Advancing drops on curved and flat surfaces

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Abstract: *The paper is concerned with the dynamics of advancing liquid blobs of fluid on curved and flat solid surfaces, such as cycloids and inclined planes. We investigate the kinematics of such blobs on hydrophobic surfaces with emphasis on the shape of the interface as the fluid advances. A theoretical model is proposed that captures the shape of the interface at early times. Also, the trajectory of the fluid, as it detaches from the cycloid, is investigated and compared with theoretical predictions. We find a good qualitative agreement between predictions and experimental data. As an extension of the present findings, we also investigate the shape and the dynamics of advancing drops on cycloids, placed in a viscous outer immiscible liquid. We find both similarities, in terms of kinematics, and specific differences in the shape of the advancing drop.*

Key Words: *Newtonian fluids, drop trajectory, liquid blob, inclined plane, cycloid*

1. INTRODUCTION

On an inclined surface, a solid object can either slide or roll down, depending on its shape. If the solid object is replaced by a liquid the shape can alter and a variety of motions are possible. The changes a drop of fluid undergoes while moving down a slope have been studied and various similarity solutions have been proposed [1]. However, analytical models of spreading cannot account for the influence of surface tension at the front, but one finds that the effects of surface tension on the spreading of the blob as a hole can be ignored [2].

The shape and motion of a droplet also depends on the properties of the surface. In the case of water, if the surface is hydrophilic, the droplet will slide along it, but if it is hydrophobic, a motion of rotation develops [3]. In addition, the dynamics of liquid droplets are affected by the outer medium's viscosity. This influence has been analyzed on drops rolling down a plane [4]. When the drops are larger than the capillary length, a sliding motion is preferred by the system, whilst when the drops are below the capillary length rotation is induced. The latter effect is also induced by a viscous outer fluid.

In this paper, we study and visualize the dynamics of water droplets on two hydrophobic surfaces, an inclined plane and a cycloid-shaped surface (see Figure 1). A theoretical model is adapted in order to describe the shape of the interface at early times for the movement of the drop on the inclined plane. We also investigate the shape and the dynamics of advancing drops on cycloids, placed in a viscous outer immiscible liquid.

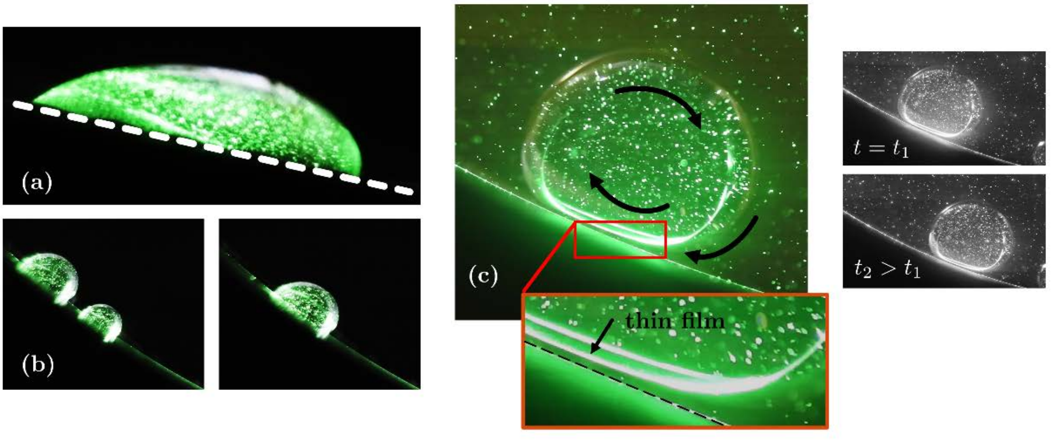

Fig. 1 a) Advancing blob of liquid on an inclined plane; b) Rolling droplets on a cycloid-shaped surface; c) Sliding drop of water surrounded by sunflower-seed oil on a cycloid-shaped surface. A thin film of oil always separates the drop and the solid surface.

2. EXPERIMENTAL DETAILS

The experimental set-up consists of two surfaces, an inclined plane and a cycloid-shaped surface, onto which we placed small drops of liquid, as depicted in Figure 2. We used 3D-printed surfaces, two brachistochrone curves (Fig. 2-b) and one planar surface having an inclined angle of 6°, which we coated with a layer of hydrophobic spray.

The working liquids are water and a mixture of water and glycerin 8 times more viscous than water (25% glycerin in water). The experiments were performed with air as the surrounding fluid, but the cycloids were also placed in a glass tank filled with sunflower-seed oil, 55 times more viscous than water. The material properties of the working fluids are presented in Table 1.

For the inclined plane, we used basic syringes to form drops of water and glycerin, which were recorded by a fast camera, shooting at 400 fps, as they moved along the surface. Regarding the cycloids, the drops consisted of water and they were formed using Hamilton syringes. For a better visualization we added reflective microspheres of 10 μm in diameter to the water drops and/or to the external medium.

This mixture was hit by a laser beam, which allowed us to perceive the drop as it advances on the surface.

The experiments were firstly performed without a surrounding liquid, for both the inclined plane and the cycloid-shaped surface. The cycloids are also immersed in a glass tank with sunflower-seed oil which was seeded with the same reflective microspheres in order to perceive the movement of both the inner and outer phase.

Table 1. Material properties of the working liquids

Fluid	η $(\boldsymbol{mPa\ s})$	σ $(\boldsymbol{N/m})$	ρ $(\boldsymbol{kg/m^3})$
Water	1	0.072	1000
Sunflower-seed oil	55	0.030	926
W-G 50%	8	0.020	1143

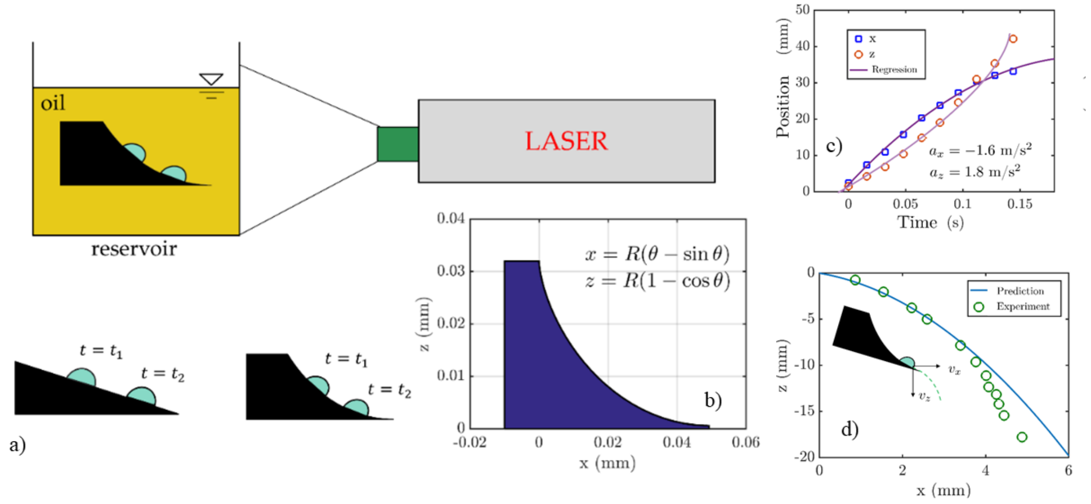

Fig. 2 a) Schematic representation of the experimental set-up; b) Depiction of the cycloid and its equations; c) Estimate of the components of the acceleration of a rolling droplet on a cycloid-shaped surface; d) Comparison between the predictions of equations (1) and experimental data in terms of the trajectory of a drop leaving the solid surface.

3. RESULTS

We first analyze the movement of a sliding drop on a cycloid-shaped surface and its trajectory onto and as it leaves the solid surface. Figure 2-c shows the position of the drop at several moments in time. We find an accelerated motion in the z direction and a decelerated motion in the x direction. When the drop leaves the solid surface, its trajectory is described by Newton's law, which reads as

$$a_x = \frac{dv_x}{dt} = \frac{kv_v^2}{m}, \quad a_z = \frac{dv_z}{dt} = \frac{kv_z|v_z|}{m} - g, k = C\frac{\rho A}{2}, \tag{1}$$

where a_x, a_z are the components of the acceleration vector, m is the mass of the droplet, ρ is the density of air, $A = \pi D^2/4$ with D as the drop diameter, and C as the drag coefficient. For a droplet with a diameter of 3 mm, leaving the solid surface (inclined at 34°) at a velocity of 0.13 m/s the drag coefficient is of order unity, the trajectory of the drop taking the form shown in Figure 2-d.

The experimental data agrees well with the predicted trajectory. However, we observe large differences as the drop advances. The cause of the observed differences comes from the rotation of the droplet which causes a loss in kinetic energy.

The advancing viscous blob of fluid (W-G 50 %) takes the shape depicted in Fig. 1-a. The shape onto which it is deposited is hydrophobic and the drop advances in a combined movement of rotation and translation. The shape can be approximated by a similarity solution that was originally proposed for the case of a spreading viscous blob of fluid on an inclined plane [1]. The solution is presented in a general implicit form. We assume a linear dependence which reads

$$h = f\left(x - h^2 t\frac{\rho g \sin\alpha}{\eta}\right) \rightarrow h = x - h^2 t\frac{\rho g \sin\alpha}{\eta}, \tag{2}$$

where h is the height of the drop, η is the viscosity and $\alpha = 6\,^{\circ}$ is the angle of the inclined plane. Figure 3 shows a comparison between the predictions of equation (2) at early times

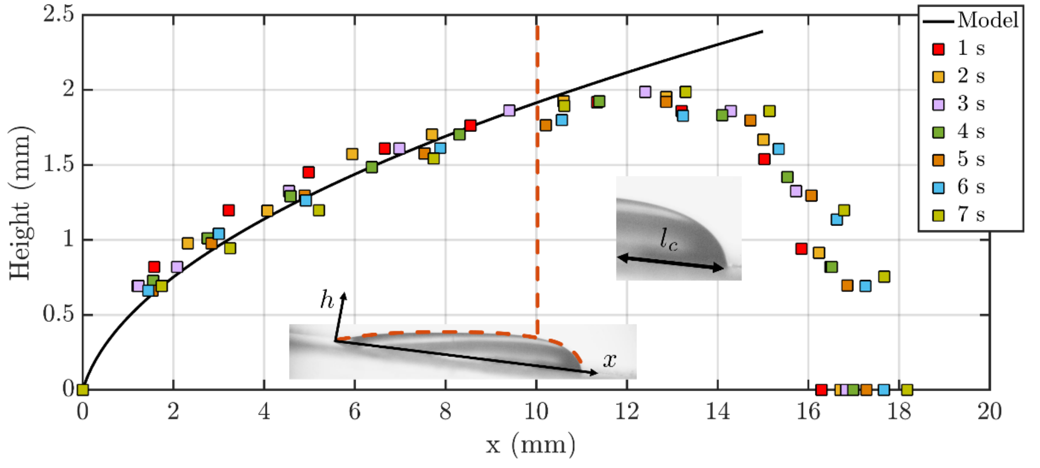

Fig. 3 Predictions of equation (2) (solid line) in terms of the shape of an advancing blob of liquid on an inclined plane. The experimental data shows the height of the liquid blob as a function of x at several values of time.

$(t = 0.015\ s)$ and experimental data in terms of the height of the blob at several values of time. We observe that even though the model is not designed to tackle such situations (hydrophobic surfaces), the rear end of the blob does not change considerably with time and can be approximated by the above-mentioned equation. The front of the drop is under the influence of surface tension, which basically spans over one capillary length ($l_c^2 = \sigma/\rho g$), the model not being capable of capturing this specific shape. The overall shape of the blob does not vary considerably with time. However, we observe some increase in time of the distance between the front and the rear end of the drop, which suggests a slow spreading of the blob as it advances on the solid surface.

When the external medium is a viscous immiscible liquid, the shape of the drop is dramatically altered (Figure 1-c and d). The main causes are drag forces acting at the interface and buoyancy, which acts in reducing the net gravitational pull. We observe that, as the drop advances, a thin lubricating film remains between the drop and the solid surface. In these cases, modeling the shape of advancing drops implies knowledge of the hydrodynamic pressures in the thin lubricating layer.

4. CONCLUSIONS

The overall shape of a sliding drop deposited on a hydrophobic inclined plane does not change dramatically as the drop advances. We find good qualitative agreement with previous models assuming a linear implicit relation of the one reported in [1,2]. When the external medium is a viscous immiscible liquid, the shape of the drop is dramatically altered due to the reduced force of gravity and the thin lubricating film entrained between the drop and the solid surface.

REFERENCES

[1] D. J. Achenson, *Elementary fluid dynamics*, Oxford University Press, pp. 245-248, 1990.

[2] H. E. Huppert, (1986). The intrusion of fluid mechanics into geology, *Journal of Fluid Mechanics*, Vol. **173**, 557-594

[3] S. P. Thampi & R. Govindarajan, Rolling motion in moving droplets, *Pramana*, Vol. **84**(3), 409-421, 2015.

[4]. M. R. Rahman & P. R. Waghmare, Influence of outer medium viscosity on the motion of rolling droplets down an incline, *Physical Review Fluids*, Vol. **3**(2), 023601, 2018.