Multiple drop impact on heated surface

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The paper reports results on the secondary atomization produced by the impact of three water drops impacting simultaneously on a heated wall. A detailed comparison between single and multiple drop impacts is given. Two boiling regimes were studied keeping the wall temperature below and above the Leidenfrost temperature. The effect of wall roughness were also studied by changing the impact surface. By image analysis techniques secondary drop number and diameters were measured and compared. An estimation of the total liquid mass removed from the wall by secondary atomization is also given.

1. Introduction

When a drop impacts onto a heated surface, smaller droplets can be generated (the so called secondary atomisation, i.e. the production of droplets of smaller diameter respect to the impacted drop diameter) due to both inertial effects (when the impact kinetic energy is large enough) and thermal effects (when the surface temperature is larger than the liquid saturation temperature). The study of this phenomenon has a great number of applications and a deeper knowledge of drop-wall and drop-drop interaction phenomena can be usefully applied in many fields such as surface cooling by water sprays, impact of fuel spray on the internal wall of I.C. engines, etc. Many parameters are expected to influence the atomisation regimes, like drop impact characteristics (diameter, velocity, liquid properties), surface characteristics (wettability roughness, thermal effusivity) and wall temperature.

There exist extensive studies of single droplet impact on various surfaces and many characteristics of such phenomenon were already pointed out by many authors. The outcomes of the impact are strongly influenced by the surface characteristics: dry and wet surfaces were shown to produce very different morphologies [1] and surface roughness was shown to have large influence on the splashing threshold [2].

The prediction of the outcomes of spray (i.e. multiple drop) impact on a solid surface is still not attainable, as there exists a gap between the knowledge reached with single drop impact analysis and the phenomena characterising a spray impact. A large difference between single droplet and multiple droplet impingement outcomes is indeed expected to exist, as drop-drop interaction on the surface is expected to produce liquid fingers than may break-up in secondary drops [3]. Some recent experimental and theoretical works on impingement of droplet pairs on isothermal surfaces are available [4,5] in the open literature. Impact of single drops on heated surface has been studied by many years with the intent of analysing the heat and mass transfer mechanisms (see for example [6]), finding the effect of surface characteristics on the boiling regimes (see for example [7]), studying the secondary atomisation [8] etc. The study of multiple drop impact on heated surface is instead just at the beginning but it represents the unavoidable intermediate step toward a better comprehension of the spray-wall interaction. The present paper is an attempt to bridge such a gap, by studying experimentally the impact of multiple water drops of millimetric size onto a heated surface, with particular attention to the drop-drop interaction on the wall.

2. Experimental Set-up

The experimental set-up comprises an aluminium alloy (AlMg3) impacting wall, electrically heated to reach temperatures larger than 330°C with good uniformity along the wall. As the main aim of the present investigation was to study the effects of interaction among drops impacting simultaneously on a heated surface, a drop generator was developed and assembled. The generator was capable to produce on demand an array of drops, with diameter ranging between 2 to 4 mm, using a pressure pulse to detach droplets from needles of internal diameter ranging between 0.4 to 0.6 mm. The pressure pulse imparts an initial velocity to the detaching droplets, which are subsequently accelerated by gravity to reach velocity up to 6m/s. The impact velocity was then measured by means of multiple exposed pictures taken by a CCD camera (below described). For the present study, three needles positioned on a line at a distance of 5mm from each others were used to produce three identical drops impacting almost instantaneously on the heated wall. Fig. 1 shows the sequence of the generation of an array of three drops on a line.

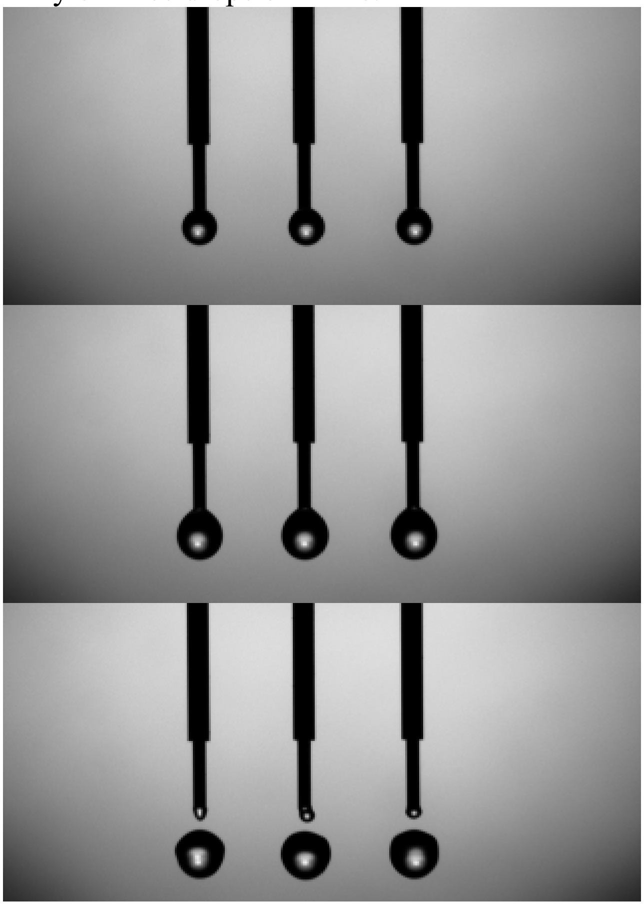


Figure 1. Generation of a drop array

Different impacting geometry can be studied by modifying the position and number of the needles. A CCD camera (SensiCam PCO, Colour, 1280x1024 pixels) was used to acquire the images of the impact. The illuminating system and the CCD camera were triggered by an infrared light barrier system, through a TTL signal produced by the delay generator circuit. A commercially available image analysis code (Image ProPlus) was used as main environment and home built routines were developed for performing background subtraction, contrast enhancement, filtering and measurement output parameters like average drop diameter, roundness, etc. The set-up consented to measure drop size from 40μm to few millimetres.

3. Results and Discussion

As pointed out in many previous studies [7,8] the wall temperature is the main parameter to determine the regime of heat transfer and, as a consequence, the regime of secondary atomisation. In the present study two wall temperatures were chosen to represent the two main boiling regimes (bubble boiling when $T<T_{Leidenfrost}$, film boiling when $T>T_{Leidenfrost}$) and the effect of surface roughness was analysed by using two surfaces having different roughness, data are reported in Table 1.

Table 1 Characteristics of the impacting surfaces.

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

The main objective of the present investigation were to compare the effects of drop-drop interaction on secondary atomisation after the impact on a heated surface with the case of single drop impact. The dynamic conditions (drop impact velocity = 2.55 m/s and diameter = 3.1 mm) were such that the secondary atomisation would not take place if the surface were not heated and in figure 2 the impact of three drops on the surface heated at 80°C shows clearly that the sole secondary atomisation taking place is that due to the drop-drop interaction, for single drop the outcome under the same conditions would be the sticking of the drop on the wall (see also [8]).

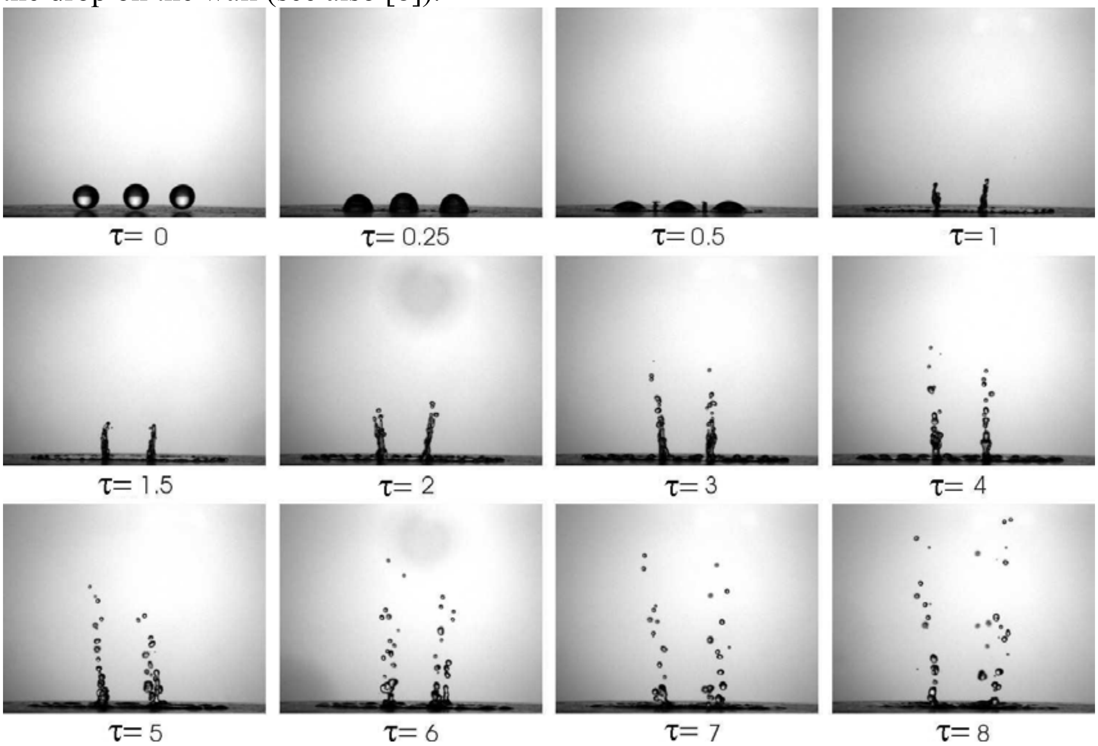
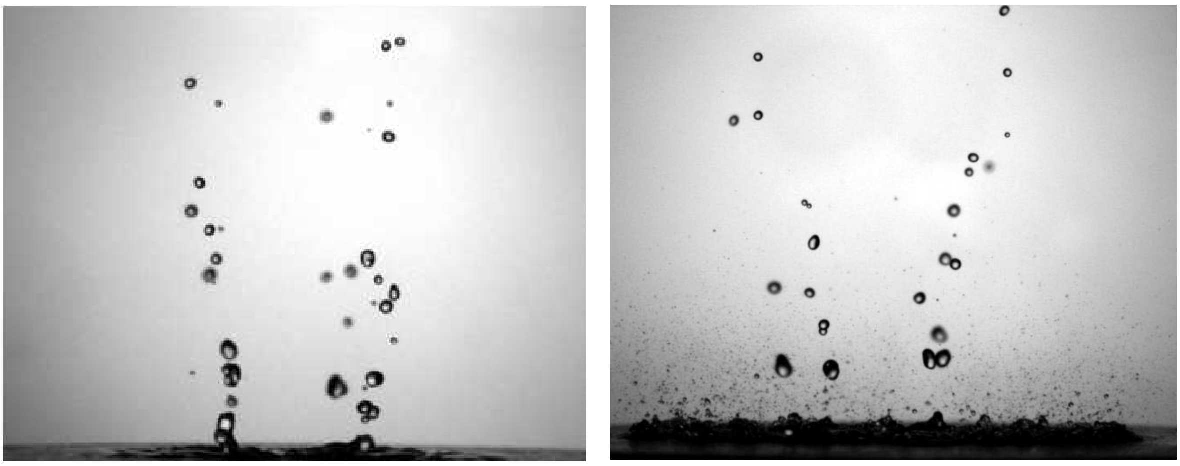


Figure 2. Impact of the drop array on the surface at 80°C.

This impact condition was chosen in order to show the sole effect of boiling regimes on secondary atomisation. 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 drop (or drop array) was impacting. After performing an experiment with the drop array, collecting data for different times after impact (usually up to 24 ms after impact), two needles out of three have been 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 so to have a statistically acceptable sample size. The temperatures chosen to represent the above mentioned regimes were: 145°C and 260°C. In the present study the distance between the impacting drop (for the drop array case) was maintained constant to 5 mm, leading to a non-dimensional drop distance of: l/D=1.6. Tests were performed to understand the influence of the distance between impacting drops and it was found that larger distances produce scarce interaction between drops and smaller distances may give some problem of drop-drop interaction before impacting. The value chosen here is a good compromise between the above mentioned opposing requirements. From the acquired images it was possible to draw information about morphology of the impact and quantitative information about droplet size.

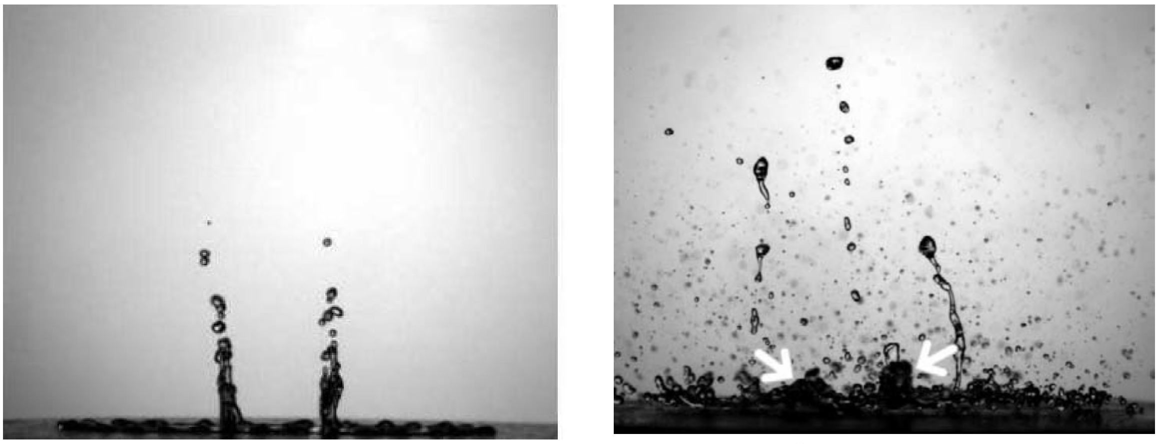
3.1 Morphology

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 column that subsequently break-up to form drops of relative large size.



τ=8, T=80°C τ =8 T=145°C, Rz=14.5

Figure 3. Impact of the drop array on the surface at 80°C and at 145°C (bubble boiling regime).



τ =3 T=80°C τ =3, T=260°C, Rz=14.5

Figure 4. Impact of the drop array on the surface at 80°C and at 260°C (film boiling regime).

This effect is present also for higher temperature (figures 3 and 4), although the secondary atomization produced by the phase transition modifies the morphology: for 145°C the lamellas interaction is very similar to that at 80°C (figure 3), whereas at 260°C, the secondary atomization and a further phenomenon (that will be better explained below) almost completely masks this effect (see figure 4, the arrows show the lamellas interaction).The three jets appearing in figure 4 are protruding from the center of the impacted drop and are not due to the lamellas interaction. A new effect of temperature on morphology can be seen by observing the images in figure 4: the impact of drops on a surface at high temperature (T_w=260°C) produces almost immediately a jet protruding from the drop center, that subsequently break-up in relatively large droplets. This effect is present also in single drop impact and cannot then be attributed to the drop-drop interaction (see figure 5).

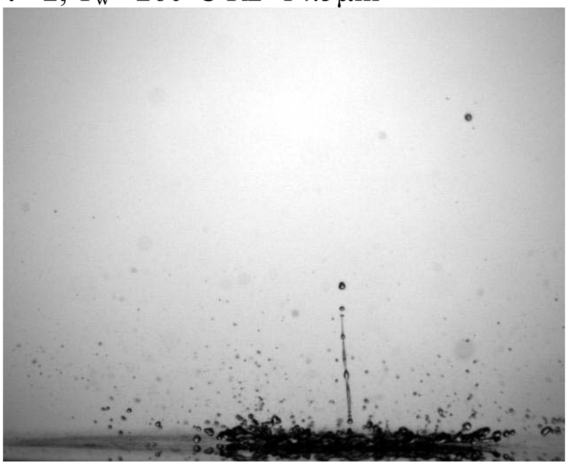
(a) (b)

Figure 5. Impact of drop array (a) and single drop (b) on heated surface at T_w=260°C for five different nondimensional times: $\tau = tV/D$=1, 2, 3, 5 and 8.

On the other hand, the effect is peculiar of high wall temperature, as by further analysis it was confirmed that for T_w lower than 230°C no similar jets can be observed. The surface roughness may have an important effect on the jet formation, the diameter of the central jet appears to be lower at lower roughness, but the effect has a quite large variability and no conclusive measurements of jet size were performed. It is worth to notice that the effects of lamella interaction (i.e the formation of liquid column between the impacting droplets) are slightly more visible for lower roughness (see figure 6).

τ =2, T_w =260°C Rz=14.5μm

τ =2, T_w =260°C Rz=14.5 μm



τ =2, T_w=260°C Rz=1.6 μm

τ=2, T_w =260°C Rz=1.6 μm

Figure 6. Single drop and drop array impact on surfaces of different roughness under the film boiling regime (T_w=260°C).

3.2 Droplet size and number

The image analysis of the acquired pictures allowed to quantify the size of the secondary drops, however some limits must be considered. The size resolution is about 50 μm as the pixel equivalent size is 23μm and droplets having size smaller than 2pixel are not considered by the analysing software, then the reported size must be considered an average evaluated in the range of particles larger than about 50μm. Previous analysis [8] have shown that most of the droplets are smaller than 50μm and, even if their contribution to the total volume is small, the actual mean diameter is therefore smaller than that evaluated only by image analysis. Moreover, as the image analysis allowed to measure the minimum and maximum diameter, a filter rejecting the droplets having an aspect ratio lower than 0.7 was used. As above mentioned, 25 pictures were collected for each time and a first analysis consisted in evaluating the number of secondary droplets detected in each picture; clearly the measurement system is not capable to detect all the droplet effectively produced by secondary atomisation, so that the number reported may be considered as a lower limit. Also the “out-of-focus” can lead to an overestimation of the drop diameter, even if a quantitative estimation of the error is not given.

Figure 7 reports the average number of secondary drops vs. time after impact (the reported number of drops is "per frame", averaged over the 25 pictures taken for each time). The number of detected secondary drops was normalised by dividing by the number of impacting drops (1 for the single drop, 3 for the drop array). The dimensionless time ranges from 0 to 20 for the bubble boiling regime and from 0 to 9 for the film boiling regime. The choice of the time interval takes origin from a compromise between the data analysis duration and the fact that for longer times the processes appeared to reach a stationary condition, i.e. a condition of continuous boiling for T_w = 145 °C and a vapour levitation of the liquid lamella for T_w = 260 °C. In the second case, since the lamella breaks horizontally in few, deformed, large droplets, the macro for the image analysis is not giving anymore suitable results.
The number of drops produced by the impact for T_w=145°C is clearly lower for the array respect to the single drop impact (see figure 7). This can be connected to the fact, already mentioned, that the lamella interaction produces a removal of liquid from the wall (see figure 3) then decreasing the possibility of generating droplets by bubble boiling.

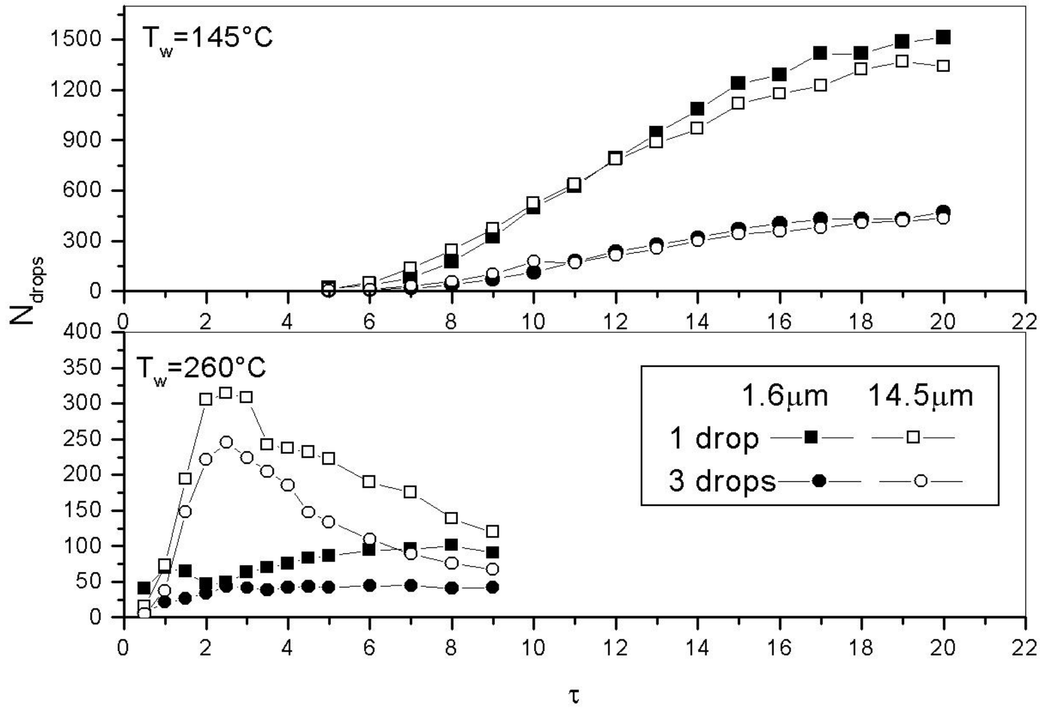


Figure 7. Number of secondary drops collected per image. The number of drops is normalized by the number of impacting drops (1 for single drop and 3 for drop array).

It is also interesting to observe that the influence of surface roughness is of minor importance for this regime.
For the higher wall temperature (T_w=260°C), the difference in number of secondary drops between single drop and drop array is less pronounced but still evident. In this case is again the lamella interaction that is likely to be responsible of the difference: although the liquid removal from the wall is much lower, the decrease of the liquid wall contact area during the first stage of impact may reduce strongly the possible drop production.
For the film boiling regime, the effect of roughness is more consistent: the number of secondary drops is much larger for the rougher surface (see figure 7) at the very beginning of the impact.
The effect of temperature is then enormous and consistent with the results of the morphological analysis: for low temperature (T_w=145°C) the drop production starts at about τ=5 and increases with time as boiling go on, whereas for the high temperature case (T_w=260°C) the drop production starts at the very beginning of impact.

The secondary drop size was measured as above mentioned and drop Sauter mean diameter is reported in figures 8 and 9 for both regimes, surface roughness and impinging drop number.

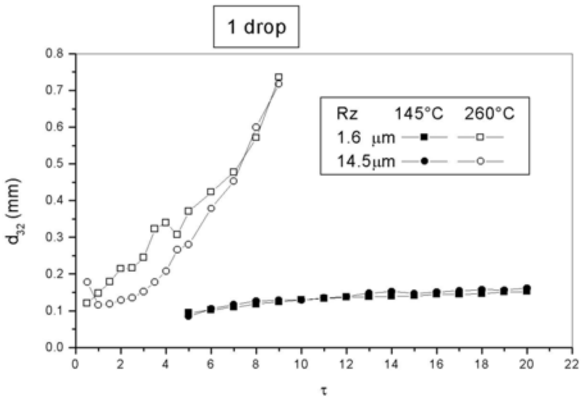


Figure 8. Secondary drop SMD for different surface temperature and roughness due to the impact of a single drop.

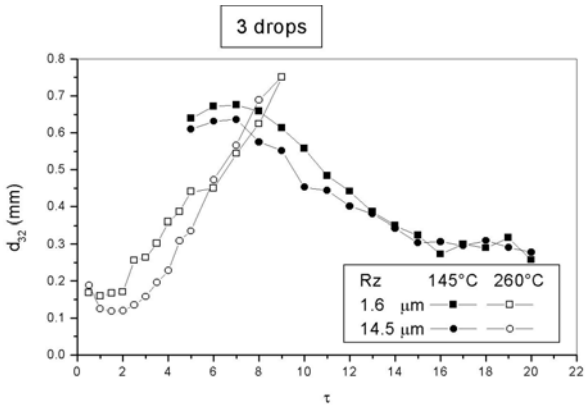


Figure 9. Secondary drop SMD for different surface temperature and roughness due to the impact of the drop array.

The effect of surface roughness is almost neglectful for the bubble boiling case (T_W=145°C), both for single drop and drop array. For the film boiling regime (T_W=260°C), the rougher surface produces smaller droplets (maximum relative differences are of the order of 50 %) at the very beginning of the impact (up to τ=5), then the effect disappears at later times.
The effect of drop-drop interaction and wall temperature are instead enormous. For the single drop impact at lower temperature (T_W=145°C) the drop size increases slowly with time, virtually independent from the surface roughness: the non-dimensional Sauter mean diameter (d_{32}/D) goes from about 0.03 to about 0.05. For the higher temperature, the increase with time is much faster and again the non-dimensional SMD goes from about 0.045 to about 0.23, in about the half of time. The large value of secondary drop diameter for the high temperature case is again consistent with the finding of the morphological analysis: the lamella detachment from the wall, caused by the vapour film formed below it, and its subsequent break-up is the cause of the increase of the average drop size. The comparison of figures 8 and 9 shows again the strong effect of drop-drop interaction for the bubble boiling regime (T_W=145°C): the average drop size is much larger at the beginning of impact for the drop array case than for the single drop. The drops coming from the liquid columns produced by the lamella interaction are large compared to those produced by the lamella rupturing by bubble formation, then the large average drop size observed at the beginning of impact for the drop array is due to these droplets, later on those droplets are masked by the large production of small drops and the drop size tend to get close to that find in single drop impact.
For the film boiling regime (T_W=260°C) the difference between single drop and drop array is not detectable and the effect of roughness is more consistent, this in full agreement with the morphological analysis.

3.3 Droplet volume
As previously pointed out, not all the secondary droplets produced by the impact can be detected by the measurement system; on the other hand, the depth of field of the optical configuration is such that a large amount of droplets actually produced can be detected (thanks also to the image analysis procedure, that allow to enhance contrast in a optimised way and to collect data about drops virtually out of focus). It is then of a certain interest to evaluate the total volume of the secondary drops *detected* by the technique, that is lower than

that of droplets actually produced (and thus can be considered a lower limit). This volume can be considered a first estimation of the total volume removed from the wall by secondary atomisation. The total volume can be easily evaluated from the data collected and after being non-dimensionalised by the impacting drop volume was plotted in figure 10 and 11.

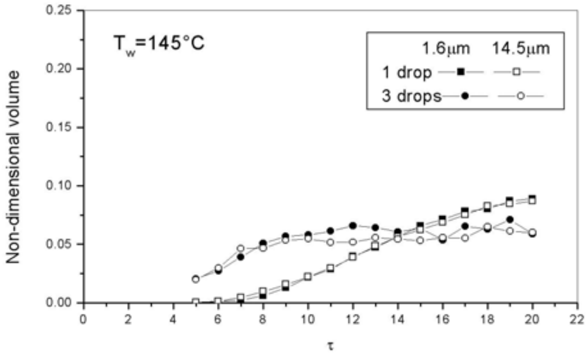


Figure 10. Secondary drop volume for different surface roughness due to the impact of a single drop and a drop array for T_w=145°C.

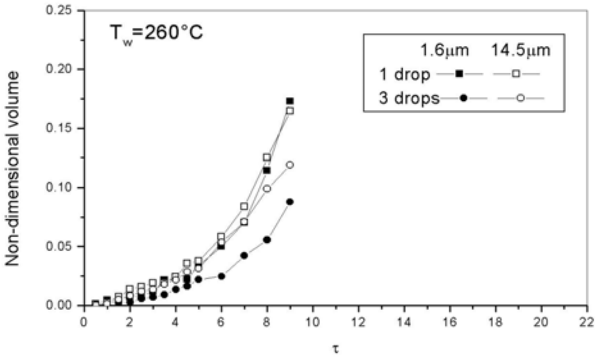


Figure 11. Secondary drop volume for different surface roughness due to the impact of a single drop and a drop array for T_w=260°C.

The non-dimensional volume is defined as:

$$V_{nd} = \frac{\sum_{j=1}^{N_s} d_j^3}{\sum_{1}^{N_p} d_{p,j}^3}$$

where the summation on the denominator of the fraction is extended to the number of primary drops (N_p=1 for single drop, N_p=3 for drop array).

For the bubble boiling regime, the volume removed from the wall is higher at the beginning of impact for the drop array, due to the large drops coming from the lamella interaction. However, as time goes, the volume removed by the secondary atomisation due to boiling (i.e. smaller droplets) increases for the single drop case as more droplets are ejected from the lamella; for the drop array instead the increase of volume removed by boiling is lower, due to the lower amount of liquid (per impacting drop) left on the wall caused by drop-drop interaction. For the latter case, the phenomenon may also be influenced by the possible decrease of the wall temperature due to the presence of a larger amount of liquid on the wall; however the wall effusivity is large enough to assure that the wall temperature variation is modest (an estimation of contact temperature lead to temperature variation of the order of 5°C). The total mass removed after a non-dimensional time of 20 is about the 5% of the impinging one for the drop array and about the 8% for the single drop, but it should be reminded that these values have to be considered with great care, and mainly used for qualitative comparison between different cases.

For the film boiling regime, the amount of liquid removed from the wall by secondary atomization increases more quickly than for bubble boiling reaching the 8-10% for the drop array, and the 16% for the single drop. In this case the liquid removal from the wall by the drop-drop interaction is lower, but the liquid lamella levitation by the vapour film formed after impact and its subsequent break-up are responsible of the large volume removal by boiling.

4. Conclusions

The study of a synchronised droplet array impinging on heated surfaces led to the following conclusions:

- The spreading lamellas of close droplets strongly interact to form jets raising from the surface and breaking up in relatively big droplets. The phenomenon is entirely due to inertia effects, but it is influenced by the surface temperature: at temperature below saturation (T_w=80°C) and characterizing the bubble boiling regime (T_w=145°C) the lamella interactions is almost the same, but when wall temperature is raised above the Leidenfrost temperature and film boiling regime take place (T_w=260°C), the effect almost disappears.
- At temperatures higher than 230°C, the impact of single drop and drop array give place to the ejection of a jet from the center of the impacting drops, whose characteristics depend on the surface roughness and wall temperature.
- The number of drops produced by the impact divided by the number of impacting drop is significantly lower for the drop array than for single drop, mainly due to the fact that lamella interaction remove liquid from the wall. For bubble boiling regime the number of drop increases continuously with time starting at non-dimensional times ($\tau = tV/D$) larger than 5, for film boiling the larger drop production takes place just at the beginning of impact ($\tau \approx 2$), but its maximum value is always lower than the maximum value for bubble boiling. The surface roughness does not influence droplet generation for bubble boiling, whereas for film boiling the rougher surface produces a larger number of drops.
- The secondary droplet diameter (SMD) is much larger for film boiling regime than for the bubble boiling one, mainly due to the fact that in the former case the lamella levitation and subsequent break-up (due to the vapor film formed below it) produces a larger amount of big droplets.
- A rough estimation of the volume of liquid removed from the wall by the secondary atomization was performed: under bubble boiling conditions (T_w=145°C) the amount of liquid removed appears to be much lower than that removed under film boiling conditions (T_w=260°C).

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6. References

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