass tube was 7.5 cm above the plate. The flow rate (q) in these experiments was about 8 $cm^3\,s^{-1}$, and the jump radius was about 1.8 cm. In another set of experiments, primarily used to measure the drop dimensions, water issued out of a nozzle with 40 : 1 area ratio (exit diameter = 1 cm), connected to a 20 l glass flask. The flask was supported on a semi-inflated rubber tube to minimize disturbance. A 15 cm diameter glass plate was kept 14 cm below the nozzle exit. A mirror below the glass plate kept at 45° to the vertical allowed simultaneous recording of the side and top views of the drop. The flow rate in these experiments was 3.1 $cm^3\,s^{-1}$ and the jump radius was about 1.25 cm. In the second set a smaller glass plate was used so as to be able to position the camera closer to the drops; to get a stable jump we had to use the lower flow rate. We made detailed measurements of sizes for drops of water, soap solution and engine oil. The temperature was typically about 28°C when the experiments were conducted. The measured values of the surface tension for the soap

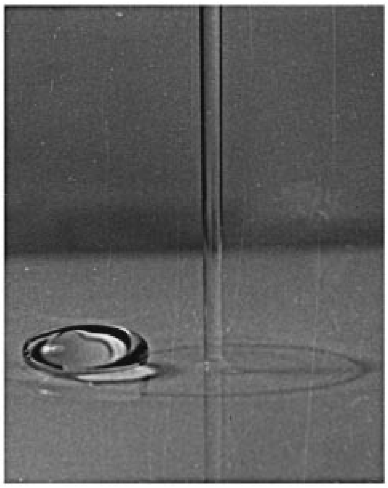

FIGURE 1. Photograph of a levitating water drop (the 0.75 ml drop is about 1.6 cm in diameter and is about 0.6 cm high). The impinging water jet and the circular hydraulic jump are also seen.

solution is 31.5 dynes cm^{-1} and for the oil is 23.0 dyne cm^{-1}. The dynamic viscosity of the oil is 0.11 Pa s^{-1} and its density is 769 kg m^{-3}.

In all the experiments the flow was laminar and steady. Initially the thickness of the water film decreases with radius and then due to viscous effects it increases gradually. At the hydraulic jump the change in thickness of the water film is rapid. Downstream of the jump the height increases with radius initially and then decreases. The essentials of the flow upstream of the jump were given by Watson (1964). Using Watson's relations the film thickness (h_w) is between 0.02 cm and 0.03 cm in both the experiments. The estimated free surface velocity is about 100 cm s^{-1} at 1.5 cm from the centre of the jet for the larger flow rate experiments and it is about 40 cm s^{-1} at 1 cm from the centre of the jet in the smaller flow rate experiments. The free surface velocities just upstream of the jump in the larger and smaller flow experiments are respectively 60 cm s^{-1} and 25 cm s^{-1}.

The liquid which is to be floated is taken in a hypodermic syringe and injected carefully just above the water surface and just upstream of the hydraulic jump. The injected liquid forms a drop and 'floats' over the water surface. Figure 1 shows the impinging jet and a 'floating' water drop.

3. Observations

We now present experimental observations of the phenomenon. The injected liquid drop stays at the position of the hydraulic jump; larger drops extend beyond the jump. If injected slightly away from the jump, upstream or downstream, the drop moves radially to position itself at the hydraulic jump. Liquid drops move in the azimuthal direction, sometimes in an oscillating manner. The speed of this motion is greater for the smaller drops. When many drops are injected, they rebound like solid bodies during collision and at times two drops may coalesce to form a single drop. Typically the smaller drops stay without breaking for about 5 min. We believe a cleaner experiment can extend the life indefinitely. Breakage of a water drop occurs in <0.04 s, the time between successive frames in our video recording. To float large drops care has to be taken to minimize disturbance levels and have a stable jump. Thus, experiments were done mostly at night. We found that drops of water, glycerol, soap water solution and engine oil would float. However, drops of several liquids including ethanol and methanol failed to float over the water film.

A variety of drop shapes (figure 2) is obtained depending on the volume of the drop and the drop liquid properties: flattened hamburger-bun shaped (1 ml water drop and 0.86 ml oil drop), shapes which oscillate between nearly spherical and elongated egg shapes (0.12 ml water drop and 0.04 ml soap solution drops) and nearly spherical shaped (small drops, 0.03 and 0.04 ml water drops and 0.02 ml oil drop). At the lower flow rate ($q = 3.1\,\mathrm{cm^3\,s^{-1}}$) we did not observe the oscillation between spherical and elongated shapes. The larger soap-solution drops are not static; the upper surface of the drop jiggles about.

Dye injected into a water drop mixes rapidly suggesting a motion inside the drop. Water drops seeded with aluminium particles ($\approx 50\,\mu\mathrm{m}$) reveals a complicated flow pattern. The life of the drop is reduced drastically when aluminium particles are used. In the case of the more viscous liquids, glycerol and engine oil, the motion is much slower. Flow visualization using dye in glycerol and oil drops indicated that the fluid motion is predominantly in the radial direction outwards in the bottom of the drop and inwards in the top portion.

A standing ripple, analogous to the bow shock in front of a bluff body in supersonic flow, on the film surface, barely visible to the naked eye, surrounds the drop on the upstream end. The hydraulic jump is distorted in the vicinity of the drop. A wake in the form of two dimples on either side of the drop and about a diameter downstream is also seen. The dimples are clearly visible only for the larger drops and only when viewed at a particular angle. The dimples probably correspond to vortices. However, unlike the familiar Kármán vortices behind a circular cylinder in uniform flow at high Reynolds numbers, these vortices are not shed and are not swept downstream. The vortices presumably get their vorticity from tilting of the upstream azimuthal component of vorticity.

There should not be any physical contact between the liquid drop and the water surface. Otherwise, in the case of miscible liquids, at least, the drop would just mix and flow with the water. Liquid drops are supported on an air film present between the liquid drop and the water surface. The presence of the air film was confirmed by a mirror-like reflection from the bottom of the drop and the measurement of an almost infinite electrical resistance between the liquid drop and the water film.

In the following sections we give a theory for the levitation, give an estimate of the velocities induced within the drop, look at the factors which influence drop shape and look at how the film flow is affected by the drop. Finally, we discuss other circumstances where similar levitation may be observed, and why it is not possible to levitate drops of some liquids on a water film.

4. Theory

In the rest of the paper we denote the length (measured in the flow direction of the deformed drop) by L, the height by H and the breadth by B. The equivalent diameter of the drop is D ($\pi D^3/6 =$ volume of the drop). The film surface velocity is U_S and the velocity induced in the drop is U_D. In all the analyses below we leave out constants that are $O(1)$; thus, for example, $LBH = D^3$.

The levitation of the liquid drop over the water surface can be explained by lubrication theory. A schematic of the flow configuration with a liquid drop and

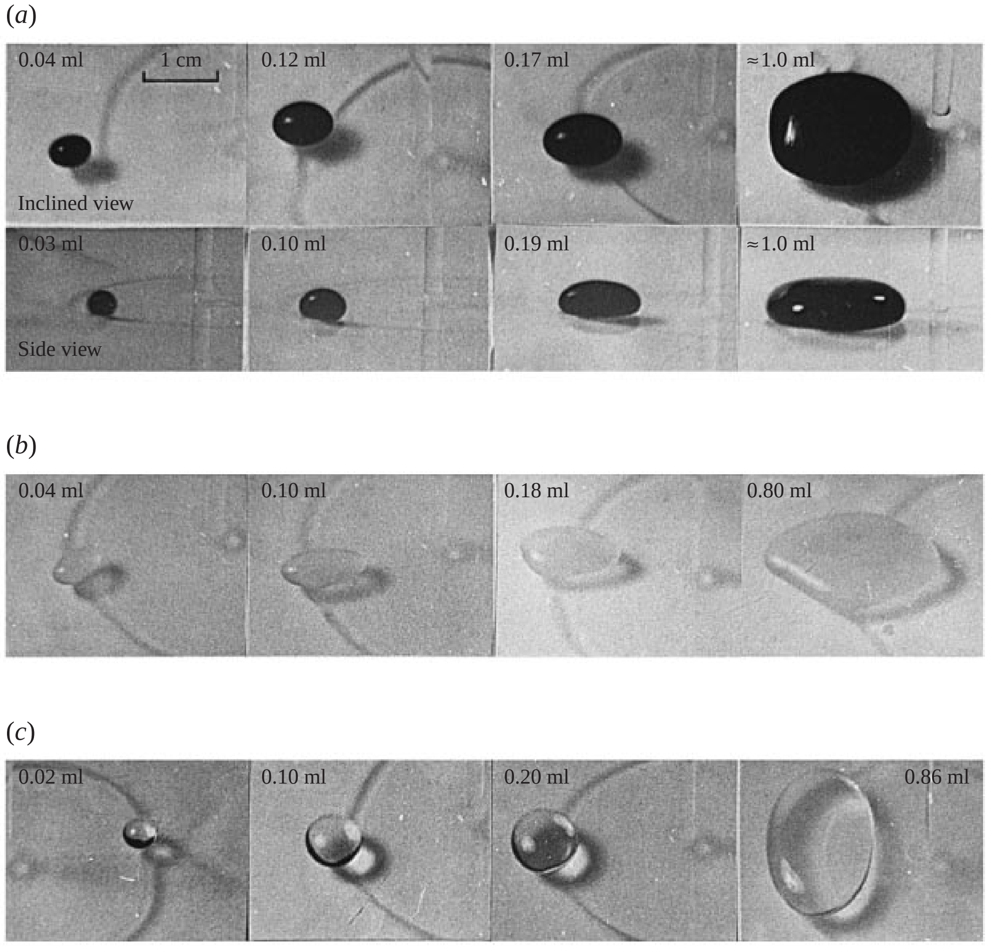

FIGURE 2. Drop shapes for three liquids: (*a*) water, (*b*) soap solution and (*c*) engine oil for a range of drop sizes. The flow rate is about 8 $cm^3 s^{-1}$ and the jump radius is about 1.8 cm. Side and a view inclined at about 35° to the vertical are shown for the water drops and only the inclined views for drops of the other two liquids. Small water and oil drops dominated by surface tension (low Bo and We) are nearly spherical. The larger drops of the three liquids are flattened by gravity (high Bo) (this is evident from the side views of water drops). Water drops larger than 0.12 ml and all the soap solution drops shown elongate due to motion induced (high We) within them. Little motion is induced in the oil drops ($We \ll 1$) and they do not elongate; in the large oil drop contraction in the longitudinal direction is because of the opposing shear and pressure forces. Scale indicated is same for all the pictures.

the coordinate system is shown in figure 3. Z is the vertical distance from the glass surface, X is the distance along the flow in the central plane of the liquid drop and Y is measured perpendicular to the plane of the figure; $h_a(X, Y)$ is the thickness of the air film between the liquid drop and the water surface and $h_w(X, Y)$ is the thickness of water layer on the glass surface. The motion in the film and the motion in the liquid drop drags air into the gap between the water surface and the liquid drop. A reduction in h_a in the air-flow direction results in a pressure build-up according to bearing theory. A qualitative picture showing the pressure variation in the air gap is given in figure 4. This pressure supports the drop. The same pressure acts on and has to be supported by the water film surface. To solve the problem we would

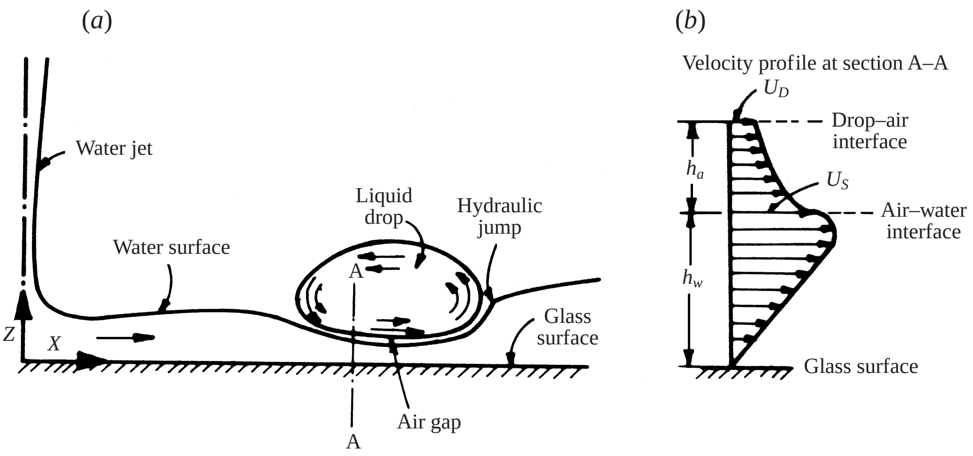

FIGURE 3. (*a*) Schematic showing the water jet, flowing water film, air gap and induced motion (shown by arrows) in the drop. (*b*) Velocity profile in the air layer and the water film. Induced velocity in the drop, U_D, is small for viscous drops. Film thickness $h_w \approx 0.1\,\mathrm{mm}$ and air-gap thickness, h_a is estimated to be $\approx 10\,\mu\mathrm{m}$.

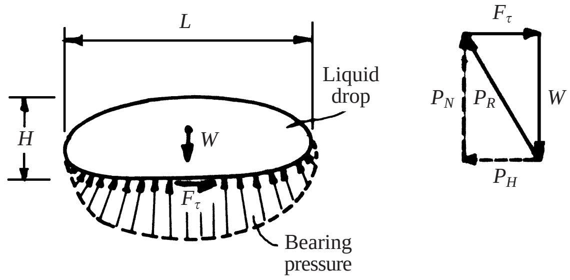

FIGURE 4. External force balance; weight (W) of the drop is balanced by the vertical component (P_N) of the resultant force (P_R) developed due to bearing action. The horizontal component of bearing force P_H balances the shear force (F_r) exerted by the air motion.

need to solve the Reynolds equation in the air gap and the Navier–Stokes equations within the drop and in the water film. The equations and the boundary conditions are coupled and the computation is likely to be difficult and intensive.

Estimates, however, can be obtained from results of standard bearing theory. We estimate the thickness of the air film by assuming the gap to be that between two plane surfaces with a fixed inclination. This is not a bad approximation because the bearing action strongly depends on the variation in film thickness but not on the curvature of the two surfaces. The surface velocities in the Y- and Z-direction are neglected as the flow is predominantly in the radial direction. The load (W = drop weight) carried by this system is given by (Cameron 1966),

$$W = f_L \mu_a U L_y \frac{L_x^2}{h_o^2}, \tag{4.1}$$

where U is the effective surface velocity in X-direction, and is the algebraic sum of film surface velocity (U_S) and fluid velocity at the drop surface (U_D), μ_a is air viscosity, f_L is the non-dimensional load carrying capacity of the system which depends on L_y/L_x, and the inclination ratio (χ) ($\chi = (h_i/h_o) - 1$). h_o is the minimum air film thickness below the drop, h_i is air film thickness at the entry and L_x, L_y are length along the flow and width respectively over which the bearing action occurs. The load carrying capacity is maximum at $\chi = 1$ (Cameron 1966), for all values of L_y/L_x. Assuming $L_x \simeq L_y \simeq D$ (diameter of the spherical drop), $f_L = 0.06$ (Cameron 1966) and $\mu_a = 1.8 \times 10^{-5}\,\mathrm{N\,s^{-1}\,m^{-2}}$ we obtain for $U = 1.0\,\mathrm{m\,s^{-1}}$ and for a 1 cm diameter, 0.6 cm high drop the air gap to be about 14 μm. This gap is much greater than the value of about 0.01 μm (Mackay & Mason 1963) that would be required for coalescence, and which is expected when the gap is within the range of intermolecular forces of the liquid. For small drops, L_x and L_y are expected to be less than D; for large drops, L_x and L_y will be greater than D. An estimate of the bearing area may be obtained using the results of the analysis of a sessile drop with contact angle $= 180°$ (Homentcovschi, Geer & Singler 1998). The component of bearing pressure force in the horizontal direction will support the shear force acting on the drop; the hydraulic jump is essential for the horizontal equilibrium. We must state here that experimental observations suggest the levitation is obviously stable. Any tendency for the drop and film surface to come closer together locally is countered by an increase in bearing pressure there.

5. Motion within the drop

Motion within the drop is caused by the air film exerting a shear stress on the drop. The surface velocity of the liquid drop can be estimated by equating the rate of work done on the liquid drop by the shear and the rate of dissipation in the liquid drop:

$$\text{rate of work done on drop} \sim \mu_a U_D \frac{(U_s - U_D)}{h_a} LB,$$

$$\text{rate of dissipation in liquid drop} \sim \mu_d \frac{U_D^2}{H^2} D^3,$$

where μ_a is air viscosity and μ_d is viscosity of drop liquid. Equating the two and rearranging terms, we get the drop surface velocity,

$$U_D \simeq \frac{U_s}{1+K}, \tag{5.1}$$

where $K = h_a\mu_d/(H\mu_a)$ and f_V is a constant ($\sim O(1)$). For a 1 ml water drop $K = 0.166$ and $U_D \simeq 0.80 U_S \simeq 0.56\,\mathrm{m\,s^{-1}}$; for the same size oil drop $K = 60$ and U_D is only $0.011 U_S \simeq 7.5$ mm s^{-1}. The experimentally observed value of U_D for the oil drop is about 6 mm s^{-1}, in reasonable agreement with the estimated theoretical value. In the case of water, due to rapid mixing of the dye, the surface velocity of the drop could not be determined.

6. Drop shape

Two factors influence the drop shape: (i) the internal forces due to surface tension, gravity, and motion within the drop and (ii) the external forces on the drop.

Let us consider the internal forces first. The relevant quantities are the drop size (D), velocity within it (U_D), surface tension (σ_d), density (ρ), and acceleration due to gravity (g); the effect of drop viscosity μ_d comes indirectly through equation (2) for U_D. Two non-dimensional parameters can be found from these quantities: Bond number $(Bo) = \rho g D^2/\sigma$, a measure of the ratio of the effects of gravity to surface tension, and Weber number $(We) = \rho U_D^2 D/\sigma$, a measure of the ratio of inertia force

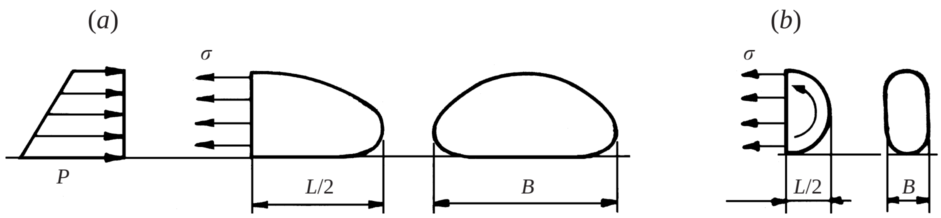

FIGURE 5. Internal force balance: (*a*) balance of forces between those due to hydrostatic pressure and surface tension and (*b*) balance of forces between those due to surface tension and momentum change as induced motion in the drop turns through 180°. The arrow in (*b*) indicates induced motion within the drop.

to surface tension. Note that we have taken the velocity U_D induced in the drop and not the water film velocity U_S; as shown in equation (5.1), U_D is function of several parameters, U_S being one of them.

Let us first look at the balance of forces due to surface tension and gravity on one half of a drop (figure 5 *a*). The configuration is very similar to a sessile drop (Paddy 1969). There is, however, one difference: in our case in addition to the weight, horizontal forces due to the shear in the air gap and due to the pressure at the jump are present. In the limit of $Bo \to 0$ surface tension forces dominate and the drop will be nearly spherical. In the limit of large Bo (large drops) we expect flattened drops. For large Bo, a simple balance of forces assuming a flat top surface shows that the drop height becomes independent of drop volume; $H \simeq (2\sigma/\rho g)^{1/2}$. The above discussion is valid when the fluid motion within the drop is negligible ($We \simeq 0$). Such a situation is obtained in the viscous drops – the engine oil drops in figure 2.

Now we consider the effects of surface tension and fluid motion. Fluid velocity within the drop is predominantly in the X-direction, positive in the lower portion and negative in the upper portion. Here the momentum change (as the fluid turns through 180°) and the force due to surface tension balance (figure 5 *b*).

The effect of the fluid motion within the drop is to increase the drop dimension in the plane of motion. When $We \simeq 0, L/D \simeq 1$, i.e. the drop is nearly spherical. When gravity can be neglected (i.e. when Froude number $(Fr) = U_D^2/gD(= We/Bo)$ is large) the situation is similar to rotating drops. In none of the drops shown in figure 2 is this condition satisfied. However, when we did experiments with small water drops and a high-speed film flow we did observe that the drops would assume a flattened rotating disc shape.

For the water and soap solution drops effects of gravity and fluid motion are both important. In such cases, we may expect gravity to flatten the drop in the vertical direction, induced velocity to make the drop longer (i.e. increase L) and surface tension tend to make it spherical.

Next we discuss the second factor – the external forces – which affects the drop shape. Consider the external force balance (figure 4). The weight of the drop is balanced by the bearing force. The effect of the bearing pressure is to make the bottom bearing surface of the drop nearly flat. In the horizontal direction, the shear force exerted by the air layer balances the horizontal component of bearing pressure, which mostly acts at the hydraulic jump. The horizontal forces reduce the length of the drop.

The shape of the drop depends on an interplay of the forces discussed above. The above analysis can also explain the many shapes in figure 2. At large values of Bond

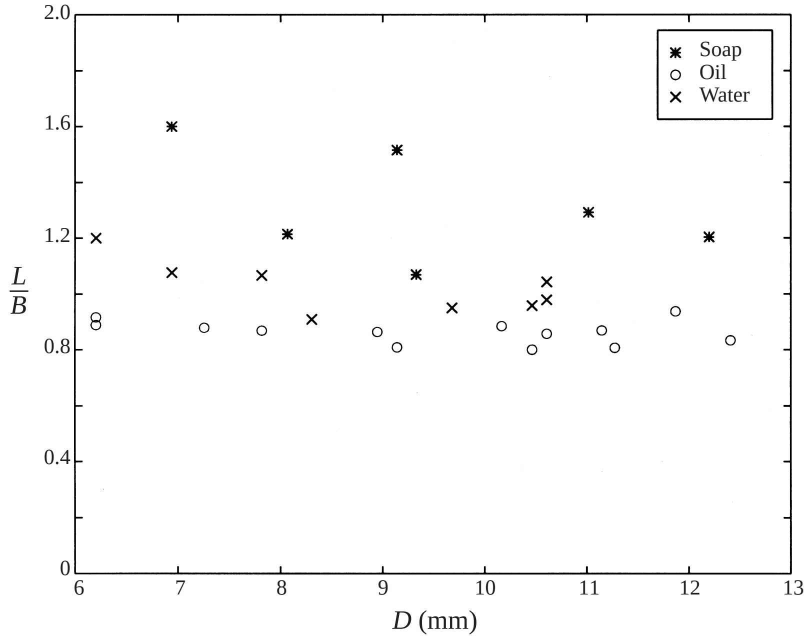

FIGURE 6. Aspect ratio (L/B) of drop versus equivalent drop diameter for three drop liquids: water, soap solution and engine oil.

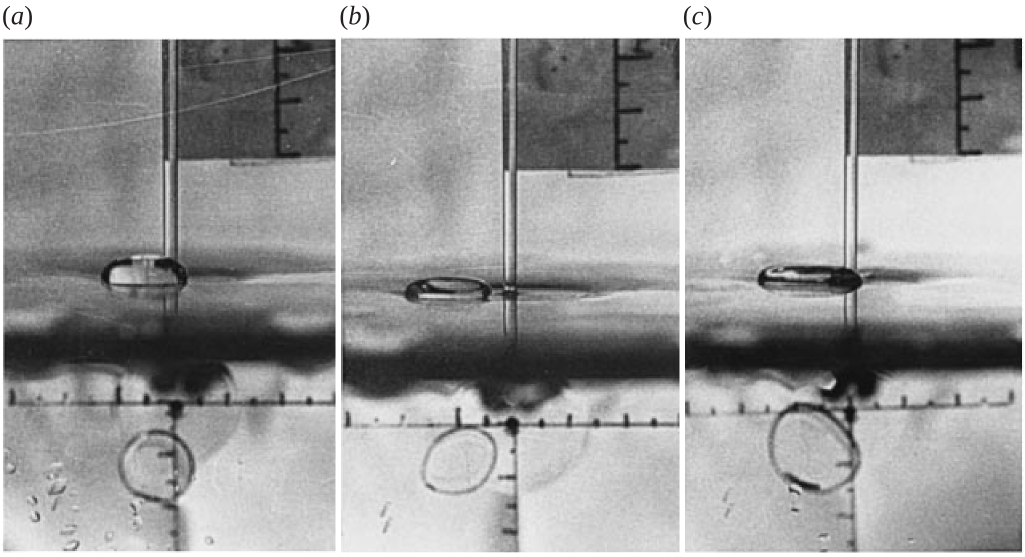

FIGURE 7. Side and top views of levitating drops: (*a*) water, (*b*) soap solution, (*c*) engine oil. Drop volume $\simeq 0.7$ ml. The flow rate is about $3.3\,\mathrm{cm^3\,s^{-1}}$ and the jump radius is about 1.25 cm. The top view is an image in a mirror at 45° below the glass plate.

number gravity is dominating and we obtain the flattened hamburger-bun shaped drops (1 ml water drop). When both Bo and We are of the same order we obtain elongated flat shapes. These shapes may be stable as for the 0.18 ml soap solution drop; they may be unstable, oscillating between an elongated and nearly spherical shape, as for the 0.12 ml water drop and 0.04 ml soap solution drop. The effect of fluid motion is easily seen by comparing the shapes of similar sized oil and soap solution drops: the soap solution drops are elongated (in the flow direction) in comparison with the oil drops. The shortening effect due to the external horizontal forces is clearly seen in the large oil drop (0.86 ml oil drop).

Figure 6 shows the aspect ratios (L/B) plotted versus the equivalent drop diameter, D, for the large water, soap solution and oil drops. The estimated error in the dimension measurement is less than 1 mm. The data are from the smaller flow rate ($= 3.1\,\mathrm{cm}^3\,\mathrm{s}^{-1}$) experiments. The height of the large drops for each of the liquids was nearly constant with drop volume: about 5 mm for water and about 3 mm for soap solution and the oil. The theoretical estimate of the height, $= 2(\sigma/\rho g)^{1/2}$ (mentioned above), gives values of 5.3 mm, 3.6 mm and 3.3 mm respectively for water, soap solution and oil. From the figure we see that $L \simeq B$ for water whereas $L > B$ for soap solution and $L < B$ for oil. It appears that for the water drops the elongating tendency of the fluid motion within the drop is cancelled by shortening tendency of the external force giving $L \simeq B$. The soap solution drops continuously change shape for $D \simeq$ 8–10 mm. The values of the aspect ratio fluctuate between 1.2 and 1.6 for this range of drop sizes (the data points in the figure are not average values but from single realizations). Figure 7 shows the simultaneous top and side views of drops having equivalent diameters $\simeq$ 11 mm for each of the three liquids.

7. The film flow

We now discuss some aspects of the water film. The drop affects the film flow in several ways. Besides the formation of the capillary wave and the two wake vortices, the increased pressure below the drop should also reduce the film velocity. To estimate this reduction consider the integral momentum equation in the radial direction (Arakeri & Achuth Rao 1996):

$$c_1 \frac{\mathrm{d}}{\mathrm{d}X}\left(\frac{U_S^2}{2}\right) = -\nu \frac{U_S}{h^2} c^2 - g \frac{\mathrm{d}h_w}{\mathrm{d}X} - \frac{1}{\rho}\frac{\mathrm{d}P}{\mathrm{d}X}.$$

U_S is the surface velocity in the film, and c_1 and c_2 are constants which depend on the velocity profile shape. The terms on the right hand side are respectively the viscous term, hydrostatic pressure term and any imposed pressure gradient. In our case the pressure gradient is due to the bearing pressure. Consider the change in velocity (ΔU) as the water flows a distance ΔX from just upstream of the drop to a station below the drop. For a typical case $U \sim 70\,\mathrm{cm\,s}^{-1}$, $h_w \simeq 0.02$ cm, drop height $\simeq 0.5$ cm and $\Delta X \simeq 1$ cm,

$$\begin{aligned}\frac{\Delta U}{U_S} &\simeq -\frac{\nu}{h^2}\frac{\Delta X}{U_S} - \frac{g\Delta h}{U_S^2} - \frac{\Delta P}{\rho U_S^2}\\ &\simeq -0.36 - 0 - 0.1.\end{aligned}$$

Here we have assumed $(\Delta P)/(\rho\, g) =$ drop height and change in film height $(\Delta h) = 0$. Thus the change in film velocity due to the drop bearing pressure is only about 10 %, and most of the change is due to viscous forces which anyway would be present even in the absence of the drop. In all the cases we have considered the change in the film velocity due to bearing pressure may be neglected. It is clear, however, that the maximum drop height cannot be more than the dynamic pressure head in the film flow; it sets an upper bound on the drop height for a given film velocity.

8. Further remarks

Alcohol drops failed to levitate on the water film because of the following reasons. When the alcohol drop is placed near the water film, due to its low boiling point and high solubility in water, alcohol in the drop evaporates and dissolves into the water. As the surface tension of the alcohol is lower than that of water, water in the film surface just below the alcohol drop will be driven outwards. This outward motion, in the water film, below the alcohol drop will momentarily stop the bearing action resulting in the complete mixing of the alcohol drop with the water film. (Alcohol drops can float over an alcohol surface as reported by Cai (1989) because of zero concentration gradient across the air film.) Despite glycerol being soluble in water and a high concentration gradient obtained across the air film, glycerol drops are supported on water because of its lower rate of evaporation. We found a simple way of checking whether a drop comprising one liquid can levitate over the surface of another liquid. Have a stationary film of one liquid in a shallow container and using a syringe, direct a stream of small drops of the other liquid with a velocity and at a small angle to the film. For those pairs of liquids where levitation is possible, the drops levitate as long as the drops have sufficient velocity; where levitation is not possible, the drops immediately mix with the stationary liquid.

The phenomenon of a liquid drop supported by a thin film of air is not restricted to the particular flow configuration reported here. When water is trickling down on to a container of water, one may see small water drops form and float on the water surface. The drops are distinguished from the more commonly occurring air bubbles by their high speed of motion on the liquid surface. This phenomenon was also observed by Cai (1989) in the study of a liquid drop striking a stationary liquid surface. The phenomenon, however, was not explained in the paper. The size of these drops was of the order of 1–2 mm and had a life span of about 5 s. A drop can be supported by bearing action only as long as the drops are in motion. Drops of size larger than 3–4 mm can be supported only in the special circumstances of thin fluid flow and hydraulic jump as obtained in our experiments. The hydraulic jump is necessary to anchor the drop.

Related phenomena are at work when a translating liquid drop bounces off another liquid drop (Qian & Law 1997) or off a stationary liquid surface (Wallace & Hobbs 1977). Qian & Law (1997) have recently experimentally established regimes of coalescence, bouncing and coalesence followed by separation in droplet collision. The bouncing is due to the pressure buildup as the gas between the drops is squeezed. Coalescence occurs when the two drop surfaces approach each other to distances less than about 0.01 μm. This can occur when either the pressure buildup is not high enough (low drop approach velocities) or when the initial kinetic energies of the drops overcomes the pressure (high drop approach velocities). Qian & Law (1997) have shown that both the drop properties and the ambient gas properties can influence the regimes. We are not aware of any detailed study of drops bouncing off a stationary surface. In this case also, presumably, the amount of pressure buildup due to the squeeze action would determine whether bouncing or coalescence would occur. In both the above cases, pressure buildup in the air film is transient, whereas in our experiments the bearing pressure is steady, caused by the motion of the drop and film surfaces.

9. Conclusion

We have observed that it is possible to support a large liquid drop ($\sim$1 ml) on an air bearing between the drop and the film flow formed by a vertical jet of water impinging on a horizontal surface. Motion within the drop is set-in due to shearing action in the air film. The induced velocity in the drop depends on the viscosity of the drop liquid. The shape of the liquid drop is determined by an interplay of effects due to inertia, gravity, surface tension and viscosity. Alcohol drops could not be supported on the water surface due to its high rate of evaporation and solubility.

We believe only a thin film can support large drops. In a thick film its surface will have to deform enough to support, by surface tension and/or hydrostatic pressure, the drop weight. This deformation will be of the order of the drop height. At the same time, the necessarily small air gap has to be maintained between the drop surface and film surface to develop the required bearing pressure. An experiment using a very viscous liquid jet (so as to obtain thick, laminar film flows) may be done to check the above contention. Also, with jets of different liquids it would be possible to obtain a wide range of film velocities which was not possible in our experiments.

Useful discussions with Professors K. S. Gandhi and V. H. Arakeri are gratefully acknowledged. We thank Mr Murali R. Cholemari for conducting experiments related to results in figure 6.

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