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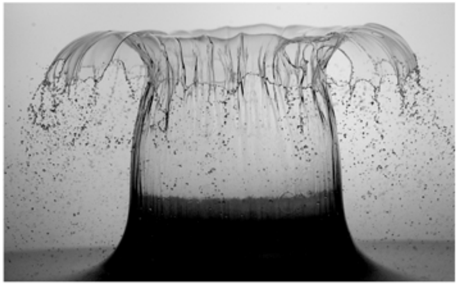
Wrapping up a century of splashes



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Few fluid phenomena are as beautiful, fragile and ephemeral as the crown splash that is created by the impact of an object on a liquid. The crown-shaped phenomenon and the physics behind it have mesmerised and intrigued scientists for over a century, and still the scientific world has not yet uncovered all of the secrets of the splash. This is exemplified in a particularly striking manner in Marston *et al.* (*J. Fluid Mech.*, vol. 794, 2016, pp. 506–529) where a 6 m tall vacuum chamber is employed to study the splash formed upon impact of a sphere onto a deep liquid pool, at both atmospheric and reduced ambient pressures. They shed light into the classical problem of the surface seal and study the buckling of the splash. With an almost magical touch they devise a method to create a splash without the liquid and the sphere ever coming into contact. The images that accompany the paper – taken with state-of-the-art high-speed cameras – are as stunning as the physics that is uncovered in them.

Key words: instability, interfacial flows (free surface), thin films

1. Introduction

There are few phenomena in fluid physics that are as beautiful and at the same time so ephemeral as the splash that is created when an object impacts on a liquid surface. Indeed, much of the beauty of the splash would remain unnoticed if it were not for the advent of fast photography. By the turn of the nineteenth century, Worthington (1908) used an ingenious set-up to capture the splash of an impacting droplet, the duration of which was too short compared to the shutter time of the mechanical photographic devices available at that time. He used an electric spark to illuminate the event in a dark room, triggered by a 'timing sphere' which, using electromagnets, was made to fall at exactly the same time as the droplet in the dark room. This resulted in astonishingly crisp images such as the one shown in figure 1(*a*).

The development of modern day high-speed photography (Versluis 2013; Josserand & Thoroddsen 2016) added submillisecond time resolution to the measurements.

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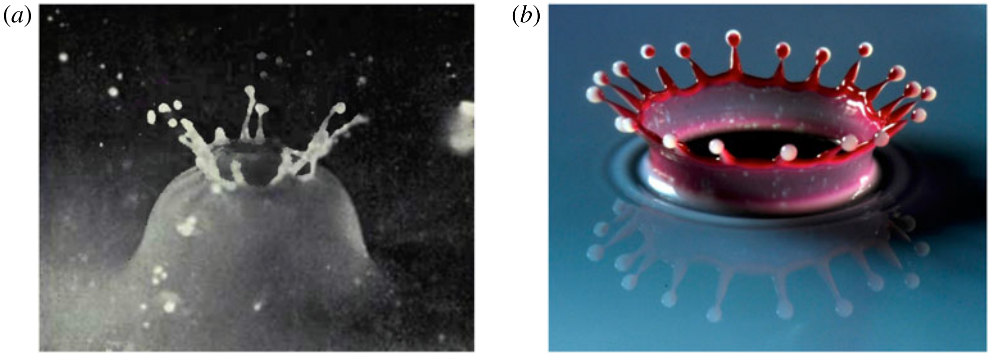

FIGURE 1. (*a*) Splash created after the impact of a rough sphere onto a liquid as recorded by Worthington (1908). (*b*) Impact of a milk droplet containing red dye onto milk. This image has been created using high-speed still photography (from Versluis 2013).

This adds valuable insight into the dynamics of the splash. An example is the splash that results from the impact of a droplet onto a shallow pool and very much resembles a king's crown (cf. figure 1(*b*)). From this, we learn how liquid of both the impacting droplet (coloured red) and the liquid pool (in white) combine during the formation of the splash. Both colours remain visible throughout; even at the very tip of the droplets that crown the splash.

The reason behind the creation of the splash may already be understood from the flow of an ideal fluid. This is the famous Wagner problem where it is proven that the liquid that needs to be displaced from below an impacting plate leads to the formation of a sharply peaked splash at its edge (Wagner 1932; Scolan & Korobkin 2001). The finer details however, such as the exact shape of the splash, the reason behind its break up into droplets and the surface seal and buckling are much more difficult to fathom and notoriously hard to describe theoretically (Yarin 2006; Krechetnikov 2010; Zhang *et al.* 2011; Peters, van der Meer & Gordillo 2013). For example, the precise mechanism that produces exactly the number of droplets in the crown splash seen in figure 1(*b*) remains subject to scientific scrutiny.

Marston *et al.* (2016) deal with a particularly complex problem, namely that of the surface seal and its companion, the buckling instability.

2. Overview

The paper of Marston *et al.* (2016) studies the markedly thin splash that is created by a sphere impacting onto a deep liquid pool (figure 2). While penetrating into the liquid, the sphere creates a void in its wake which is open to the ambient air. As this void deepens and expands, air needs to flow into the cavity – indicated by the red arrows in figure 2(*b*) – which creates a lower pressure at the inside of the splash, causing it to close in upon itself, the so-called surface seal. In order to systematically study this phenomenon the authors controlled the ambient pressure during the impact experiment. More specifically, they built a 6 m tall vacuum chamber, allowing for ambient pressures ranging from just above the vapour pressure (1/16 bar) to atmospheric values (1 bar).

As expected Marston *et al.* (2016) found a significant dependence of the surface seal phenomenon on the ambient pressure. However, the delay of the crown splash seal at lower pressures was not as large as one would expect if only the pressure difference were responsible for the closure. Together with the observation that the

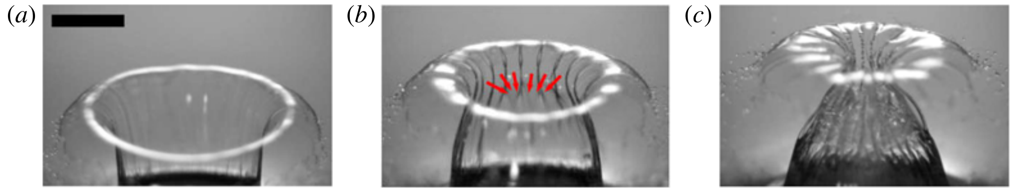

FIGURE 2. Surface seal and buckling instability of a 10 mm diameter sphere impacting on water. The images are taken at $t = 2.7$, 3.5, and 4.4 ms from impact and the red arrows in (*b*) indicate the airflow into the void (from Marston *et al.* 2016).

closure speed is largely independent of ambient pressure, this strongly points to the importance of yet another force for the surface seal, namely that due to surface tension. They argue however that both forces are significant, and even if surface tension in the end may drive the collapse of the splash, the surface seal phenomenon should be viewed as the confluence of pressure and surface tension effects.

The paper is not only ingenious in its conclusions, but also in the smaller details. Such as the velocity of the sheet of which the splash is built, measured by tracking particles that happen to be present in the crown. Or the thickness of the sheet, estimated from the opening speed of holes that spontaneously form inside the splash.

The second part of the article is about the buckling of the splash, which occurs approximately when the splash, during closure, progresses through a cylindrical shape, as is clearly visible as the wavy pattern along the circumference of the splash in figure 2(*b*) and the vertical ribbon-like structures of figure 2(*c*). The onset of the buckling is an example of a hydrodynamic instability. This is a phenomenon in which the liquid spontaneously changes its shape and/or appearance. The waves that emerge on an otherwise quiet lake subject to the action of the wind result from such an instability, just like the break up of a thin water stream from a faucet into droplets. The size of the ultimately observed structures, such as the length of the wave and the diameter of the droplets, are already determined by this initial instability. More precisely, by that unstable wavelength that has the largest growth rate.

But Marston *et al.* (2016) went beyond the mere characterisation of the buckling instability and connected the wavy pattern that is visible in the crown in figure 2(*b*) all the way down the cavity to another instability, namely one that occurs on the surface of the sphere. The waves created by this contact line instability could be traced over the entire cavity wall and connected to the wavelength of the buckling instability arising in the splash. Thus it appeared that the buckling instability inherited its wavelength from the contact line instability on the sphere.

This, in itself, is already a remarkable conclusion, but the authors did not stop there. They asked themselves what wavelength they would observe in the splash in the absence of the contact line instability. This would have been a rather artificial question if the authors had not come up with a trick to actually realise such a situation in experiment. They exploited the Leidenfrost effect, the observation that a droplet can be made to hover for minutes on its own vapour, when deposited on a plate which is heated to a temperature above the Leidenfrost point. When a metal sphere heated to well above the Leidenfrost point impacts on a liquid, a vapour layer forms around the entire sphere, which creates a void and a splash without ever coming into physical contact with the liquid. This almost magical trick completely avoids the contact line instability. The conclusions that the authors could draw from this experiment was that, in absence of the contact line instability, the buckling still occurred with a wavelength slightly different from that observed in the original experiment, but that its growth was significantly postponed. This stands to reason, since now the buckling instability needed to occur on its own, without being assisted by the wave pattern imposed by the contact line instability.

3. Future

Many strong conclusions were drawn in Marston *et al.* (2016) but arguably the most significant one is that of the link between the contact line and buckling instabilities, which appears to be connected to the fact that the most unstable wavelengths in both cases happen to be similar. An intriguing point is what would happen if this were not the case. The authors tried to control the wavelength of the contact line instability by etching patterns and creating alternating hydrophobic–hydrophilic stripes on the surface of the sphere. A great idea which unfortunately failed, yet strengthens the diameter scaling for the buckling that was proposed in the article. However, since the buckling and the contact line instability appear to be governed by different physics, would it be possible to separate the most unstable wavelengths by going to a different scale? Or would it be conceivable to induce a different type of instability on the cavity wall by adapting the shape of the object?

One of the remaining puzzles in the field is determining what controls the number of droplets that is produced from the crown splash. The work of Marston *et al.* (2016) suggests that the number of droplets in some cases may not be controlled by an intrinsic instability of the crown's rim, something that has been assumed in most of the works that have dealt with this problem. Instead it may very well be connected to another instability, such as the contact line or buckling instability. In this light, it would be challenging to see if the number of droplets can actually be controlled by imposing another instability onto the splash. It is even conceivable that a link between the two instabilities as observed by the authors may actually be more common, and something that the fluid dynamics community should be aware of.

A final word of praise must go to the superb, almost artistic, quality of the images that are presented in Marston *et al.* (2016). They bring experimental research based on high-speed imaging to a very high standard, which is commendable for all areas of science in which imaging techniques play an important role.

References

JOSSERAND, C. & THORODDSEN, S. T. 2016 Drop impact on a solid surface. *Annu. Rev. Fluid Mech.* **48**, 365–391.

KRECHETNIKOV, R. 2010 Stability of liquid sheet edges. *Phys. Fluids* **22** (9), 092101.

MARSTON, J. O., TRUSCOTT, T. T., SPEIRS, N. B., MANSOOR, M. M. & THORODDSEN, S. T. 2016 Crown sealing and buckling instability during water entry of spheres. *J. Fluid Mech.* **794**, 506–529.

PETERS, I. R., VAN DER MEER, D. & GORDILLO, J. M. 2013 Splash wave and crown breakup after disc impact on a liquid surface. *J. Fluid Mech.* **724**, 553–580.

SCOLAN, Y.-M. & KOROBKIN, A. A. 2001 Three-dimensional theory of water impact. Part 1. Inverse Wagner problem. *J. Fluid Mech.* **440**, 293–326.

VERSLUIS, M. 2013 High-speed imaging in fluids. *Exp. Fluids* **54** (2), 1–35.

WAGNER, H. 1932 Über Stoß- und Gleitvorgänge an der Oberfläche von Flüssigkeiten. *Z. Angew. Math. Mech.* **12** (4), 193–215.

WORTHINGTON, A. M. 1908 *A Study of Splashes*. Longmans, Green, and Co.

YARIN, A. L. 2006 Drop impact dynamics: splashing, spreading, receding, bouncing. *Annu. Rev. Fluid. Mech.* **38**, 159–192.

ZHANG, L. V., TOOLE, J., FEZZAA, K. & DEEGAN, R. D. 2011 Evolution of the ejecta sheet from the impact of a drop with a deep pool. *J. Fluid Mech.* **690**, 5–15.

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