Multiple regime heat transfer correlation for spray/wall interaction and thermo-induced secondary atomization characteristics

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Abstract

In this work a multiple regime heat transfer correlation is empirically derived for intermittent spray/wall interaction using simultaneous measurements of droplets characteristics and surface thermal behavior considering two fluids with a different latent heat of evaporation (HFE-7100 and acetone). Thermo-induced secondary atomization is also evaluated based on transient size-axial velocity correlations measured for intermittent cooling with HFE-7100, and it is observed that this mechanism is not significantly affected by the duty cycle, and it is enhanced at low superheating degrees, where an eventual thin liquid film formed on the surface is more likely to endure after the end of injection.

Introduction

The application of an intermittent spray for two-phase cooling has been recently proposed as a new technological concept for providing a system with better performance and control over heat transfer mechanisms such as thin film boiling [1]. Also, one of the advantages of using an intermittent spray is the ability to control the amount of liquid injected by proper matching the frequency of injection and pulse duration through the duty cycle, defined by the percentage of cyclic time where an injection event occurs: $DC = f_{inj} \cdot \Delta t_{inj}$, where f_{inj} is the injection frequency and Δt_{inj} the pulse duration, e.g. in order to ensure the required stability in the thin film boiling mechanism.

However, to accurately model this phenomenon it is important to understand the effects underlying the phenomenological relationality between the impinging spray characteristics and heat transfer mechanisms. This relationality is a crucial point in the knowledge of heat transfer processes, however, some contradictions can be found in the literature of what parameters actually govern heat transfer. For example, while Arcoumanis and Chang [2], Bernardin et al. [3] and Chen et al. [4] argued that droplet axial velocity plays a dominant role in governing local, time-resolved heat transfer. In Estes and Mudawar [5], and Rybicki and Mudawar [6] it is argued that volumetric flux is of much greater significance in characterizing spray heat transfer than drop velocity. In Sawyer et al. [7], Yao and Cox [8] and Cabrera and Gonzalez [9] arguments are presented for the spray mass flux, and in Rini et al. [10] for the droplet number flux as the main parameters governing heat transfer. However, in Pikkula et al. [11] it is the Weber number ($\rho U^2 d/\sigma$), and in Chen and Hsu [12] it is the initial wall superheat (T_w-T_b) that is considered to be the primary parameter affecting heat flux. Therefore, there is still much uncertainty as to what are the actual parameters that mainly affect spray/wall heat transfer in general. In the present case of intermittent spray cooling, it is worth questioning about the parameters governing heat transfer phenomena, taking into account the spray dynamic behavior along an injection cycle. However, this requires simultaneous measurements of the spray characteristics and also, of the heat transferred in the cooling process. Only with this simultaneous information we can expect to accurately correlate both and usefully contribute for the development of numerical CFD models. This is the first objective of the work presented here.

Furthermore, in Moita and Moreira [13], a study performed on single drop impact onto a heated surface, in a nucleate boiling regime, has shown that the result of bubble explosion activity after droplet spreading is the production of relatively large secondary droplets, through a thermo-induced break-up mechanism. Therefore, it is expected that during the injection cycle, and also when consecutive injections begin to interact, a thin liquid film is formed and thermo-induced break-up events occur. This means that part of the mass injected to cool the surface does not remain in the thin liquid film for this purpose, but instead, is emanated from the wall in the form of secondary droplets. However, it is still unclear how much is secondary atomization affected by this mechanism in intermittent spray cooling. Therefore, the second objective of this work is to evaluate the influence of operating parameters on this induced secondary atomization process.

Experimental Approach

Intermittent fuel delivery

The flow configuration is that of a spray striking perpendicular onto a flat aluminum disc with a 10 mm radius (r_{disc}), which is heated by an electric resistance

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and a copper plate uniformly distributing heat to the disc. 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 (fig. 1).

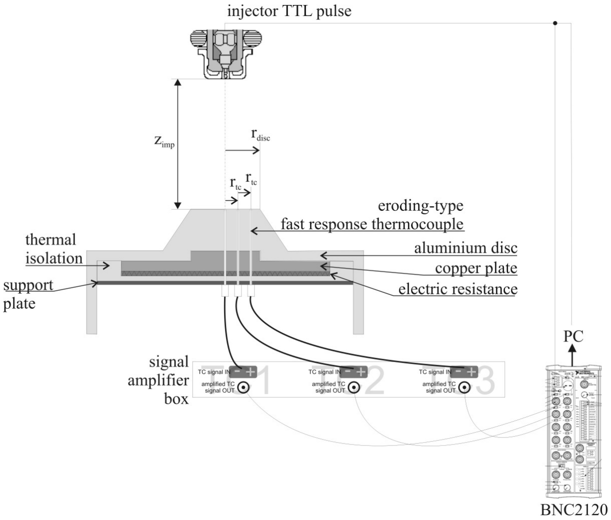

Fig. 1 Experimental setup

The injection frequency, pulse duration and number of injections are software controlled by a NI5411 arbitrary function generator from National Instruments. Two liquids were used in this experiment: acetone and a dielectric fluid HFE-7100 produced by 3M. Their thermophysical properties are listed in Table 1: specific mass (ρ); dynamic viscosity (μ); surface tension (σ); boiling temperature (T_b); and latent heat of vaporization (h_{fg}). The variation of HFE-7100' properties with temperature is given by 3M and those of acetone follow Reid et al. [14].

Table 1 Fluids thermophysical properties

Fluid	**ρ (kg/m^3)**	**μ (kg/m/s)**	**σ (mN·m)**
HFE-7100	1488	5.7×10^{-4}	13.6
Acetone	790	3.2×10^{-4}	23.7
	c_p (J/kgºC)	**T_b (ºC)**	**h_{fg} (kJ/kg)**
HFE-7100	1177	61	111.6
Acetone	2161	56.3	534

Heat transfer measurement

Three "Medtherm" eroding-K-type thermocouples were assembled in the disc and spaced by 4 mm (r_{tc}) with the first thermocouple located at the disc centre as depicted in fig. 1. Thermocouples 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 processing. Inaccuracies in temperature due to electronic noise increase as the surface temperature decreases and were found to be smaller than ±1% at ambient temperature.

Spray characteristics measurement

Local time-resolved measurements of droplet size and velocity are simultaneously made at 2 mm above the surface, with a two-component phase Doppler (PDA) DANTEC system consisting of a 55X transmitting optics, a 57x10 PDA receiving optics, oriented at 30º with negligible changes in the refractive index, and a 58N10 Covariance processor.

The number fluxes of droplets depend on the effective cross-section area of the PDA measurement volume, which is calculated according to Roisman and Tropea [15] and Panão and Moreira [16]. Error propagation analysis showed that errors are smaller than 10% for all phase-averaged flux quantities.

Results and Discussion

The operating conditions where intermittent spray cooling is performed are listed in Table 2.

Table 2 Working conditions

Case	**f_{inj} (Hz)**	**Δt_{inj} (ms)**	**p_{inj} (bar)**	**ΔT_{wb} (ºC)**	**Z_{imp} (mm)**	**Fluid**
1-16	10, 20, 30, 60	5, 7.5, 10, 15	3	43.7	50	HFE-7100
17-18	10	5, 10	4	43.7	50	HFE-7100
19-22	10, 30	5	3	43.7	30, 40	HFE-7100
23-26	10, 30	5	3	20, 70	30	HFE-7100
27-34	10, 20	5, 7.5, 10, 15	3	43.7	50	Acetone
35-38	30, 60	5, 10	3	43.7	50	Acetone

Spray intermittent behavior

Simultaneous measurements of droplet size and velocity and surface temperature are phase-averaged within a total of 400 injections for a spray pulsed at 20 Hz with pulse duration of 10 ms. The results are depicted in Fig. 2 and allow to correlate the dynamic behavior of the spray with surface temperature variations. It is obvious that the spray dynamics conditions the cooling. However, it has been previously justified that it is necessary to have synchronized measurements of the droplets characteristics and surface cooling if the two are to be accurately correlated [16, 17]. As pointed in the introduction, there is still considerable uncertainty about which parameters actually govern heat transfer. In Panão and Moreira [18], a first approach to resolve this uncertainty in multiple-intermittent spray systems is performed and it was concluded that heat transfer during intermittent spray cooling occurs under three time-dependent regimes associated with the spray dynamic behavior (Fig. 2).

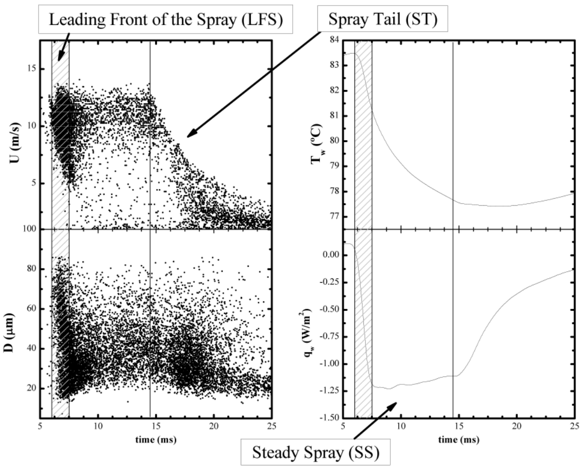

Fig. 2 Spray dynamic behavior

The first occurs during the leading front of the spray period (LFS), for 0.75-1 ms after the first drop impacts and is characterized by an intense size and velocity gradient of impinging droplets, as well as in the wall heat flux. In this regime, heat transfer mainly depends on the number flux of droplets, a result equally observed by Pautsch & Shedd [19], Estes & Mudawar [20] and Yao & Choi [21] for continuous sprays.

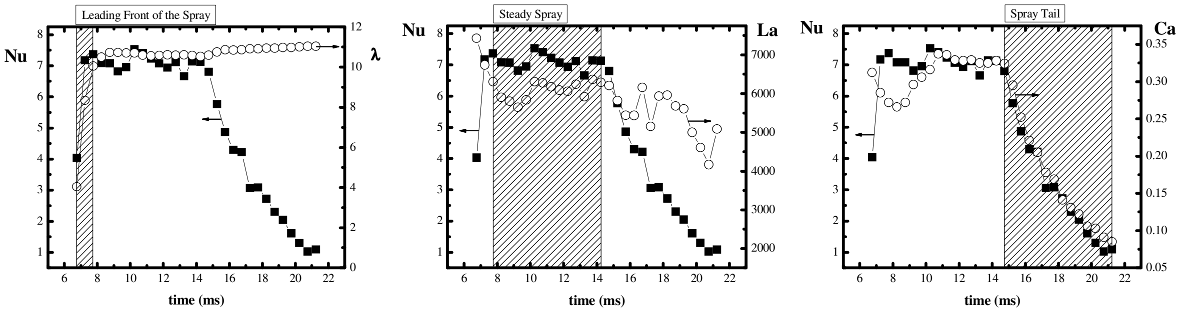

Fig. 3 Correlation between spray dynamic behavior, expressed in several dimensionless forms depending on the injection period, and the heat transfer associated with the cooling process.

The second time-dependent regime occurs during the steady spray period (SS) during which a quasi-steady behavior of the impinging spray dynamics and heat flux removal are observed until the end of injection. Previous work as shown that heat transfer in this period is mainly governed by variations of the mean drop size [16].

The third and final time-dependent regime is the spray tail period (ST) during which droplet velocity and heat transfer decrease simultaneously. Previous work showed that these two are correlated [18]. The axial velocity decreases due to the loss of pressure forces after the injector closes. The consequential decrease in the wall heat flux allows the recovery of the surface temperature as seen in Fig. 2.

Dynamic spray/wall interaction heat transfer correlation

Given the spray dynamic behavior, a single correlation for the entire period has been shown to be inaccurate [18]. Therefore, multiple regimes should be taken into account. Namely, each regime can be correlated with a dimensionless parameter expressing a characteristic of the spray dynamics. In the leading front of the spray the average number of drops impacting in the vicinity of each other, as defined by Roisman and Tropea [21] is expressed as $\lambda = \pi \delta r^2 \cdot \delta t_{bin} \cdot \dot{n}''$, where δr is the interaction radius (500 μm) and δt_{bin} a phase-average time-bin (0.5 ms). In the steady spray, heat transfer is correlated with the Laplace number ($La = \rho \sigma D_d / \mu^2$) because of its dependence on mean drop size, as shown in Panão and Moreira [16], and finally, in the spray tail, the heat transfer is correlated with the axial velocity expressed by the Capillary number ($Ca = \rho U_d \nu / \sigma$), as shown in Fig. 3.

The search for correlations associated with local measurements, according to the work of Arcoumanis and Chang [2], necessarily implies that the axial velocity of impinging droplets, even if indirectly, may empirically contribute to the heat transfer process, thus, the Capillary number is included in every time-dependent regime.

Besides the Capillary number, in Panão and Moreira [17] the Jacob number ($Ja = c_p(T_w - T_b)/h_{fg}$) has been considered to express the importance of phase-change in the local heat transfer, therefore, it will also be considered in every time-dependent regime of the spray dynamic behavior. The final form of the correlations can then be expressed as:

$$\mathrm{Nu} = \begin{cases} f(\lambda, \mathrm{Ja}, \mathrm{Ca}),\ t_{impact} \le t(\mathrm{ms}) \le t_{impact} + 1 \\ f(\mathrm{La}, \mathrm{Ja}, \mathrm{Ca}),\ t_{impact} + 1 \le t(\mathrm{ms}) \le t_{impact} + \Delta t_{inj} \\ f(\mathrm{Ca}, \mathrm{Ja}),\ t_{impact} + \Delta t_{inj} > t(\mathrm{ms}) \end{cases} \tag{1}$$

where t_{impact} is the instant of impact and Δt_{inj} is the pulse duration. The phase-average quantities used in the dimensionless groups above were:

i) the average heat transfer coefficient is defined as

$$\overline{h}_w = \overline{\dot{q}''_w} \cdot \left(\overline{T}_w - T_f\right) \tag{2}$$

with

$$\overline{\dot{q}''_w}\left(t_j = t_i + 0.5\delta t_{bin}\right) = \frac{1}{\delta t_{bin}} \int_{t_i}^{t_i+\delta t_{bin}} \dot{q}''(t)\,dt \tag{3}$$

and $\overline{T}_w$ as the ensemble average wall temperature in the time-bin δt_{bin};

ii) the ensemble average of the axial velocity of impinging droplets;

iii) and the average diameter of a volume based size distribution [22]

$$D_{43} = \frac{\sum_i d_i^4}{\sum_i d_i^3} \tag{4}$$

The results for the derived correlations are depicted in fig. 4, including the correlation expression in each time-dependent period, as well as the associated uncertainty.

Thermo-induced secondary atomization

In order to extract as much energy as possible from the surface for an efficient cooling, any portion of the mass injected which does not remain on the surface, will not contribute to the cooling process. Since spray impingement implies a secondary atomization upon impact, it means that secondary droplets emerge by hydrodynamic impact mechanisms, such as rebound and splash, but also, according to Cossali et al. [23] and Moita and Moreira [13], secondary droplets can be generated by thermo-induced effects departing from a vigorous bubble boiling associated with phase-change at the impinging surface. In these later experiments on single and multiple drop impactions, the size of the thermo-induced secondary droplets is expected to be relatively large, compared with secondary droplets formed by hydrodynamic impact mechanisms. Little is described about the influence of these thermo-induced effects on the axial velocity.

The results used for discussing the effects of operating parameter on thermo-induced secondary atomization process in intermittent spray cooling consider the size-velocity (axial component normal to the impinging wall) correlation varying in time and all measurements extrapolated to the wall. According to Panão and Moreira [24], the parameter which controls the cooling process in intermittent spray cooling is the duty cycle (DC). A lower duty cycle (DC = 5%), where less interaction between consecutive injections is expected, is compared with a higher DC (30%) in figs. 5 and 6. It is noteworthy that one of the macroscale structures caused by spray impaction - the formation of a wall-jet vortex as imaged in fig. 5 - will further drag the secondary droplets meanwhile produced, enabling their re-impaction on the heated surface, which will benefit the cooling process. Also, secondary droplets of relatively large sizes are measured, with the same order of magnitude as impinging droplets, which may result from two possible outcomes: i) either hydrodynamic mechanisms associated with multiple drop interactions [23]; ii) or else thermo-induced break-up mechanisms. Both kinds are known to produce larger and slower droplets.

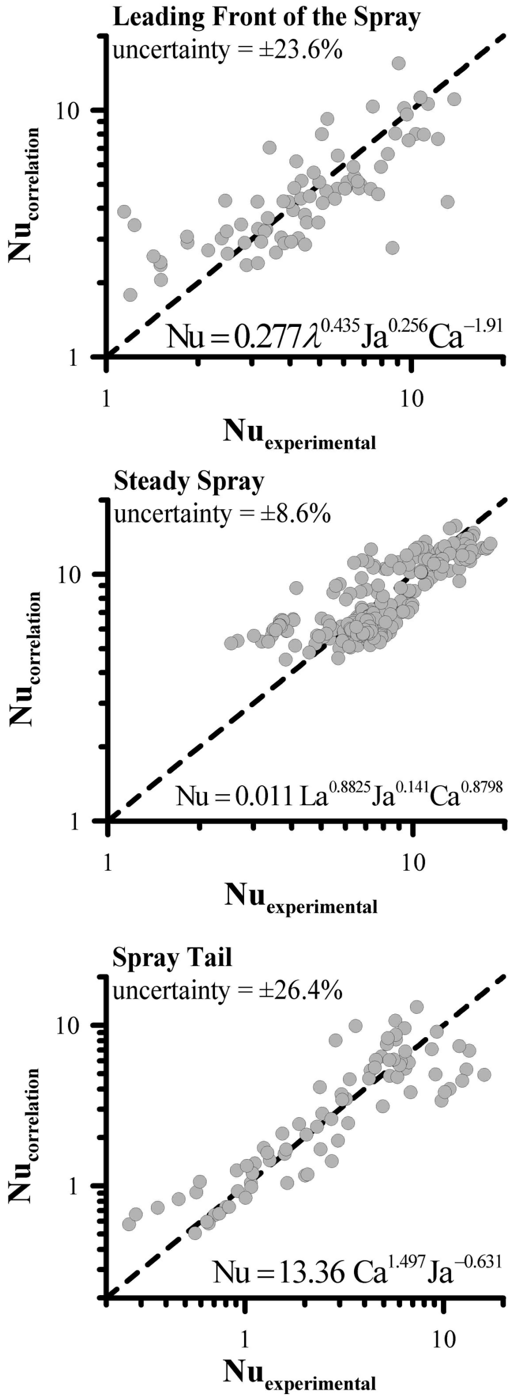

Fig. 4 Dynamic empirical correlations for intermittent spray cooling, valid for $10 \le f_{inj} \le 30$ Hz, $5 \le \Delta t_{inj} \le 15$ ms, $3 \le p_{inj} \le 4$ bar, $20 \le T_w(0)\text{-}T_b \le 70$ºC and $30 \le Z_{imp} \le 50$ mm.

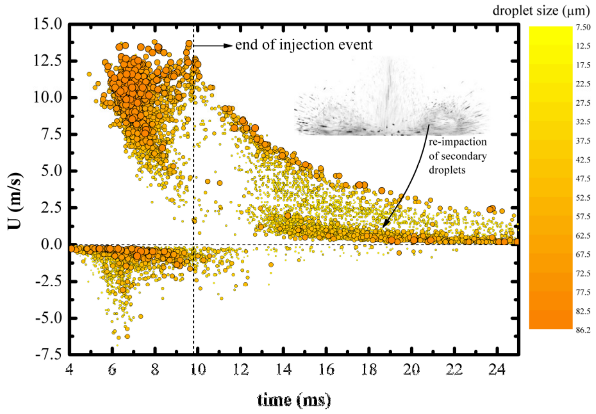

Fig. 5 Size-axial velocity temporal correlation at a duty cycle of 5% with a 5 ms pulse.

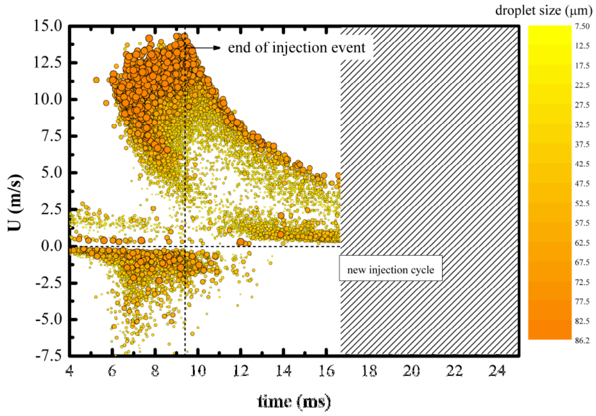

Fig. 6 Size-axial velocity temporal correlation at a duty cycle of 15% with a 5 ms pulse.

One may expect that different wall temperatures emphasize the importance of a thermo-induced secondary atomization relatively to hydrodynamic impact mechanisms, as depicted in fig. 7, where low (5%) and high (15%) duty cycles are also compared. It is observed that, in both duty cycles, an increase of the wall temperature leads to a decrease in the number of secondary droplets emerging from the wall after the end of injection. It is reasonable enough to associate this effect with thermo-induced secondary breakups, since multiple drop interactions are expected to remain unaltered because the issued spray remains the same for each DC considered.

It is likely that a lower wall temperature increases the probability that an eventual thin liquid film, formed during the injection event, remains longer exchanging heat with the surface, although at a lower vaporization rate, consequently enabling thermo-induced secondary mechanisms to act after the end of injection and produce more secondary droplets, as in the cases with $T_w = 81°C$. Moreover, when a larger interaction between consecutive injections is expected, such as increasing the duty cycle to 15%, negligible differences are observed between the secondary droplets characteristics and those in former case with DC = 5%.

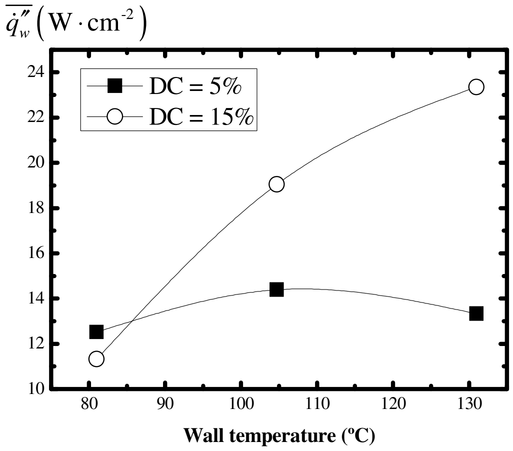

Fig. 8 Average wall heat flux as a function of the wall temperature for two injection frequancies.

Despite this, fig. 8 shows that heat transfer is affected by changing the duty cycle, namely, with

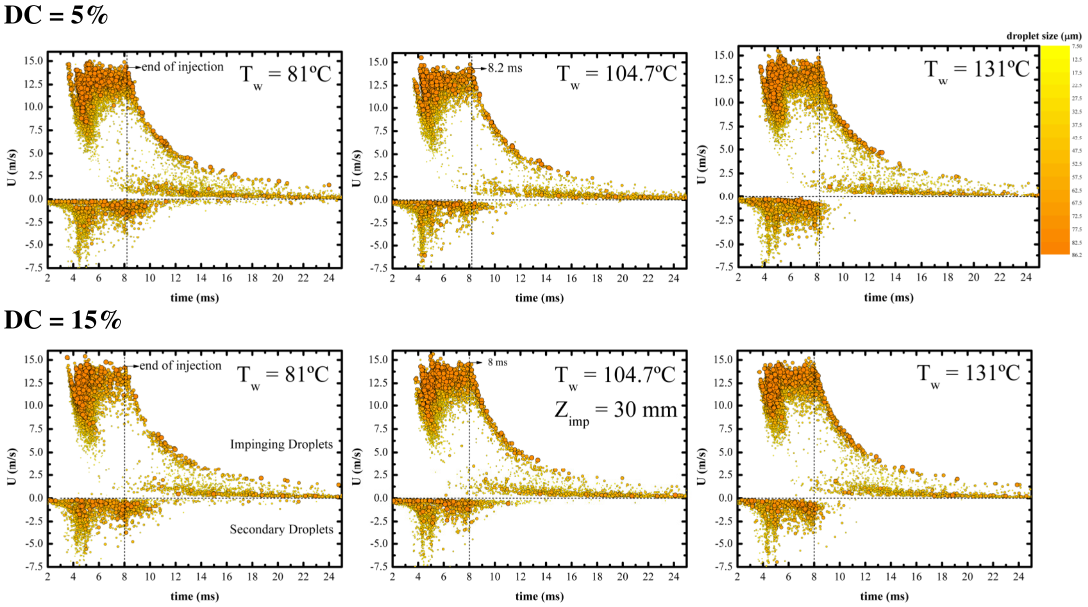

Fig. 7 Size-axial velocity temporal correlations considering the variations of wall temperature for a low (5%) and a high (15%) duty cycle.

DC = 5%, the cooling heat flux is close to it local maximum critical value (Critical Heat Flux – CHF), while with DC = 15%, not only more heat is extracted but the regime also changes, since the CHF condition has not been reached. Even if the duty cycle alters the local cooling heat transfer regimes [24], a greater interaction between consecutive cycles does not seem to affect thermo-induced secondary atomization mechanisms.

Conclusions

The dynamic behavior of the cooling process associated with the impact of an intermittent spray turns inaccurate the use of a single empirical correlation to estimate heat transfer using dimensionless groups such as, for example, Nusselt, Capillary, Laplace, or Jacob numbers. Instead, a multiple regime heat transfer correlation is empirically derived for intermittent spray/wall interaction using two fluids with a different latent heat of evaporation (HFE-7100 and acetone).

Thermo-induced secondary atomization is also evaluated based on transient size-axial velocity correlations measured for intermittent cooling with HFE-7100, and it is observed that this mechanism is not significantly affected by the duty cycle, and it is enhanced at low superheating degrees ($T_w - T_b$), where an eventual thin liquid film formed on the surface is more likely to endure.

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