Drop propulsion in tapered tubes

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Abstract – We present the results of a combined experimental and theoretical investigation of the motion of wetting droplets in tapered capillary tubes. We demonstrate that drops may move spontaneously towards the tapered end owing to the Laplace pressure gradient established along their length. The influence of gravity on this spontaneous motion is examined by studying drop motion along a tilted tube with its tapered end pointing upwards. Provided the tube taper varies, an equilibrium height may be achieved in which the capillary force is balanced by the drop’s weight. We deduce the family of tube shapes that support a stable equilibrium.

Introduction. – In 1712, Hauksbee observed that a drop of orange oil bridging two non-parallel plates propels itself in the direction of maximum confinement, that is, into the gap [1]. The drop asymmetry is responsible for the motion: this wetting liquid meets the plates with a different curvature on its leading and trailing edges, so that a differential Laplace pressure is established between the drop extremities and drives the liquid to the region of maximum confinement. A similar motion takes place in a tapered tube [2], a geometry that will be the subject of our investigation. Related curvature-driven motions may also arise for wetting drops on conical fibers, for which the sign of the curvature is reversed, so that the drop is propelled away from the cone tip [3].

For multiphase flow in natural porous media, constrictions or enlargements of the pore channels will necessarily generate displacement and reconfiguration of drops or bubbles. Such geometries also exist in man-made microfluidic devices, and can be used to control the topology and dynamics of two-phase systems, such as emulsions or foams [4]. Finally, the motion of drops in confined geometries arises in the biological world; for example, a class of shorebirds transport prey-laden water droplets mouthward by opening and closing their beaks in a tweezering motion [5–7].

We here study the behaviour of liquid slugs in tapered tubes. If inserted into a fluid bath, conical tubes cause the liquid to rise via capillary action [8,9], but Tsori demonstrated that even this simple system displays surprisingly rich behaviour [10,11]. For example, a wetting liquid either rises to a finite height, or to the top of the tube if the cone angle exceeds a critical value. Here we consider a wetting drop initially placed in the widest part of an inclined tapered tube, and examine the equilibrium position of the drop. While one might first expect this equilibrium to be obtainable directly from Laplace’s formula, we here demonstrate that it is potentially unstable, and that its very existence depends on the detailed shape of the tube.

Initial observations. – We consider drops (or slugs) in tapered tubes that are open at both ends. The tubes are thin relative to the capillary length, so that the menisci bounding the slugs can be considered hemispherical. The liquid wets the solid and meets it with zero contact angle. This condition implies that nanoscopic wetting films develop and progress ahead of the menisci, eliminating contact angle hysteresis, and so favouring drop motion in response to forces. Here, the forces driving motion are gravity and the capillary force arising from the curvature difference of the two menisci, as follows from the tube’s tapered geometry. The cone opening angle $\alpha$ will be taken small relative to unity. One expects capillary-induced slug motion in a tilted tube to be eventually halted by gravity, as shown in fig. 1. Our experiment consists of determining when a drop equilibrium position exists, then measuring the position $z_o$, as a function of the tube shape and tilt angle.

Our capillary cones were created by heating and pulling glass capillary tubes. By fixing a given load at the tube extremity, we generate a constant force that draws and
Capillary trumpets. – A question naturally arises in light of our experiments. How was it possible to observe in many cases equilibrium positions for the drops (figs. 1 and 3)? The answer lies in the tube shape: while conical tubes have no stable equilibrium, spayed tubes may do. If the tube walls become parallel above the equilibrium position (z < z₀), the drop will not move upwards, because the local capillary force vanishes with α; similarly, if the tube splays below z₀, the liquid may be sustained by a strong capillary force at z₀ and so avoid falling down.

We proceed by considering trumpet-shaped tubes, whose inner radius a is defined by a(z) = δ + αz + βz². We again assume that L ≪ z, and further assume a sufficiently small splay that δ > αz + βz², a condition fulfilled in the experiments (for which β < 5 m⁻¹). In this limit, the volume can be written as Ω ≈ πδ²L. Finally, L will be sufficiently large that the volume of liquid in the menisci may be neglected, which for a drop of volume Ω = 3 mm³ is ensured provided δ < 0.7 mm, another condition fulfilled in the experiments.
Fig. 2: Fluid slugs of wetting silicone oil, whose capillary length $\kappa^{-1}$ is 1.5 mm. For sufficiently thin tubes (radius smaller than $\kappa^{-1}$), the menisci assume a hemispherical form (a). For larger tubes, asymmetric distortions appear due to gravity (b). Gravity points downward.

Fig. 3: Equilibrium position $z_o$ of drops of silicone oil placed in a tapered glass tube, inclined at an angle $\phi = 30 \pm 5^\circ$ relative to the horizontal, as a function of the drop volume $\Omega$. The equilibrium position is independent of the drop volume.

We focus on the case $\alpha = 0$, so that the tube radius is given by $a(z) = \delta + \beta z^2$, but return to the more general quadratic form in the appendix. The dependence of the capillary force $F(z) = dE/dz$ on drop position $z$ is readily calculated, and the drop’s ability to climb is assessed by comparing $F(z)$ to the drop weight $W = \pi \rho g \delta^2 L \sin \phi$. Figure 4 indicates the $z$-dependence of the net force, $F(z) - W$, on a drop in a quadratic tube inclined at an angle $\phi = 30^\circ$ relative to the horizontal. Three values for the tube splay $\beta$ are considered.

When $\beta$ is small (bottom curve), the weight always exceeds the capillary force: there is no equilibrium height and the drop falls to the bottom of the tube. In this case, the tube is too close to a cylinder to allow any upward motion. When $\beta$ is intermediate (middle curve), two equilibrium positions arise, the stability of which are determined by the local sign of $dF/dz$. When $dF/dz$ is positive, the drop is brought back to equilibrium when perturbed, corresponding to a stable equilibrium (S). We note that only the higher of the two equilibrium positions (i.e. that of smaller $z$) is stable. For large $\beta$, only an unstable equilibrium (U) arises: the capillary force is enhanced by the large tube splay, so the drop climbs until reaching the top of the tube.

In fig. 5, we present a phase diagram indicating the different drop behaviors as a function of the tube geometry. For the sake of similarity to our experiments, we consider drops of millimetric size ($\Omega = 3 \text{ mm}^3$) and tubes tilted by $\phi = 30^\circ$. The three regimes correspond to those described in fig. 4. For a given $\delta$ and increasing $\beta$, i.e. for a cylindrical tube that gets progressively more splayed, we define two values $\beta_{\text{min}}$ and $\beta_{\text{max}}$ that bound the three cases. For $\beta < \beta_{\text{min}}$ the tube is too parallel for the drop to climb (zone I). For $\beta > \beta_{\text{max}}$, the splay of the tube is
so large that the drop can only climb (zone III). Between these extreme values, $\beta_{\text{min}} < \beta < \beta_{\text{max}}$, the drop can reach a stable-equilibrium position (zone II). The boundary between zones II and III is given by $z_0 = 0$, and so deduced by solving the equation $F(0) = W$, which yields

$$\delta = (2\kappa^{-2}\Omega\beta/\pi \sin \varphi)^{1/4}. \quad (3)$$

The boundary between zones I and II is determined numerically, for a given $\delta$, by finding $\beta$ such that the maximum of the curve $F - W$ (in fig. 4) is zero.

**Discussion.** – In our experiments, we observed stable-equilibrium positions for wetting drops in tapered tubes (figs. 1 and 3). However, our theoretical investigation indicates that such equilibria are only possible by virtue of a finite tube splay. Our relatively crude fabrication technique inevitably induces such splays: the inner radius of our tubes can be written $\alpha = \delta + z^2$, with typical $\beta$-values between 1 and 3 m$^{-1}$ and $\delta$-values between 0.2 and 0.5 mm. For typical drop volumes ($\Omega = 3$ mm$^3$), and tilt angles (30$^\circ$) considered experimentally, stable-equilibrium positions are anticipated. Figure 5 indicates that the observed drop behaviour, specifically their tendency either to climb in the tube or reach a stable equilibrium, is consistent with our predictions.

In the limits considered in our model, the Laplace pressure difference between the ends of the drop can be written $4\gamma \beta zL/\delta^2$. Integrating over the surface area $\pi \delta^2$ of the tubes yields a capillary force $4\pi \gamma \beta zL$. Balancing this force with the drop weight $W \approx \pi \rho g \delta^2 L \sin \varphi$ leads to an equilibrium height:

$$z_0 \approx \delta^2 \kappa^{-2} \sin \varphi/4\beta. \quad (4)$$

This form clearly indicates that the equilibrium position can be fixed by the trumpet geometry: a large splay ($\beta$ large) favours small $z_0$ (the drop climbs towards the tip), while a wide tip ($\delta$ large) favours the fall of the drop (large $z_0$). For typical values of these parameters, $z_0$ is expected to be centimetric and independent of the drop volume, as observed in fig. 3.

A more quantitative comparison between experiments and eq. (4) can be done by collecting all our data, and plotting the measured $z_0$ as a function of the quantity $\delta^2 \sin \varphi/\beta$ (which has the dimension of a volume) that characterises the trumpet shape and inclination. The data were obtained by varying $\varphi$ between 1 and 50$^\circ$, $\beta$ between 0.1 and 5 m$^{-1}$ and $\delta$ between 0.1 and 0.6 mm. Figure 6 shows that all the data collapse onto a straight line with slope $0.166 \pm 0.010$ mm$^{-2}$, in excellent agreement with the value $\kappa^2/4 = 0.111$ mm$^{-2}$ anticipated from eq. (4).

We have demonstrated that wetting drops in a tapered capillary tube have a tendency to climb under the influence of capillary action. Depending on tube shape, liquid placed at the base of the tube may either remain stationary, climb until reaching an equilibrium position, or be drawn upwards to the top of the tube. Examining the range of validity of the phase diagrams presented in figs. 5 and 7 requires a careful experimental study that is left as a subject of future research.

The discussion can be extended to partially wetting drops. In this case, the capillary force (per unit length)
along the length of the tube becomes $\gamma \cos \theta$, instead of $\gamma$, where $\theta$ denotes the contact angle between solid and liquid. This leads in eq. (4) to equilibrium positions, $z_0 = \frac{z_0}{\cos \theta}$, that are further from the tip than in the case of complete wetting. However, partial wetting is generally accompanied by contact angle hysteresis, which opposes all propulsive forces and so tends to pin the drop. The pinning force arising from a hysteresis $\Delta \cos \theta$ is $2\pi \gamma \delta \Delta \cos \theta$, which dominates the capillary force if $\Delta \cos \theta$ is larger than approximately $\beta z L/\delta$. This is typically expected to be true: $\Delta \cos \theta$ is an order one quantity, while $\beta z L/\delta$ is typically between 0.01 and 0.1 in our study. The capillary force that might otherwise propel partially wetting droplets in tapered tubes is thus likely to be overcome by contact angle hysteresis. This justifies a posteriori our choice of wetting liquids, which not only maximizes the capillary force, but eliminates contact angle hysteresis. We further note that non-wetting liquids ($\theta > 90^\circ$) will tend to produce motion in the direction opposite that considered here, due to the change of sign of the menisci curvatures. For bubbles in a wetting liquid, both the gravity and curvature are reversed, so that we expect our discussion (for example, eq. (4)) to be valid.

Finally, our study suggests new directions in the design of porous solids, on which conical apertures might serve either to promote or resist drop penetration. One expects such examples to have evolved naturally in the biological world. For example, on the scale of insects, where capillary effects are critical [13], both designs could be useful: tubes with appropriate splays can either facilitate fluid uptake (e.g. in drinking through a proboscis), or prevent drop penetration into other body parts and so promote water-repellency. Nature raises related problems of spontaneous capillary-driven fluid motion in other geometries. For example, nectar is drawn mouthward along the tongues of hummingbirds through the action of surface tension [14]. Moreover, capillary feeding in shorebirds, though physically distinct in that it relies critically on contact angle hysteresis and boundary motion [7], may also benefit from beak flexure and beak splay [15] for reasons that have yet to be made clear.

**Appendix**

We here consider the general case of tubes with inner radius $a(z) = \delta + \alpha z + \beta z^2$. The force $F(z)$ acting on the drop can again be calculated and compared to the drop weight, from which we can deduce a phase diagram analogous to fig. 5. We show in fig. 7 the $(\delta, \beta)$-plane of such a diagram, for $\alpha = 1.5^\circ$ and $\Omega = 3 \text{ mm}^3$. The three zones are similar to those in fig. 5. In zones I and III, a drop is unstable: it either slides downwards (in zone I) or climbs upwards (in zone III). Equilibrium is only possible in zone II. The principal difference with fig. 5 is the marked diminution of the stable zone II: at small $\beta$ (left of point A), one now passes directly from zone III to zone I by increasing $\delta$; there is no intervening stable equilibrium. This emphasizes the destabilizing effect of the opening angle $\alpha$. The coordinates of point A may be found by solving the system of equations $2\pi \kappa - 2\alpha \delta^2 + 2\pi \beta \Omega - 7\pi \sin \delta = 0$ and $-\pi \delta^3 + \pi \alpha^2 \delta^2 + \beta \Omega \alpha = 0$. We note that increasing $\alpha$ shifts the point A to the right, and so further diminishes the zone of stability.

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