IMPACT OF SINGLE AND MULTIPLE DROP ARRAY ON A LIQUID FILM

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ABSTRACT

The paper reports an experimental investigation of water drop array impact onto a thin liquid film. The drops were of millimetric size and were impacting simultaneously on the liquid film. Different impact velocities (275<We<515) and film thickness were investigated. A high resolution CCD camera was used to visualize the phenomenon and image analysis techniques were then used to extract quantitative data from the images. Comparison with single drop impact, under the same experimental conditions, allowed to evidence the effect of crown-crown interaction of secondary atomisation and, generally, on the impact morphology. Liquid structures are formed by the crown interaction and their subsequent break-up give rise to further secondary atomisation if the impact velocity is sufficiently high. The crown interaction can produce splashing also for impacting conditions under which single drop impact would not give rise to splash, thus lowering the splashing threshold.

INTRODUCTION

There exists experimental evidence that a spray impacting onto a surface, even if initially dry and heated, is leaving a spreading, wavy liquid film [1]. The subsequent impact of drops occurs then onto a wetted surface. It is widely recognised that drop impacts onto dry and wetted surfaces are considerably different (see for example [2,3]).

The outcomes of a drop impact onto a solid surface covered by a liquid film can result into a disruptive phenomenon (*splashing*) when the impact velocity (Weber number) is sufficiently high [4], initiating with the generation of a liquid crown. From the crown some jets may be ejected and secondary droplets can be generated (a phenomenon usually defined as *secondary atomisation*). A large number of physical variables may influence the splashing, among them the characteristics of the impacting drop (velocity, density, viscosity, surface tension, oscillations, impact angle and impact frequency), the solid surface characteristic (If the liquid film is thin) and the liquid film thickness are probably the most important. If the impact velocity is sufficiently high, a liquid lamella is ejected when the drop touches the liquid film and *prompt splash* may take place with formation of very small secondary drops. Subsequently, a liquid crown is formed yielding liquid jets that breaking-up produce secondary drops (*late splash*).

The prompt ejection of the liquid lamella, already observed by Worthington [5,6], was initially considered caused by the formation of a compression pressure wave inside the drop after the impact [7,8,9]. Recently Weiss and Yarin [10] showed that the pinching of the jet may be due to a torus-like deformation formed by inertia effects at the very beginning of the impact as in fact the time-scales for the jetting formation due to the liquid compression should be much shorter than the observed pinch-off timing.

The formation of the crown and its speed were theoretically analysed in the case of impact on a wetted solid surfaces by Yarin and Weiss [11] and they suggested a dependence of the crown radius on time following a square root law. Roisman and Tropea [12] generalised the theory suggesting that the crown radius should depend on the liquid film thickness. Trujillo and Lee [13] extended the theory to the viscous case showing that the viscosity plays a small role for the compared regimes. Under proper impacting conditions, liquid jets are generated from the crown rim, lately they can break-up to form the secondary drops. The dimensionless group $K = WeOh^{-0.4}$ was found to be the discriminating variable of the splash [4,11,14,15,16,17]: when K is greater than a critical value (function of the film thickness) the splashing occurs.

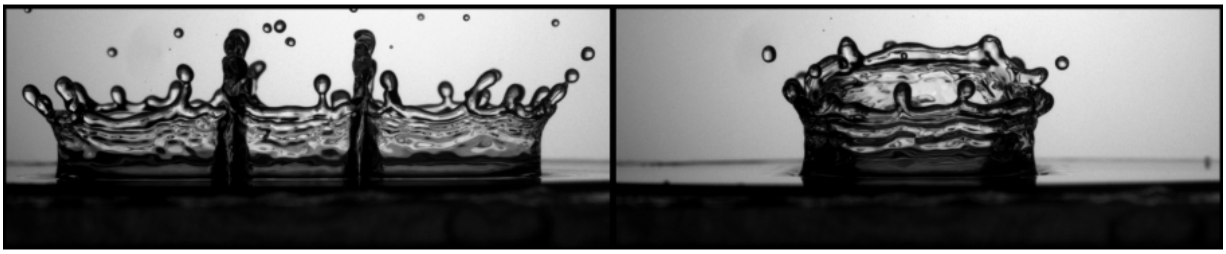
The effect of adjacent drop impact onto a liquid film is expected to modify the splash outcomes, as the crown-crown interaction may strongly change the morphology. The study of such phenomenon is an unavoidable step toward a better comprehension of the spray-wall interaction, as the results obtained from single drop impact, although indispensable for the understanding of the complex phenomena taking place after impact, cannot be straightforwardly extrapolated to multiple drop impact.

The present paper reports the first investigation of this phenomenon under well defined impacting conditions. The range of investigated Weber number (110-500) was chosen to span over the splashing threshold (see [4]) to evidence the effect of crown-crown interaction also when single drop splash is inhibited.

EXPERIMENTAL SET-UP

An innovative drop array generator, capable to produce drop arrays "on-demand" of various configurations, was designed and built. Distilled and de-gassed water was used as working liquid. An array made by three drops on a line was used as it is the simplest configuration to study the effect of adjacent drop interaction. The drops were impacting vertically on the surface. After performing an experiment with the drop array, collecting data for different times after impact (up to 100 ms after impact, at least 30 pictures were collected for each time to have a statistically acceptable sample size), two needles out of three were screened to allow a single drop falling with the same impact conditions of the experiments with the array. The liquid film was made by filling a thin pound by the working liquid. The liquid film thickness was measured by a mechanical gauge: a steel needle was lifted by a micrometric screw and the distance from the pound bottom and the upper liquid surface was measured with accuracy better than 30μm. A capillary based draining system assured the control of the film thickness, whose repeatability was estimated to be better than 50μm. The impacting drop size was kept constant to 3.1 mm.

A high resolution CCD camera was used to acquire the images from two different viewpoints (see figure 1) and image analysis allowed to measure different parameters like: secondary drop diameter, crown size (diameter and height), jet number etc. The phenomenon was observed acquiring pictures at short intervals (from 0.8 to 1.9 ms) during the first period of impact (about 20 ms) and with larger intervals later on, to cover all the crown evolution period. As the main target of this first work was to analyse the effect of crown-crown interaction on the splashing mechanism, experiments were repeated under exactly the same conditions for single drop impact. Three impact velocities and three liquid film thickness (h) were analysed, allowing to cover the ranges 110-515 for the Weber number, and the range 0.2-1.0 for the non-dimensional film thickness ($\delta=h/D$).



(a) (b)

Figure 1. Front view (a) and side view of the drop array impact

RESULTS AND DISCUSSION

The images acquired by the CCD camera allowed to evidence the effect of crown-crown interaction on the splashing outcomes. The image analysis allowed also to quantify the effects through the measurements of secondary drop size and distribution, and some crown parameters, like crown heights and diameters. The emphasis will be put on the morphology of the drop-drop interaction phenomena, comparing to the single drop impact under the same conditions.

Morphology of the Impact

The three drop line-arrays were produced with a frequency low enough to assure that no interactions between subsequent drop array impacting on the liquid film may take place. Figure 2 and 3 reports the sequence of the impact for an impact velocity of 3.48m/s and film thickness of 0.6 mm. The non-dimensional time reported is always evaluated as: $\tau=tV/D$. The main characteristics of the phenomenon can be inferred from the comparison of the pictures reported. The crown evolution during the interval $\Delta\tau=1$ is practically the same for single and multiple drop impact, as during this time the crowns generated by the impact do not interact effectively. After this first non-interacting period, that obviously depends on the crown velocity, (which in turn depends on impact velocity) and the drop spacing (defined as the distance between the centre of adjacent drops, 7.5mm in the present case) the crowns start interacting and generating two liquid sheets (one for each crown-crown interaction), moving vertically (the second and third column of figure 2 show clearly those structures from two different viewpoints).

Figure 2. Sequence of impact for single (1st column) and multiple drop impact (front view: 2nd column, side view: 3rd column)

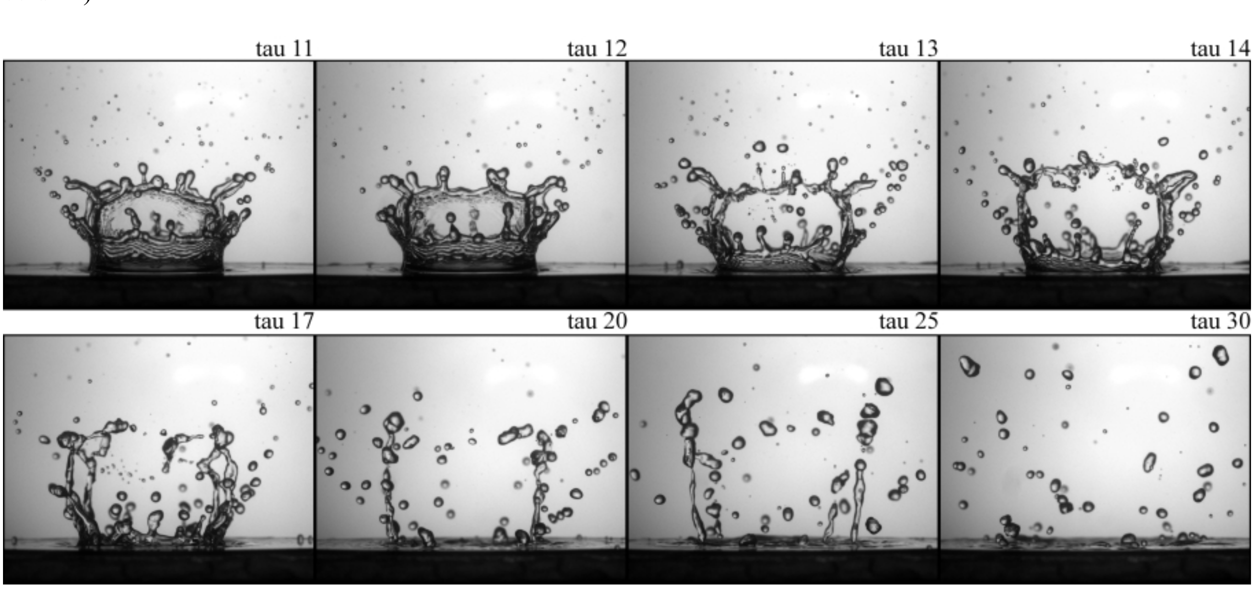


Figure 3. Side view of three drops impacting simultaneously at V=3.48m/s, on a film 0.6mm thick.

This effect is quite important relatively to secondary atomisation, as in fact those liquid sheets subsequently break-up (τ=11 and τ=14 in figure 2) yielding drops and liquid ligaments of relatively large size when compared to the size of the droplets generated by prompt splash (figure 2, τ=1) and crown splash. These liquid sheets are characterised by an upper rim moving upward and growing in size, from which jets may protrude and break up (by Rayleigh instability , τ=11 figure 2). Later on, the inner liquid lamella pierces and the rim breaks into large drops and ligaments (see the sequence of figure 3).

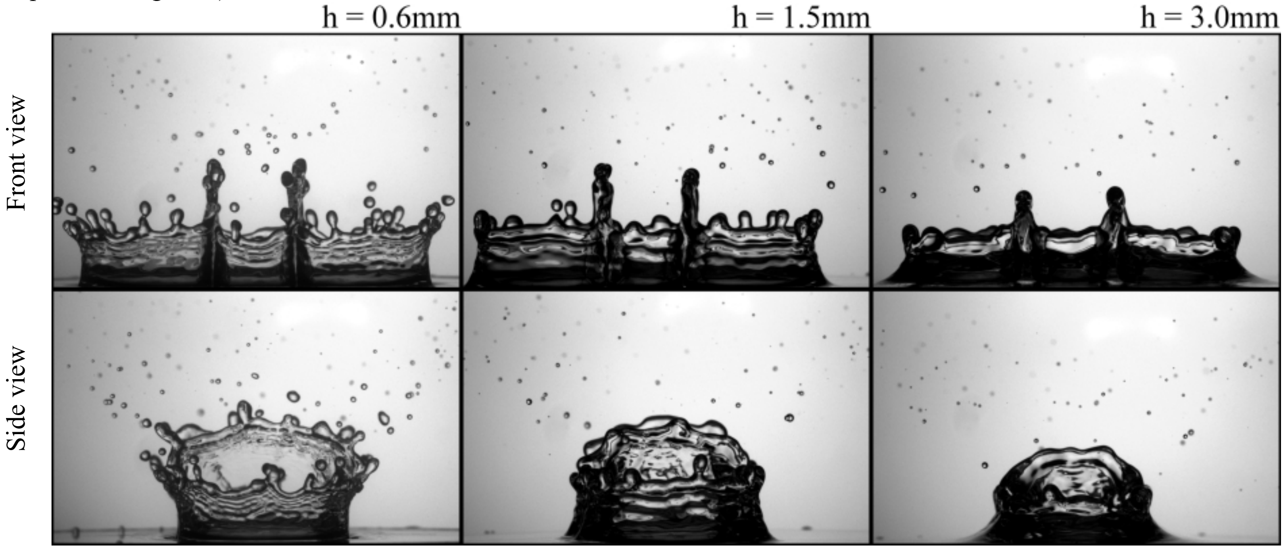


Figure 4.a Effects of film thickness on the liquid structure evolution (τ=10).V=3.48 m/s

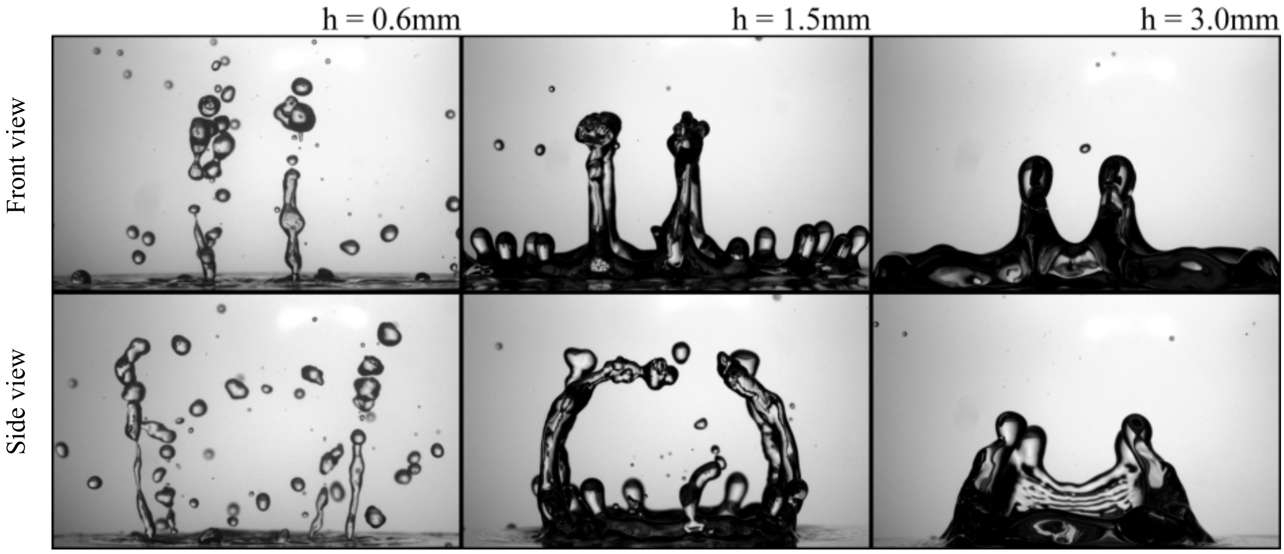


Figure 4.b Effects of film thickness on the liquid structure evolution (τ=25).V=3.48 m/s

The effect of the film thickness (*h*) is quite critical, as increasing *h* decreases the tendency to generate secondary drops (splash is inhibited by film thickness increase). Figures 4 reports the effects of film thickness on the liquid structure evolution. The impact kinetic energy is dissipated quickly with larger liquid thickness, thus the crown-crown interaction is weakened and the vertical liquid sheet growth is slower. Moreover, for the larger film thickness, the energy let to the liquid sheet is not enough to cause the disruption and surface tension prevails, causing the implosion of the structure. The effect on secondary atomisation is remarkable: only the prompt splash, generated just at the drop impact, produces secondary drops for the larger film thickness, whereas the late splash is completely inhibited. For the thinner film (*h*=0.6mm) the rupture of the vertical liquid sheets produces a considerable amount of splashed drops. Also the effect of impact velocity is important.

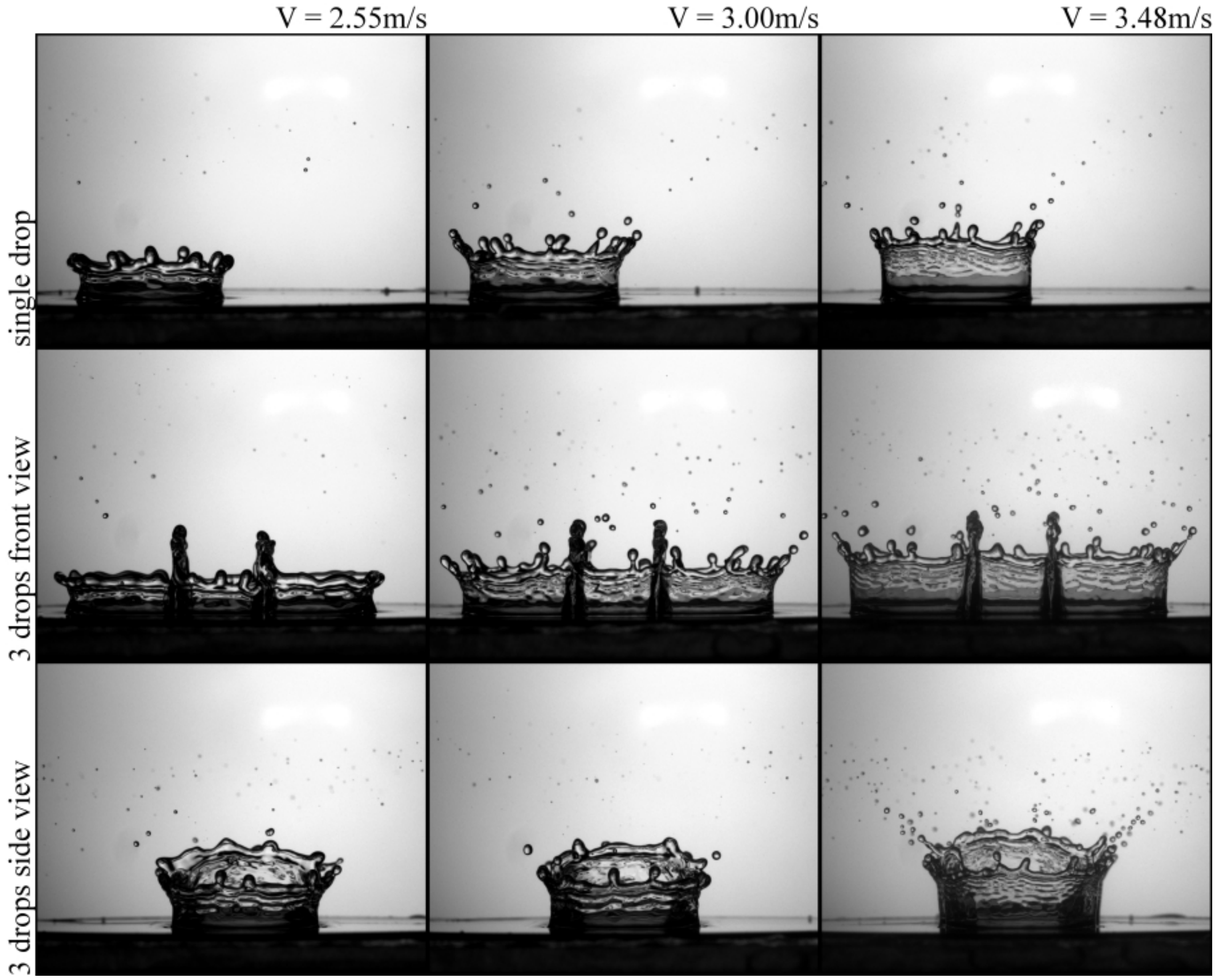


Figure 5 a. Effect of impact velocity at τ=7 for a film thickness of 0.6 mm.

Figure 5 reports the effect for a film thickness of 0.6 mm at two different times after impact, and for three different impact velocity. The decrease of the impact velocity tends to inhibit splashing. It is interesting to notice, by comparison with the single drop impact, that the effect of crown-crown interaction is to improve splashing due to new sites of jet formation on the liquid sheet rim (see the case τ=7, V=3.48 m/s, comparing multidrop and single drop impact), and to produce a later splashing thanks to the disruption of these liquid sheets (see the case τ=13), an effect that it is obviously not present in single drop impact. As expected the crown-crown interaction improves splashing.

Another main result is that splashing may still take place also for impacting condition below the critical threshold for the single drop case, the break-up of the liquid sheet generated by crown-crown interaction yields secondary drops of relatively large size.

At low impact velocity, the liquid sheet evolve without generating secondary droplets, living at the end a sort of liquid bridge (coming from the outer sheet rim). If the kinetic energy of the impacting drop is high enough, the liquid bridge may break-up, otherwise it may survive for larger times (see figure 6).

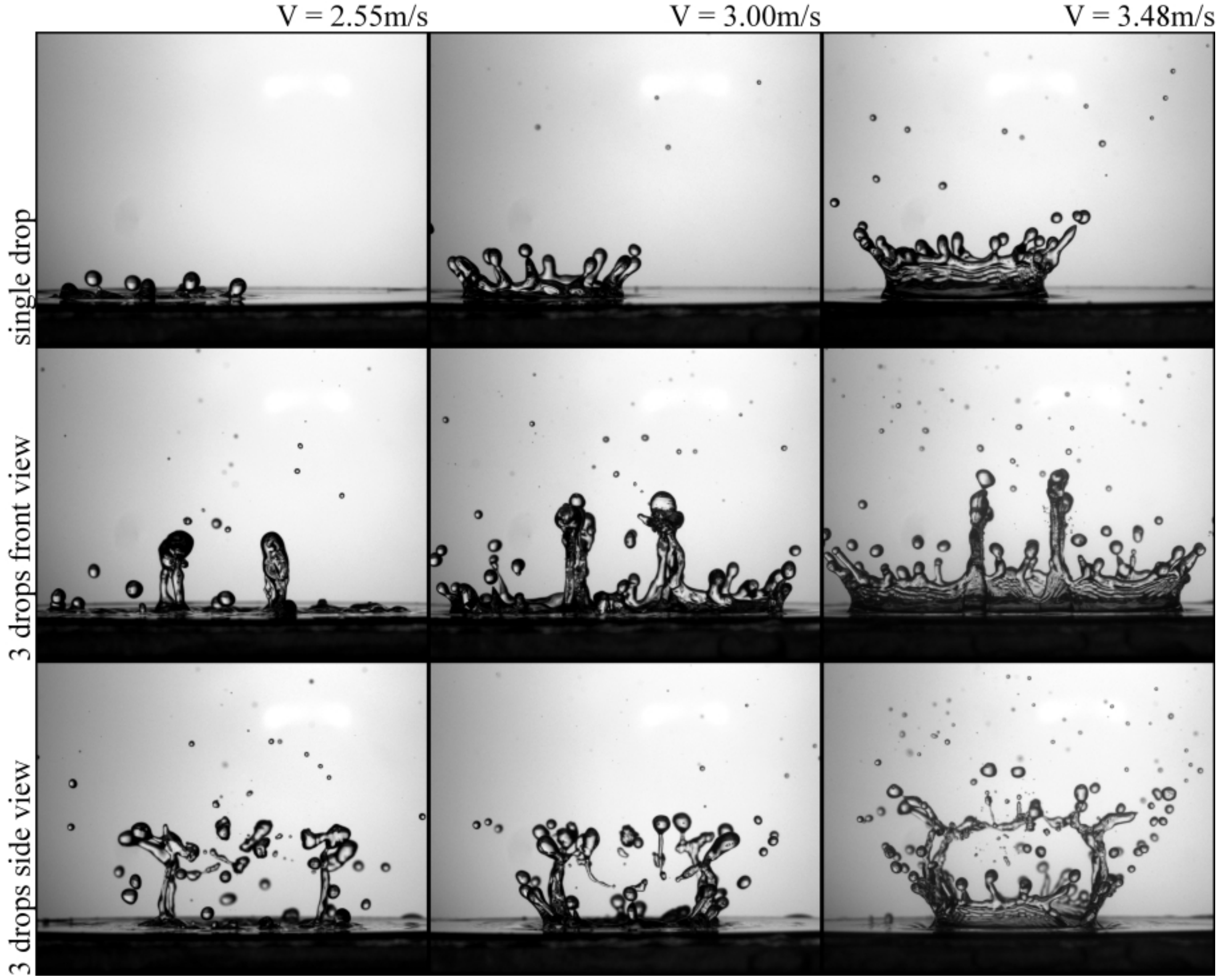


Figure 5b. Effect of impact velocity at τ=13 for a film thickness of 0.6 mm.

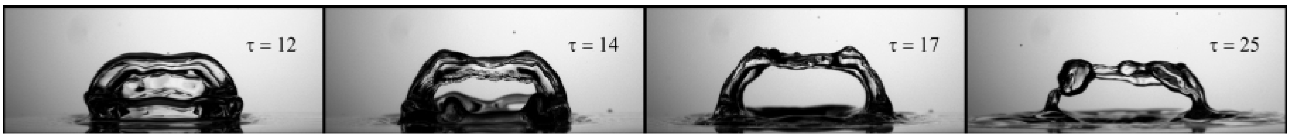


Figure 6. Liquid bridge left by crown-crown interaction at low impact velocity V=2.55 m/s, h=1.5 mm.

Quantitative Analysis

The quantitative effect on secondary atomisation was investigated performing an image analysis of the pictures obtained by the CCD camera.

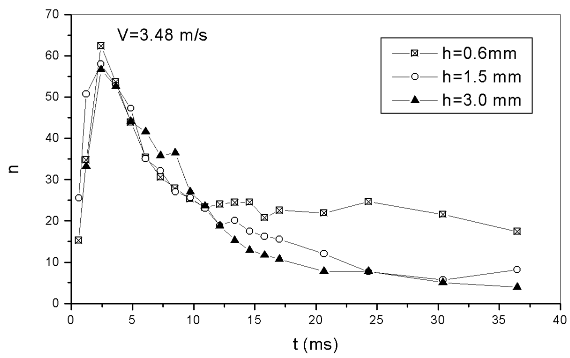


Figure 7. Average number of drops detected per pictures, for the highest impact velocity (3.48 m/s) and three film thickness for single drop impact.

Image analysis was obtained by applying a procedure comprising background subtraction, grey level enhancement, filtering and finally detection of drops. These operations were repeated on all the picture taken at different times after impact, and at each time and for each experiment 30 pictures were taken and analysed, to get an acceptable sample size. Figure 7 reports the average number of drops detected per pictures, for the highest impact velocity and three film thickness for single drop impact, whereas figure 8 reports secondary drop number for single and multiple drop impact (the number of secondary drops is divided by the number of impacting drops). It must be noticed that those data are not representing the total number of drops produced by the splash, as many drops may result out of focus or (in later times) out of the interrogation area. However, the results can be used in comparative form among different experiments. It is interesting to notice that the effect of film thickness is small for the early times (i.e.

during prompt splash) whereas it become important for the late splash. Also, the effect of multiple drop impact seems more important for larger film thickness. The average drop size reported in figure 9 for single and multiple drop impact shows the already observed weak dependence on the film thickness for the early period, but a larger effect for the late impact period, mainly showing that decreasing film thickness increases the secondary drop diameter. The interaction between the spreading lamellae does not appear to have a relevant effect on the average drop size, as the drops coming from the break-up of the vertical liquid sheets are of average diameter similar to those produced by the break-up of the jet protruding from the liquid crowns.

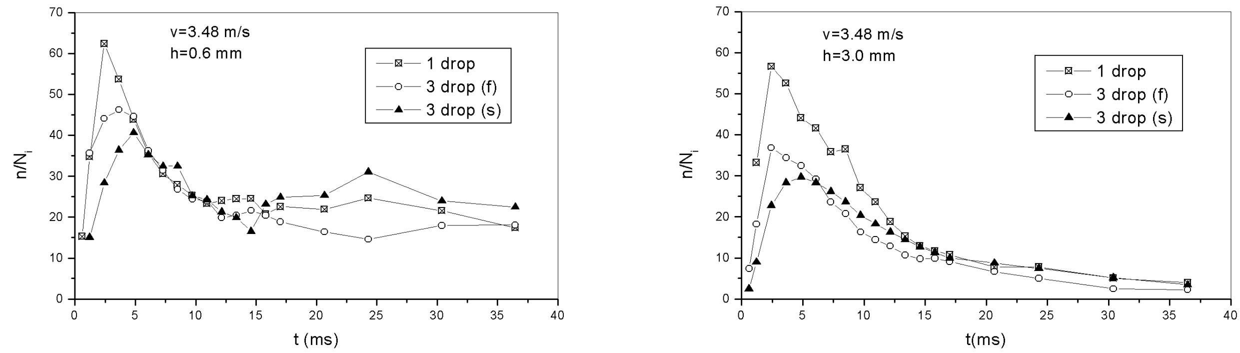


Figure 8. Secondary drop number for single and multiple drop impact (the number of secondary drops is divided by the number of impacting drops) for two film thickness.

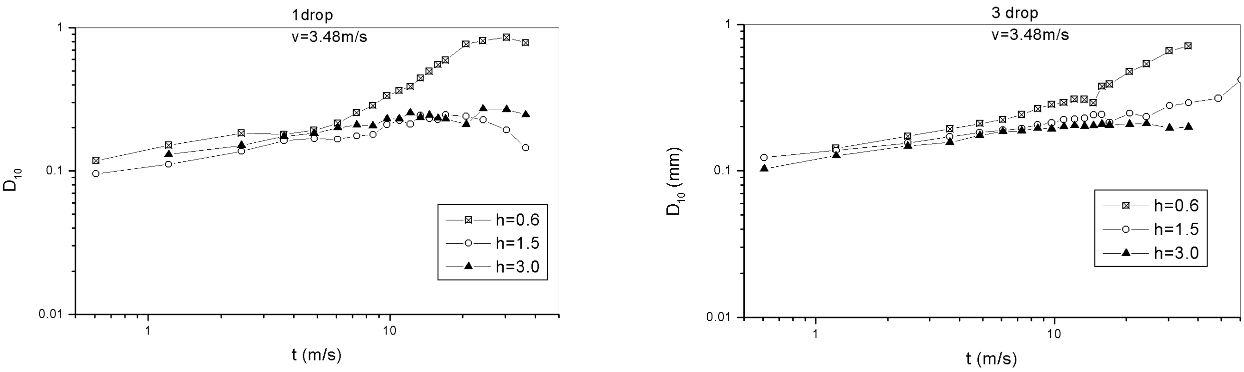


Figure 9. Average drop size for single and multiple drop impact

The effect of impact velocity is much stronger, since the atomisation improves increasing the impact velocity both for single and multiple drop impact (see figure 10). The effect on secondary drops size is peculiar, for single drop impact the lower velocity (closer to the splashing limit) case is characterised by a smaller drop size, due to the fact that only prompt splash (yielding small droplets) is effective in this case, whereas crown splash is virtually inhibited.

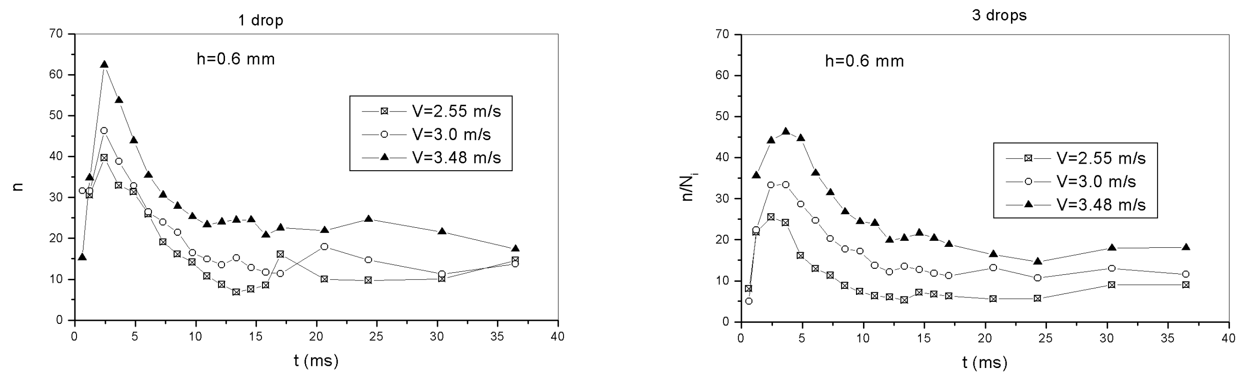


Figure 10. Effect of impact velocity for single and multiple drop impact.

For multiple drop impact, the drop-drop interaction produces larger droplets that increases the drop diameter to a size similar to that of those produced by crown splash.

CONCLUSIONS

The reported investigation about multiple drop impact on liquid film led to the following conclusions:

- The impact morphology is strongly modified relatively to single drop impact, the liquid sheets produced by crown-crown interaction may yield further secondary atomisation during splashing, and the splashing threshold seems to be lowered by this phenomenon.

- Impact velocity strongly influences the break-up of the liquid sheets produced by interaction, that may either splash or implode depending on the kinetic energy available.
- As for single drop, a certain influence of film thickness on secondary drop size is observed, but the interaction among adjacent drops does not seem to change significantly the outcomes.
- The number of splashed drops shows a dependence on the impact velocity (the higher the velocity the larger the number) and the number of secondary drops produced per impacting drops is slightly smaller for multiple drop impact.

NOMENCLATURE

Latin Symbols

D	Drop diameter
h	film thickness
l	drop spacing
T	temperature
V	Drop impact velocity
We	$\frac{\rho V^2 D}{\sigma}$ Weber number

Greek Symbols

δ	non-dimensional film thickness
ρ	density
σ	surface tension
τ	$\frac{tV}{D}$ non-dimensional

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