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Drops sliding down an incline at large contact line velocity: what happens on the road towards rolling?

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Drops sliding down an incline exhibit fascinating shapes, that indirectly tell a lot on wetting dynamics. In a stimulating paper, Putehneveethil, Kumar & Hopfinger (*J. Fluid Mech.* 2013, vol. **XX** pp. XX-XXX) have renewed this subject by considering water and mercury drops sliding at high speed. The second case involves not only inertial effects but also large contact angles, which tends to bridge the gap remaining with the limit situation of drops rolling down a hydrophobic plane. The results ask puzzling questions on how to take into account several effects, neglected in previous studies: inertia at high speed contact line, large contact angles, nature of the dissipation at small scale, and respective weight of sliding and rolling degrees of freedom...

Keywords. drops, wetting, dewetting, interface singularities.

1. Introduction

Drops sliding down an incline offer a simple way to explore wetting dynamics, though the practice is not so simple, as one needs reasonably smooth and well controlled substrates. It is perhaps why, up to the 90's, pioneering works mainly addressed only the yield threshold and its connections with static hysteresis (Dussan, 1987). Later, a successful modeling of drop velocity just above threshold was built (Kim et al. 2002), while several works addressed surprising shape changes when the drop velocity was progressively increased (Podgorski et al. 1999, Le Grand, Daerr & Limat 2005). In particular, a remarkable instability of the drop rear was identified, in which a conical tail develops, similar to what is found at the tip of triangular films pulled out of a bath in coating applications (Blake & Ruschak, 1979). The laws governing the cone geometry, as well as the flow structure have been clarified by further experiments and modeling in the lubrication limit (see Winkels et al., 2011 for a review). Strongly confined between two inclined contact lines, on which the flow lines must end perpendicularly, the flow adopts a self similar structure that has been checked by particle image velocimetry (Snoeijer et al. 2005). This self-organisation significantly constraints the geometry adopted by the cone, whose typical angles are described by appropriate generalisations (Limat & Stone 2004, Snoeijer 2005, Snoeijer 2007) of the well known 'hydrodynamical model' of wetting proposed years ago by Voïnov. Even the typical curvature radius R regularizing the cone at small scale was identified and has been shown to be proportional to the microscopical cut-off length of the model l_m (below which liquid sliding is allowed), times an exponential function of the inverse of the capillary number (Peters et al. 2009): $R \simeq l_m \exp(\theta_S^3/[9Ca])$ in which θ_S is the limit static receding contact angle, and $Ca = \mu U/\gamma$, where μ is the

dynamic viscosity, U is the drop velocity, and γ is the surface tension. This exponential function reflects by inversion the logarithmic thickness profile found in the hydrodynamical model. This fair success was however to be qualified at best, as experiments with water revealed unexpectedly low values of l_m , sometimes even subatomic (Podgorski, Flesselles & Limat 2001, Winkels et al 2011). This fact was suspected to be linked to the effect of liquid inertia, neglected in these works.

Indeed the behaviour of drops reaching high Reynolds number, in the range of scales involved by drop shape selection or drop geometry measurements remained largely unknown. Another limitation was the low values of equilibrium contact angles explored, and also the very limited number of contact angles considered (45° for silicon oil, and 60° for water). Clearly, these limitations prevent one from understanding how things change when one moves from sliding drops in partial wetting conditions (Podgorski et al. 1999, Kim et al. 2002) to drops rolling on hydrophobic substrates (Mahadevan & Pomeau 1999, Richard & Quéré 1999), in which both velocities and contact angles are increased dramatically. This question is far from trivial as the divergence of viscous stresses invoked in hydrodynamical modeling of contact line (see for instance Snoeijer & Andreotti, 2013) disappears in situation of drop rolling (Mahadevan & Pomeau 1999), the transition scenario remaining to be written.

2. Overview

It is on this road, that Putehnveethil et al (2013) have investigated the behaviour of high speed drops of water and mercury. They first reconsider the calculation of drop velocity due to Kim et al. 2002 by introducing some boundary layer at the solid/liquid interface, in which the shear remains localized. This leads the authors to propose a new mobility law for sliding drops that works nicely for both water and mercury. They then adopt a strategy very similar to le Grand et al. (2005), by extracting advancing and receding angles from side views, as long as the drop shape does not become too three-dimensional, and comparing the results to available models of wetting dynamics. I have no doubts here that these data will raise passionate debates between the ‘fans’ of each description, and I here only focus on the main points that I have noticed. First, though the classical hydrodynamic description with a slip length relaxing the viscous stresses near contact line can again perfectly fit the data, the slip length required appears to be too much small and even unphysical. This is reminiscent of Winkel’s finding for water corners (2011). Also, inertia terms added by Cox, in a generalized version of this description appear to be negligible, which is not a surprise as the effective Reynolds number built on the local thickness vanishes asymptotically near contact line. Approaches in terms of activated jumps at the contact line give also reasonable fits and reasonable orders of magnitude, but the price to pay seems to admit a rather strong asymmetry between wetting and dewetting. At this point, the authors also consider the so-called interface creation model, which conception of surface tension raised controversies recently, and explain that a careful choice of parameters could group the data with those of Le Grand et al. while restoring a certain symmetry. In my opinion, in presence of wetting hysteresis, this principle of symmetry is questionable, and using an asymmetrical description of activated jumps at small scales, possibly combined at large scale with viscous dissipation as below, will remain for many people a simpler alternative.

Finally, the authors prove that even in their unusual situation, there is something reminiscent of the cone formation at the drop rear. This was far from being obvious, as preliminary attempts (Peters and Daerr, unpublished) suggested it disappeared for increasing contact angles. Modeling the observed structure remains however puzzling as

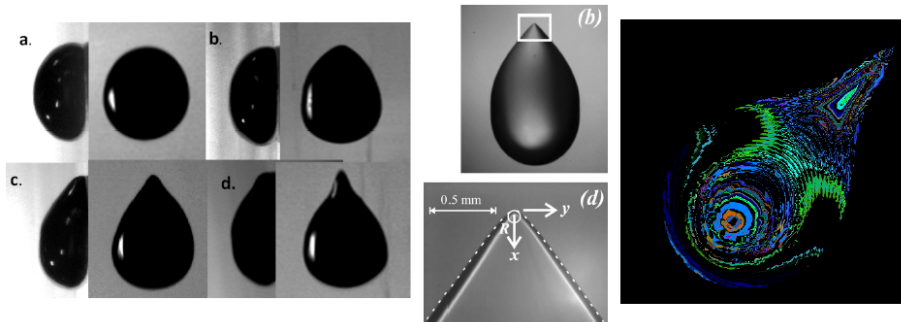


FIGURE 1. From left to right: mercury drops observed by Puthenveetil et al. (2013), a silicon oil drop observed by Peters et al. (2009) with the definition of the tip radius R , and a recent numerical simulation using a VOF method by Maglio & Legendre (2013).

the inertial terms (of order $\rho U^2/x$ where x is the distance to the cone tip) definitely do not scale as the capillary pressure gradient (γ/x^2) induced by surface tension γ , while this one was balanced at all scales by the viscous dissipation ($\mu U/x^2$) in the lubrication limit (Limat & Stone, 2004).

3. Future

From a pure hydrodynamical point of view, perhaps the most puzzling question seems to me as follows: a hydrodynamical model describes reasonably well the observed spatial self organisation (logarithmic profiles, correlations between angles, self-similar structure of the flow etc), but the price to pay (at least for water and now mercury) seems to be the acceptance of an unphysical subatomic cut-off. Here, though convenient for a clear presentation, it is not necessarily a good thing to oppose models against each other as incompatible approaches. As often suggested, we are perhaps faced with a situation in which two sources of dissipations are mixed, each one being relevant at a different scale. This can be illustrated by what is sometimes called the ‘combined model’ (Petrov & Petrov 1992), whose simpler form in the small contact angle limit can be summarized as follows:

$$\theta^3 = \theta_m^3 \pm 9Ca \log(\xi/l_m), \quad \theta_m^2 = \theta_S^2 \pm 2\alpha Ca, \quad (3.1)$$

in which θ is the slope of the interface at a distance ξ from the contact line, the logarithmic dependence accounting for viscous dissipation (‘bending’ of the interface), while the static equilibrium angle θ_S is replaced by a microscopic effective value θ_m taking into account some extra forces acting at very small scale. Here, α is some microscopic sliding constant, that could be related to molecular interactions with thermal activation mechanisms (see again for instance Petrov & Petrov 1992), or to the a priori unknown effect of surface defects on the pinning of the contact line (Rolley & Guthman, 2007), or to any other source of dissipation at microscopic scale. In the limit $\theta_S \ll \alpha \ll \theta_S^2/(2Ca)$, one can easily reorganize (3.1) to obtain an ‘à la Voïnov’ description that would read $\theta^3 = \theta_S^3 \pm 9Ca \log(\xi/l'_m)$, where l'_m is an effective cut off given now by the relationship $l'_m = l_m \exp(-\alpha/[3\theta_S])$, that can be indeed much smaller than l_m . A trivial extension to the 3D description of the corner tip in Peters et al. (2009) is possible and would indeed lead to the same microscopic apparent scale in the formula ruling the contact line curvature R at the cone tip. Again, though the hydrodynamic description of the spatial interface structure remains perfectly correct, its extrapolation at small scale seems to lead to an unphysically too small cut-off, but this is only reflecting the existence of a

very large dissipation occurring at microscopic scales, of different physical origin than the classical internal bulk viscous dissipation of the liquid.

With this respect, the key obstacle for further progress could be our imperfect knowledge of microscopic mechanisms dissipating at small scales. In particular, one would need very well controlled substrates having well defined interaction rules with the contact line (traps distribution, pinning/depinning known rules, etc). Out of reach in the 80's or 90's, despite several attempts, such substrates can be devised now by combining the present expertise of surface chemistry, with nanotechnology facilities in clean rooms. An obstacle is however that it seems easier to fabricate perfectly hydrophobic materials than surfaces of controlled wettability. In addition, it will always be difficult to vary at will the values assumed by the reference static contact angle. Here, a powerful assistance could come from numerical simulations of contact lines (see among others Koh et al. 2009), that have made huge progress by adapting interface codes (VOF and level set methods) to contact line dynamics (see for instance Maglio & Legendre 2013), allowing even the inclusion of inertia effects as well as finite slopes of the interface. Complex situations could then be explored, even in parameter regions which are not accessible to analytical models or experiments. With these two inputs (controlled substrates and highly efficient numerical codes), our knowledge of the behaviour of drops (and thus of contact lines), even at high velocity and high contact angle could be completely renewed.

To conclude, I also mention here an unsolved question, considered recently by several authors (see among others Thampi, Adhikari & Govindarajan 2013): when contact angles are increased, how does a drop will choose between rolling and sliding, and is it even possible to have mixed states combining these two degrees of freedom? To my opinion, this can also strongly affect the interpretation the data obtained for wetting dynamics with drops flowing down an incline, which still remain an open-ended question.

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