DROP ARRAY IMPACTS ON HEATED SURFACES: SECONDARY ATOMIZATION CHARACTERISTICS

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ABSTRACT

The paper reports on experimental investigation of multiple drop impacts on heated surfaces. A line array made by three drops of millimetric size impacts on high effusivity surfaces at moderate Weber numbers (110-660) and different surface temperatures to encompass various boiling regimes. A CCD camera and a Phase Doppler Anemometer were used to measure the size of the secondary droplets formed after impact, in a range from 5.5 μm to few mm. The effect of adjacent drop interaction was studied by comparison with single drop impact under the same experimental conditions. The effect of drop spacing was studied by varying the array configuration. The effect of surface roughness is also addressed. Quantitative results are reported together with a qualitative analysis of the impact morphology. A strong effect of the surface temperature on the mean drop size was observed and related to the boiling regimes. The drop spacing was found to influence the drop size of secondary droplets, but the effect is strongly related to the impact velocity.

INTRODUCTION

When a spray impinges onto a surface heated over the liquid saturation temperature, a strong heat transfer from the wall to the liquid takes place. When the wall temperature is sufficiently high a rapid phase transition occurs. To try to understand the complex phenomena characterising the impact, single drop impact was deeply studied by many researchers and work is still needed to obtain a sufficient understanding of the phenomenon. On the other hand, it was observed that extrapolation of data obtained from single drop impact to spray impingement is not straightforward as superposition of effects does not hold. The morphology of the impact of a single drop impact on a heated wall is obviously completely different compared to the isothermal case [1,2]. During the liquid lamella spreading the vapour bubbles generated by the heat transfer rupture the liquid lamella yielding secondary droplets.

The impact phenomenon is influenced by many parameters related to the drop characteristics like impact velocity, surface temperature, impact angle, surface tension, viscosity, etc., and also solid wall properties such as surface wettability [3], effusivity [4,5] and roughness [6,7] are known to influence the process. The boiling regimes, and consequently the atomisation regimes, are usually classified by the surface temperature, relatively to two well known temperatures: the Nukiyama temperature (T_N) and the Leidenfrost temperature (T_L) that was found to depend on many parameters [8]. At low wall temperature (below T_N) the production of secondary droplets is accompanied by a strong lamella contraction after spreading [9,10]. At high wall temperature (above the Leidenfrost temperature) a vapour film is formed under the spreading lamella, yielding a rather different process morphology [10]. There exists experimental evidence [11,12,13] that the interaction among adjacent impacting drops modifies the impact outcomes. One of the major parameter of interest is the drop spacing, as closer drops interact strongly after impact, whereas beyond a certain distance the phenomenon resemble the single drop impact.

The paper analyses experimentally the simultaneous impact of adjacent drops onto a large effusivity (aluminium) hot wall, under moderate Weber numbers ($110 < We < 515$) for different boiling regimes.

EXPERIMENTAL SET-UP

The experimental set-up comprised an impacting wall, made of an aluminium alloy ($AlMg_3$) circular disc, electrically heated from below (350W maximum heating power). The uniformity of the wall surface temperature was checked experimentally, by local measurements of surface temperature, and also through a numerical simulation of the thermal behaviour under different heating conditions. A "on demand" drop array generator was developed and built.

Arrays of millimetric water droplets (distilled and de-gassed water was used) impacting simultaneously on the wall could be generated (discrepancy better than 100µs can be obtained by careful experiment setting), avoiding any production of satellite droplets. Impact velocity was changed by lifting the drop generator at different distances from the impacting wall, with accuracy better than 0.1mm, and measured by means of the CCD camera . Droplet diameter could range from 2.2 to 3.7 mm, but it was kept constant at 3.1 mm for the present experiments.

A CCD camera (colour SensiCam PCO, 1024x1280pixels) was used to acquire the impact images and the acquisition and illumination systems were driven by a light barrier system. A commercial image analysis code (Image Pro-Plus) was used as main environment to develop home built routines for measuring output parameters like average drop diameter, roundness, and post processing allowed rejecting drops having sphericity lower than a given value. Due to the optical set-up (CCD array size and long distance microscope objective), the minimum measurable diameter was about 40µm. A Dantec PDA (Phase Doppler Anemometer) was also used to measure simultaneously the secondary drop velocity (one component) and size. The transmitting optics uses an Ar-Ion, air cooled, mid-power laser (300mW) at the wavelength of 514.5nm (green light). An off-side angle of 70° was chosen, since it reduces to a minimum the sensitivity of the measurements to the refractive index as the secondary drop temperature was unknown. The set-up allows measuring the drop size from 5.5µm to 250 µm and this overlaps partially the range allowed by using the CCD camera (from 40µm to few millimetres), allowing to reconstruct the entire drop size PDF from few mm to millimetres. The acquisitions were triggered by the same system used for the CCD camera

An array made by thee drops on a line was investigated as this was considered the most useful and simple form to obtain first information on the drop-drop interaction processes, due to the symmetry of the configuration.

Wall temperatures was varied from 80°C to 260°C, two surface roughness were used (see Table 1) and impact velocities ranged between 1.65 and 3.48 m/s. The drops were impacting vertically on the surface at a rate low enough to assure that no residual liquid was present on the wall when the subsequent drops were impacting. After performing an experiment with the drop array, collecting data for different times after impact (up to 30 ms after impact), two needles out of three were screened to allow a single drop falling with the same impact conditions of the experiments with the array. At least 25 pictures were collected for each time to have a statistically acceptable sample size. Two values of impacting drop spacing (defined as the distance between the centre of two adjacent drops, see Figure 1) were used (5.5 mm and 8 mm); larger spacing produces scarce interaction between drops and smaller ones may give some problem of drop-drop interaction before impacting (the single drop case can be seen as the asymptotic case: $s=\infty$)

Surface	**Rz**	**Ra**
A	1.6 µm	0.21 µm
B	14.5 µm	2.84 µm

Table 1 Characteristics of the impacting surfaces.

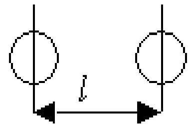


Figure 1. Drop spacing

The PDA measurement points were chosen in order to investigate the radial symmetry (broken by the in-line configuration of the drop array) and the vertical development of the secondary drop diameter, on three planes at 2, 4 and 9 mm from the wall.

RESULT AND DISCUSSION

The pictures acquired by CCD camera allowed to examine the impact morphology of this complex phenomenon, and the image analysis allowed to quantify the size of the secondary drops, with a resolution of about 50 µm, as the pixel equivalent size was 23µm. The secondary drop size range cannot be encompassed by the single use of PDA (D_s from 5.5 µm to 250 µm) or the image analysis technique (IAT , D_s>50µm).

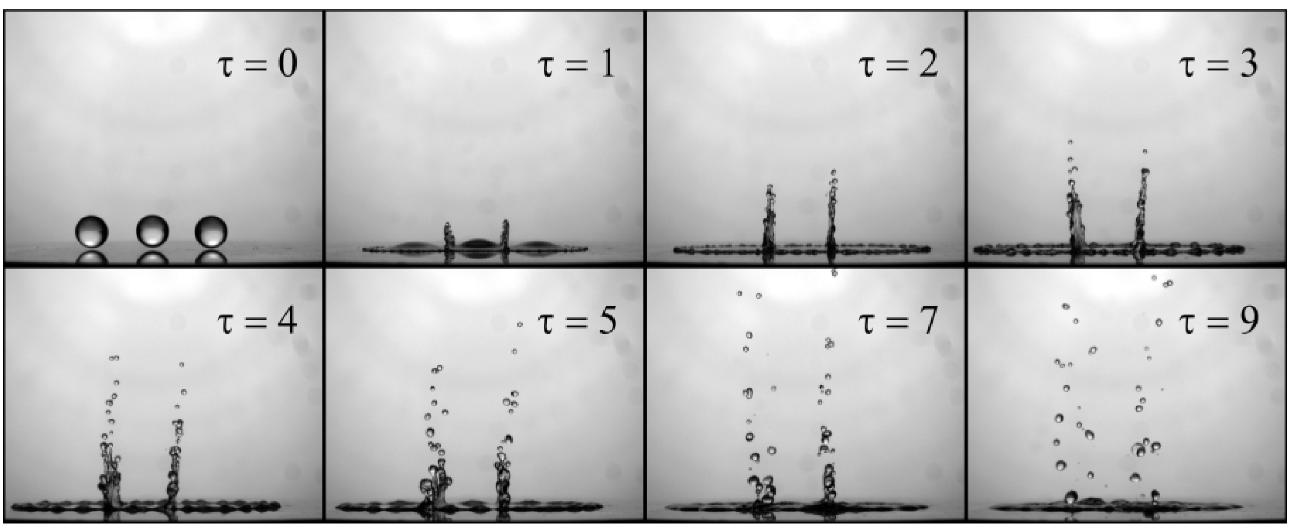


Figure 2. Impact of the drop array on the surface kept at a temperature (80°C) lower than the liquid saturation

temperature

The fact that the sizing ranges of the two techniques partially overlap hinted the idea to use the data from both techniques to reconstruct the size PDF in the whole range, from 5.5μm to few millimetres. A scaling of the two PDFs was performed by equating the average values in the region were the two size ranges overlap. However, the statistical analysis of the secondary droplets is different using the IAT and the PDA technique, since in the first case the drop population at a given time is made by all the droplets generated until that time which are still inside the large acquisition area above the impacted surface, while with the second technique (PDA) the size distribution is defined by the instantaneous and local flux of the secondary droplets. In the present case, since the PDA measurement shown an almost uniform distribution around the impact point, to compare the results of the two techniques the diameter probability distributions for PDA data was obtained integrating on space over all the measuring points and integrating on time (from impact time to the actual time). The non-dimensional time defined as τ=tV/D will be used throughout the paper.

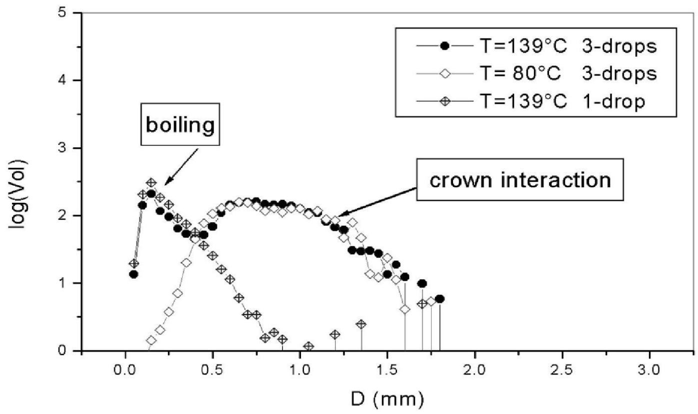


Fig. 3 Secondary droplet volume (Vol) distribution for single drop (cross-diamond) and three drops (solid markers) impacts at 139°C and three drop impacts at 80°C (open markers); τ=15, V=2.55m/s.

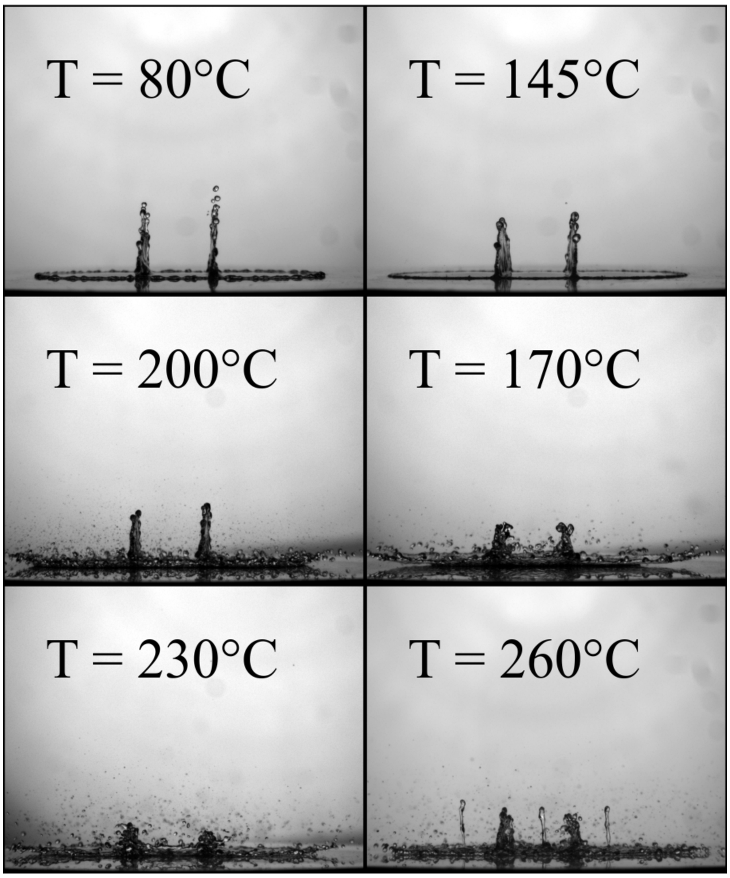


Figure 4a. Effect of wall temperature on the impact of a line drop array at τ = 2, (drop spacing = 5.5 mm, Rz=1.6 mm, V= 2.55 m/s).

The main effect of multiple drop impact can be appreciated in Figure 2 were the impact of the linear drop array on a surface heated at 80°C is shown. The interaction between the liquid lamellas generated by the drops produces liquid sheets that subsequently break-up to form drops of relative large size. This effect is present also for higher temperature (Figures 4), although the secondary atomisation produced by the phase transition modifies the morphology. In Figure 3 the secondary drop “volume distribution” at a given time (τ=15) is reported. The distribution for the “cold” case (T_w = 80°C, without boiling, open markers) originates only by the “splashing” due to the lamella interaction (one should notice that for the single drop, with the same conditions, no secondary atomisation occurred, since impacting conditions are well below the splashing limit for dry surfaces).

For a single drop the atomisation is possible only due to the nucleate boiling (cross-diamond markers in Fig. 3) and small droplets are produced. When a drop array is impacting onto a heated surface, both phenomena are present and we have a bunch of small droplets but also the larger droplets coming from the lamella interaction (solid markers in Fig. 3).

The effect of wall temperature on impact morphology can be appreciated in Figure 4. The drop array impact shows a clear transition from “cold” conditions to “bubble regimes” and finally to the film boiling regimes, as it was already found for the single drop impact [1]. The dynamical interaction between the spreading lamella changes radically the phenomenon with respect to the single drop case for low and medium temperatures.

For the highest temperature (film boiling) the liquid sheets produced by the interaction are destroyed after a short time. In details, Figure 4a-b show the impact for six temperatures, with a drop spacing of 5.5 mm, onto an $AlMg_3$ surface with Rz=1.6 mm. The impact velocity is 2.55 m/s. At 200°C, at τ = 8 (Figure 4b), the lamella is broken and levitates completely from the surface, whereas with a surface only 30°C colder, the lamella still wets the surface and evaporates slowly respect to the dynamical effects and the nucleate boiling time scales. At 200°C a phenomenon (more remarkable for higher temperatures) starts, i.e. the liquid sheets originated by the dynamical interaction are easily broken-up and the lamella parallel to the surface breaks too producing larger drops raising from the surface.

At 260°C these phenomena are stronger and faster: the transient nucleate boiling is rapid and leads to a more massive lamella breaking into big secondary droplets. A new effect of temperature on morphology can be seen by observing some of the images in Figure 4a: the impact of drops on a surface at high temperature (T_w=260°C) produces almost immediately a jet protruding from the drop centre, that subsequently breaks in relatively large droplets (the three jets appearing in Figure 4a for T_w=260°C are protruding from the centre of the impacted drop and are not connected to the lamellae interaction). This effect is present also for single drop impacts and then in cannot be attributed to the drop-drop interaction, but it is not present at lower temperature and it is then connected to the film boiling regime. The jet ejection is in fact peculiar of high wall temperature, as a further analysis confirmed that for T_w lower than 230°C no similar jets can be observed.

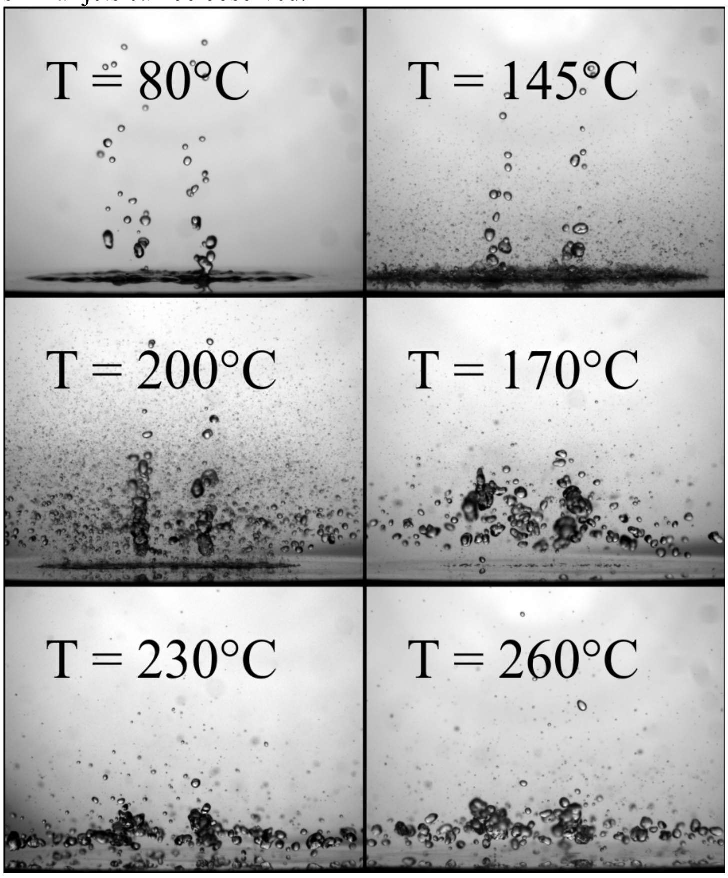


Figure 4b. Effect of wall temperature on the impact of a line drop array at τ = 8, (drop spacing = 5.5 mm, Rz=1.6 mm, V= 2.55 m/s).

The secondary drop diameter was evaluated using the extended PDF and it is reported as a function of time for different wall temperatures in Figure 5. The comparison with the results obtained for single drop impact (Figure 5-a) shows some interesting features. For wall temperature in the range of transition and film boiling (170°C to 260°C) the difference is small, showing that the effect of dynamical interaction (which produces a limited number of secondary drop of large size, as the result relative to T_w=80°C shows) is not so important. This is consistent to the visual observation that the thermal effects overwhelm the dynamical ones, reducing the liquid ejection due to lamella interaction.

For the bubble boiling regime (T_w=145°C), the dynamical effect is instead quite important, as again seen in Figure 5-a and 5-b: the mean diameter is strongly influenced by the lamellae interaction reaching values, at the beginning, larger than those found for T_w=80°C (due only to dynamical interaction). This is probably due to the thermal effects: the bubble boiling that begins to take place during lamella spreading may reduce the kinetic energy available for interaction thus increasing the diameter of those drops formed from the ejected liquid sheets, as it can be observed in experiments at different impact velocities.

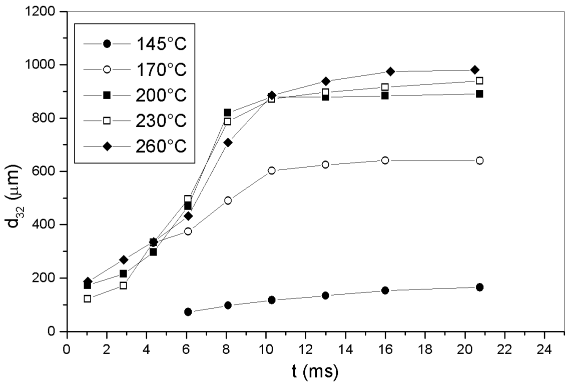


Figure 5-a. Sauter mean diameter (evaluated through the extended PDF) for V=2.55 m/s, for single drop impact.

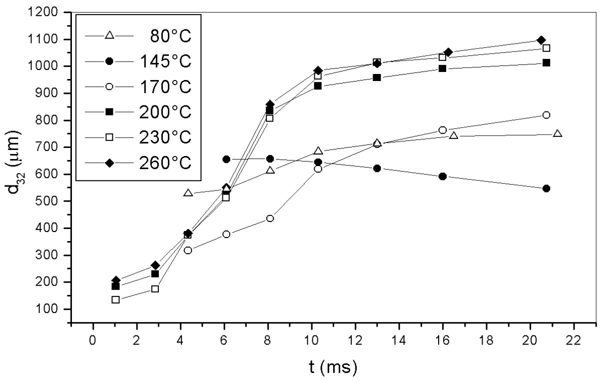


Figure 5-b. Sauter mean diameter (evaluated through the extended PDF) for V=2.55 m/s for single multiple impact.

The effect of wall roughness was also investigated. The number of secondary droplets generated by the impact seems to be greater with a rougher surface, perhaps due to the fact that the transient boiling regime appears more intense. Furthermore for a smooth surface the jets ejected from the drop centre have a smaller diameter. For the higher wall temperature (T_w=260°C) the effect of roughness is more consistent: the number of secondary drops is much larger for the rougher surface at the very beginning of the impact. The wall roughness was found to have relatively small effects on secondary drop diameter (see Figure 6).

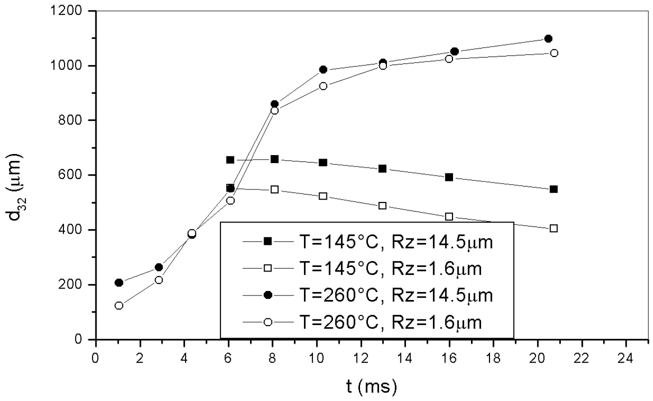


Figure 6. Effect of wall roughness on secondary drop size, for both bubble and film boiling regimes (drop spacing l=5.5 mm)

For the film boiling regime there is practically no effect at all, whereas a decrease (more than 20%) of the secondary average drop size is observed for the bubble boiling regime (T_w=145°C), when surface roughness is decreased of an order of magnitude. It seems possible to ascribe such variation to the relative increase of the smaller droplets (produced by boiling) respect to the bigger one (produced by lamella interaction). However, it can be stated that the roughness plays a non-determinant role in defining the final mean diameter.

Experiments at three different impact velocities were performed to show the effect of dynamical interaction on the secondary mean diameter. Increasing the velocity, the drop spacing along the trajectory increases due to aerodynamic interaction among the falling drops, thus to maintain the same drop spacing at impact, the value was increased at 8 mm for all the impact velocities. Figure 7 show the results for both boiling regimes (the wall roughness was kept constant, as a results of the previously shown experimental outcomes). The effect of impact velocity on secondary drop diameter is not very relevant for the bubble boiling regime, however a consistent increase of the size is observed when the impact velocity increases, as the lamellae interaction is more intense for larger velocities, thus increasing the relative number of the larger drops produced by the breaking of the liquid sheets, respect to the small ones produced by boiling . Incidentally, it is worth to notice the effect of drop spacing by comparing the results in figure 6 to those in figure 7. For the film boiling regime, the same effect is much more evident and opposite with behaviour for bubble boiling.

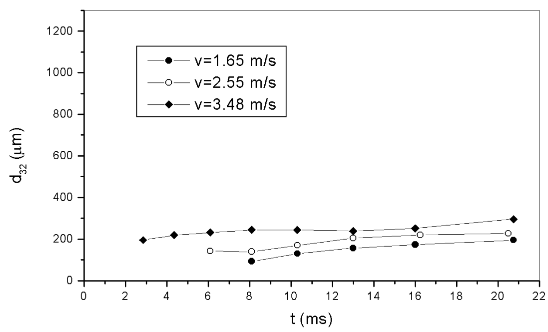


Figure 7-a. Effect of impact velocity for bubble boiling regime (drop spacing l=8mm).

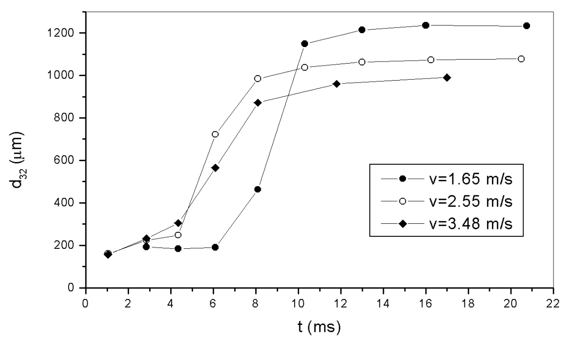


Figure 7-b. Effect of impact velocity for film boiling regime (drop spacing l=8mm).

A possible explanation may be linked to the larger spreading of the liquid lamella with velocity, obviously accompanied by a decrease of its thickness, that is expected to result in a smaller droplet size when the liquid lamella levitates and ruptures. It is interesting also to analyse the effect of velocity on the dynamical interaction alone, which can be well observed when the wall temperature is lower than the liquid saturation temperature (T_w = 80°C in the present case). The increase of impact velocity produces a decrease of the secondary drops (see Figure 8) that in this case are produced only by dynamical interaction between adjacent drops. This effect may be explained by the increase of the liquid jet vertical velocity accompanied by the decrease of their thickness, thus yielding smaller drops after break-up.

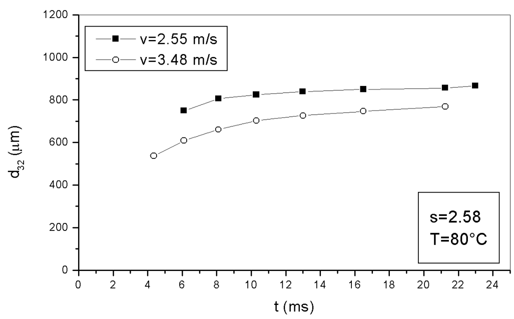


Figure 8. Effect of drop impact velocity on secondary

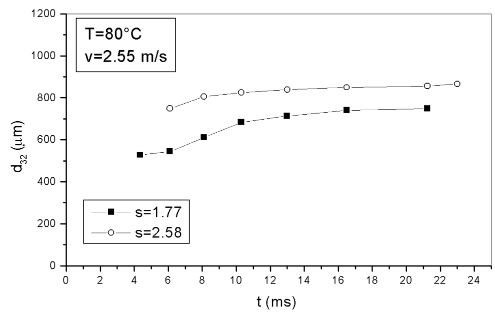


Figure 9. Effect of drop spacing on secondary drop size

drop size for T_w=80°C (no boiling).

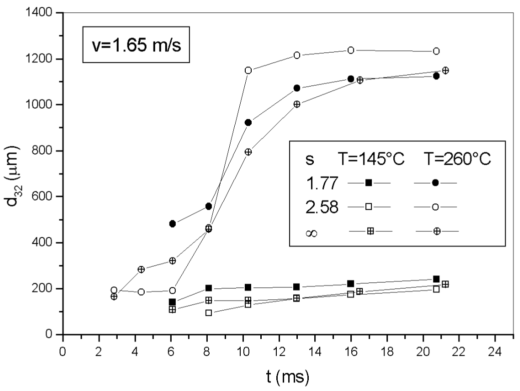
for T_w=80°C (no boiling).

Drop spacing is expected to have a large effect mainly on the dynamical interaction mechanism. In fact, there obviously exists an upper limit for drop spacing above which the phenomenon becomes practically identical to a single drop impact. A non-dimensional drop spacing will be used, defined as the ratio between the drop spacing divided by the drop diameter. Figure 9 shows the secondary drop diameter for drop impact over the surface kept at 80°C, to evidence only the dynamical effects. The decrease of spacing decreases the drop size, as the lamella interaction is stronger, and larger inertial effects produce liquid sheets having larger velocity and consequently smaller thickness, thus yielding smaller drops.

For boiling regimes the picture is very different. For low impact velocity (V=1.65 m/s) the lamella interaction is obviously less intense, also for the smaller spacing. For *s*=2.58, Figure 10 shows that no secondary drops are generated by lamella interaction, thus explaining why for bubble boiling the secondary drop size is the same for single (*s*=∞) and multiple drop impact. Decreasing spacing some effects can be observed for the bubble boiling regime with a small increase of mean secondary droplet size.

For the film boiling regime (again for the lower velocity) at the beginning of interaction the larger the spacing the smaller the drops, whereas at later times the situation is the opposite. The phenomenon is quite complex and different qualitative explanations can be given, although further experiments are needed. For larger spacing, the drop ejection from dynamical interaction is low or inexistent, thus the size at the beginning of the impact is closer to that of single drop, whereas for lower spacing relatively large drops are ejected at the beginning of interaction by dynamical effects. Later on, the size of secondary drops is defined by the lamella thickness (that in this regime levitates and breaks into large drops): for smaller spacing, the lamella thickness is expected to be lower, due to the initial liquid ejection caused by dynamical interaction, whereas for large spacing the lamella is thicker as the weak dynamical interaction is sufficient just to reduce the lamella spreading, then the secondary drop size is larger, also when compared with single drop as in that case nothing opposes to lamellae spreading.

For larger impact velocity (V=2.55 m/s), the effects for film boiling (T_w=260°C) are similar to those seen for lower impact velocity. The effects for the bubble boiling regime (T_w=145°C) are instead much stronger and the effect of dynamical interaction is here more evident, as in this case this is the only source of large drops.



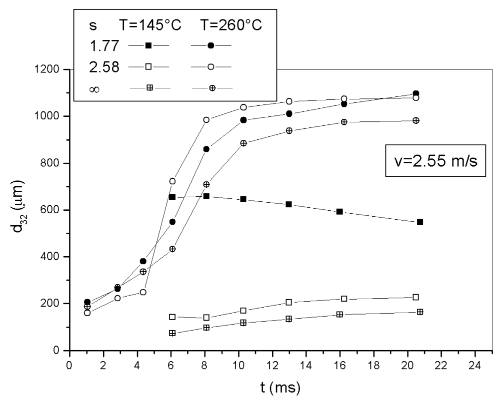


Figure 10. Effect of drop spacing for both boiling regimes and two impact velocities : a) 1.65 m/s; b) 2.55 m/s. The single drop case corresponds to s=∞.

CONCLUSIONS

The experimental characterisation of the impact of a drop array on a high effusivity heated surface led to the following conclusions:

- The main effect of the multiple drop impact is due to a dynamical interaction between the spreading lamella. In the case of multiple drops, the lamella interact and form a kind of liquid crown, which is ejecting large secondary droplets.
- The drop array impact shows a clear transition from “cold” conditions to “bubble boiling” regimes and finally to the film boiling regimes. The dynamical interaction between the spreading lamella changes radically the phenomenon with respect to the single drop case for low and medium temperatures. For the highest wall temperatures (film boiling) the liquid sheets produced by the interaction are destroyed after a short time.
- The increase of wall temperature increases the average drop size, and the drop-drop interaction enhances this effect.
- The wall roughness has very small effects on the secondary drop size for the film boiling regime, and a small but detectable effect for the boiling regime.
- The increase of impact velocity increases the drop size for bubble boiling regime, when impacting drops are close enough to allow strong drop-drop interaction, whereas it decreases the drop size for film boiling regimes.
- Drop spacing is an important parameter both for defining splashing threshold for impact on cold (T_w<T_{sat}) walls and for influencing the drop size in both boiling regimes.

NOMENCLATURE

Latin Symbols

D	Drop diameter
l	drop spacing
Rz, Ra	roughness
s	non-dimensional drop spacing
T	temperature
V	Drop impact velocity
Vol	Volume
We	$\frac{\rho V^2 D}{\sigma}$ Weber number

Greek Symbols

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

Subscripts

L	Leidenfrost
N	Nukyiama
s	secondary
sat	saturation
w	wall

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