Experimental Observation of the Collision of a Crown with a thin Wall Film during Early Oblique Droplet Impact

J. L. Stober*[1], K. Schulte[1], M. Santini[2]
[1]Institute for Aerospace Thermodynamics, University of Stuttgart, Germany
[2]Department of Engineering and Applied Sciences, University of Bergamo, Italy
*Corresponding author: jonathan.stober@itlr.uni-stuttgart.de

Introduction

In most spray impact scenarios in technical applications, many droplets impact obliquely on a wetted wall. The mechanisms behind crown and finger formation as well as the splashing characteristic during oblique drop impact are not yet fully understood. Recent oblique impact experiments showed a sudden change in splashing characteristics with an increase in impact velocity. At a certain point, it changes from a late detachment of secondary droplets from one single central finger to splashing starting much earlier and many droplets detach from several fingers. Additional experiments with a higher magnification were conducted to make the early phase of crown development visible and to explain the change in impact morphology.

Experimental Setup

To achieve an oblique impact, the droplet has to be ejected with a horizontal velocity component. Figure 1 (A, B) shows the droplet generator, which was built for that purpose, based on the patent by Santini et al. [1]. It consists of a carriage which is accelerated back and forth in a controlled way by a linear motor. A blunt syringe needle is fixed on it and is supplied with Isopropanol by a piezoelectric pump. Figure 1 (C) illustrates the detachment process. During the high deceleration phase at the front turning point, the fluid within the needle is pushed outwards due to its own inertia and forms a ligament, from which droplets detach. Only the first droplet, with the highest velocity and diameter, reaches the impact point, while the subsequent droplets follow a shorter trajectory. In this study, a needle with an inner diameter of 1.5 mm resulted in droplets in the range of D ≈ 1.5 mm. The produced droplets are nearly spherically and do not oscillate as can be seen from Figure 1 (D), which shows the droplet prior to the impact on the film. Potential oscillations resulting from the forced detachment thus have been damped before impact.

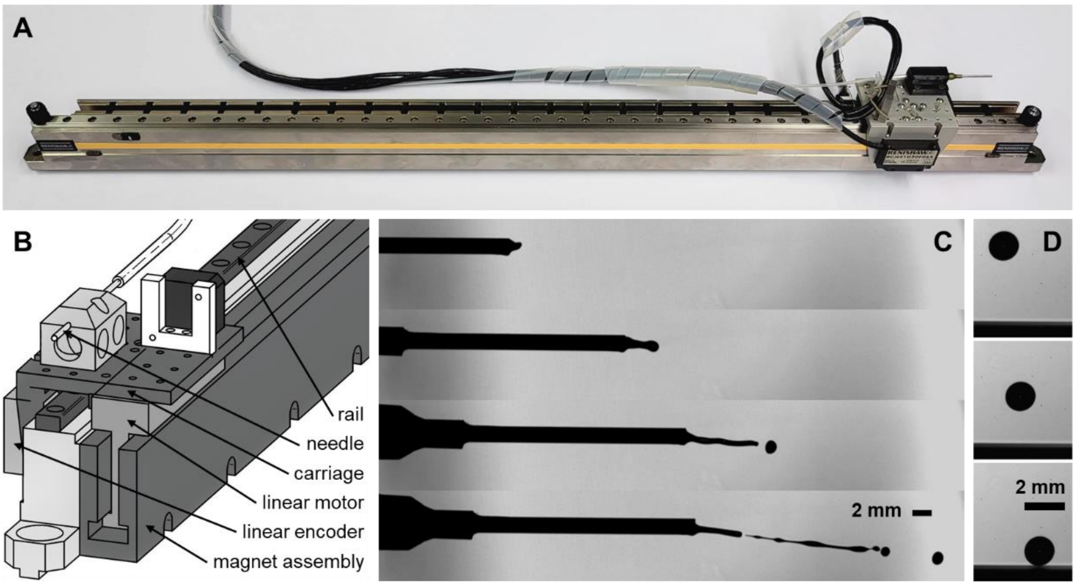

Figure 1. (A) Foto of the oblique droplet generator, (B) sketch of the droplet generator according to the patent by Santini et al. [1], (C) high-speed camera recording of the detachment process, (D) high-speed camera recording of droplet prior to impact onto the liquid film.

The experimental setup is illustrated in Figure 2. The imaging system comprises two synchronized high-speed cameras (Photron Fastcam SA-X2) capturing the process from two perspectives: a side view (blue dash-dotted line) and a front view (red dashed line). For each camera, an LED with a lens acts as a light source for the backlit shadowgraphy. The cameras record with a frame rate of 12,500 fps and a resolution of 1,024 x 1,024 pixels. This results in a relative resolution of 12.1 µm/px for the side view and 21.1 µm/px for the front view. For the impact area, a smooth sapphire glass plate with a size of 50 mm x 50 mm and a thickness of 2 mm is used. The liquid film of isopropanol covers the complete glass plate and is held by its surface tension. The size of the glass plate ensures a flat film in the middle of the plate, where the droplet impacts. Its thickness is measured by a confocal chromatic sensor continuously from below during the experiment to monitor changes due to evaporation. The position and inclination of the droplet generator can be adjusted, as well as the detachment velocity. With that, different impact angles and velocities can be realized independently from each other.

A sketch of the oblique droplet impact onto a wall film is shown in Figure 3. The droplet diameter is determined utilizing an in-house Matlab program, which analyses the side view of the high-speed camera recordings, assuming a spherical shape. Similarly, the impact velocity and angle are also calculated using a Matlab program evaluating the last ten frames before impact. The three different impact conditions shown in this study are summarized in Table 1.

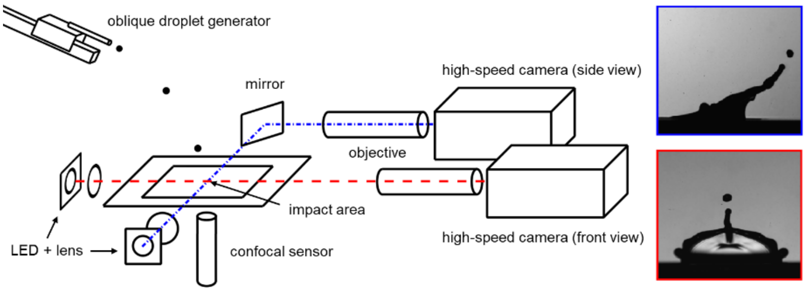

Figure 2. Schematic representation of the experimental setup.

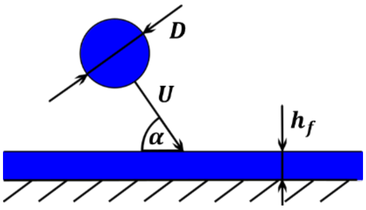

Figure 3. Sketch of an oblique droplet impact onto a wall film.

Table 1. Impact conditions and fluid properties at 22°C

	Exp 1	Exp 2	Exp 3	Uncertainty
Droplet diameter D	1.45 mm	1.49 mm	1.62 mm	± 0.014 mm
Impact velocity U	3.10 m/s	3.35 m/s	3.38 m/s	± 0.025 m/s
Impact angle α	61.7°	59.3°	59.6°	± 0.41°
Dimensionless film thickness δ	0.26	0.24	0.22	± 0.004
Weber number $We = \rho D U^2/\sigma$	508	610	675	
Ohnesorge number $Oh = \mu/\sqrt{\rho\sigma D}$	0.143	0.141	0.136	
Density ρ		784.3 kg/m³		
Surface tension σ		21.5 mN/m		
Dynamic viscosity μ		2.24 mPa/s		

Results and Discussion

Figure 4 presents high speed recordings of the experiments summarized in Table 1. In the left column, the side and front view of the crown development shortly after impact are shown, and in the right column, the resulting crown shape at maximum extension is shown for the front view. For experiment 1 there is no interaction of the early crown with the wall film (A1). This leads to an undisturbed growth of the crown with a stable rim. Only at the front one single central finger forms, from which secondary droplets detach consecutively (B1). With an increase in impact Weber number (experiment 2), the middle part of the early crown on the front side starts to touch the wall film (A2). This introduces disturbances to the rim at this part and leads to a partial rupture of the crown with the growth of two to four comparably thin fingers (B2). Multiple secondary droplets are ejected. With a further increase in Weber number the collision of the crown with the wall film intensifies. We now observe a collision of the complete front side of the crown and the ejection of tiny droplets (A3). This is followed by a rupture of the rim at the complete front half of the crown leading to many fingers and many secondary droplets (B3).

An increase in the number of fingers and secondary droplets with an increase in Weber number is well known and was described before for normal droplet impacts as well as oblique impacts, [2-3]. However, the here described change in splashing characteristic is not only resulting from the general increase in Weber number, but additionally by the collision of the early crown with the wall film. This leads to a more fundamental and sudden change in finger formation for small variations of Weber number.

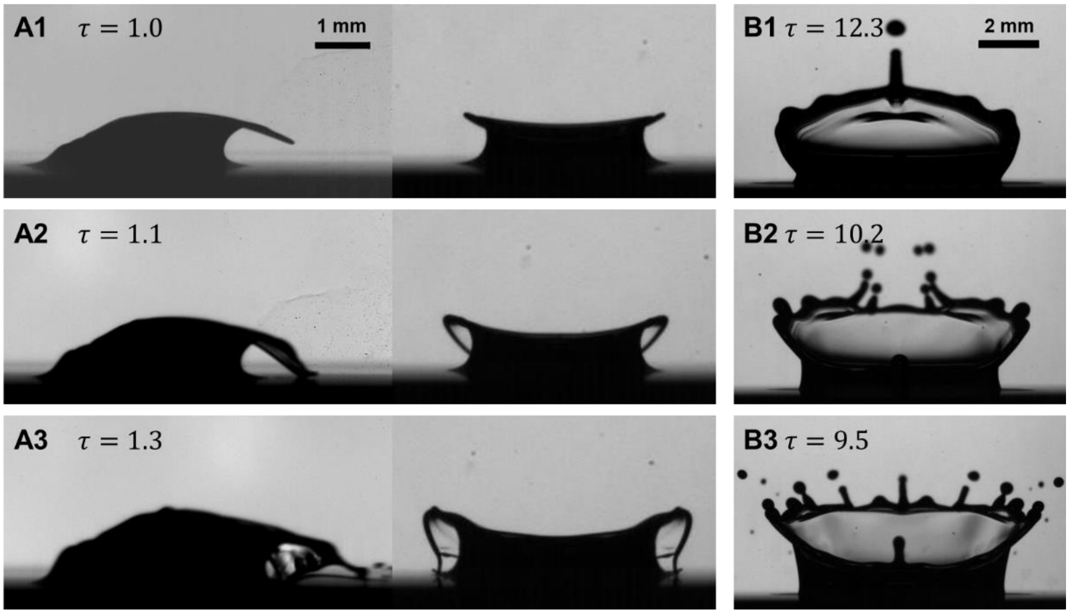

Figure 4. (A) Early crown morphology side and front view, (B) late crown morphology front view for Experiment 1 We = 508, Experiment 2 We = 610, Experiment 3 We = 675, at the dimensionless time after impact $\tau = tU/D$.

Nomenclature

D	droplet diameter [mm]
h_f	wall film thickness [mm]
Oh	Ohnesorge number [-]
U	impact velocity [m/s]
We	Weber number [-]
α	impact angle [°]
δ	dimensionless film thickness [-]
σ	surface tension [mN/m]
μ	dynamic viscosity [mPa/s]
ρ	density [kg/m³]

References

[1] M. Santini, G.E. Cossali, M. Marengo, „Device and Method for Drops Generation“, WO 2010/021004 A1, PCT/IT2008/000554, 22 August 2008

[2] Cossali, G.E.; Coghe, A.; Marengo, M. “The impact of a single drop on a wetted solid surface.” Experiments in fluids 1997, 22, 463–472. https://doi.org/10.1007/s003480050073

[3] Okawa, T.; Shiraishi, T.; Mori, T. “Effect of impingement angle on the outcome of single water drop impact onto a plane water surface.” Experiments in Fluids 2008, 44, 331–339. https://doi.org/10.1007/s00348-007-0406-z