

Drop Impact Dynamics

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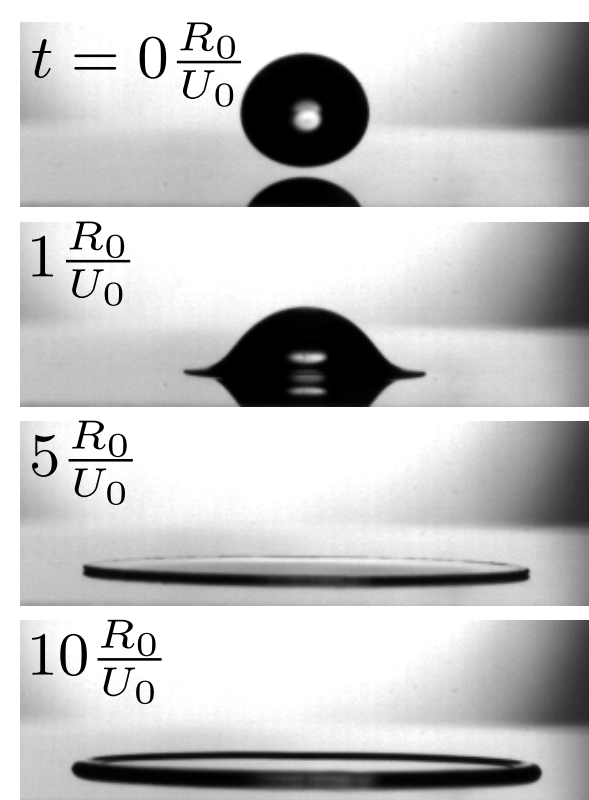
Overview

We examine the impact of a liquid drop onto a smooth and dry solid surface in the regime of negligible atmospheric effects. This study is motivated by recent experiments showing that, at sufficiently low ambient air pressures, drop impact at a speed of several m/s does not produce a splash [1,2]. Instead liquid is ejected from the drop in a thin sheet that expands outwards along the solid surface without lifting upwards off the surface. This non-splashing ejection dynamics is inaccessible in previous atmospheric-air-pressure experiments. Here we simulate the impact of a 18 cSt liquid drop at 1/10th of ambient pressure. As in the experiments, no splash is formed. We find that liquid is ejected outwards from the contact region in an axisymmetric stagnation-point flow. Viscous effects at the solid surface modify this flow and create a boundary layer which is spatially uniform and thickens over time. The sheet evolution slows as the boundary layer thickens, eventually saturating at a constant value, one consistent with the boundary layer thickness over the impact time-scale.

[1] L. Xu, W. W. Zhang & S. R. Nagel, Phys. Rev. Lett. **94** 184505 (2005).

[2] C. Stevens, N. Keim, W. W. Zhang & S. R. Nagel, APS-DFD.FC003S (2007).

Experimental Results



A drop of 10 cSt oil impacts a dry substrate at 5.4 m/s. The air pressure is 0.43 atm. No splash results [2].

Formulation

Solve Navier-Stokes equation in two fluids, equivalent to silicon oil and air. \mathbf{u} is the velocity field, p the pressure field, and ρ the density. δ_S is a delta function on the interface, and κ and $\hat{\mathbf{n}}$ are the curvature and normal vector on the interface.

$$\nabla \cdot \mathbf{u} = 0; \quad \frac{D\mathbf{u}}{Dt} = -\frac{1}{\rho} \nabla p + \nu \nabla^2 \mathbf{u} + \frac{1}{\rho} \sigma \kappa \delta_S \hat{\mathbf{n}}$$

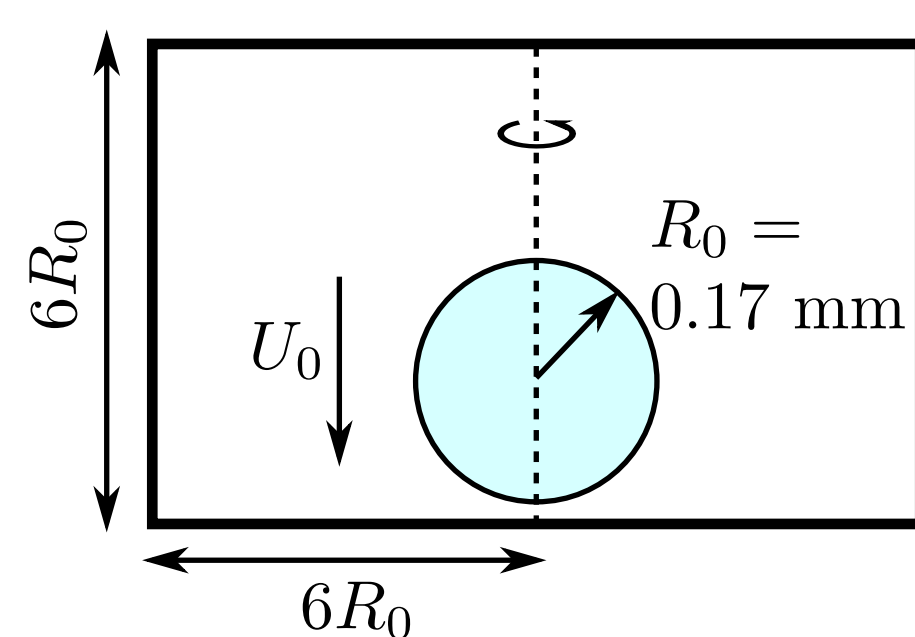
Viscous dissipation

Surface tension

$$Re = \frac{\text{inertial}}{\text{viscous}} = \frac{UL}{\nu} \quad We = \frac{\text{inertial}}{\text{surf. tension}} = \frac{\rho U^2 L}{\sigma}$$

Simulation Code

Impose axisymmetry.



No-slip and non-wetting boundary conditions on bottom surface \Rightarrow Resembles hydrophobic solid surface

We use two similar codes. Both use

- First-order differencing schemes
- Multigrid pressure solver

Interface is tracked differently:

- 1 Explicit tracking with Lagrangian markers
- 2 Reconstruct interface from volume fractions

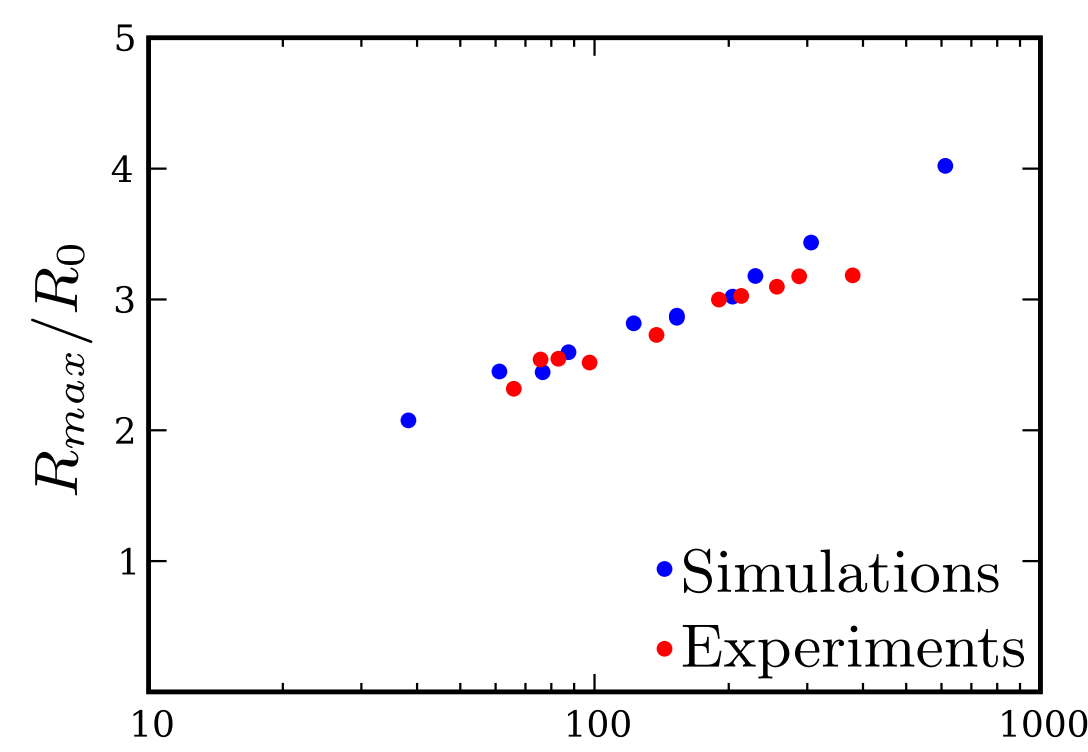
The results from both methods agree.

Lafaurie *et al.*, J. Comp. Phys. **113**, 134 (1994)

Popinet and Zaleski, Int. J. Numer. Meth. Fluids **30**, 775 (1999)

Validation

Clanet conducted experiments on drop impact onto super-hydrophobic surfaces. Our simulations show the same maximal spread as observed experimentally.



Clanet *et al.*, JFM **517**, 199 (2004)

Overall Deformation

A simulation of a drop, with $\nu = 18$ cSt and $\sigma = 21$ dynes/cm, impacting a solid surface at 2 m/s. The gas density is equivalent to 0.1 atm. The computational domain was discretized into 256×256 cells.



$t = 0$ $\frac{R_0}{U_0}$

High pressure slows drop and expels a thin sheet.

$1.1 \frac{R_0}{U_0}$

The drop expands into a sheet of constant thickness h .

$4.9 \frac{R_0}{U_0}$

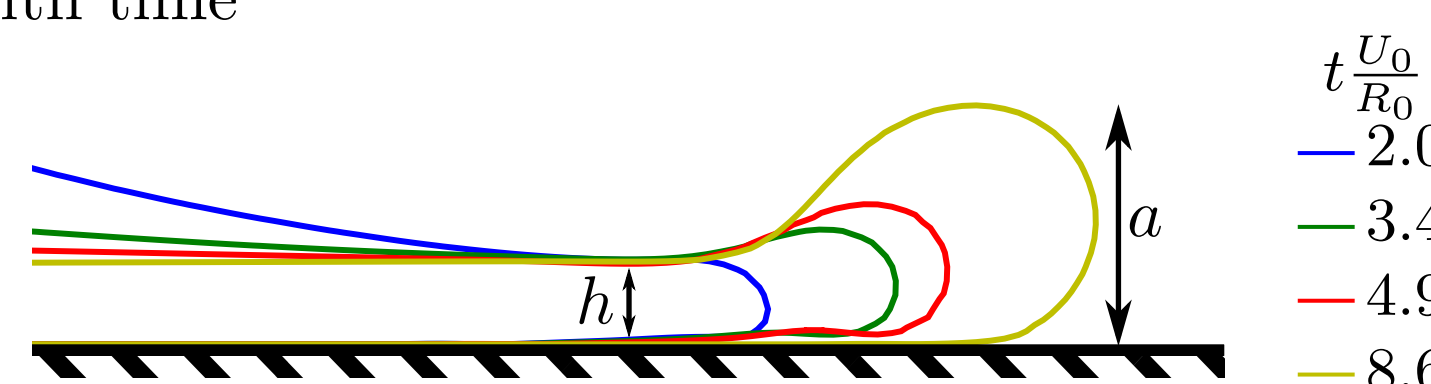
Eventually, the rim retracts. No splash forms.

$12.6 \frac{R_0}{U_0}$

$12.6 \frac{R_0}{U_0}$

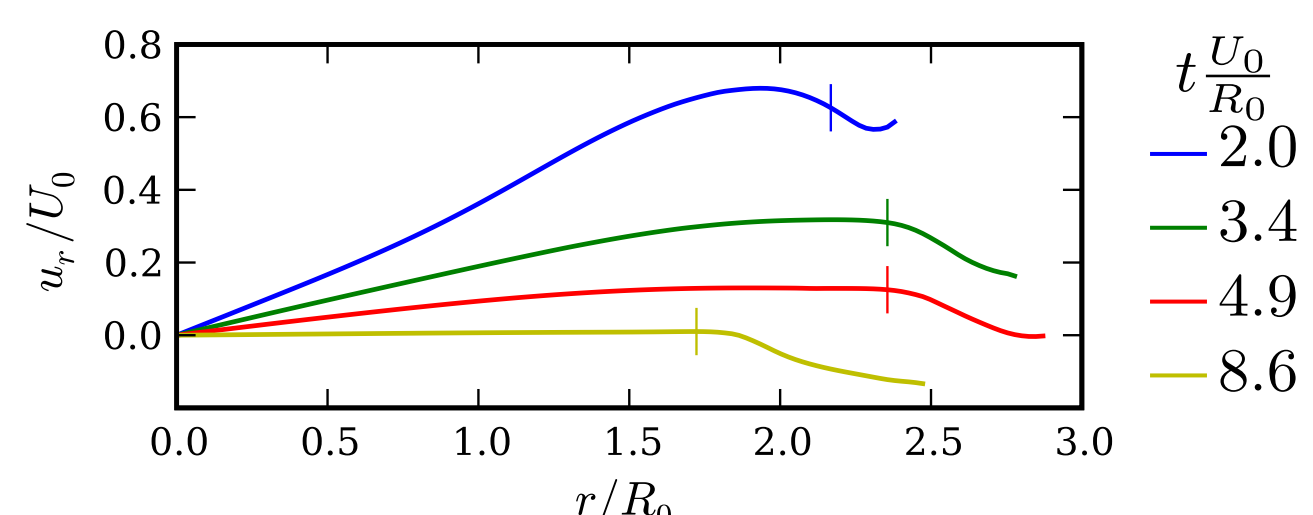
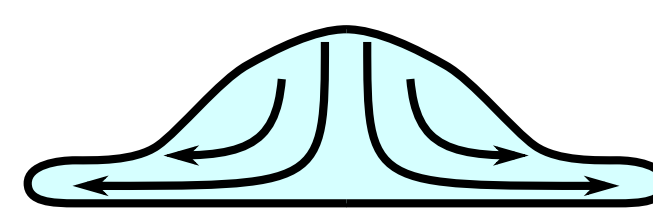
Rim Dynamics

Interface shapes near the edge of the sheet at different times after impact. The drop reaches its maximal radial extent at $t = 4.9 \frac{R_0}{U_0}$. The profiles have been shifted so that the locations of the minimum sheet thickness coincide. At early times, the sheet decreases in thickness as it approaches the edge (blue). At later times, the sheet has a uniform thickness everywhere except at the edge, where a significant rim has formed (yellow). Strikingly, the minimum thickness of the sheet h has essentially the same value as time goes on. In contrast, the rim height a grows with time

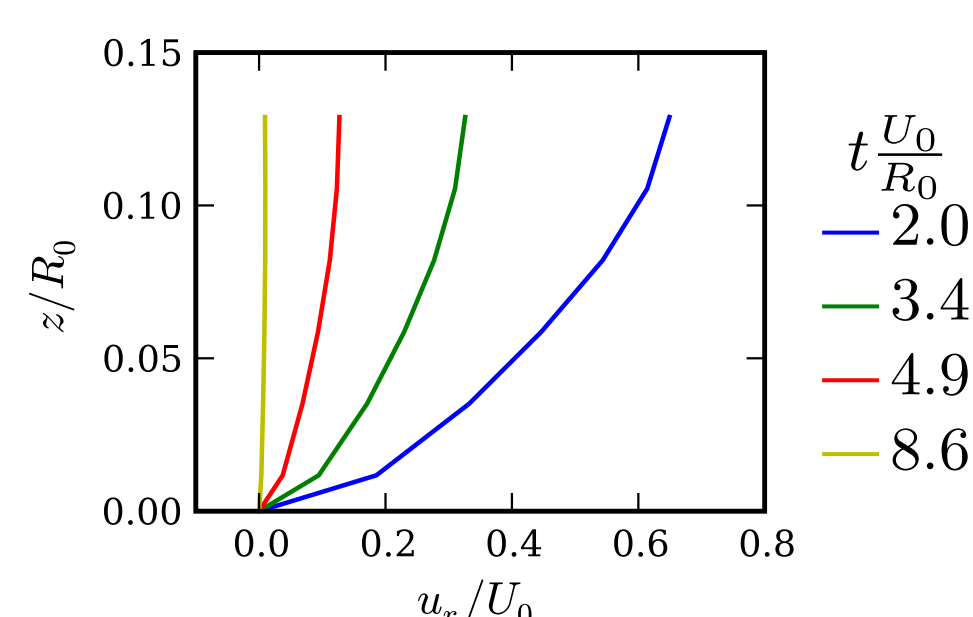


Radial Ejection Flow

The flow inside the drop is initially a uniform translation. Upon impact, liquid is ejected outwards from the contact region.



Within the ejected sheet, the radial velocity increases with radius. The vertical ticks mark the beginning of the rim. (Velocities at $z = 0.1R_0$)



The radial velocity at the location of minimum thickness shows significant variation with depth. The radial outflow is not a plug flow.

Estimate for Sheet Thickness

To estimate the minimum sheet thickness, we note that δ , the boundary layer height in a fluid element which has been in contact with the substrate for a time interval τ , is

$$\delta \sim \sqrt{\nu \tau}$$

where τ in general depends on r , the radial position of the fluid element. However, if the leading-order flow is a linear straining flow

$$\mathbf{u} = \frac{r}{2t} \mathbf{e}_r - \frac{z}{t} \mathbf{e}_z,$$

the contact time $\tau(r)$ simplifies. Roughly, $\tau \approx r/u_r \approx \frac{1}{2}t$. As a result, the viscous boundary layer generated by impact is

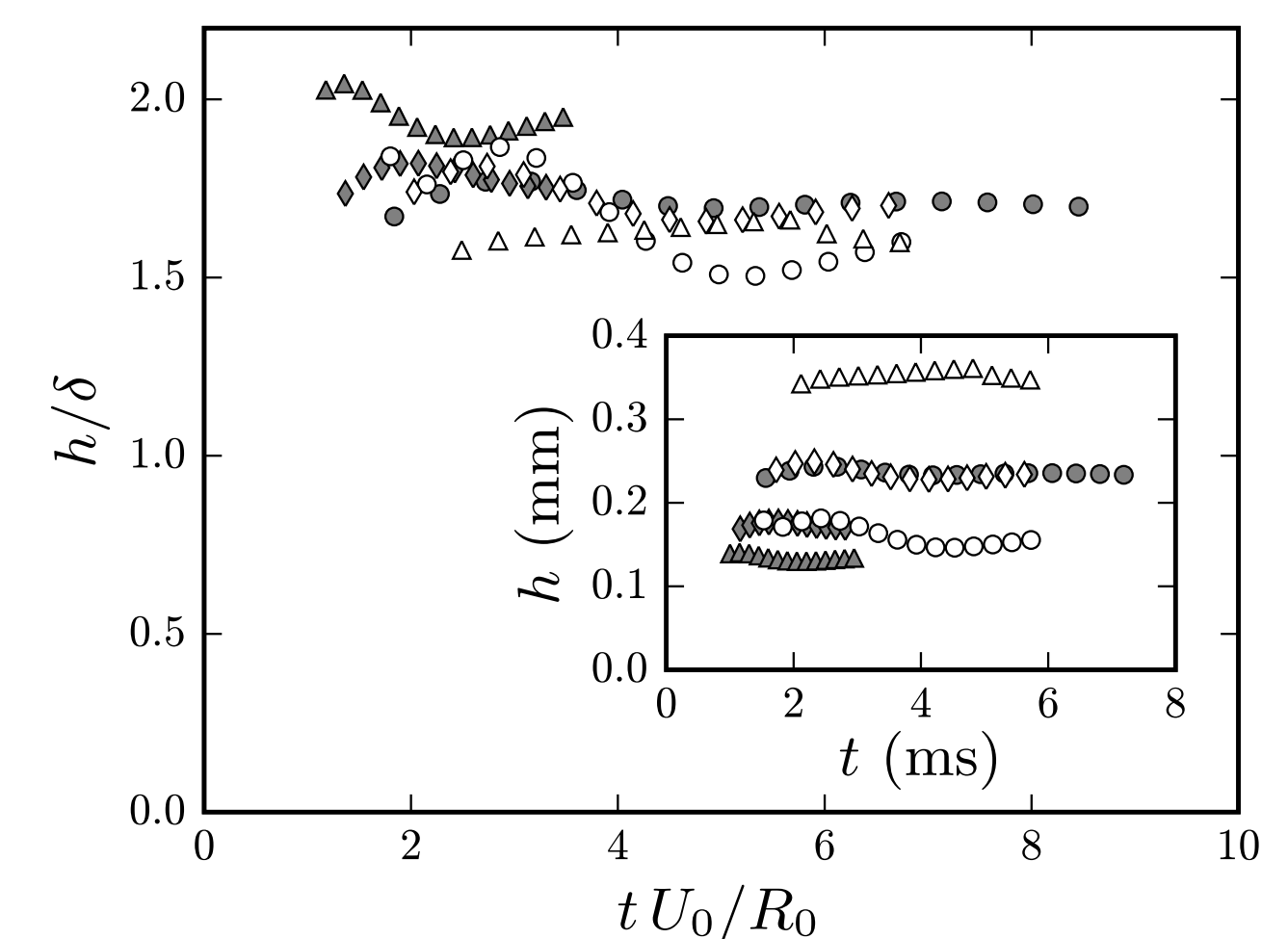
$$\delta \sim \sqrt{\nu t}.$$

This is a spatially-uniform layer whose thickness increases with time. As the boundary layer thickness grows to become comparable with the sheet thickness, the ejection flow slows and the sheet thickness saturates. Assuming that this saturation occurs on the time scale of impact, R_0/U_0 , yields the estimate

$$h \approx \delta \approx \sqrt{\nu R_0} = R_0 Re^{-1/2}$$

for the minimum film thickness.

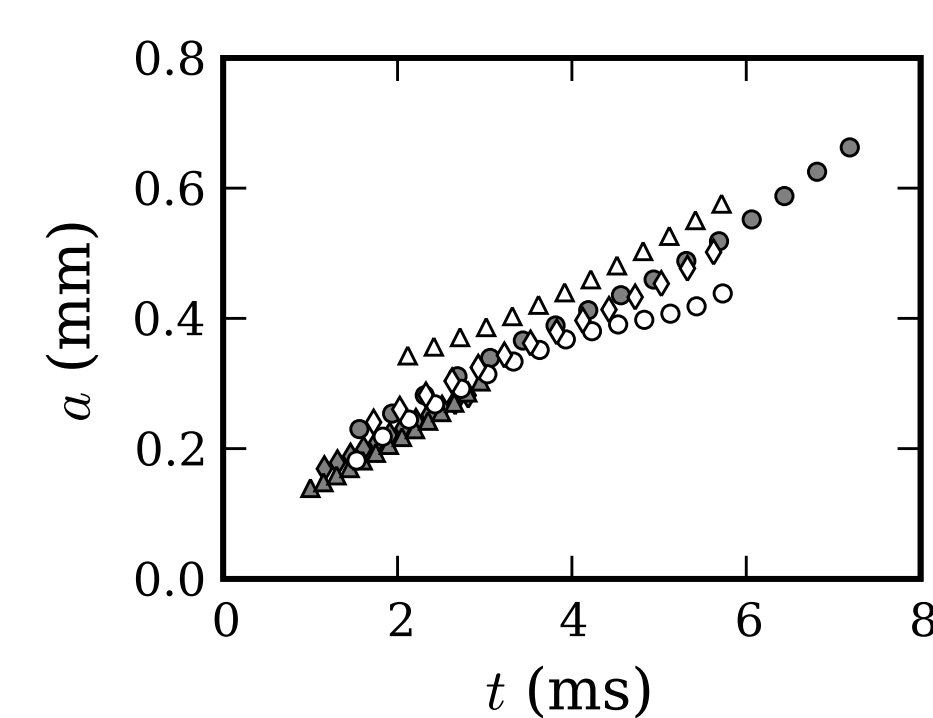
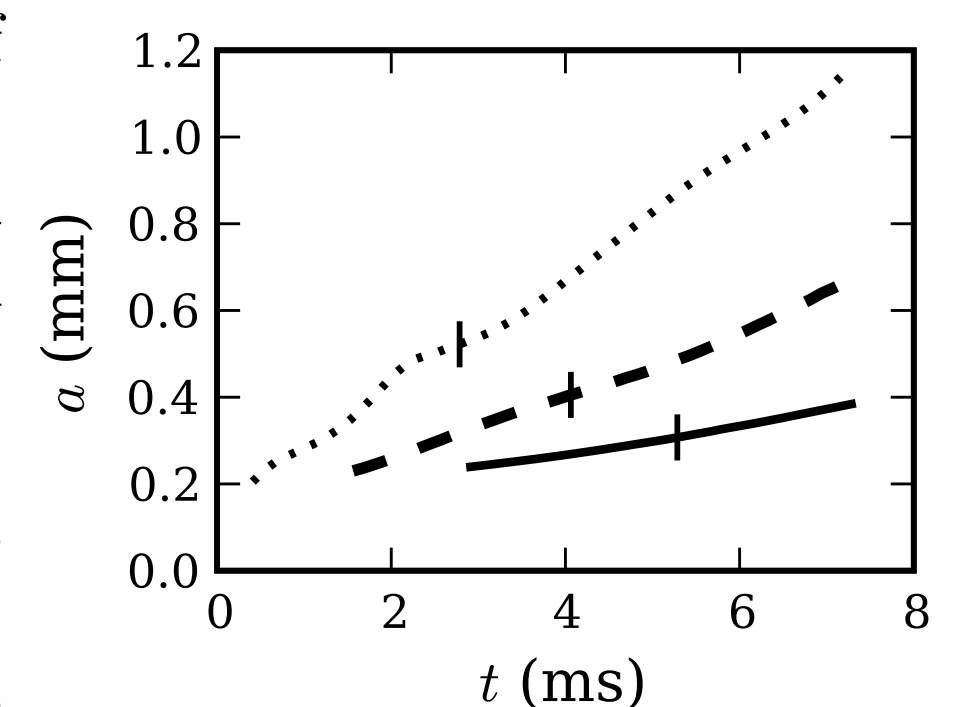
We have checked the proposed scaling for h by simulating impact at different speeds (2–8 m/s), with liquids of different viscosities (9–45 cSt), and for different values of surface tension (5.25–84 dynes/cm). We find that the value of h does not change significantly with the surface tension (data not shown) but does change with the impact speed and the liquid viscosity (inset). Rescaling the different $h(t)$ curves via the proposed boundary-layer estimate collapses results from all the simulations.



$U_0 = 2$ (●), 4 (◆), and 6 m/s (▲) and $\nu = 20$ cP.
 $U_0 = 2$ m/s and $\nu = 10$ (○), 20 (◇), and 50 cP (△).

Growth of the Rim

The growth of the rim height a for three different values of surface tension: 5.25 (solid), 21 (dashes), and 84 dynes/cm (dots). The vertical lines mark times when the drop has attained its maximal radial extent. Surprisingly the rim growth has the same time dependence regardless of whether the drop is expanding outwards or retracting.



The rim growth data for liquids of the same surface tension but different viscosities (open symbols) or different impact speeds (closed symbols; same legend as above). In contrast to h , the rim growth over time varies little with the liquid viscosity or the impact speed.

Conclusions

Thickness of liquid sheet set by boundary layer.
 \Rightarrow Viscous effects crucial in these impacts.

Rim growth dependent on surface tension, independent of radial motion.