

Droplet Lamella Lift Dynamics and Surface Wettability

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Abstract

Droplet impact on dry, smooth surfaces remains an issue for a variety of important applications such as fuel injection, spray cooling, metallurgy, pesticides and coatings. The mechanisms that initiate splashing are highly complex and differ from those on rough or pre-wetted surfaces. In this work, droplet wettability on a smooth, dry surface is examined to quantitatively evaluate its influence on splashing. Water droplets of approximately 3.5 mm diameter and velocities ranging from 2.2-3.5 m/s were dropped onto a smooth, Plexiglas surface. Hydrophobic and hydrophilic coatings were applied to the surface in order to change wetting characteristics. It was found that the hydrophilic surface required higher gas densities for splashing to occur and vice versa for the hydrophobic surface. Focusing on the spreading lamella, a momentum balance was derived with consideration of the chemical affinity or adhesive force of the liquid to the impact surface. The lamella lift from the surface was assumed to be induced by the displaced surrounding gas during spreading. This provides an explanation for the vertical velocity component of corona splashing on dry, smooth surfaces. Consideration of the adhesive force between the lamella and impact surface may also provide an explanation for the seemingly paradoxical effect of droplet viscosity to both promote and inhibit splashing.

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Introduction

The ability to accurately predict the occurrence of splashing of single droplet impacts remains of interest due to a number of important applications including materials processing, ink printing, spray cooling, fuel injection, fire suppression and irrigation. Many mechanisms for splashing have been proposed, however a complete picture of the phenomenon is yet unattained. The phenomenon was first studied by Worthington [1]. Since then, many mechanisms have been proposed to explain splash formation. At high droplet impact velocities over 100 m/s, an internal pressure shockwave may form to initiate splashing [2, 3]. At lower velocities, splashing may still be initiated through a redirection of spreading momentum to the location of lowest surface energy [4-6]. Surface roughness plays an important role by obstructing to flow of momentum along the impact surface, forcing a redirection vertically. Splashing of this form has been referred to as “prompt” splashing [7]. However, splashing may also take place on smooth surfaces, though of a distinctly different nature. Splashing of this type is labeled “corona” splashing because of the distinct crown shape that forms at the leading edge of spreading [7]. It is this, lesser-studied mechanism of splashing that we examine further in this paper.

Recent research has shown that changing the pressure or density of the surrounding air may significantly alter the threshold of splashing [8-10]. Accordingly, the shear stress between the droplet and the surrounding gas becomes a key parameter to prediction of splashing. In a recent study, Xu [8] provided supporting evidence for this claim by discovering that as the ambient pressure drops to 0.17 atm, splashing was suppressed. Further description of the interaction between a water droplet and ambient gas during impact was presented by Jepsen et al. [9], who used the Schlieren photography method to provide experimental evidence of gas movement, which varied with the ambient pressure during a water slug impact onto a solid surface. Recently, Liu et al. [10] confirmed the validity of this effect under super-atmospheric conditions.

Many experimental correlations exist to predict the quantitative threshold of splashing during droplet impact and most are based on the Weber number (We) and the Reynolds number (Re) or some combination of the two [5, 10-12]. These studies have related the threshold of splashing to liquid properties, most importantly the surface tension and viscosity, droplet size and velocity, and to the impact surface characteristics. Correlations may often be divided into those that predict a direct relationship between droplet viscosity and impact kinetics required for splashing [5, 11], and those that predict an inverse relationship [8, 10, 12]. A direct relationship means that increasing viscosity would have a tendency to suppress splashing (following intuition) and vice

versa for the latter. Clearly these correlations would diverge widely in their splash predictions through a broad range of fluid properties. Xu [8] also found a transition point in which the gas density required to splash changes from an inverse to direct function of viscosity. A recent work [13] examined splashing through a wide range of liquid viscosities, and adjusted existing splash correlations for low and high viscosity regimes, separated by a transition $Re \approx 500$. Causes for the observed phenomena, however, could not be fully explained.

In this study, a more in-depth study of the mechanisms of splashing is presented by focusing on the spreading lamella, which has been found recently by Bird et al. to be critical to splashing [14]. By considering the forces acting on the lamella, the as yet unknown mechanism for the vertical velocity component of splashing on dry, smooth surfaces may be determined. This analysis also brings to consideration an adhesive force, dependent upon the chemical affinity or wettability between the liquid and solid surface. Surface wettability has been shown to play an important role in droplet impact dynamics [15, 16], affecting the spreading and recoil behavior during impact. But to the authors’ knowledge, this parameter has not been studied specifically for its effects on splashing. Some experiments are performed using water droplets impinging onto surfaces treated to be hydrophilic and hydrophobic to verify the existence of an adhesive force. Consideration of this adhesive force may also explain transition of viscosity from a direct to inverse relationship with air density with respect to splashing.

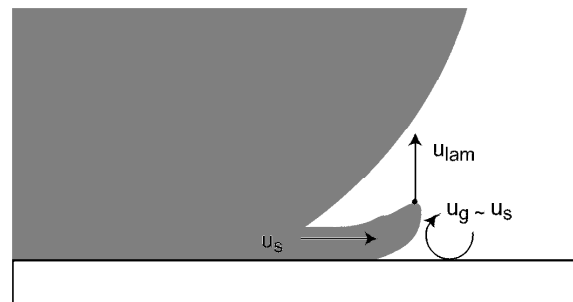


Figure 1: A schematic of lamella lift and the relevant velocities.

Lamella Lift Dynamics

As noted before, it has already been proven that the ambient air pressure has a significant effect on splashing. This has been explained by Jepsen [9] as a compressive effect in which the gas below the droplet is compressed and forced outward, while causing a shear-

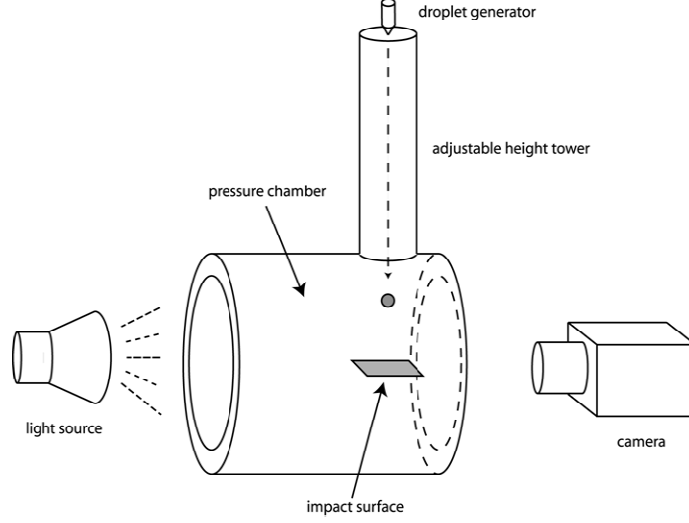


Figure 2: Schematic of the experimental apparatus.

ing force on the droplet surface. A closer look at the splashing dynamics, however, reveals that splashing is initiated and continues long after droplet impact. Splashing is more likely initiated post-impact, at the leading edge of the spreading lamella. Therefore, a closer look at this location is warranted. Splashing requires some vertical momentum in order for satellite droplets to separate from the surface and the bulk droplet. With this as a premise, a requirement for splashing is that the lamella lifts off of the impinged surface. Referring to Figure 1, a momentum balance may be performed at the lamella edge:

$$\rho_l V \frac{du_{lam}}{dt} = \frac{1}{2} \rho_g u_g^2 C_d S - \sigma L - F_{lg} \quad (1)$$

where F_{lg} is some adhesion or chemical affinity that the liquid has on the impinged surface. The term on the left is the vertical momentum of the lamella. This is equated to the momentum imparted on the lamella by the gas motion minus the opposing effect of surface tension and adhesion. We may assume that as the lamella spreads radially outward, the surrounding gas is displaced upward, creating a vertical velocity, $u_g \sim u_s \approx \sqrt{Du_o / 4t}$. The thickness of the lamella will scale with the boundary layer thickness so $L \sim \sqrt{v_l t}$.

The surface area, S , is determined by the L and the perimeter of the lamella:

$$P = 2\pi r(t) \approx 2\pi \int \sqrt{\frac{Du_o}{4t}} \approx 2\pi \sqrt{Du_o t} \quad (2)$$

A requirement for lamella lift is that its vertical momentum be greater than zero. Therefore, we may set the LHS of Equation 1 to zero to determine the threshold conditions for lift. Substituting and rearranging terms, we have:

$$\frac{\pi}{4} \rho_g (Du_o)^{3/2} C_d \sqrt{v} = \sigma \sqrt{v_l t} + F_{lg} \quad (3)$$

Lift is most likely to occur at the earliest possible time after impact since the air velocity will decrease significantly with time. This is the moment when a distinct lamella layer extends beyond the outer boundary of the bulk droplet. According to Bird et al. [14], this time is $t_c \sim v / u_o^2$. Substituting and simplifying again:

$$\rho_g C_d Re^{3/2} v_l^2 = \frac{\rho_l Re v_l^2}{We} + F_{lg} \quad (4)$$

Because of the very low Re existing with respect to the lamella thickness, C_d may be computed using:

$$C_d = \frac{1.328}{Re^{1/2}} \approx \frac{1.328 \sqrt{v_g}}{\left(\frac{Du_o v_l}{4}\right)^{1/4}} \quad (5)$$

which is for the average drag coefficient for laminar flow over a flat plate [17]. Interestingly, if we ignore F_{lg} , Equation 4 simplifies to a form very similar to [11]:

$$\left(\frac{\rho_g \mu_g}{\rho_l \mu_l}\right)^{1/4} Oh Re^{9/8} = 1 \sim \frac{1}{\mu^{3/8}} \quad (6)$$

This analytically derived expression shows that splashing should always decrease with increasing liquid viscosity, following intuition. As will be shown later, the regime in the high Re range where viscosity appears to promote splashing may actually be due to the F_{lg} term.

Experimental Confirmation of Adhesion

We now examine the F_{lg} term of Equation 1 by experimentally confirming an adhesive effect and discussing its implications on splashing. Experimental details are as follows: A precision pneumatic micro-liter valve with a stainless steel tip of various outer diameters is used to generate droplets of approximately 3.5 mm diameter. The distance from the nozzle tip to the impact surface was adjusted using three separate towers of varied length to produce impact velocities of approximately 2.2, 2.6 and 3.5 m/s. A smooth Plexiglas surface with less than 0.8 μm in roughness was used as the impact surface and was chemically treated to be hydrophilic and hydrophobic using commercially available products (Rain-X, Blue Coral-Slick 50, Ltd., Cleveland, OH). For the hydrophilic case, the water droplets completely wetted the surface; while the hydrophobic case produced a contact angle of about 130° (untreated Plexiglas produces a contact angle of 150°). Intuitively, the F_{lg} term should be larger for the hydrophilic case. All experiments were performed isothermally at room temperature and within a custom-made aluminum pressure chamber (Figure 2) to vary ambient pressure from 0.5-6 atm. Clear polycarbonate windows permitted imaging of the impact phenomena with a Phantom V7.1 high-speed camera set at 20000 fps. Images were backlit with a high-power tungsten lamp with light diffuser. Impact outcomes for each of the tested cases were verified by repeating each case 4 times. For cases of questionable outcomes or high variability, more measurements were taken and the results averaged. Cases where splashing and non-splashing occurred equally are designated as “threshold”.

As shown in Figure 3, the adhesive effect is confirmed by the experimental data. The columns designated Lo, Mid and Hi represent data for each drop height. Column widths indicate the spread in impact velocities. The hydrophilic surface clearly requires higher gas density to induce splashing. This is most evident at the 2.6 m/s impact velocity.

The experimental data may also be used to verify the F_{lg} term in Equation 4. Plots of the ratio of the air term with the surface tension term reveals a difference in splash threshold ratio between the hydrophilic and hydrophobic surfaces (Figures 4a,b). The hydrophilic data requires a higher gas density to induce splashing.

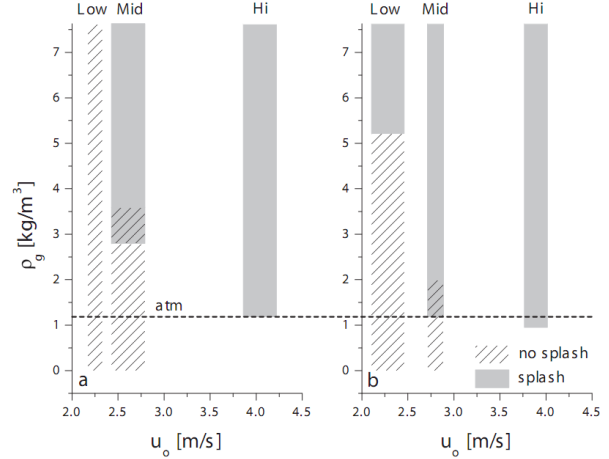


Figure 3: Experimental results with (a) hydrophilic and (b) hydrophobic surfaces. Impact diameters are approximately 3.5 mm

The difference in threshold represents a relative quantity for F_{lg} , 4×10^{-9} N in this case. Using this value to correct the hydrophilic data brings the threshold to the same level as the hydrophobic data (Figure 4c). This suggests that F_{lg} is a constant, dependent only on the chemical affinity of the liquid to the impact surface, and not a function of kinematic properties.

A major implication of recognizing the F_{lg} term is shown in Figure 5 with the lift threshold as a function of viscosity. It reveals that there is a non-obvious viscosity corresponding to the minimum energy to induce lift. This minimum point changes with F_{lg} . A very similar curve was measured experimentally by Xu [8] by varying the viscosity of the droplet, drawing attention to the seemingly paradoxical effect of viscosity in which it can both promote and inhibit splashing. As the quantity of the surface tension term becomes comparable to the F_{lg} term, a reversal of the role of viscosity can be seen.

Conclusions

Analytical advancements were made in explaining and predicting the onset of splashing of single droplets impinging on a flat smooth surface. By considering lamella lift to be a requirement for splashing, a momentum balance may be performed on the lamella. Vertical momentum may be imparted on the lamella by the displaced surrounding gas. The inclusion of an adhesion term in the lift threshold was confirmed experimentally using hydrophilic and hydrophobic surfaces and may explain the paradoxical effect of viscosity on splashing.

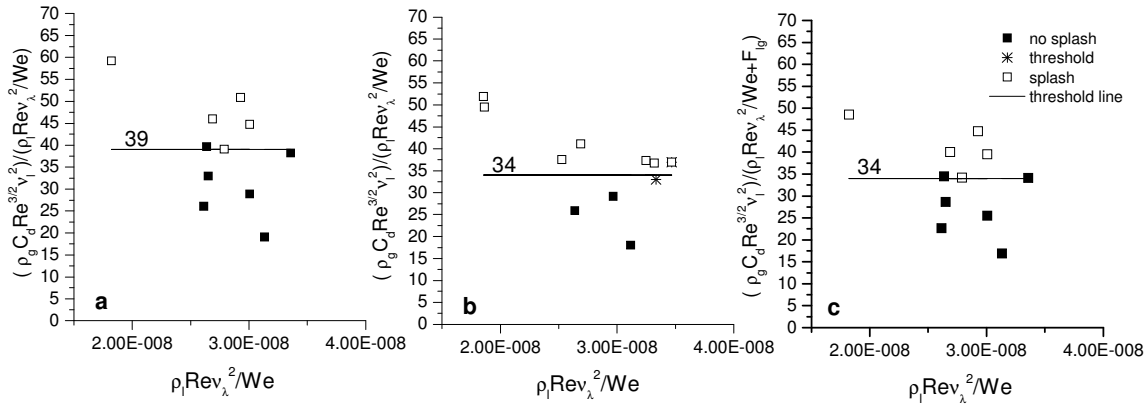


Figure 4: Threshold requirements for lamella lift for water droplets impinging onto a (a) hydrophilic and (b) hydrophobic surface. The addition of the F_{lg} term (c) lowers the hydrophilic threshold to that of the hydrophobic surface.

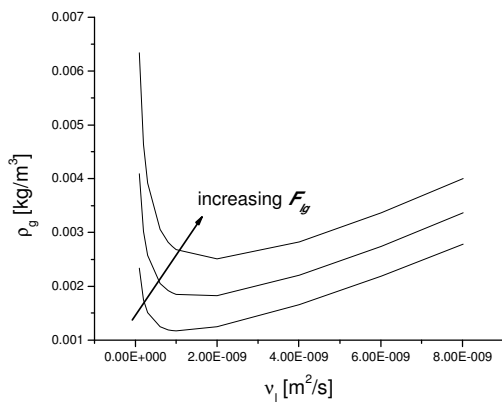


Figure 3: A parametric analysis of the effect of v_l on the threshold ρ_g required for lamella lift using a water droplet with $D = 3.6$ mm and $u_s = 2.8$ m/s.

Nomenclature

F_{lg}	adhesive force
C_d	coefficient of drag
g	acceleration
k	wave number
L	ligament thickness
Oh	Ohnesorge number
Re	Reynolds number
S	surface area of lamella edge
t	time
u	velocity
V	volume of ligament

Greek

λ	wavelength
ν	kinematic viscosity

σ surface tension

Subscripts

g	gas
l	liquid
lam	lamella
mom	momentum
o	impact

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