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SECONDARY ATOMIZATION CHARACTERISTICS IN INTERMITTENT SPRAY COOLING

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ABSTRACT

This paper reports an experimental study on the secondary atomization characteristics in intermittent spray cooling for thermal management systems. The emphasis of this study is on the characteristic size of secondary droplets, representing a mass fraction of the impinging spray which does not remain on the wall for cooling purposes as desired. The approach developed in our analysis consists of reconstructing a measured discrete size distribution as a Log-Normal distribution function, assessing the reliability of this fitting using the Shannon-entropy concept, as understood in information theory, and henceforth, study the characteristic size distribution of droplets produced by secondary atomization through the geometric mean diameter and the standard deviation of the Log-Normal distribution function. The standard deviation is a quantitative expression of the secondary drop size polydispersion. The analysis of the results presented emphasizes that an increase of the duty cycle, as this approaches the working condition of a continuous spray (100%), shifts the geometric mean diameter of secondary droplets to larger sizes and the secondary spray polydispersion tends to decrease for DC < 30% and is inverted for DC > 30%. Preliminary parametric studies on the superheating degree, injection pressure and impingement distance show that the relative geometric mean diameter, between secondary and primary droplets, is only affected by the impingement distance, whereas the secondary drop size polydispersion is mainly influenced by the superheating degree and impingement distance.

INTRODUCTION

Power density in microprocessors experience an exponential growth (50 times over the last decade), thus becoming one of the most important constraints in their design [1]. This requires advanced cooling techniques and thermal management systems, which are both efficient and able to control the cooling process.

In previous works, intermittent spray cooling has been suggested as a new technique which integrates current strategies using the continuous injection of cooling liquid and the ability to control the cooling potential by using an intermittent spray and properly adjusting its duty cycle [2, 3]. The duty cycle is defined as the percentage of the cycle time where cooling liquid is injected. However, this cooling depends on the joint effect between hydrodynamic drop impact mechanisms, and those thermally induced [4], determining the amount of impacting fluid remaining on the wall for cooling, and the portion which emanates from the wall in the form of secondary droplets. Therefore, the characterization of primary and secondary droplets in terms of their size and velocity is crucial for an accurate description of the flow, to investigate the physics underlying secondary atomization mechanisms and to the development of numerical models.

The approach followed in this paper is motivated by the recently proposed modelling of polydispersed sprays presented by Beck and Watkins [5]. This modelling uses the full polydisperse nature of the spray captured by its moments, which are further transported using an Eulerian formulation. This apparently suggests the ability to reconstruct, for example, the number-distribution of drop sizes at any point in space and time in the modelling scheme. For this reason, the first set of results presented here shows that size distributions of droplets in intermittent spray cooling experiments can be reasonably described by Log-Normal distribution functions. Secondly, the characteristic parameters of the Log-Normal continuous function (geometric mean diameter, d_g, and standard deviation, γ) are analyzed in order to investigate the effect of the spray intermittency in secondary atomization. This analysis also includes a preliminary parametric study on the net effects of the superheating degree (ΔT_{wb}), impingement distance and pressure of injection.

EXPERIMENTAL SETUP

The flow configuration is that of a spray striking perpendicular onto a flat aluminum disc with a 10 mm radius (r_{disc}), heated by an electric resistance coupled with a copper plate for uniformly distributing heat to the disc (Fig. 1). The injector is a BOSCH pintle-type with 0.79 mm of pintle diameter inserted in a hole with 0.9 mm and the spray produced has a hollow-cone structure. The fluid is supplied to the injector by a 2L tank pressurized with N_2 and its temperature is 22±2ºC.

The injection frequency, pulse duration and number of injections are software controlled by a NI5411 arbitrary function generator from National Instruments. The cooling liquid is a dielectric fluid produced by 3M, the HFE-7100, with specific mass (ρ) = 1488 kg m^{-3}; dynamic viscosity (μ) = 5.7×10^{-4} kg m^{-1} s^{-1}; surface tension (σ) = 13.6 mN m^{-1}; boiling temperature (T_b) = 61ºC; liquid specific heat (c_p) = 1177 J kg^{-1} K^{-1}; and latent heat of vaporization (h_{fg}) = 111.6 kJ kg^{-1}. The variation of HFE-7100' properties with temperature were provided by the manufacturer (3M).

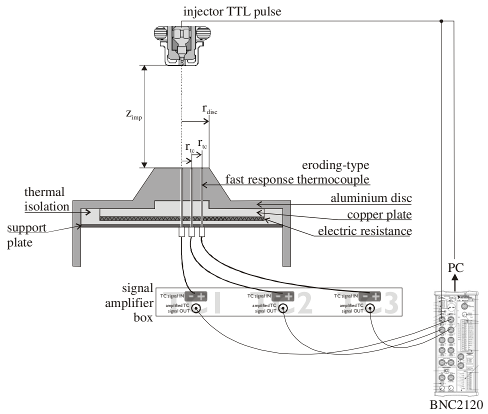


Fig. 1 Experimental setup

The disc has three “Medtherm” eroding-K-type thermocouples assembled, spaced by 4 mm (r_{tc}) with the first thermocouple located at the disc centre as depicted in Fig. 1. Thermocouple’ signals are sampled at 50 kHz with a NI6024E National Instruments DAQ board plus a BNC2120, and the electrical signal is amplified with a gain of 300 before being processed to obtain surface temperature values. Inaccuracies due to electronic noise were inversely proportional to the surface temperature and represent an uncertainty smaller than ±1%.

Local time-resolved measurements of droplet size and velocity are simultaneously made at 3 mm above the surface, with a two-component Phase Doppler Interferometer (PDI) DANTEC system consisting of a 55X transmitting optics, a 57x10 PDI receiving optics, oriented at 30º for maximizing the signal visibility with negligible variations of the refractive index, and a 58N10 Covariance processor. The droplets impinging on the wall are distinguished from those produced by secondary atomization mechanisms through the axial velocity component (U). A positive axial velocity indicates impinging droplets, otherwise, secondary droplets. According to Panão and Moreira [6] the accuracy error obtained in each discrete drop size distribution is less than 2%. Table 1 contains all the case studies used in this work. In each case, 100 series of 40 injection cycles were performed for averaging purposes. The parametric variations include the frequency (f_{inj}), duration (Δt_{inj}) and pressure (p_{inj}) of injection, the superheating degree (ΔT_{wb}) and the impingement distance (Z_{imp}).

Table 1 Working conditions used in the experiments.

f_{inj} (Hz)	Δt_{inj} (ms)	p_{inj} (bar)	ΔT_{wb} (ºC)	Z_{imp} (mm)
10, 20, 30, 60	5, 7.5, 10, 15	3	43.7	50
10	5, 10	4	43.7	50
10, 30	5	3	43.7	30, 40
10, 30	5	3	20, 70	30

RESULTS AND DISCUSSION

The analysis considers that size distributions of primary and secondary droplets can be approximated by Log-Normal distributions with reasonable accuracy. This approximation is made by estimating the characteristic parameters of a Log-Normal distribution (geometric mean diameter, d_g, and standard deviation, γ) which fit into the discrete size distribution. From the modeling point of view, the usefulness of using this characterization approach is to reconstruct the measured discrete probability distribution as a continuous probability function and potentiate the mathematical treatment of measured discrete information.

Before applying this reconstruction approach, a detailed analysis of the impinging droplets during an injection cycle shows that a significant number of droplets appears after the end of injection (see Fig. 2) and it is likely that these correspond to secondary droplets eventually dragged by the wall-jet vortex structure formed after spray impact, inducing their re-impaction on the wall [7]. However, if we consider all impinging droplets in the entire cycle, the right side of fig. 2 shows that a bi-modal size distribution is obtained, eventually due to the presence of secondary droplets. If this information would be considered in the analysis of the entire injection cycle, it leads to an inaccurate hydrodynamic correlation between the primary droplets impinging on the heated surface, and secondary droplets generated from this impact. To resolve this inadequacy, our empirical approach is to consider only the data within a certain time interval, including the time before the spray impacts on the wall (t_{imp}), the pulse duration (Δt_{inj}) and 2.5 ms into the spray tail period. The result is depicted on the left side of Fig. 2 where the discrete probability distribution is no longer bi-modal.

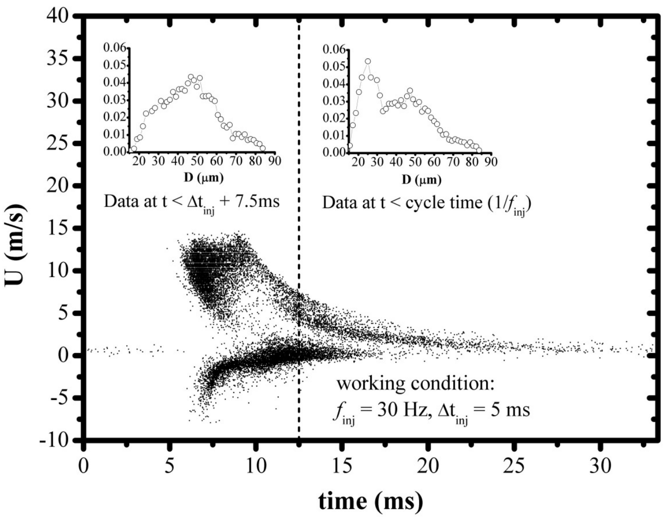


Fig. 2 Effects of the presence of secondary droplets, with positive axial velocity in the size distribution of impinging drops at t > Δt_{inj} + 7.5 ms, and t_{imp} = 5 ms.

To assess how well the Log-Normal distribution fits the measured discrete size distribution, we used the concept of entropy as understood by information theory, designated as Shannon-entropy, $H(p)$ [8]. For a discrete probability distribution, the Shannon-entropy is given by

$$H(p) = -\sum_{k=1}^{N_{bins}} p_k \ln(p_k) \qquad (1)$$

with N_{bins} as the number of bins, or size-classes, within the drop size spectrum and p_k as the probability of occurrence of a certain size-class k. The definition of N_{bins} is important because if these bins are too wide, the information about the dispersion of values within the spectral range could be compromised. On the other hand, if these bins are too narrow, most of them might end up without any data points. This is why Chang *et al.* [9] proposed the use of Fibonacci series as a reliable way for calculating the number of bins.

If we apply Fibonacci series to divide the spectral range of a drop size distribution by classes, each representative size class is the sum of the two previous representative size classes. As this series moves toward large numbers, the ratio between consecutive classes tends to $0.5\cdot(5^{0.5}+1) \approx 1.618$. Following Aldana [10], interlaced Fibonacci sequences (J) have been used to produce a finner mesh in the discrete probability distribution of drop sizes, such that the number of size classes could be obtained by the relation

$$N_{bins} = J\frac{\ln\left(N_{drops}\right)}{\ln\left(1.618\right)} \qquad (2)$$

where N_{drops} corresponds to the number of drops, or more generally, the number of data points. According to Aldana [10], six interlaced Fibonacci series, J = 6, provides an excellent tool for estimating of the number of bins or classes.

For the Log-Normal distribution function, the Shannon-entropy can be derived analytically as

$$S = \frac{1}{2}\left(1+\ln\left(2\pi\gamma^2\right)\right)+\ln\left(d_g\right) \qquad (3)$$

The closeness between the values obtained in equations (1) and (3) are associated with the assessment of how accurate is the fitting of the Log-Normal distribution function to the experimental discrete distribution of primary and secondary droplets in each of the cases summarized in Table 1. These results are depicted in Fig. 3. The Log-Normal continuous distribution function is able to reasonably describe discrete size distributions of impinging and secondary droplets in intermittent spray cooling experiments with a net uncertainty of ± 2.7%, although in the case of secondary drop size distributions, this value goes up to 5%.

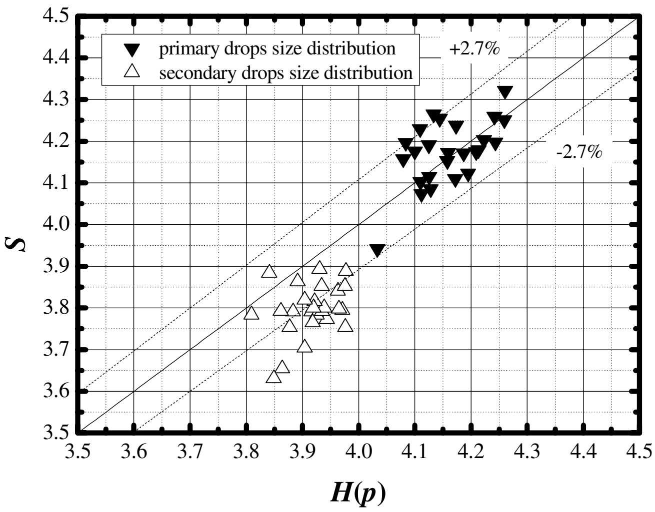


Fig. 3 Comparison between the Shannon-entropy of the measured discrete size distribution and the fitted Log-Normal for the primary and secondary droplets.

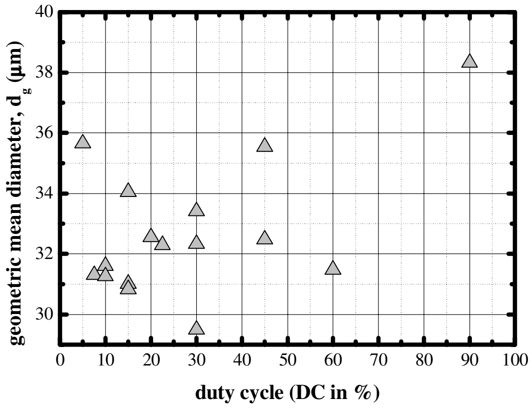
The former analysis based on information theory concepts supports the use of characteristic parameters in the Log-Normal distribution function to further investigate the effect of the duty cycle on secondary atomization and also in the preliminary analysis of the net effects of the superheating degree, pressure of injection and impingement distance.

Effect of Duty Cycle on Secondary Atomization

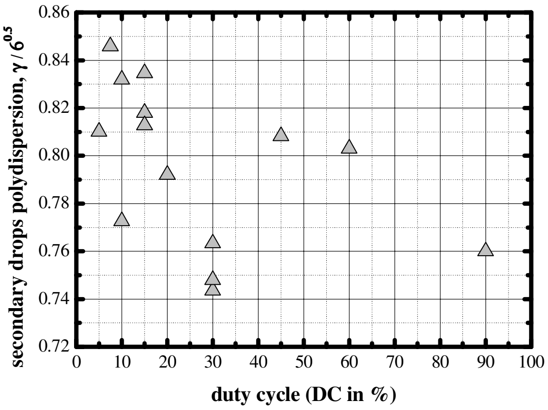
Previous research works have used the Log-Normal distribution to characterize the secondary atomization in single-drop and spray-impact experiments [11-14]. Although some correlations can be found in the literature for the geometric mean diameter, this parameter depends on the experiment, for example, in the impact of droplets with very different sizes, the geometric mean diameter characterizing secondary atomization is expected to be different. However, if the impact mechanisms remain the same for different experiments, the polydispersion degree, expressed by the standard deviation γ, is expected to be the same. Throughout the text the terms standard deviation and polydispersion are used with the same meaning. Therefore, particular emphasis is given in our analysis to the polydispersion in secondary atomization through the Log-Normal standard deviation.

For a single drop impact on a thin liquid film, Stow and Stainer [11] have measured a non-linear behaviour of the standard deviation ($\gamma \in [0.823; 1.712]/\sqrt{6}$) with the liquid film thickness ($\delta_f = h_f/d_b \in [0.0075, 0.1125]$). Samenfink *et al.* [12] for the impact of a single-size stream of droplets (d_b) onto liquid films obtained polydispersions of $\gamma \in [1.009; 1.065]/\sqrt{6}$, correlated with the drop impact momentum, s_{cd}, the impact angle, α_b, and the dimensionless film thickness, δ_f, as $\gamma = 0.3696\cdot s_{cd}^{-0.1772}\cdot\alpha_b^{0.09163}\cdot\delta_f^{0.03177}$. Schmehl *et al.* [13] used a fixed polydispersion value in their CDF simulations of $\gamma = 1.102/\sqrt{6}$. And in the approach of Wu [14], the maximum entropy formalism is used to estimate the analytical polydispersion which allows obtaining the probability distribution with the maximum Shannon-entropy and the value resulted in $\gamma = 1/\sqrt{6}$, close to previously reviewed values found in the literature. However, as suggested by the results of Stow and Stainer [11] and Samenfink *et al.* [12], it should be emphasized that if the standard deviation is fixed, any numerical methods supported by this assumption fail to capture the dynamic nature of the secondary spray polydispersion. An additional note is the scarce information available in the literature for the standard deviation of secondary droplets resulting from the spray impaction onto hot surfaces, relatively to which the work presented here intends to contribute.

In the case of Intermittent Spray Cooling, the duty cycle (DC) has been identified as the most important parameter for controlling surface temperature [15]. Therefore, it is worth questioning if there is any correlation between this parameter and secondary atomization. The first set of results analyzed are depicted in Fig. 4 for the experiments in the first row of Table 1. As the operating condition approaches that of a continuous spray (DC = 100%), the geometric mean size of secondary droplets tends to increase (Fig. 4a), although the values for DCs below 30% are quite scattered. Relatively to the polydispersion degree (Fig. 4b), a decrease of 13% is measured between a DC of 5% until 30%, and no clear trend is discerned for DC > 30%. However, compared to the values earlier mentioned for the standard deviation, the secondary drop sizes resulting from spray impaction on a heated surface, appear to be less polydispersed than experimental data on unheated surfaces, with $\gamma < 0.85/\sqrt{6}$.



(a)



(b)

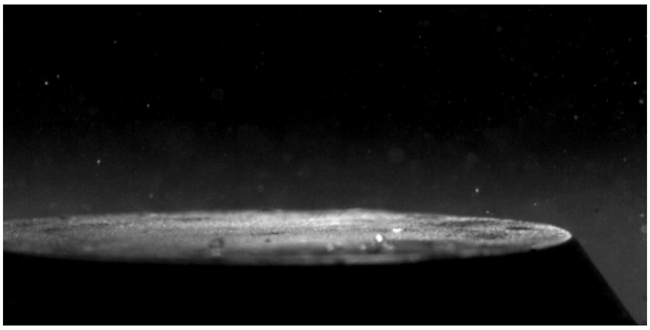
Fig. 4 Effect of the duty cycle in the (a) Geometric mean diameter and (b) standard deviation of secondary droplets.

It has been previously shown that the DC does not change the spray characteristics before impact and the effect of increasing it toward 100% is to form a liquid film as depicted in Fig. 5, which mitigates (not suppresses) phase-change, but enhances secondary atomization due to the shorter 'dead-time' between consecutive injection cycles [15]. However, what seems to be a larger concentration of droplets, as DC increases, corresponds to a size distribution shifted to slightly larger sizes which could be the result of the presence of a liquid film and the enhancement of drop-drop interaction [16, 17], however, no significant changes are observed in secondary droplets polydispersion (Fig. 4b).

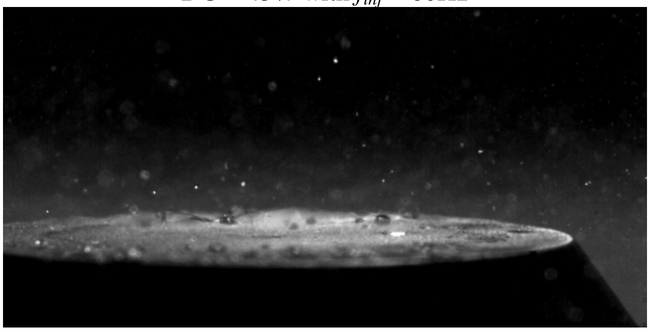
The following step is to correlate the information between the characteristic parameters of the Log-Normal distribution function of secondary droplets and the characteristic parameters of primary droplets, *i.e.* the geometric mean diameter d_g and standard deviation γ, between secondary (s) and primary (p) droplets.

In the case of $d_{g,s}/d_{g,p}$, the bottom plot in Fig. 6 shows that a mild linear increase is measured (around 2%). And the results obtained for the relative polydispersion show a monotonically behaviour of it as a function of the duty cycle (DC), allowing to derive an empirical correlation as

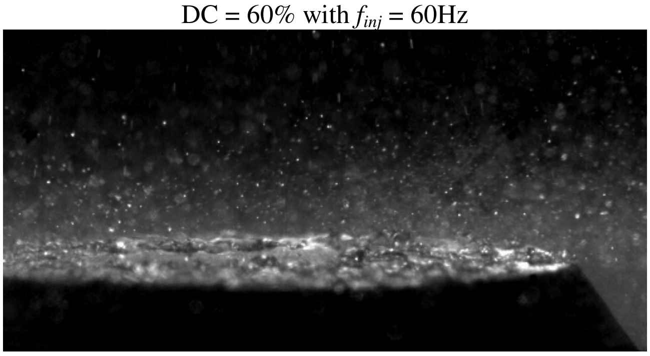
$$\frac{\gamma_s}{\gamma_p} = 1.194 - 0.02\mathrm{DC} + 2.16\times10^{-4}\,\mathrm{DC}^2 \qquad (4)$$
$$R^2 = 0.715,\ e_r = \pm 10.6\%$$



DC = 45% with f_{inj} = 60Hz



DC = 60% with f_{inj} = 60Hz



DC = 90% with f_{inj} = 60Hz

Fig. 5 Images at 18 ms after the impact moment of the last in a series of 40 injections cycles. For a 60 Hz frequency of injection, the duty cycle is change by a proper matching the pulse duration.

Although recognizing the limited applicability of this empirical correlation, we will focus the analysis on its interpretative value. First, it has been previously argued, and visualized in Fig. 5, that above a certain DC, a liquid film is formed between consecutive injections, meaning that secondary atomization mechanisms may vary with the duty cycle. While this is consistent between an impinging spray, which does not change with DC [13], and the shifting of $d_{g,s}$ to larger sizes (see Fig. 4b), in the case of the secondary spray polydispersion, while no trend is observed above a DC of 30%, the relation between γ_s and γ_p indicates in that range, an inverted behaviour of the polydispersion tendency, relatively to primary droplets. Earlier in the introduction, it has been alluded that the secondary spray polydispersion is associated with the mechanisms which produce secondary droplets. Therefore, to interpret the result depicted in Fig. 6a, when the system approaches the working condition of a continuous spray (DC = 100%), the outcome of the impact mechanisms onto liquid films become dominant over other outcomes when this impact is made onto a relatively dry surface, as with shorter duty cycles. So, it is likely that the polydispersion inverted tendency is related with this change of mechanism producing secondary droplets.

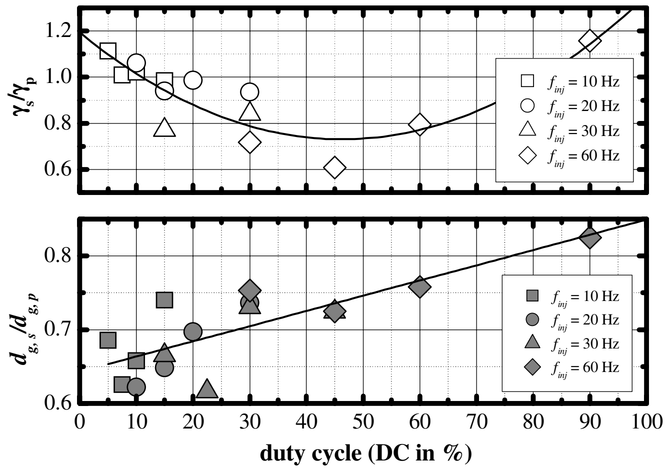


Fig. 6 Ratio of geometric mean diameter and standard deviation of the Log-Normal distribution function are correlated with the duty cycle (DC) between primary and secondary droplets.

Finally, it should be noted that the results presented in Fig. 6 have predictive potential and can be used to estimate the polydispersion in the secondary atomization of intermittent spray cooling simulations.

Other parametric effects on Secondary Atomization

This paper also includes a preliminary study of the net effects of parameters such as the superheating degree (ΔT_{wb}), injection pressure (p_{inj}) and impingement distance (Z_{imp}) on secondary atomization. The analysis is based on the relative geometric mean diameter (left side of Fig. 7) and the standard deviation, or size polydispersion of secondary droplets (right side of Fig. 7). The results for the relative geometric mean diameter, depicted in Fig. 7, are not significantly affected by the superheating degree, nor the injection pressure, except when the impingement distance increases, leading the a decrease of $d_{g,s}/d_{g,p}$, independently of the injection frequency, here representing the degree of interaction between consecutive injection cycles.

In the case of the secondary drop size polydispersion, the net effect of the superheating degree is non-linear, with a local maximum, and more pronounced for lower injection frequencies. Any condition other than this maximum tends to produce a more uniform distribution of secondary droplets, relatively to the primary. The net effect of the injection pressure and impingement distance is to decrease the secondary drops size polydispersion, slightly in the first case and more evident in the second case. A noteworthy comment is that the decrease observed in the impingement distance net effect is more influenced by an increase of $d_{g,p}$ of primary drop mean size, than the one exerted by the secondary drops mean size. This could be the result of some evaporation of smaller droplets as the trajectory toward the wall increases [18].

The results in this preliminary threefold parametric study suggest that the spray intermittency (injection frequency and pulse duration) does not play a significant role in the net effects associated with the superheating degree, injection pressure and the impingement distance. Therefore, these results should be valid if the spray is intermittent or continuous, and suggest the importance of the superheating degree in the secondary drop size polydispersion, and the importance of the impingement distance for the mean size and corresponding polydispersion of secondary droplets. In order to improve predictions of secondary atomization when the impact is made on heated surfaces, more experimental studies on these two parameters are encouraged.

SUMMARY

The objective of this paper is to characterize the secondary atomization resulting from intermittent spray cooling. This characterization is used to further investigate the effect of the system' determining parameter, the duty cycle, as well as the net effect of other constructive parameter, such as the superheating degree, injection pressure and impingement distance.

The approach followed in the analysis implies to reconstruction of the measured discrete probability distribution of secondary droplets by fitting a Log-Normal distribution function, and assessing the fitting procedure using the entropy concept as understood by information theory. The analysis of the results presented emphasizes that:

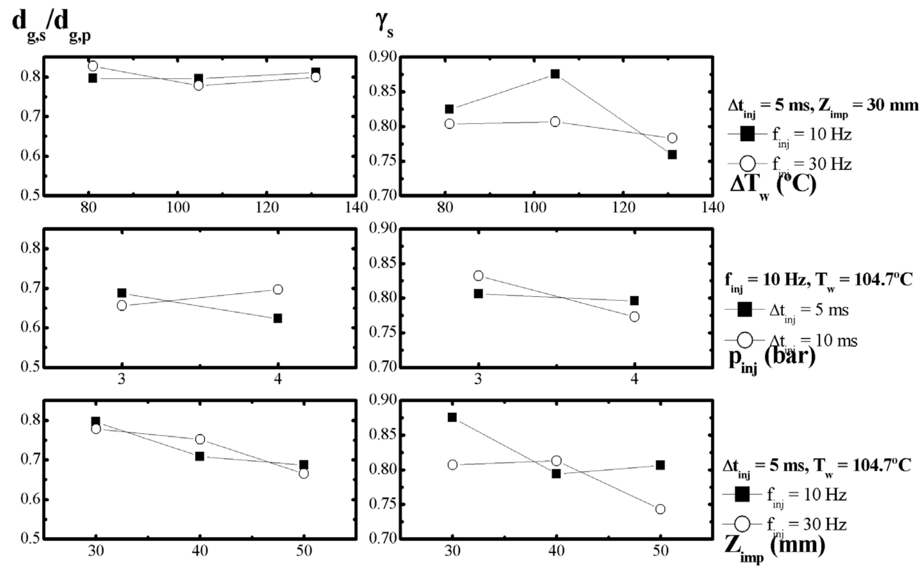


Fig. 7 Preliminary results of the net effects of the wall temperature, injection pressure and impingement distance on secondary atomization

- an increase of the duty cycle, as it approaches the working condition of a continuous spray (100%), shifts the geometric mean diameter of secondary droplets to larger sizes;
- the relative polydispersion between secondary and primary atomization (γ_s/γ_p) is consistent with the decrease of γ_s observed until DC = 30%, but this trend is inverted for DC > 30%;
- other preliminary parametric studies show that the relative geometric mean diameter ($d_{g,s}/d_{g,p}$) is only affected by the impingement distance;
- the secondary drop size polydispersion is mainly influenced by the superheating degree and impingement distance, however, more experiments are required to improve the understanding of these net effects for the development of future numerical models.

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NOMENCLATURE

Symbol	Quantity	SI Unit
d_b	Drop diameter before impact	µm
d_g	Geometric mean diameter	µm
DC	Duty cycle	%
f_{inj}	Injection frequency	Hz
h_f	Liquid film thickness	mm
H	Shannon-entropy	-
p_{inj}	Injection pressure	bar
S	Analytical Shannon-entropy	-
T_b	Liquid boiling temperature	ºC
T_w	Wall temperature	ºC
U	Drop axial velocity	m/s
Z_{imp}	Impingement distance	mm
Greek		
δ_f	Dimensionless film thickness	-
Δt_{inj}	Injection duration	Ms
ΔT_{wb}	Superheating degree ($T_w - T_b$)	ºC
γ	LogNormal standard deviation	-
Subscripts		
p	Primary	
s	Secondary	

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