Subpatterns of thin sheet splash on a smooth surface

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Abstract:

An experimental study of the impact of glycerol solution droplets with varying viscosity on solid dry smooth surface is presented in the paper. Three subdivided patterns of thin sheet splash were observed based on the sequence of the breakup of thin sheet and its rim. Specifically, Pattern 1 is characterized by the breakup of the rim with the thin sheet being intact, Pattern 2 by the almost simultaneous breakup of both the rim and the thin sheet, and Pattern 3 by the breakup of the rim followed by the breakup of the thin sheet. The effects of Weber number and Ohnesorge number on the transitions of these subpatterns were determined over large ranges of their values, and a regime nomogram in the parametric space of *We*-*Oh* was obtained.

Keywords: Droplet impact; thin sheet splash; viscosity effect, Weber number; Ohnesorge Number

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1. Introduction

Droplet impact on a solid surface or a liquid pool is a very common phenomenon in industrial processes such as inject printing, pesticide spraying, and bloodstain pattern analysis. When the impact velocity is relatively high, interfacial disturbance often appears at the lamella growing from the droplet and eventually leads to droplet splash with distinct patterns such as prompt splash and thin sheet splash (aka corona splash). Extensive studies have been conducted to understand these droplet splash patterns[1-3].

The prompt splash usually happens in a short period of time after initial contact, and it generates secondary droplets from the contact line without the occurrence of thin sheet. Surface roughness was found to promote prompt splash by delaying the ejection time of thin sheet[1]. Prompt splash was also inhibited by insufficient capillary forces because of polymer additive in the liquid[4].

For thin sheet splash, the development of thin sheet is crucial and therefore has been investigated experimentally and theoretically[5-6]. The specific definition of important components of thin sheet splash is shown in Figure 1. The thin sheet is usually lifted from the surface [7], the rim is the outer edge of the thin sheet with a number of bulges growing outwardly from the rim, and the contact line is the inner edge of the thin sheet. Some of the sufficiently grown bulges are connected to the rim by ligaments. Wang, et al. [8] found that the rim thickness is governed by instantaneous, local rim acceleration. Thoroddsen, et al. [3] discovered two types of thin-sheet movement for thin sheet splash: at a moderate impact velocity, the tip of the lamella ejects randomly secondary droplets before it contracts to the contact line; at a higher impact velocity, the splash occurs directly at the contact line. Riboux and Gordillo [9] calculated the mean sizes and velocities of the ejected secondary droplets by using a one-dimensional approximation describing the flow in the ejected liquid sheet and the balances of mass and momentum at the border of the sheet. Latka, et al. [1] observed that a droplet might undergo prompt splash initially and then generate a thin sheet which breaks up later to cause thin sheet splash. Regardless of these noteworthy studies, the formation of crown-like thin sheet and the ejection of secondary droplets for thin sheet splash still needs to be further investigated and discussed, and more experimental and theoretical investigation are needed to sort out the different ideas proposed to explain them [10].

Various theories were proposed for the mechanism of thin sheet splash. The growing thin sheet is often treated as a viscous boundary layer with a thickness of $\sqrt{\nu t}$, where ν is the kinematic viscosity of the liquid, and t is the time after the initial contact. Yoon, et al. [11] compared the description of Rayleigh-Taylor instability, Plateau-Rayleigh instability, and Kelvin-Helmholtz instability on finger formation, which is the finger-like protrusion distributed along the rim. They found that the shear-driven Kelvin-Helmholtz theory is well suited for describing droplet impact onto both a smooth surface and a liquid pool. Agbaglah, et al. [12] observed that the instability of the rim is driven by both the Rayleigh-Taylor and the Rayleigh-Plateau instability because of the initial rim acceleration.

Various models for droplet splash threshold were proposed based on experimental data [13-14] and theoretical analyses [7]. The splash threshold on dry surfaces depends on the surface tension [15], the ambient gas pressure [16-17], and the surface roughness [18]. However, there is no correlation that can unify the splash threshold.

The liquid viscosity was found to greatly influence the droplet spreading and splash processes. Xu et al. [19] experimentally showed that the viscosity plays different roles in low- and high-viscosity regimes. Reducing ambient gas pressure makes possible to observe the processes of thin sheet in the low-viscosity regime [2]. Non-monotonic effect of viscosity on maximum spreading diameter at relatively small Weber number was experimentally observed by Qin, et al. [20]

The effect of liquid viscosity (quantified by Ohnesorge number) on thin-sheet splash at different Weber number is the focus of the present work. High-resolution images of splash process captured by a high-speed camera provide great details about the ejection of secondary droplets, which could shed a light on understanding the droplet splash mechanism.

2. Experimental specifications

The experimental set-up has been described in detail in the previous papers of the authors [18] and will be briefly summarized here. The experiments were conducted at room temperature (20°C) and atmospheric pressure so that the important influences of ambient gas [19] are considered to be unchanged in the study. Other important factors of surface roughness and surface treatment are not considered in the study, where a smooth stainless steel surface (R_a=0.025μm) was used. Different glycerol solutions used in the experiment provide a wide range of viscosity from 1.6 mPa·s to 25.08 mPa·s. The densities (ρ=1023-1184 kg/m^3) and surface tensions (σ= 0.058-0.070 N/m) of these glycerol solutions are nearly constants, allowing us to isolate the effect of viscosity. In the present study, We ranges from 13 to 800 and Oh from 0.0038 to 0.1400.

Reproducible droplets of diameter D_0=2.4±0.1 mm were generated by using a syringe. Droplets are released from a height ranging from 2 cm to 120 cm to reach a terminal velocity from 0.6 m/s to 4.1 m/s before impact, which was recorded by a phantom V611 high-speed camera equipped with a long focus microscope. The spatial and temporal resolutions of images are 100 pixel/mm and 10,000 fps. The camera was tilted by 15° for three-dimensional droplet surface morphology, such as the fingering disturbance and thin-sheet evolution. The vertical velocity was corrected by a factor of cos15°.

According to the above description, the present experiment involves only five controllable variables: the droplet impact velocity U_0, the droplet diameter D_0, the droplet density ρ, the droplet viscosity μ, and the surface tension coefficient σ. Dimension analysis shows that the present problem is controlled only by two non-dimensional parameters, namely the Weber number $We=\rho D_0 U_0^2/\sigma$ and the Ohnesorge number $Oh=\mu/ (\rho\sigma D_0)^{1/2}$. Both the real time t and the normalized time $\tau = tU_0/D_0$ were used for characterized the splash dynamics. It should be recognized that any quantitative conclusions to be drawn in the present study are limited to the set of non-dimensional parameters and the fixed standard atmospheric air and the chosen smooth steel surface. Confusion should be avoided that droplet impact on solid surface is independent of surrounding gas and surface.

3. Phenominological Description of subdivided splash patterns

Most of the splash cases in this work result in thin-sheet splash, and a few prompt splash cases were observed at small *Oh* for the 20% and 30% glycerol solutions. For the liquids with the smallest and the largest viscosity (the 10% and 70% glycerol solutions, respectively), droplet splash was not observed even at the largest Weber number up to 800. The most interesting observation of the present experiment is that the thin sheet splash can be divided into three distinct patterns based on the different development of the rim and the thin sheet.

The splash in Pattern 1 is characterized by the breakup of ligament while the thin sheet is being pulled back to the contact line as presented in Figure 2. The splash process of 60% glycerol solution droplet at We=307 and Oh =0.0287 is presented as a typical case for this pattern. It is seen that the thin sheet is generated from the contact line and reaches its maximum spreading diameter at t=1.1ms. The thin sheet is surrounded by a thick rim, from which bulges grow outwardly. While the contact line keeps expanding at t=1.2ms, the thin sheet and the rim are pulled back inwardly, rendering the wavy rim. At t=1.4ms, the thin sheet is completely pulled back to merge into the contact line, and the rim deforms to the ligaments that are connected to the bulges. At t=1.7ms, the ligaments break up, and the bulges are ejected as secondary droplets. This time instant that the splash happens is defined as t_s. Such a pattern is similar to the literature case of a 60% glycerol solution droplet at Re=1060, which was described as “the front is pulled back toward the center” by Thoroddsen, et al. [3]. The pattern was also be observed in the experiment with droplets of 2:1 glycerol/water mixture by Palacios, et al. [21].

The splash in Pattern 2 is characterized by the nearly simultaneous breakup of rim and thin sheet, as shown in Figure 3. A representative case of Pattern 2 is shown in Figure 3 for a 40%

glycerol solution droplet at *We*=525 and *Oh*=0.0104. The thin sheet is levitated from the surface with an significant angle at t=0.5 ms, when some of the bulges are already shed from the rim. The rim and the thin sheet start to collapse at t=0.6ms and are completely broken at t=0.7ms. The contact line remains smooth compared with that in Pattern 1. It is noted that the bulges can either be distributed in the rim without ligament or be ejected before the rim and the thin sheet break as presented in Figure 3. The simultaneous breakup of thin sheet and rim is consistent with that in the literature case of 50% glycerol at 3 atm by Vu, et al. [6].

The splash in Pattern 3 is characterized by the rim breakup as a whole subsequent to the breakup of the thin sheet. The representative case of 50% glycerol solution droplet at *We*=729 and *Oh* = 0.166 is shown in Figure 4. It is noted that, different from that in Pattern 2, the thin sheet is almost parallel to the surface instead of being significantly levitated. At t=0.3ms, the thin sheet contacts with the surface at some point, as indicated by the red arrow in the enlarged image. The thin sheet contracts back to the contact line but is stuck in half way at t=0.4ms. Such a halted contraction is caused by ruptures at the local contacts [3]. The rim is eventually stripped off from the contact line as an intact ring and keeps expanding at t=0.7ms. Finally, the rim breaks up into secondary droplets. It is noted that sometimes the rim might also break when the thin sheet collapses. Being different from the break of the rim into secondary droplets with varied direction and velocity in Pattern 2, the bulges from the rim in Pattern 3 still spread outwardly with same velocity and angle even if they are not connected.

To summarize the different behaviors of the rim in the distinct patterns: the rim is pulled back to the contact line in Pattern 1, directly breaks up together with the thin sheet in Pattern 2, and is separated from the contact line in Pattern 3. The contact line grows many ligaments connected with the bulges in Pattern 1, but it remains quite intact in both Pattern 2 and Pattern 3.

4 Influence of *We* and *Oh* on thin-sheet splash subdivided patterns

4.1 Influence of *We* on splash patterns

The impact outcomes of glycerol solutions under different *We* and *Oh* are presented in Figure 5 based on the definition of prompt splash and three subdivided thin-sheet splash as discussed above. Weber number has different effects on the impact outcomes for liquids with different viscosity. For the liquids with low viscosity such as 25% and 30% glycerol solutions, the thin sheet splash cases over a large range of Weber numbers can be classified as Pattern 2. In these cases, the thin sheet is levitated, the instability of rim and the ejection of the bulges appear very early, as shown in Figure 3.

Splash patterns 1, 2 and 3 were observed for the liquid with higher viscosity such as 40% and 50% glycerol solutions. As the Weber number increases, the droplet splash transitions from Pattern 1 to Pattern 2 and then to Pattern 3. At small *We,* instead of the instantaneous breakup, the thin sheet and rim are stabilized by the larger viscosity. The thin sheet is fully developed and then pulled back due to surface tension, resulting in Pattern 1. Further increase of *We* leads to faster spreading and instability of the thin sheet, resulting Pattern 2. When the droplet reaches a critical Weber number that tends to stabilize the lifted thin sheet, the rim is also stabilized without ejecting secondary droplets from the bulges, thus the rim is ejected outwards as a whole ring, resulting Pattern 3.

Another notable change is the significant decrease of the angle between the thin sheet and surface. When the thin sheet is close to the surface and much thinner than the rim[22], it might have local contact with the surface and be ruptured during its spreading, resulting in Pattern 3. The critical Weber number was found by Palacios, et al. [14] to be smaller for liquids with larger Ohnesorge number. The same tendency of critical Weber number is also shown in Figure 5 ($We_c \approx 700$ for 40% glycerol solution and $We_c \approx 632$ for 50% glycerol solution).

For the liquid with higher viscosity such as 60% glycerol solution, Pattern 1 spans over a larger Weber number range due to the stabilization caused by the increased viscosity. The transition between Pattern 1 and Pattern 3 for 60% glycerol solution was found at around $Re \approx 1500$ and $We \approx 1700$ by Thoroddsen, et al. [3]. The critical Weber number is larger than that found in this work, possibly due to the different surface in the experiment. Some of the thin sheets of pattern 1 also are close to the surface, but when the local contact happens, the thick rim and large bulges in the rim fail to continue spreading or ejecting outward.

4.2 Influence of *Oh* on splash patterns and thresholds

Ohnesorge number also affects the impact outcomes in different ways at different Weber numbers. At intermediate $We \approx 400$, the rim and thin sheet simultaneously breaks up as Pattern 2 for the liquids with relatively small Oh. The rim grows thicker at higher Oh [23] and is stable enough to be fully developed until being pulled back to the contact line as Pattern 1.

At higher $We \approx 600$, Pattern 3 was observed between Pattern 2 and Pattern 1 with the increase of Oh. For the liquids with low Oh (such as the 20% and 25% glycerol solutions), the instability of the rim grows quickly during the spreading and leads to Pattern 2. Further increase of Oh not only stabilizes the rim and the thin sheet as such shows no ejection of bulges from the rim, but also reduces the angle between the thin sheet and the surface. The thin sheet develops until it has local contact with the surface, ruptured by the holes caused by the contact, and meanwhile the rim remains stable and keeps spreading as a whole. Larger bulges are accumulated in the rim of 60% glycerol solution, thus although some of the thin sheet contact with the surface, the thick rim and bulges fail to continue spreading outwardly but be pulled back to the contact line as pattern 1.

The non-monotonic change of impact outcome with increasing Oh indicates the different roles of viscosity in low- and high-viscosity regime. In the high-viscosity regime, the droplet is stabilized by viscosity against the restraining pressure of the gas on the spreading liquid. However, in the low-viscosity regime where the viscous force is relatively small, the droplet is mainly stabilized by surface tension [19]. The increased viscosity would promote the thickness of the edge [24] and leads to lower stabilizing stress, eventually causes smaller We_{cr}.

Furthermore, Xu [25] proposed that μ_0=3.4 mPas is the boundary for the inviscid regime and viscous regime for silicone oil while investigating the critical ambient pressure, where the inviscid regime is stabilized by the surface tension and the viscous regime is stabilized by the liquid viscosity. The value of μ_0 in this work for glycerol solution lays on Oh=0.0166 (μ==6.72 mPas), which is also illustrated by Xu [25] that μ_0 depends on conditions such as the impact velocity, surface tension and wetting conditions.

5. Conclusion

We investigated the splash process of glycerol solution droplets over large ranges of Oh and We. The most significant observation is that the thin sheet splash can be divided into three splash patterns according to the sequence of the thin sheet breakup and the rim breakup. In general, Pattern 1 occurs in the cases of high liquid viscosity, because viscous force stabilizes the thin sheet so that the rim breaks up first when being pulled back inwardly. Patterns 2 and 3 occur in the cases of lower liquid viscosity, where the thin sheet to tend to breakup simultaneously with the rim because of the reduced viscous stabilization. However, in Pattern 3 occurring at higher Weber numbers, the thin sheet is insufficiently levitated so that the instability waves may locally contact with the solid surface, resulting in the thin sheet breakup prior to the breakup of the rim. These new experimental observations imply that the specific evolutions of thin sheet and its rim must be considered in the efforts of developing predictive models for droplet splash.

There is a critical Weber number that the levitated thin sheet becomes close to the surface, which is decreased with increasing Ohnesorge number. The thin sheet could have local contact with the surface without enough levitated angle and leads to the rupture of the thin sheet and ejection of the rim as a whole. The critical splash threshold We_{cr} first decreases and then increases with the increase of viscosity due to the different stabilize force in low and high viscous region. The viscous force tends to act as stabilize force in high viscous region. In low viscous region where the viscous force is relatively small, the droplet is mainly stabilized by surface tension, and is promoted to splash due to the destabilization caused by larger rim thickness with the increase of viscosity. The splash is significantly delayed by the increased viscosity. The thin sheet in this work is ejected in a short time after the impact less than 0.5ms, both surface roughness and ambient pressure have an effect on t_{ej} [1, 26].

Future work could be focused on the origin and development of thin sheet. The sub-divided thin sheet splash patterns have distinct number and velocity of secondary droplet and should be considered in modelling.

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Reference

1. Latka, A.; Strandburg-Peshkin, A.; Driscoll, M. M.; Stevens, C. S.; Nagel, S. R., Creation of prompt and thin-sheet splashing by varying surface roughness or increasing air pressure. *Phys Rev Lett* **2012,** *109* (5), 054501.
2. Stevens, C. S.; Latka, A.; Nagel, S. R., Comparison of splashing in high- and low-viscosity liquids. *Physical review. E, Statistical, nonlinear, and soft matter physics* **2014,** *89* (6), 063006.
3. Thoroddsen, S. T.; Takehara, K.; Etoh, T. G., Bubble entrapment through topological change. *Physics of Fluids* **2010,** *22* (5), 051701.
4. Vega, E. J.; Castrejón-Pita, A. A., Suppressing prompt splash with polymer additives. *Experiments in Fluids* **2017,** *58* (5).
5. Riboux, G.; Gordillo, J. M., Boundary-layer effects in droplet splashing. *Physical review. E* **2017,** *96* (1-1), 013105.
6. Vu, H.; Banks, D.; Aguilar, G., Examining viscosity and surface wettability on lamella lift dynamics and droplet splashing. *Atomization & Sprays* **2011,** *21* (4), 303-315.
7. Josserand, C.; Thoroddsen, S. T., Drop Impact on a Solid Surface. *Annual Review of Fluid Mechanics* **2016,** *48* (1), 365-391.
8. Wang, Y.; Dandekar, R.; Bustos, N.; Poulain, S.; Bourouiba, L., Universal Rim Thickness in Unsteady Sheet Fragmentation. *Physical Review Letters* **2018,** *120* (20).
9. Riboux, G.; Gordillo, J. M., The diameters and velocities of the droplets ejected after splashing. *Journal of Fluid Mechanics* **2015,** *772*, 630-648.
10. Yarin, A. L., Drop impact dynamics: splashing, spreading, receding, bouncing…. *Annual Review of*

Fluid Mechanics **2006,** *38* (1), 159-192.
11. Yoon, S. S.; Jepsen, R. A.; James, S. C.; Liu, J.; Aguilar, G., Are Drop-Impact Phenomena Described by Rayleigh-Taylor or Kelvin-Helmholtz Theory? *Drying Technology* **2009,** *27* (3), 316-321.
12. Agbaglah, G.; Josserand, C.; Zaleski, S., Longitudinal instability of a liquid rim. *Physics of Fluids* **2013,** *25* (2), 166-1874.
13. Wal, R. L. V.; Berger, G. M.; Mozes, S. D., The splash/non-splash boundary upon a dry surface and thin fluid film. *Experiments in Fluids* **2005,** *40* (1), 53-59.
14. Palacios, J.; Hernández, J.; Gómez, P.; Zanzi, C.; López, J., Experimental study of splashing patterns and the splashing/deposition threshold in drop impacts onto dry smooth solid surfaces. *Experimental Thermal and Fluid Science* **2013,** *44*, 571-582.
15. Goede, T. C. D.; Laan, N.; Bruin, K. D.; Bonn, D., Effect of wetting on drop splashing of Newtonian fluids and blood. *Langmuir : the ACS journal of surfaces and colloids* **2017,** *34* (18).
16. Stevens, C. S., Scaling of the splash threshold for low-viscosity fluids. *EPL (Europhysics Letters)* **2014,** *106* (2), 24001.
17. Liu, J.; Vu, H.; Yoon, S. S.; Jepsen, R. A.; Aguilar, G., Splashing Phenomena during Liquid Droplet Impact. *Atomization & Sprays* **2010,** *20* (4), 297-310.
18. Tang, C.; Qin, M.; Weng, X.; Zhang, X.; Zhang, P.; Li, J.; Huang, Z., Dynamics of droplet impact on solid surface with different roughness. *International Journal of Multiphase Flow* **2017,** *96.*
19. Xu, L.; Zhang, W. W.; Nagel, S. R., Drop splashing on a dry smooth surface. *Phys Rev Lett* **2005,** *94* (18), 184505.
20. Qin, M. X.; Tang, C. L.; Tong, S. Q.; Zhang, P.; Huang, Z. H., On the role of liquid viscosity in affecting droplet spreading on a smooth solid surface. *International Journal of Multiphase Flow* **2019,** *117*, 53-63.
21. Palacios, J.; Hernández, J.; Gómez, P.; Zanzi, C.; López, J., On the impact of viscous drops onto dry smooth surfaces. *Experiments in Fluids* **2012,** *52* (6), 1449-1463.
22. Driscoll, M. M.; Nagel, S. R., Ultrafast interference imaging of air in splashing dynamics. *Phys Rev Lett* **2011,** *107* (15), 154502.
23. de Ruiter, J.; Pepper, R. E.; Stone, H. A., Thickness of the rim of an expanding lamella near the splash threshold. *Physics of Fluids* **2010,** *22* (2), 022104.
24. Ruiter, J. D.; Pepper, R. E.; Stone, H. A., Thickness of the rim of an expanding lamella near the splash threshold. *Physics of Fluids* **2010,** *22* (2), 144.
25. Xu, L., Instability development of a viscous liquid drop impacting a smooth substrate. *Physical review. E, Statistical, nonlinear, and soft matter physics* **2010,** *82* (2 Pt 2), 025303.
26. Driscoll, M. M.; Stevens, C. S.; Nagel, S. R., Thin film formation during splashing of viscous liquids. *Physical review. E, Statistical, nonlinear, and soft matter physics* **2010,** *82* (3 Pt 2), 036302.

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