

Dynamics of Viscous Drop Impact

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Splashing is a common phenomenon occurring when a liquid drop impacts on a smooth, dry surface at high velocity. It has been discovered that the pressure of the surrounding air is important in causing a splash [1]. Moreover, it has been found that viscous splashing follows a different mechanism than the splashing of an inviscid liquid [2]. The relationship between the threshold pressure, P_T , and the impact velocity, V_0 , for viscous splashes is investigated; P_T demonstrates a weak dependence on impact velocity above 2.0 m/s. The composition of the gas in which splashing occurs is varied to gain insight on the role of gas molecular weight on P_T in the viscous regime. Viscous drop impact does not follow simple scaling behavior with gas molecular weight.

INTRODUCTION

Several aspects involved in splashing have been studied since the late 1800's, at the time of Worthington [3]. However, splashing is an example of a common occurrence which is not completely understood. There are many different behaviors which can be exhibited as a drop hits a surface, depending on the properties of the drop and surface. This study deals with the case of a liquid drop hitting a smooth substrate. After impact, the drop spreads before breaking up into smaller droplets. It has been found that several factors play a role in creating a splash. The role of surface tension σ , impact velocity V_0 , drop diameter D , surface roughness R_a , and viscosity ν have been investigated. For extreme values of these parameters, such as low impact velocity or high surface tension, the splash upon drop impact can be suppressed [4].

It is difficult to expect that surrounding air plays a crucial role in creating a splash. However, a splash can be suppressed in a low pressure environment [1]. Publications prior to this discovery did not consider surrounding air in splashing. The pressure range in which splash transitions into no-splashing regime is known as the threshold pressure P_T . Threshold pressure of a splash varies based on drop parameters, such as D or V_0 . Figure 1 demonstrates this splashing behavior for the case on an inviscid drop of

silicone oil of 3.1 ± 0.1 mm diameter hitting a smooth dry glass microscope slide at 4.0 m/s.

INVISCID DROP IMPACT

A relationship was developed between threshold pressure and impact velocity for inviscid liquids (0.68 to 2.60 cSt). Although threshold pressure is expected to decrease with increasing impact velocity, there is a region below the characteristic velocity V^* in which the curve is non-monotonic (figure 2A). Immediately below V^* , lower pressure helps the drop to splash. This trend appears for other liquids and gases [1].

It is not clear what physical property of the gas is important. Therefore, Xu et al. varied the gas of the surrounding atmosphere to better understand air's role. The gases have very different molecular weights, Helium of 4 daltons, air of 29 daltons, krypton of 83.8 daltons, and SF_6 of 146 daltons. The inset of figure 2B shows P_T versus V_0 for the four gases. The trends have the same qualitative shape, although the values of P_T are different. Xu et al. found a data collapse for the region of velocity higher than V^* . For the inviscid case, the scaling is obtained by plotting $(M_G/M_{air})^{0.5}P_T$ versus V_0 , as shown in the main plot of figure 2B. This paper reports on determining the relationship between P_T and V_0 for viscous splashes.

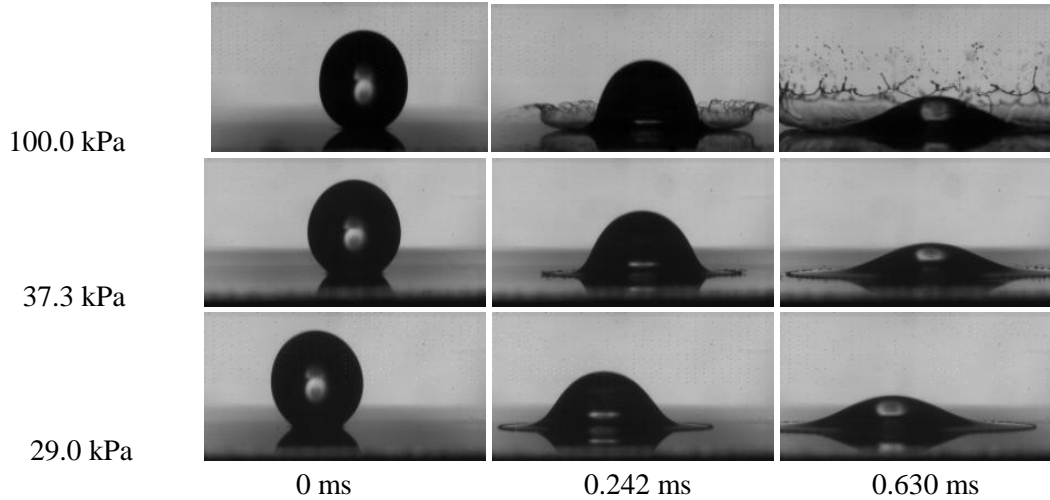


Figure 1. Images of drop impact onto a glass surface under different air pressures. A 1.4 cSt silicone oil drop of 3.1 ± 0.1 mm diameter splashes at impact velocity of 4.0 m/s. The drop splashes when at atmospheric pressure, $P = 100$ kPa. At threshold pressure, 37.3 kPa, the splash just begins to form, releasing few droplets, as shown in row 2. No splash occurs at 29.0 kPa, below P_T , although all other related parameters remain the same. Images from L. Xu.

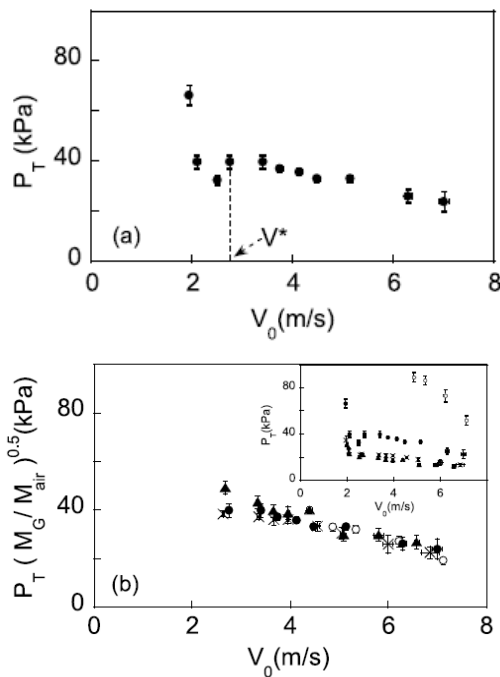


Figure 2. Threshold pressure P_T is plotted as a function of impact velocity V_0 . There are two distinct regimes which are separated by V^* . Error bars indicate range from a splash releasing few droplets to a splash which is completely suppressed. (A) P_T versus V_0 of inviscid liquid in air. (B) Scaled threshold pressure versus

impact velocity for four gases: air, He, Kr, and SF_6 . The inset shows P_T vs. V_0 for four gases. From L. Xu, W. Zhang, and S. Nagel, Phys. Rev. Lett. 94, 184505 (2005).

EXPERIMENTAL SETUP

In the experimental setup, 10 cSt silicone oil is released from a 5 mL syringe operated by a syringe pump. A Stokes is a measure of kinematic viscosity in units of m^2/s [5]. Drops are released from a stainless steel nozzle to produce drops of reproducible size of about 3.1 mm. The drops fall inside a chamber in which the air pressure can be varied from 3 to 100 kPa. The drops then impact a smooth, dry glass microscope slide; the slides are replaced after each measurement. Chambers of different heights, ranging from 0.19 m to 3.0 m, are used to create increasing impact velocity V_0 . The splashes on the substrate are recorded by a Phantom V7 high speed video camera which can record at up to 47,000 frames per second. The impact velocity and drop size are determined from the movies. Different gases can be inserted into the chamber for the surrounding atmosphere. In this experiment, three gases are used: air, Helium, and SF_6 .

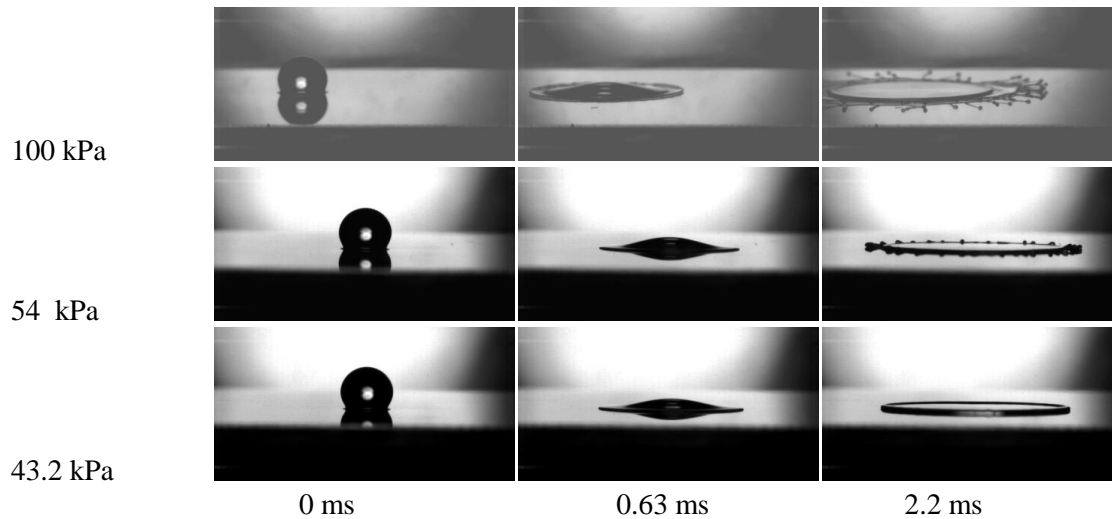


Figure 3. Photographs show progression of splashes of 10 cSt drops of silicone oil. A drop of 3.1 ± 0.1 mm diameter drop hits a smooth glass surface at 5.0 m/s under different air pressures. The splash occurs at a later time, and droplets are emitted from the rim near its maximum extent. Threshold pressure is at 54.0 kPa.

VISCOUS SPLASHES

The experiments discussed deal with the low viscosity range, below 2.60 cSt [1]. However for higher viscosities, there is another regime in which little is known. As illustrated in figure 3, viscous splashes occur at later time after impact, 0.6 ms after impact as compared to 0.24 ms for inviscid splashes. The appearance of the splash is also significantly different for the viscous regime. The viscous splash forms only after the drop has reached its maximum extent, while the inviscid splash immediately ejects a corona that breaks up into droplets [6]. Despite very different appearances, both viscous and inviscid splashes are suppressed below some threshold pressure.

P_T VS. V_0 – VISCOUS DROP IMPACT

For viscous liquids, viscous stress presumably stabilizes the drop making it harder to splash [5]. This leads to a higher threshold pressure at a given impact velocity. For instance,

P_T shifts higher by about 10 kPa for 10 cSt fluid at increasing impact velocities. Threshold pressure versus impact velocity of 10 cSt silicone oil drops of 3.1 ± 0.1 mm diameter is plotted in figure 4 [7]. For viscous splashes in a low pressure environment, it is difficult to determine whether a drop splashes. The transition is not as sharp as in the inviscid case of drop impact. Thus, fluctuations in the range of threshold pressure lead to a large range of P_T of about 8 to 10 kPa. The low end of the pressure range represents the point where small droplets are extended but not released from the rim of the drop. At the upper end of the range, several droplets are released from the splash at a small angle to the rim.

The data of figure 4 shows a monotonic trend, demonstrating the expected trend of decreased P_T as impact velocity is increased. However, there is also surprisingly a weak dependence of P_T on V_0 above 2.0 m/s. These observations show that viscosity has significant effects on not only the way in which the drop splashes but also the point in P_T occurs.

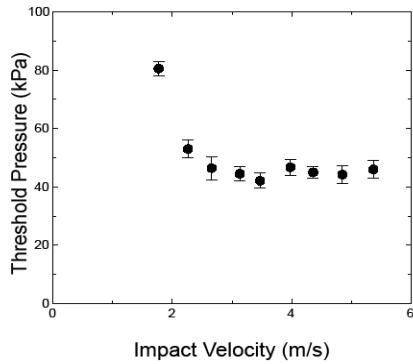


Figure 4. P_T versus V_0 plot of 10 cSt drops of silicone oil of 3.1 ± 0.1 mm diameter in the background atmosphere of air. The error bars give the range where droplets just begin to be released from the rim once the drop is expanded. The midpoint is the threshold pressure.

P_T VS. V_0 FOR VARIED GASES IN BACKGROUND ENVIRONMENT

We varied the gas of the background atmosphere to three gases with very different molecular weights. As shown in figure 5, the values of threshold pressure decrease with increasing gas molecular weight. The trend in data of helium gas differs greatly from that of air and SF_6 . There is no simple scaling with gas molecular weight as in inviscid splashing [1].

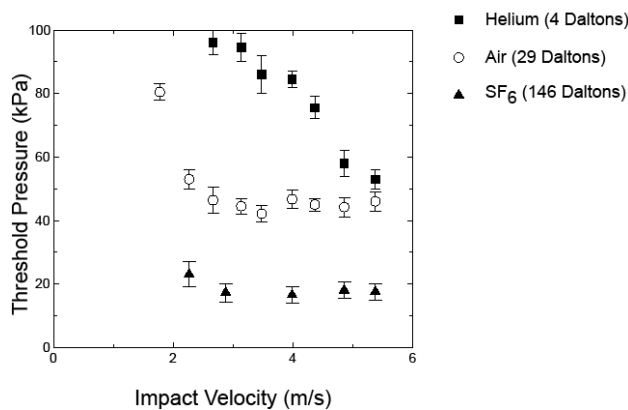


Figure 5. P_T versus V_0 for three gases ranging from 4 to 146 daltons.

CONCLUSIONS

This project involved exploring splashing in the viscous regime. We found the threshold pressures of viscous splashes using three gas compositions in the surrounding atmosphere: air, Helium, and SF_6 . In each case, threshold pressure as a function of impact velocity is developed and shows a monotonic trend. Higher velocities lead to a lower threshold pressure to suppress the viscous splash. However, viscous drop impact does not follow a simple scaling behavior with gas molecular weight as in the case of inviscid splashing. The findings of this paper can help to better understand the basic principles of the splash.

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- [1] L. Xu, S. Nagel, and W. Zhang. Phys. Rev. Lett. **94**, 184505 (2005).
 - [2] M. Driscoll et al., 2008 Annual Meeting of Div. Fluid Dyn. of APS.
 - [3] A. M. Worthington, Proc. R. Soc., London **25**, 261 (1876-1877).
 - [4] A.L. Yarin, Annu. Rev. Fluid Mech. **38**, 159 (2006).
 - [5] Acheson, Elementary Fluid Dynamics. Clarendon: 1990.
 - [6] L. Xu. Phys. Rev. E. **75**, 056316, 2007.
 - [7] C. Stevens et al, APS DFD FC03 (2007).