Splashing Modes in Droplet Impacts onto Sub-Millimeter Microstructures

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Introduction

Predicting whether splashing occurs in a droplet impact is important in a variety of technical applications, such as spray painting, plant-protective agent application and in fluid injection into combustion chambers [1]. In many cases, impacting droplets can interact with structure sizes which are smaller, but of similar magnitude as the droplet diameters. While no universal splashing limit has been found for rough or structured surfaces with small feature sizes, empirical correlations for splashing have been reported in the literature [2,3]. However, the effect of larger surface structures on the splashing limits has not been explored as thoroughly. Thus, in the scope of this study, we investigate whether existing splashing limits can predict the onset of splashing on structures which are only one order of magnitude smaller than an impacting droplet and explore the different splashing modes which can occur on such surfaces. In the following, after giving the experimental methods, splashing is split into prompt, finger and ligament splashing and possible limitations for all phenomena are discussed.

Experimental Methods

To record the droplet impact process, we use our four-perspective imaging setup, which uses three high-speed cameras. The top and lateral views are combined onto a single sensor as shown in figure 1, using a Photron SA-X2 high speed camera at 20 000 fps. The same camera model is used in synchronized mode for the bottom view, which is configured as a total internal reflection view to accurately track the contact lines. Lastly, a Krontech Chronos 1.4 is used for the spatial view, which is an inclined lateral view at a 90° offset with respect to the other lateral view. This camera records the impact process at a frame rate of 2500 fps. The impact parameters (droplet diameter and velocity) are determined automatically using a MATLAB script, which processes the images of the lateral view.
Three types of surface samples are used, all featuring cubic pillars on a square grid with side lengths, heights and separations of 0.1 mm, 0.2 mm and 0.5 mm. The surfaces were manufactured by LightFab GmbH Germany through selective laser etching of fused silica glass. The inherent wettabilities of the surfaces are changed between superhydrophilicity and hydrophobicity through plasma polymerization and plasma activation. The water and isopropanol droplets are dropped from a falling height of 0.15 m, 0.3 m, 0.7 m, and 1.2 m, through regular detachment from a needle with a diameter of 0.4 mm.

Results and Discussion

For droplet impacts onto sub-millimeter structures, we observe two distinct splashing regimes: prompt splashing and finger splashing. In prompt splashing, small secondary droplets are ejected at low angles. Finger splashing involves the ejection of larger fingers almost vertically, which only later break apart into secondary droplets. While no clear mechanism has been established for finger splashing, fluid redirection within grooves appears to play a role, and even at lower impact velocities, the fluid can be redirected upward, forming vertical liquid fingers that later disintegrate due to the Plateau-Rayleigh instability.
Although these two splashing modes are distinct, differentiating between them can be difficult, especially because both phenomena can occur within a single impact process.

When examining the different splashing modes, certain patterns emerge: In smaller structures, prompt splashing tends to dominate, and the liquid forms a lamella that spreads across the tops of the pillars, which inhibits finger growth. For larger structures, finger splashing becomes more pronounced, as the upward redirection of liquid is less likely to be suppressed by the lamella. The thickness of the redirected liquid sheet appears to play a critical role in determining whether finger splashing will occur. This thickness depends on several factors, including the impact velocity, surface tension, and the size of the gap between the structures. Smaller structures encourage lamella formation, while larger structures promote finger splashing, which points to a clear structure-size dependency in the splashing behavior.
For prompt splashing, we investigate an existing splashing limit proposed by Foltyn et al. [3]: As shown in figure 1, the correlation appears to work well for hydrophilic surfaces with structure sizes of 0.1 mm and 0.2 mm. However, for the 0.5 mm structures, Foltyn's correlation tends to overpredict the splashing limit, suggesting that additional factors influence the splashing threshold. The correlation also struggles with hydrophobic surfaces, where the splashing limit is lowered further.

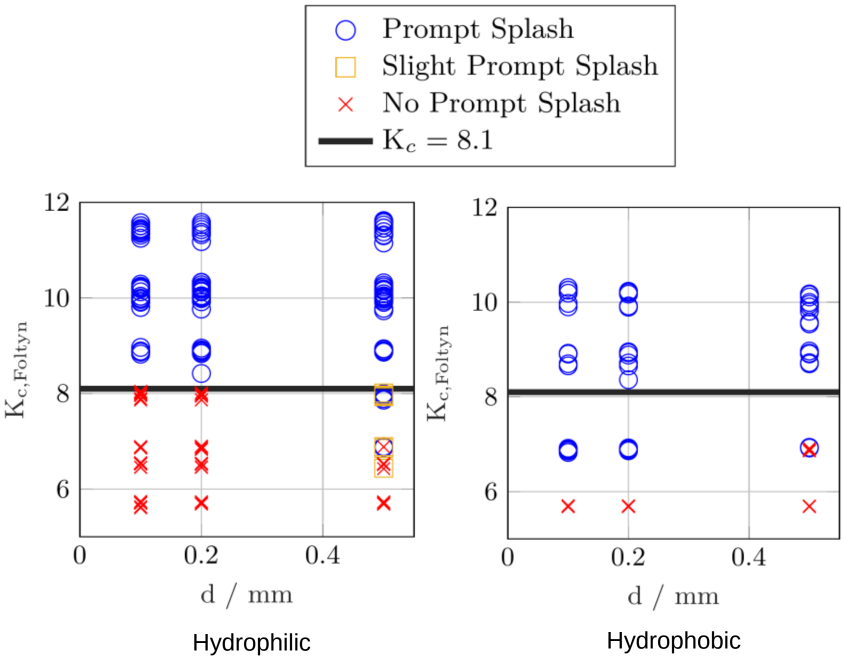


Figure 1: Prompt splashing limits for hydrophilic surfaces and hydrophobic cases.

For finger splashing, a splashing limit has been identified based on the structure-specific Weber number,

$$We_d = \frac{\rho U_0^2 d}{\sigma}$$

where ρ is the liquid density, U_0 is the impact velocity, d is the characteristic size of the structures and σ is the surface tension. The structure-specific Weber number is thus a parameter that accounts for the size of the surface features. This value seems to define a relatively clear threshold for finger splashing as shown in figure 2. However, it is suspected that additional factors, such as the Reynolds number and the ratio of structure size divided by droplet diameter, may further influence the splashing behavior. To better understand these dependencies, further measurements across a broader range of impact conditions, surface types, and droplet sizes are required. Numerical simulations could also help confirm this Weber number threshold and reveal more about the complex mechanisms driving finger splashing.

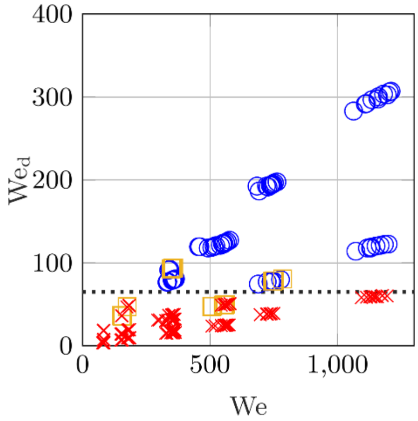
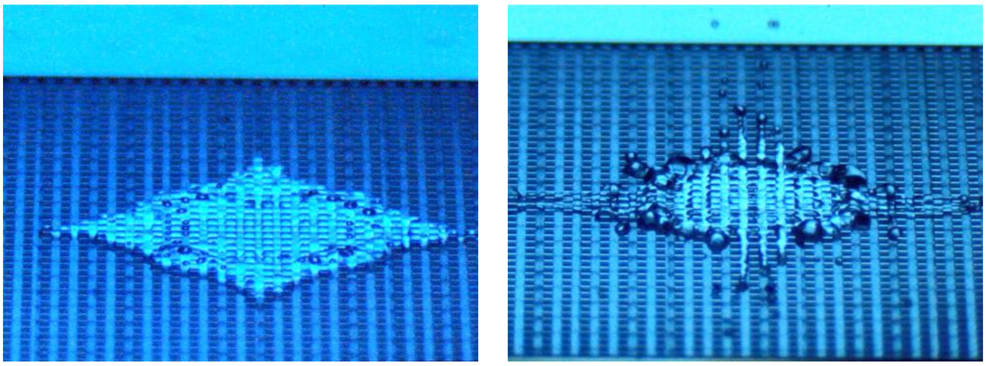


Figure 2: Finger splashing limits for all wettabilities

In addition to the primary splashing modes discussed, hydrophobic surfaces exhibit an additional splashing mode shown in figure 3, characterized by the ejection of droplets at shallow angles within the grooves. This behavior is here referred to as ligament splashing, where liquid jets propagate along the grooves of the surface structures and break up, as opposed to spreading more evenly across the surface. These jets tend to detach from the sides of the pillars and groove bottoms, eventually forming ligaments that break up due to the Plateau-Rayleigh instability. Observing and analyzing this splashing mode in greater detail requires further high-speed imaging and



Hydrophilic Hydrophobic

Figure 3: Illustration of spreading on hydrophilic surfaces versus ligament splashing on hydrophobic surfaces

further studies to identify the ejection angles and conditions that contribute to this unique phenomenon. Overall, a deeper investigation into surface wettability and structure size is needed to fully define the splashing limits for both hydrophilic and hydrophobic surfaces, particularly in the context of groove jetting and other splashing mechanisms.

Conclusion

While existing splashing limits can predict prompt splashing well for hydrophilic 0.1 mm and 0.2 mm structures, corrections for hydrophobic surfaces [4] and larger structures are necessary. Additionally, to adequately predict the overall splashing limit, a distinction into prompt splashing, finger splashing and ligament splashing is necessary. While a structure-specific Weber number appears to be predictive for finger splashing, more investigations are necessary to provide a physically sound limit for finger splashing.

References

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