

Central Sheet Formation from Simultaneous Impacts of Two Droplets on a Dry Substrate

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Abstract

This study investigates the temporal and spatial evolution of a central sheet formed due to the interaction of lamellas of simultaneous impacts of two droplets on a dry substrate. A droplet generator released two equal-sized droplets simultaneously on demand. The impact Weber number and the inter-droplet spacing were varied between 54 to 128 and $1.64D_0$ to $2.25D_0$ (D_0 : droplet diameter) respectively to study both deposition and splashing of the central uprising sheets. The sheet temporal evolution reveals its uprising ‘semilunar’ shape, cusps and finger formation, and eventual deposition or splashing behavior. The maximum height of the ‘semilunar’ uprising sheet scales with the inertial force at the lamella-lamella impact location. For cases leading to splashing, rim fingers eject secondary droplets via an end-pinching mechanism and the sizes of the ejected droplets are larger than those commonly observed for equivalent single droplet impacts.

Introduction

Single droplet impact on solid surfaces has been widely investigated and the influencing parameters of pertinent outcomes are extensively revealed. In contrast, limited studies have addressed the more prevalent multiple droplet impacts on surfaces. Upon simultaneous impacts of two droplets with high kinetic energy, the interacting spreading lamellas generate a central uprising sheet (Fig. 1), which modifies the outcome of single droplet impacts. Roisman et al. (2002) reported a theory to estimate the sheet height (H_S) with time t , limited to cases with lamella-lamella impact at dimensionless time $\tau = tV_0/D_0 > 1$ (V_0 is the impact velocity and D_0 is the initial droplet diameter). Recent studies (Gultekin et al. 2021; Ersoy et al. 2020) experimentally investigated the temporal evolution of the central sheet. However, more experimental studies are needed. The central sheet can either deposit or break into droplets and these splash/non-splash outcomes are still unknown. This study characterises these outcomes for a wide range of conditions and proposes a scaling approach.

Experimental Facility

Water droplets impacting on a smooth acrylic substrate (PMMA) were used. An in-house built micro-controlled droplet generator released two droplets at blunt needle tips, simultaneously on demand. D_0 was kept constant at 3.12 ± 0.05 mm. The impact process depends on the dimensionless inter-droplet spacing ($\Delta x^* = \Delta x/D_0$) and impact Weber number ($We = \rho V_0^2 D_0 / \sigma$), where ρ is the liquid density and σ is the surface tension). Experiments were carried out

for different We and Δx^* , achieved by varying the droplet release height and the distance between the needles, respectively. The sample size per experimental case was ≥ 3 .

The impact processes were simultaneously captured by two high-speed cameras at 9000 fps with spatial resolutions of 0.03- and 0.04-mm per pixel, for front and side views, respectively. The recorded images were analyzed using customized MATLAB routines to extract experimental data.

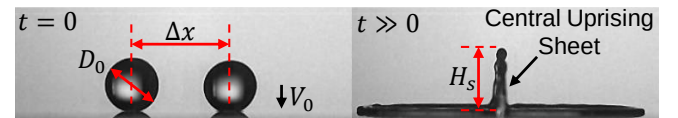


Figure 1: Simultaneous impact of a droplet pair.

Results and Discussion

Fig. 2 shows a typical temporal evolution of a central sheet for $We = 104$ and $\Delta x^* = 1.81$. The sheet rises vertically (front-view) with a rim-bounded ‘semilunar’ shape (side-view), reaches a maximum height ($H_{S,m}$) at $\tau \approx 2$, and then descends vertically due to surface tension and gravity, before depositing on the impact substrate. Multiple cusps appear at the outer sheet rim during its vertical retract. We investigated such sheet evolution for: (i) four different We cases ($We = 54, 80, 104$, and 128) with a fixed $\Delta x^* = 1.81$, and (ii) three different Δx^* cases ($\Delta x^* = 1.64, 1.96$, and 2.25) with a fixed $We = 62$. We find the dimensionless maximum central sheet height ($H_{S,m}^* = H_{S,m}/D_0$) increases with increasing We or decreasing Δx^* . $H_{S,m}^*$ depends on the lamella-lamella impact inertia, which is responsible for

the initial vertical velocity of the sheet. By analogy to a single droplet impact on a dry substrate, a lamella impact Weber number can be defined as $We_L = F_C/\sigma$, where the lamella-lamella collision force $F_C = 2\rho V_L^2 T_L$ with V_L and T_L , respectively, as the velocity and average thickness of the lamella edges during their impact (Fig. 2). We_L increases with increasing impact We or decreasing Δx^* , and Fig. 3 shows the dimensionless maximum sheet height $H_{S,m}^*$ of the ‘semilunar’ sheet as a function of We_L , for all impact We and Δx^* cases. For each case, the average and the corresponding standard deviation are presented. We find a best-fit scaling law as $H_{S,m}^* \sim We_L^{0.48}$, with R^2 value 0.99.

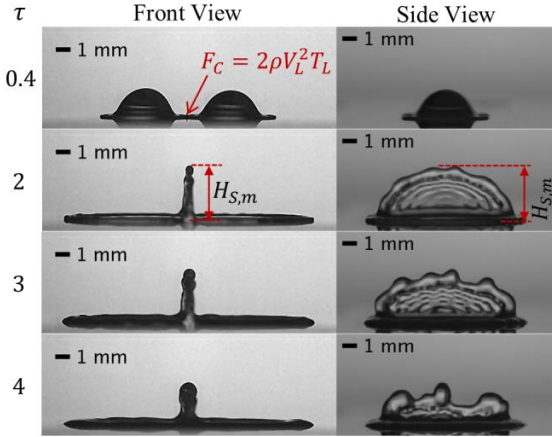


Figure 2: Deposition of uprising ‘semilunar’ sheet ($We = 104$ and $\Delta x^* = 1.81$).

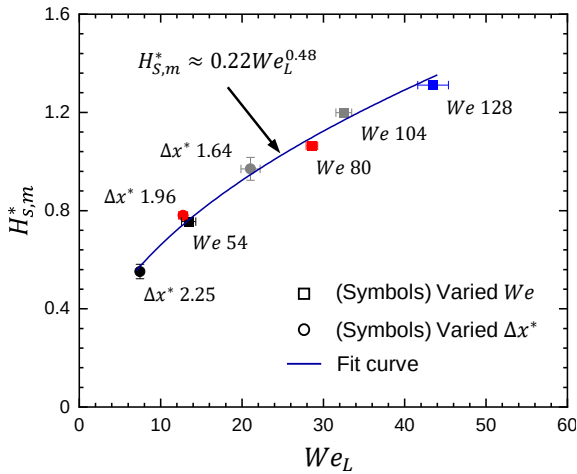


Figure 3: Effect of lamella impact Weber number on the dimensionless maximum sheet height.

For $54 \leq We \leq 128$ with $\Delta x^* = 1.81$, the central sheets reach their maximum height with insignificant rim instability, retaining the ‘semilunar’ shape. However, the rim instability becomes pronounced if the sheet rises sufficiently, as observed for an increased impact $We \approx 155$ (Fig. 4). Due to the increased sheet height, gravity starts to dominate over surface tension on decelerating the central sheet, leading to multiple cusps on the ascending sheet. Several finger-like cylindrical jets emerge from these cusps, grow with time, and

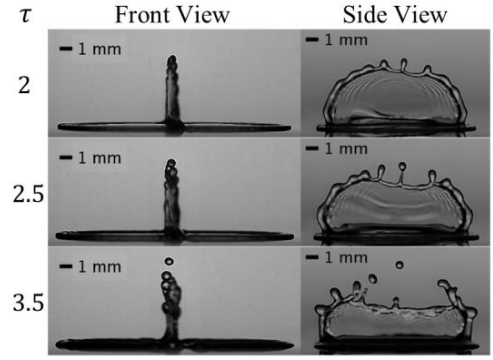


Figure 4: Central sheet splashing.

disintegrate into secondary droplets, i.e., splashing occurs. It is noted that a single droplet impact under the same conditions leads to simple deposition.

The length (l_j) and width (w) of the jets that eject secondary droplets are $l_j \approx 4.2w$, which is less than one wavelength of the fastest growing Rayleigh-Plateau (RP) instability, i.e., $\lambda_{RP} = 4.5w$ (Rayleigh 1878). Therefore, the detachment of the secondary droplets does not occur due to the Rayleigh breakup of jets, rather it occurs via ‘end-pinching’ of the retracting jets. We quantify that the arithmetic mean diameter (d_{10}) of secondary droplets is 22–26 % of the initial droplet diameter D_0 , in contrast to d_{10} of 2–3 % of D_0 for an equivalent single droplet splashing. Therefore, central sheet splashing generates one order of magnitude larger droplets than those from single droplet splashing.

Conclusion

The evolution of the central sheet formed from the impact of a droplet pair on a surface is studied and the maximum sheet height and the splashing behavior are quantified. For varied impact Weber numbers and inter-droplet spacings, the maximum sheet height scales with the inertia at lamella-lamella impact. During sheet splashing, the secondary atomization occurs via end-pinching of retracting jets and leads to overspray of much larger droplets than those from single droplet impacts.

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