

The crown: Rolling splash

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For over a century, the impact of drops on thin films or deep pools has captivated the fluid dynamics community, beginning with the seminal experiments of Worthington [1] and Edgerton [2]. This topic is fundamental to multiphase flow, with applications ranging from industrial coatings and inkjet printing to meteorology and environmental sciences. Consequently, it remains an active and inspiring area of research that has led to several comprehensive reviews on the subject [3–5]. While many studies focus on the idealized case of a perfectly spherical-shaped drop impacting vertically on a flat liquid layer, real-world scenarios often deviate from this simplified model because of various types of perturbations. For instance, Bird *et al.* [6] investigated how tangential velocity influences droplet impact on a surface, demonstrating that it can either enhance or suppress splashing depending on impact conditions. Similarly, Che *et al.* [7] conducted experimental studies on drops impacting inclined flowing liquid films, revealing a range of behaviors including bouncing, full coalescence, and asymmetric splashing.

The role of impact angle has also been explored by Gielen *et al.* [8], who examined oblique drop impacts on deep pools, highlighting the complexities introduced by non-normal collisions. Beyond these kinematic variations, the internal composition and morphology of the drop can also significantly alter the impact dynamics. Zhao *et al.* [9] studied drops containing solid particles, illustrating how particulate matter affects splashing and penetration behaviours. Singh and Kumar [10] performed numerical simulations that account for droplet impact dynamics on a deep liquid

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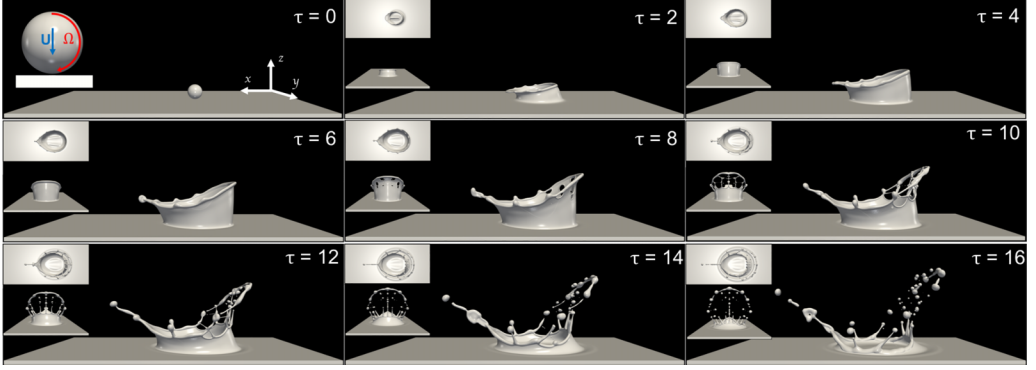


FIG. 1. Evolution of the rolling splash with $Re = 1000$, $We = 800$, $H = 0.2$, and $Rr = 1$. Snapshots are provided every $\Delta\tau = 2$ with the panels to be read going from the top left (at $\tau = 0$) to the bottom right ($\tau = 16$). See the Supplemental Material [21] for the corresponding animation.

pool with a wavy free surface. More recently, Liu *et al.* [11] designed experiments to precisely control the drop shape (either oblate or prolate) before impact, offering new insights into how initial geometries influence fluid interactions. Despite these advances, a comprehensive understanding of how various real-world irregularities collectively shape droplet impact behavior remains elusive.

The interplay of impact angle, drop composition, film properties, and external forces introduces a rich parameter space that continues to challenge experimentalists and theorists alike. Addressing these complexities is crucial for refining predictive models and optimizing practical applications that rely on precise control of droplet behavior. Although all of the different deviations are from idealized configurations, it is common for drops to rotate before impact. For instance, when a drop slides across a superhydrophobic surface, such as a lotus leaf, it often acquires rotational motion. As a result, when the drop detaches from the leaf and descends toward a liquid layer, it is likely to maintain this rotation before impact. Hence, in this work, we present simulation results that capture the three-dimensional spatiotemporal evolution of a rotating drop impacting a thin liquid layer, offering insights into this complex dynamic process.

We examine a spherical liquid droplet with a diameter D impacting a liquid layer of thickness h . Both the droplet and the underlying liquid possess a constant density ρ , dynamic viscosity μ , and surface tension σ . The droplet descends at a constant velocity U prior to impact, while simultaneously rotating at a steady angular velocity Ω about an axis parallel to the liquid layer. To analyze the system, we select characteristic scalings: D for length, U for velocity, D/U for time, and ρU^2 for pressure. In this study, we neglect the effects of gravity. The system is characterized by several nondimensional parameters, including the Reynolds number $Re = \rho U D / \mu$, the Weber number $We = \rho U^2 D / \sigma$, the layer ratio $H = h / D$, and the impact rolling ratio $Rr = 0.5 \Omega D / U$, which quantifies the relative initial contribution of pure-solid rotational motion of the drop to its purely translational vertical impact motion. Notably, the classic scenario of droplet impact is retrieved by setting $Rr = 0$. For our numerical simulations, we solve the two-phase Navier-Stokes equations within a three-dimensional Cartesian domain, $\mathbf{x} = (x, y, z) \in [0, 20D] \times [0, 8D] \times [0, 6D]$, while employing a high-fidelity Lagrangian-based level contour reconstruction method [12] to track the fluid-fluid interface. The computational domain is distributed across $20 \times 8 \times 6$ subdomains (processor cores), with each subdomain being resolved using a grid of 64^3 . Consequently, the global resolution for the simulation is $1280 \times 512 \times 384$, allowing for an accurate representation of the fluid dynamics involved in the droplet's impact on the liquid layer. We refer readers to Shin *et al.* [12] for the numerical details.

Figure 1 highlights the temporal evolution of the rolling splash configuration with the following control parameters: $Re = 1000$, $We = 800$, $H = 0.2$, and $Rr = 1$. In the absence of initial rotational

motion ($Rr = 0$), the splash outcome would have been identical to the findings of Constante-Amores *et al.* [13], where the crown shape would have remained circular. However, adding an initial rotational motion around the y axis for the drop distorts the circular shape of the thin liquid crown, giving rise to two distinct regions: an oval-shaped rear and a sharp angular front. In the early stages of the splash, a distinctive thin liquid crown forms, initially adopting an oval shape that extends more rapidly upward than backward (see Fig. 1 for $\tau = 2, 4$, and 6). In contrast, the front side, which assumes a quasiangular form, advances more swiftly forward than it does vertically. Furthermore, the rim above this thin crown exhibits differing instabilities: At the rear, it tends to form a smooth quasi-non-wavy, toroidal shape, whereas at the front, it develops a more wavy, Rayleigh-Taylor pattern (see Fig. 1 for $\tau = 2$ and 4), which seems to travel slightly faster along the rim in comparison to the global growth of the thin liquid sheet below it. Consequently, the front angular tip corresponds here to the collision point for the two laminar rim jets, leading to the formation of a “fluid-chain” jet [14–18]. A fluid chain is a periodic structure formed when two laminar liquid jets collide obliquely, creating interconnected liquid bridges or films resembling a chain. Johnson *et al.* [14] first described these formations, while Bush and Hasha [15,16] analyzed their morphology and dynamics, referring to similar structures as fluid “fishbones.” Later studies [17,18] further examined fluid chains, showing that their formation depends on parameters such as jet velocity, viscosity, and collision angle. In our case, the front fluid-chain jet extends up until it reaches a critical threshold length, at which point it undergoes a Rayleigh-Plateau instability, ultimately breaking apart into a series of small droplets.

The rear side of the crown, which appears as a curved thin film, is taller than its front counterpart. Consequently, the thickness of this film is significantly reduced, making it more vulnerable to rupture in multiple locations. This increased susceptibility leads to the formation of interfacial punctures, which subsequently evolve into expanding holes that grow radially outward. The growth of these holes can be associated with the various fragmentation mechanisms detailed in Lo *et al.* [19] (see Fig. 1 for the case where $\tau = 8$). In contrast, if the liquid sheet were to remain planar rather than adopting a curved form, the rims of adjacent holes would collide directly and head-on. Such collisions would facilitate a straightforward generation of lamella and ejecta [19]. However, the curvature of the thin film of the crown alters this dynamic. Instead of perpendicular collisions, the interaction between adjacent holes occurs at an angle. This angular head-on interaction results in the formation of spinning, twisted ribbons, which deviate significantly from the simple ejecta structures that would have emerged in a planar configuration (see Néel *et al.* [20]). This nuanced behavior emphasizes the impact of curvature on the fragmentation process and the resulting morphology of ejected materials. The term “twisted ribbons” is relatively new, introduced by Lo *et al.* [19]. It describes a liquid filament that, instead of undergoing typical capillary retraction or Rayleigh-Plateau breakup, twists into a helicoidal shape. The authors have shown that when two holes grow and collide on a curved liquid film, the merging edges form a twisted ribbonlike filament rather than a flat rupture. This structure arises from the interplay of capillary forces, film curvature, and hole dynamics.

Figure 2 vividly demonstrates the phenomenon of twisted ribbons. In this visualization, we observe that the holes forming in the upper section of the crown, situated just beneath the nearly smooth rim, interact dynamically with adjacent expanding holes, and eventually collide with the rim which in turn induces a complex, deforming spinning motion of the rim itself, while it continues to expand both radially and vertically. As time progresses (see Fig. 1 for snapshots at $\tau = 12, 14$, and 16), we can see significant changes in the morphology of the rim evolve into a wavy arch-shaped filament. The entire rear section of the crown becomes populated with elongated, spinning, and twisted filaments that ultimately retract and fragment into numerous tiny droplets, particularly noticeable in Fig. 1 at $\tau = 16$. In contrast, the front part of the crown, specifically the region lying between the rear section and the upward jet, maintains a thicker crown layer devoid of any observable punctures. Consequently, this frontal section of the crown experiences downward retraction due to the Taylor-Culick retraction effect, operating smoothly without any interfacial puncture or the expansion of holes. At the moment of film retraction, the angular-shaped rim at the top ceases to act as a source for the fluid-chain jet, as illustrated in Fig. 1 for $\tau = 14$ and 16. This

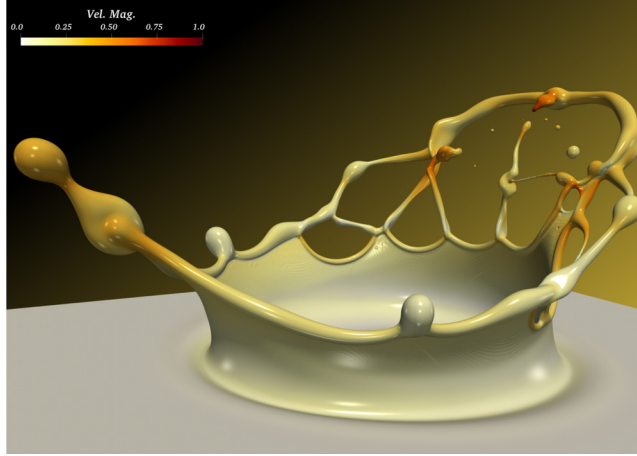


FIG. 2. The crown: A global view of the rolling splash with $Re = 1000$, $We = 800$, $H = 0.2$, and $Rr = 1$. This snapshot is generated at a nondimensional time $\tau = 9$, presented during the APS-DFD annual meeting 2024: <https://doi.org/10.1103/APS.DFD.2024.GFM.P2685516>

distinct behavior contrasts starkly with the dynamic events occurring at the rear, further highlighting the complex fluid dynamics at play in this phenomenon.

This study provides an analysis of rolling drop impacts, revealing a fascinating interplay of interfacial phenomena in extraordinary detail. Among the most remarkable observations are the formation of an unconventional crown structure, the dynamics of interfacial punctures followed by rapid hole expansion, the emergence of delicate fluid-chain formations, and the development of intricately twisted filaments that ultimately retract and fragment into a myriad of tiny droplets. These findings represent a significant leap forward in understanding the complex dynamics of rolling drop impacts, while also illuminating the intricate interplay between interfacial instabilities and fluid motion. The insights garnered from this work establish a strong foundation for future research, which could extend to a broader exploration of rolling motions under diverse impact conditions. This includes investigating the influence of varying initial drop shapes, transitioning from thin-film configurations to deep pool scenarios, and examining the effects of surface contaminants such as surfactants, and also a rolling impact scenario on substrates. Additionally, probing other regimes could yield even deeper insights into these complex phenomena. Ultimately, this research not only enriches the fundamental understanding of fluid dynamics but also opens the door to innovative applications across a range of fields, from industrial processes to advanced material design, heralding exciting possibilities for both theoretical exploration and practical advancements.

The numerical simulations were performed with the code blue [12] and the visualizations were generated using paraview.

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Data availability. The data that support the findings of this article are not publicly available upon publication because it is not technically feasible and/or the cost of preparing, depositing, and hosting the data would be prohibitive within the terms of this research project. The data are available from the authors upon reasonable request.

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