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USING DROP IMPACTS TO STUDY THE DYNAMICS OF SUB-MICRON LIQUID STRUCTURES

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ABSTRACT: We use ultra-high-speed video imaging, at frame-rates up to 1 million fps, to study the dynamics and breakup of both submicron sheets of liquid and submicron films of air. When a drop impacts onto a pool surface at sufficiently high impact velocity, it produces a fast-moving horizontal ejecta sheet, which emerges from the neck connecting the drop to the pool. This sheet can stretch to become as thin as 0.2 microns, before it breaks up into a myriad of secondary droplets. We show the rich dynamical evolution which can emerge, where this sheet can interact with the drop or the pool surface. We also identify a transition to random splashing, which is associated with a vortex shedding instability. When the drop impacts at very low velocities, the air under it can cushion the impact and prevent direct contact between the drop and the pool. The thin air layer under the drop is then stretched into a hemisphere and only ruptures when it becomes of the order of 100 nm thick. The breakup of this air is extremely rapid, but the high-speed imaging allows for well controlled studies of the air film puncturing and resulting entrapment of micro-bubbles.

INTRODUCTION. The impact of a drop onto a solid surface or a pool of the same liquid, is a canonical problem which has been studied experimentally for over a century, since the pioneering work of Worthington (1907). This physical configuration occurs in many natural processes and industrial applications, from rain erosion, pesticide application, inkjet printing, spray coating to spray cleaning, Yarin (2006). One aspect of particular importance is the splashing which can occur for high enough drop impact velocities. For example, when rain hits the ocean, the fine splashed droplets can evaporate, leaving fine salt crystals and other aerosols. If these aerosols are carried by wind up in the atmosphere, they can act as nucleation sites for cloud formation, thereby completing this transformation back into a drop. Splashing can be detrimental, such as when it affects the uniformity of coatings, or it can be beneficial for example when smaller droplets are produced within combustion chambers, when the spray hits the walls of the combustion chamber. Splashing can cause cross-contamination when inkjet printers are used in bio-medical applications.

A second effect of importance is the entrainment of air bubbles into the bulk liquid. This hastens the transport of gas, which is of great importance for organisms living in lakes and oceans. For low impact velocities the cushioning air-film under the impacting drop can stretch into a very thin hemisphere, which then breaks up into a myriad of fine bubbles. Small bubbles of gas are easily dissolved into the liquid, owing to the large capillary pressure.

Besides being of great practical importance, drop impacts also produce flow configurations which are difficult to produce in any other way. For example by entrapping a very thin disc of air under the center of the drop. The dynamics of some of these phenomena would be difficult to study in any other way, as we show in this study.

The dynamics of the impact are difficult to study due to the very rapid motions involved and also due to refraction of light through the curved free surfaces, when the drop deforms greatly during the impact. Only in the last decade have high-speed video cameras become fast enough to effectively study the details of these phenomena. Herein, we will present video images, taken at extreme frame-rates, of up to 1 million frames/sec, where new phenomena continue to be observed. We will also show numerical simulations which can capture some of the details, for the axisymmetric impact configuration.

EXPERIMENTAL SETUP. In this study we use an ultra-high-speed CCD video camera, which can take 102 frames, at frame rates up to 1,000,000 fps, designed by Etoh *et al.* (2003). This camera uses on-chip storage of the video frames, thus allowing for the rapid frame-rate without reducing the number of pixels in each frame. Each frame contains 260 by 312 px, irrespective of the frame-rate used. At the very high frame-rates needed getting sufficient lighting becomes a key issue. Herein we use high-intensity continuous metal halide lamps (Sumita). These lamps are cool, to minimize thermo-capillary effects. The imaging is done with long-distance microscopes (Leica and Mitutoyo), which give optical magnifications up to about 20, to allow for optical resolution down to about 1 μm/px.

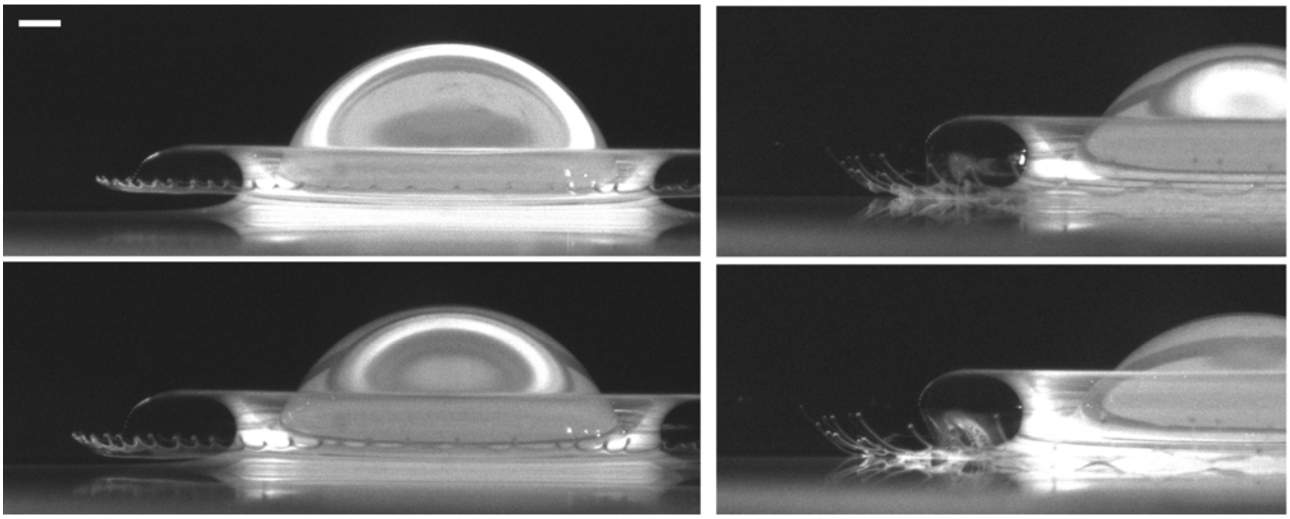

Fig. 1. The ejecta sheet produced by the impact of a drop onto a pool surface. Image-pairs taken with a dual frame PIV camera. The scale bar is 1 mm long.

THIN LIQUID EJECTA SHEETS. When a drop hits a pool, at sufficiently high impact velocity, a thin ejecta sheet emerges at high speed from the neck region connecting the drop to the pool liquid, Thoroddsen (2002). The thickness of these ejecta sheets is initially of the order of 10 μm, but subsequently can stretch and thin down to 350 nm before they break up into micro-droplets, in what we call a 'sling-shot' mechanism, Thoroddsen *et al.* (2011). We are able to deduce the thickness of the liquid sheet by measuring the velocity of the sligh-shot droplets, assuming they are ejected purely by the surface tension, which pulls the edge of the sheet. This velocity is a function of the sheet thickness. Measuring the velocity will therefore let us estimate the thickness of the liquid sheet, when it touches the pool surface. The speed by which the eject emerges increases with higher Reynolds number. However, this does not continue forever, but at a certain high impact velocity the ejecta becomes unstable and breaks immediately into fine droplets. Our imaging shows this to occur when the ejecta starts to interact with the drop surface itself. We call this interaction 'bumping' and it leads to the break-up of the ejecta. We have also successfully performed numerical simulations of this aspect of droplet splashing, where we use the open source software Gerris, developed by a French group (Popinet & Zaleski), with whom we are collaborating, Thoraval *et al.* (2012). Using generous KAUST computational resources we have been able to resolve unprecedented details of the splashing dynamics, never before possible, as shown in Figure 2 below. This is only possible with extreme adaptive grid refinement, using up to 15 levels of refinement. This has revealed the presence of a vortex street, when vortices are shed from the base of the ejecta sheet to enter the bulk liquid through the interface between the drop and the pool. The sharp corner at the base of the ejecta leads to separation of the vorticity generated by the flow past the curved free surface. The frequency of this shedding is in good agreement with the Strouhal frequency for the shedding from a cylinder, but here the dynamics occur so fast, that the period is only a few micro-seconds.

Fig. 2. Numerical simulations of the vortex street generated inside an impacting drop, similar to Thoraval *et al.* (2012). The red colour indicates liquid from the drop and the blue from the pool.

THIN AIR SHEETS. On the inverted problem, we have recently visualized the breakup of very thin air sheets, within a bulk liquid. This is accomplished by impacting a drop onto a pool of the same liquid (Figure 3). At very low impact velocities the cushioning air layer can stretch into a stable hemispherical sheet of air, which only breaks when it punctures through van der Waals forces. For water the rupture is very irreproducible, but for silicone oils the ruptures occur in identical fashion from one drop to the next, see Saylor and Bounds (2012). Our measurements using ultra-high-speed video imaging suggest this occurs when the film has thinned down to around 100 nm in thickness, Thoroddsen *et al.* (2012). We have investigated numerous liquids, of different viscosities and discovered three distinct mechanisms of film rupture for this experimental conditions, one is shown in Figure 3. For the lowest impact velocities the surface tension absorbs the kinetic energy and drop simply bounces without making contact with the pool. At slightly higher impact velocity, the hemispheric sheet ruptures at isolated points and holes grow very rapidly in the air layer. The edge of the hole can travel at over 10 m/s, for the lowest viscosity silicone oils. For still higher impact velocities, the air film ruptures simultaneously at numerous locations along a horizontal ring of ruptures. When the air-sheet unravels it leaves behind a distribution of micro-bubbles which resembles a chandelier. For the lowest viscosities, the drop can deform so much it generates an internal jet, which travels through the drop, to emerge at its bottom, where it deforms and ruptures the film. This leads to axisymmetric dynamics, where the speed of the ruptures changes depending on the local thickness of the air film. In general the film is thickest at the bottom under the drop and becomes thinnest along the sides of the hemisphere. This is indeed where it usually ruptures first. For very viscous liquids the breakup of the air sheets progresses through repeated ruptures of the edge of the hole, at speeds much larger than expected. This speed of the edge-ruptures can be an order of magnitude faster than expected by capillary-viscous balance.

DISCUSSION. The impact and splashing of a drop may seem like a very messy process. However, the very large parameter space available for study, allows us to generate various flow configurations of free-surface flows, which would be very difficult to set up in any other way. For example, the central disc of air is about 1 mm in diameter, but is only 1 micron in thickness, therefore representing an aspect ratio of one thousand. This may indeed be the best experimental configuration available to study the breakup of thin layers of gas and our early experiments have revealed many surprising effects. One can for example contemplate the impact of liquids with different properties between the drop and the pool, or the impact of a heavy liquid through a lighter intermediate liquid, which will then replace the air. Different density gases can also be employed. The vast parameter space is bound to produce more surprises in the future.

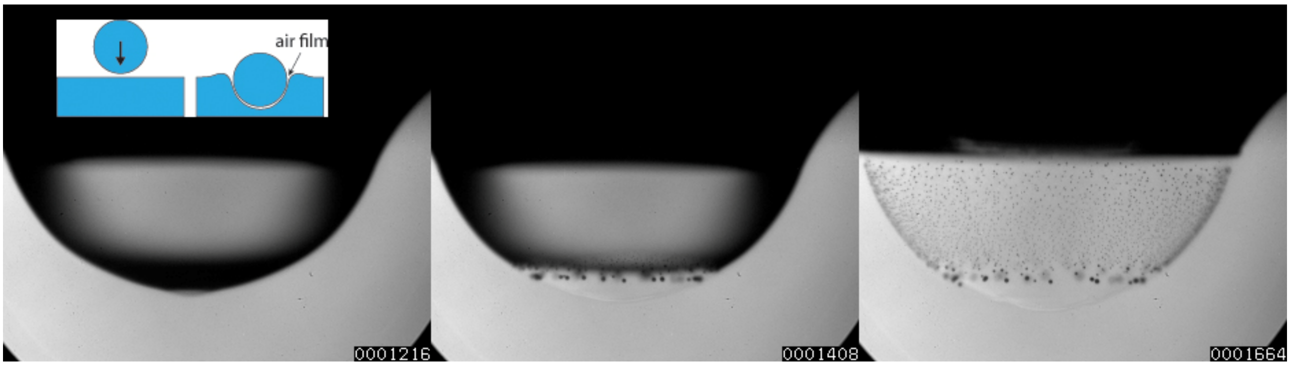

Fig. 3. The breakup of a hemispheric sheet of air caught under an impacting drop, similar to Thoroddsen *et al.* (2012). The numbers at the bottom right are in micro-seconds.

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