The Role of Viscosity Ratio on the Formation of a Residual Film after Drop Impact Onto Thin Liquid Films

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Abstract
The impact of a drop onto a liquid film is relevant for many natural phenomena and industrial applications such as spray painting, inkjet printing, agricultural sprays, or spray cooling. In particular, the height of liquid remaining on the substrate after impact is of special interest for painting and coating but also for applications involving heat transfer from the wall. While much progress has been made in explaining the hydrodynamics of drop impact onto a liquid film of the same liquids, the physics of drop impact onto a wall film with different material properties is still not well understood. In this study drop impact onto a very thin liquid film of another liquid is investigated. The thickness of the film remaining on a substrate after drop impact is measured using a a chromatic-confocal line sensor. It is interesting that the residual film thickness does not depend on the initial thickness of the wall film, but strongly depends on its viscosity. A scaling parameter is proposed for the residual film thickness, based on the viscosity ratio of drop and wall film $\chi = \rho_f \sqrt{\nu_f}/\rho_d \sqrt{\nu_d}$. The dependence of the dimensionless residual film thickness on χ is determined in the experiments for a range of impact parameters and combinations of the liquid viscosity.

Keywords
drop impact; residual film; film dynamics; thin films;

Introduction
Comprehensive reviews [1–5] describe the hydrodynamics of the impact of a drop onto solid substrates as well as thin liquids films and suggest models for their description. The drop impact is influenced by both the liquid properties such as surface tension σ, viscosity ν, density ρ, and the impact parameters which are the drop diameter D the liquid film height before impact H_f and the impact velocity of the drop U. Those quantities can be summarized into the following dimensionless groups:

$$Re = \frac{UD}{\nu}, \quad We = \frac{\rho U^2 D}{\sigma}, \quad \delta = \frac{H_f}{D}, \quad \kappa = \frac{\nu_f}{\nu_d}. \tag{1}$$

The subscripts d and f denote that the property either corresponds to the drop or the film liquid. In [6] an analytical solution of the Navier-Stokes equations for a thin spreading viscous film is obtained. Derived from this solution the authors suggest that the spreading lamella resulting from a drop impact onto a solid substrate reaches an asymptotic value of thickness at the characteristic instant when the growing boundary layer intersects with the upper surface of the impacting drop. This residual film thickness can be expressed by $h_{\mathrm{res}} = 0.79 D \mathrm{Re}^{-2/5}$. Furthermore [7] found that the residual film thickness resulting from the impact of a drop onto a liquid film of finite thickness can be described as:

$$\tilde{h}_{\mathrm{res}} \equiv \frac{h_{\mathrm{res}}}{D} = A(\delta)\mathrm{Re}^{-2/5}, \tag{2}$$

where A is a dimensionless constant depending on the initial film thickness scaled by the initial drop diameter, δ.

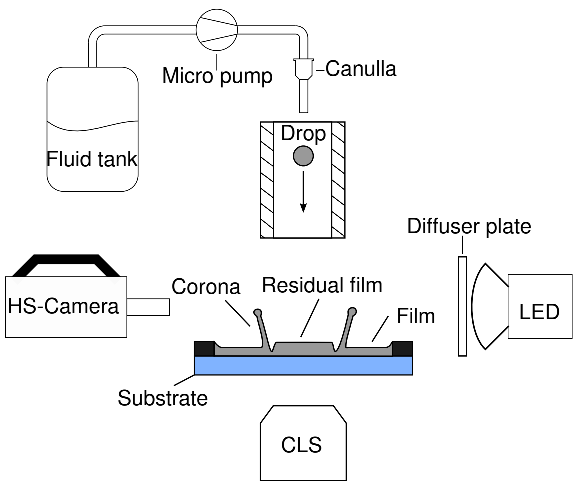


Figure 1. Schematic representation of the experimental setup.

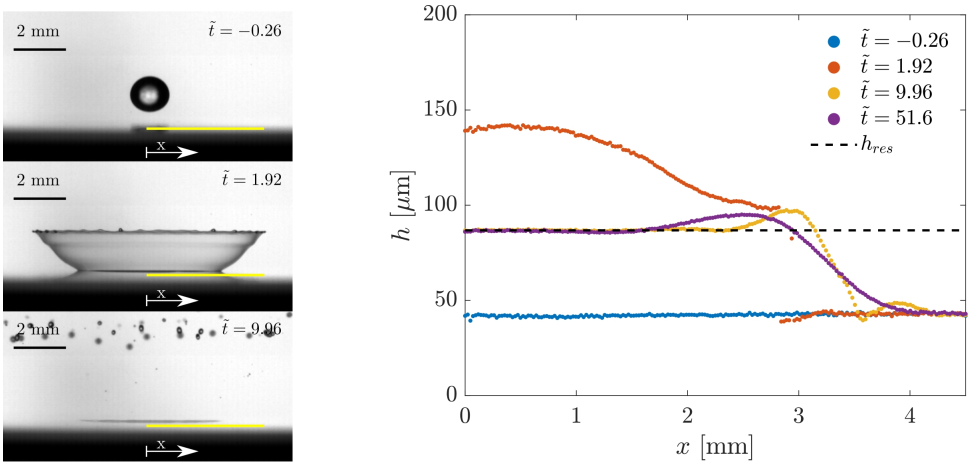
While much progress has been made in explaining the hydrodynamics of drop impact onto a liquid film of the same liquid, the physics of drop impact onto a wall film with different material properties is still not well understood. In this study the two-component as well as one-component drop impact is investigated. The thickness of the film remaining on a substrate after a drop impact is measured for a broad range of impact parameters.

Experimental setup

The experimental setup is represented schematically in Fig. 1. The setup can be divided in the main groups: drop generation system, optical system, film thickness measurement system, as well as the impact substrate. A drop is generated by pumping liquid through the micro-pump into a needle, at the tip of which a drop is formed. As soon as this drop reaches a critical mass, it drips off and falls, accelerated by gravity. The impact velocity can be varied by adjusting the height of the needle above the substrate. A high-speed CMOS camera (Photron SA-X2) is used in combination with a high performance LED (Veritas Constellation 120E) in the optical system to capture the high dynamics of drop impact. A diffusor plate is placed in front of the LED to guarantee uniform illumination. The camera operates with frame-rates in a range from 20 to 50 kHz. The impact substrate consists of an optically transparent sapphire plate with a diameter of 50 mm and a height of 0.5 mm. A liquid film is applied on top of the sapphire plate and confined either by pinning on the sapphire edge or by PVC foil.
The height of the film on the substrate is determined using a chromatic-confocal line sensor (Precitec Chrocodile, short: CLS) in combination with a CLS 0.5 LL probe. This system can determine the film thickness on a line of 4.5 mm length with a rate of 2 kHz. It allows to precisely control the film thickness before the drop impact while also providing spatial and time resolved film thickness information during and after drop impact. The CLS and the high-speed camera are synchronized by use of a NI-DAQ system in combination with an in-house LabView code. Since, in this study miscible liquids with the same refractive index of n = 1.402 are investigated investigated, no detectable interface forms between drop and film, thus the

Liquid	ν [m^2/s]	σ [N/m]	ϱ [kg/m^3]
S5	5×10^{-6}	17.72×10^{-3}	920
S10	10×10^{-6}	18.29×10^{-3}	930
S20	20×10^{-6}	18.2×10^{-3}	945

Table 1. Material properties of the liquids used in the experiments: kinematic viscosity ν, surface tension σ and density ϱ. The abbreviation "Sxx" denotes silicone oils with different respective viscosity.



(a) (b)

Figure 2. S10 drop impacting on a S10 film. (a) Consecutive images from the experiment of a S10 drop impacting on a S10 film. The yellow line indicates the location of the film thickness measurements shown in (b) whereat x represents the longitudinal coordinate of the CLS; (b) Film thickness h measured with the CLS at different dimensionless times before (blue markers) and after (orange violet and yellow markers) the impact. Impact Parameters: U=3.95 ms, D=1.55 mm, H_f =42 μ m.

measured film thickness after impact is the total thickness of both, drop and film liquid combined. The properties of the liquids used in this study are summarized in Table 1.

Results and Discussion

In Figure 2(a) recordings of the impact of a a drop of silicone oil (S10) drop onto a silicone oil film (S10) in three consecutive instants before, during, and after the impact are shown. The time can is given in dimensionless form $\tilde{t} = tU/D$. It can be observed that the drop impact results in the formation of a crown ($\tilde{t}$ = 1.92) which subsequently fragments into secondary droplets ($\tilde{t} = 9.96$). The yellow line indicates the position of the measuring line of the CLS whereat the x represents the longitudinal coordinate. The film thickness h above the substrate as a function of the longitudinal coordinate x is shown in Figure 2(b) for different times. The instants shown in this graph correspond to the high speed recordings shown in Figure 2(a). The blue graph shows the undisturbed film previous to the drop impact. The uniform film thickness of H=42μm illustrates the precisely controlled initial film thickness. At $\tilde{t} = 1.92$ a crown has formed as a result of the drop impact. The base of the crown can be recognized at the discontinuity of the orange graph at $x \approx 3$ mm. For larger times $\tilde{t} = 9.96$ the lamella height reaches an asymptotic value and forms a disk of uniform height with a rim at its edge. Even for very large times $\tilde{t} = 51.6$ the thickness of the film remaining on the substrate does not change and thus is referred to as h_{res}.

In Figure 3 the relation of the residual film height scaled by $D\text{Re}^{-2/5}$ to the initial film thickness is shown. With this scaling the ordinate represents the factor A from Equiation 2. The corresponding impact parameters are listed in Table2. In Case 1 to 7 the drop as well as the film liquid is the same. The viscosity, drop diameter and impact velocity are varied. It becomes apparent that none of these parameters influence the scaling thus all values collapse on a horizontal line at $A \approx 0.72$. It is worth to be mentioned that this value is close to the theoretical predicions of $A = 0.79$ for drop impact onto dry substrates [6]. Furthermore it can be seen, that the initial film thickness has no effect on the scaling, neither for the one-component impact of Case 1 to 7, nor the two component impact presented in Case 8 and 9. Only when the liquid of the film and drop differ as in Case 8 and 9 where the viscosity ratio of film to drop viscosity is $\kappa = 2$ and $\kappa = 0.5$ the scaling changes.

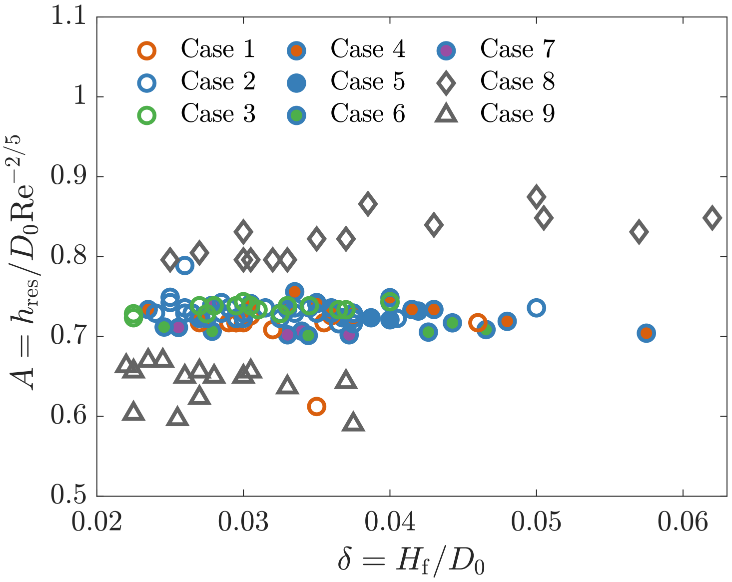


Figure 3. Film height h_{res} remaining on the substrate for varying viscosity ν, impact velocity, U drop diameter, D and initial film height H_f.

Case	Film	Drop	D [mm]	U [m/s]
1	S5	S5	2	3.2
2	S10	S10	2	3.2
3	S20	S20	2	3.2
4	S10	S10	2	4.23
5	S10	S10	1.55	3.96
6	S10	S10	3	2.45
7	S10	S10	3	3.45
8	S10	S5	2	3.2
9	S5	S10	2	3.2

Table 2. Variations of the initial drop diameter D, impact velocity U and drop and film liquids in the experimental campaign.

Residual film thickness

The residual film thickness does not depend on the initial wall film thickness. This is a predictable result since wall film thickness in our experiments is much smaller than the initial drop diameter. Therefore the influence of the wall film on the dynamic of the drop spreading at large times is negligibly small. On the other hand, the viscosity of the wall film has a significant influence on the value of the residual film thickness. This is a rather surprising result. It can be explained only by the assumption that the initial stage of drop collision and spreading has a major effect on the parameters of spreading. At this initial stage the thickness of the viscous boundary layer in the wall film is much smaller than the wall film thickness.

The velocity field in the impacting drop at short times after collision can be approximated by an inviscid flow past a circular disc [8] of the contact radius a. Consider a cylindrical coordinate system $\{r, \theta, z\}$, with the corresponding base unit vectors $\{\boldsymbol{e_r}, \boldsymbol{e_\theta}, \boldsymbol{e_z}\}$. The velocity potential for this flow relative to the wall is obtained from the well-known solution [9] can be written in the form

$$\phi = \frac{2aU}{\pi} \cos\eta \left[\sinh\xi \cot^{-1}(\sinh\xi) - 1\right] - Uz, \qquad (3)$$

where ξ, η are dimensionless elliptic coordinates defined through

$$\xi + i\eta = \sinh^{-1}\left(\frac{z + ir}{a}\right). \qquad (4)$$

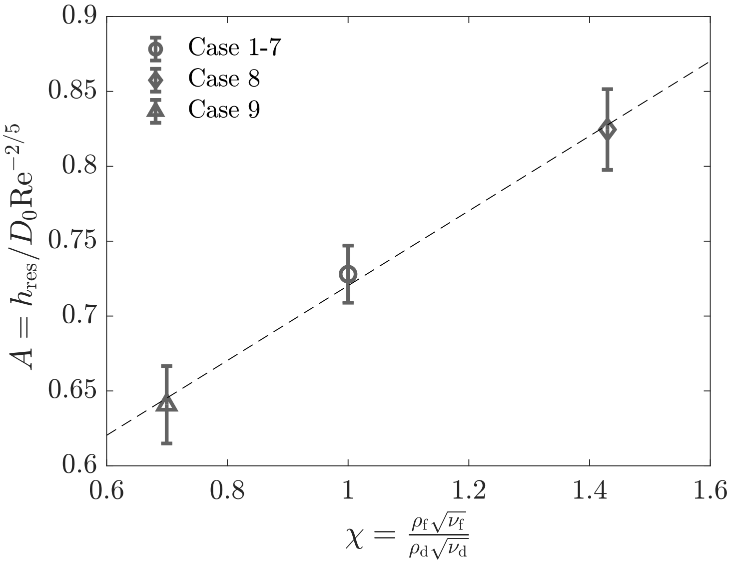


Figure 4. Influence of χ on the scaling of residual film thickness. Case 1-7 represent one component impact while in Case 8 and 9 film and drop liquid are different.

The corresponding radial velocity component $u_r = \partial\phi/\partial r$ near the impact axis $r/a \ll 1$ is obtained in the form

$$u_r = U_0 \left[\frac{2a^3 r}{\pi\left(a^2+z^2\right)^2} + \mathcal{O}\left(\frac{r^3}{a^3}\right) \right] \tag{5}$$

where the radius of the contact spot is expressed as

$$a \approx R_0 \sqrt{\frac{2tU_0}{R_0}}. \tag{6}$$

Correspondingly, the radial velocity of the interface $z = 0$ between the drop and the wall film is assumed in the form

$$u_{r\rm int} = \alpha u_r \quad \text{at} \quad z = 0. \tag{7}$$

Immediately after impact two viscous boundary layers appear in the drop and in the wall film, whose thicknesses are $h_{\nu d} \sim \sqrt{\mu_d t/\rho_d}$ and $h_{\nu f} \sim \sqrt{\mu_f t/\rho_f}$, respectively, where ρ_d and ρ_f are the liquid densities. Therefore, the stresses in the liquid drop and film regions at their interface can be estimated in the form

$$\tau_d \sim \mu_d \frac{u_r(1-\alpha)}{h_{\nu d}}, \quad \tau_f \sim \mu_f \frac{u_r \alpha}{h_{\nu f}} \quad \text{at} \quad z = 0. \tag{8}$$

Finally, the condition of the continuity of the shear stress at the interface, $\tau_d = \tau_f$, yields

$$\alpha = \frac{1}{1 + \frac{\rho_f\sqrt{\nu_f}}{\rho_d\sqrt{\nu_d}}}. \tag{9}$$

Therefore, one term which determines the initial stage of the drop spreading on a very thin liquid film is

$$\chi = \frac{\rho_f\sqrt{\nu_f}}{\rho_d\sqrt{\nu_d}}, \tag{10}$$

which potentially can influence also the characteristic velocity of the drop spreading also at large times.

Figure 4 shows the dependence of the scaling factor A on the parameter χ for three different cases where in Case8 the film is more viscous than the drop, in Case 9 the drop is more viscous than the film and Case1-7 summarizes the cases where drop and film liquid are the same. It becomes apparent that A increases with increasing χ. The effect of χ on A can be expressed by

$$A = 0.47 + 0.24\chi \tag{11}$$

which is obtained from a linear fit as represented by the dashed line in Figure 4 .

Conclusions

In this study the thickness of the liquid film remaining on a wetted substrate after drop impact is measured for a broad range of parameters with varying viscosity, drop diameter, impact velocity and initial film height. The experiments show that the scaling in equation (2) is almost not influenced by the impact velocity, drop diameter, drop viscosity or initial film height for the investigated parameter range.

For very thin initial wall films, considered in this study, the parameter A in equation (2) depends only on the parameter χ defined in equation (10) depending mainly on the viscosity ratio, but not influenced by the film thickness. This is an interesting result which indicates that the rate of the drop spreading is determined by the very initial stage of drop impact when the thickness of the viscous boundary layer in the film is smaller than the film thickness.

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