Two-phase cooling characteristics of a multiple-intermittent spray

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Abstract Among the new techniques capable of removing high heat fluxes, spray cooling appears to be a notable method with its ability of removing heat relying on phase-change (nucleate boiling), additionally to the convective heat transfer linked with fluid motion, but optimum performance requires a precise control of the liquid mass rate supplied for cooling and subsequent removal of the vapor produced. Previous works showed that a multiple-intermittent spray has the potential to achieve this by proper matching the duration of each injection with the frequency of successive injections, but the formulation of an accurate method to control the temperature of the surface demands for an exact knowledge of how the fluid dynamic characteristics of the spray correlates with the heat transfer phenomena. The work reported here addresses these issues based on simultaneous phase-Doppler anemometer measurements of the spray characteristics at impact and instantaneous surface temperature in a simplified flow geometry consisting of a pulsed spray issuing perpendicularly to a flat heated aluminum disc. Analysis of the results shows that the heat transfer behaves differently before and after closing of the injector. During the first period, the interaction occurs with a dense cluster of droplets, which is not altered by the rising thermal plume and heat transfer is governed by the number flux of droplets arriving at the surface; during the second period, interaction occurs with a sparse cluster of droplets and heat transfer is dominated by the kinetic energy of droplets at impact. The effect of increasing the frequency of injection is brought upon by the increase amount of liquid impacting onto the surface. However, comparison with results previously reported and obtained with a different cooling liquid, show that the interaction between successive injections hinders the beneficial effects of using liquids with larger latent of vaporization. The results further evidence that a multiple intermittent spray provides a spray cooling system with a more accurate control over heat transfer which increases its potential as a fast response cooling system for dynamic power dissipation devices.

1. Introduction

The miniaturization of electronics in microprocessor developments, power electronics, high power amplifiers for radar systems, internal combustion engines, fire extinguishment, rapid cooling and quenching in metal foundries, ice chiller and air-conditioning systems, dermatologic surgery are but a few of several applications where large heat dissipation rates demand for new techniques capable of removing high heat fluxes. Among these new techniques, spray cooling appears to be one of the most notable methods with its ability of removing heat relying on phase-change (nucleate boiling), additionally to the convective heat transfer linked with fluid motion.

The two-phase spray cooling event has a highly complex nature, depending on droplet size and velocity, its density or even surface roughness, making it difficult to determine the dominant mechanism controlling heat transfer. One of such mechanisms is thin film evaporation, where upon spray impact a thin liquid film forms on the surface and the highly expected heat flux removal at lower superheats is dominated by single-phase energy transfer rather than phase-change mechanisms (Pais *et al.*, 1992), albeit as superheating increases, phase-change becomes more important (Shedd and Pautch, 2005; Estes and Mudawar, 1995; Hsieh and Yao, 2006). Another mechanism occurs once air and vapor are entrained by droplets puncturing the thin film. In this case, multiple drop impacts promote the formation of secondary nuclei, which enhance turbulent mixing, and consequently produce higher heat flux dissipation rates (Rini *et al.*, 2002; Horacek *et* *al.*, 2005). However, the stability of a thin liquid film (Grissom and Wierum, 1981) and the promotion of secondary nuclei depend on the accuracy of the cooling system to balance fuel delivery and its accumulation on the surface, vaporization of the cooling liquid and vapor removal at the liquid-gas interface. In Moreira and Panão (2006), the application of an intermittent spray for two-phase cooling is proposed as a means to provide a better control over the formerly described heat transfer mechanisms.

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, in order to ensure the desired stability in the thin film boiling mechanism. In fact, while at low injection frequencies nucleate boiling is not limited neither by the delivery of liquid to the surface, nor by the removal of vapor from it, at higher frequencies, nucleate boiling is triggered by enhanced vaporization induced by piercing and mixing the liquid film with multiple drop impacts and interaction between consecutive injections (Moreira and Panão, 2006). Additionally to the effect of injection system parameters on the cooling event, it is also important to understand the influence of spray characteristics on the heat transfer mechanisms and their efficiency. Although this is a crucial point in describing the spray cooling phenomenon, some contradictions may be found in the literature. For example, while Arcoumanis and Chang (1993), Bernardin *et al.* (1997) and Chen *et al.* (2004) argued that droplet axial velocity plays a dominant role in governing local, time-resolved heat transfer, in Estes and Mudawar (1995), and Rybicki and Mudawar (2006) it is argued that volumetric flux is of much greater significance in characterizing spray heat transfer than drop velocity, although in Sawyer *et al.* (1997), Yao and Cox (2002) and Cabrera and Gonzalez (2003) arguments are presented for the spray mass flux, and in Rini *et al.* (2002) for the droplet number flux. Despite this, in Pikkula *et al.* (2001) it is the Weber number ($\rho U^2 d/\sigma$), and in Chen and Hsu (1995) the initial wall superheat that were considered to be the primary parameters affecting heat flux. Therefore, there is still much uncertainty as to what are the actual parameters that mainly affect spray/wall heat transfer, which demands that an accurately correlation between spray characteristics and heat transfer phenomena requires simultaneous measurements of both quantities.

In a previous work (Loureiro *et al.*, 2004), a method was developed to perform simultaneous measurements of droplet size, velocity, fluxes and surface thermal behavior upon spray impact onto a heated flat surface. The method is based on the combination of a phase Doppler anemometry (PDA) with eroding-K-type fast-response thermocouples and was applied in Panão and Moreira (2005) to quantify the influence of initial wall temperature, injection pressure and pulse duration on the correlation between droplet characteristics and the heat flux of single spray impacts. With these measurements, in Moreira *et al.* (2006) a new spray/wall correlation is derived for the Nusselt number, $Nu = 3.4\times10^{-5}\cdot Re^{1.51}\cdot Ja^{-0.254}$, which is valid for the nucleate boiling regime, however, it does not included the effect of injection frequency, which significantly influences spray cooling and its efficiency over the entire impact area (Moreira and Panão, 2006). The main objective of the research work is to provide further insight into the influence of intermittent spray characteristics on heat transfer, namely the effects of injection frequency, pulse duration, initial wall temperature, pressure of injection and impingement distance. However, in the present paper only the effects of injection frequency and initial wall temperature are considered. The analysis is based on detailed time-resolved simultaneous measurements of drop size, velocity and instantaneous surface temperature. From these measurements, the number ($\dot{n}''$) and mass ($\dot{m}''$) fluxes is obtained, and the instantaneous heat flux ($\dot{q}''$) calculated according to Cook and Felderman (1966), and Schultz and Jones (1973).

2. Experimental setup and diagnostic techniques

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 and a copper plate uniformly distributing heat to the disc. 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. 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.

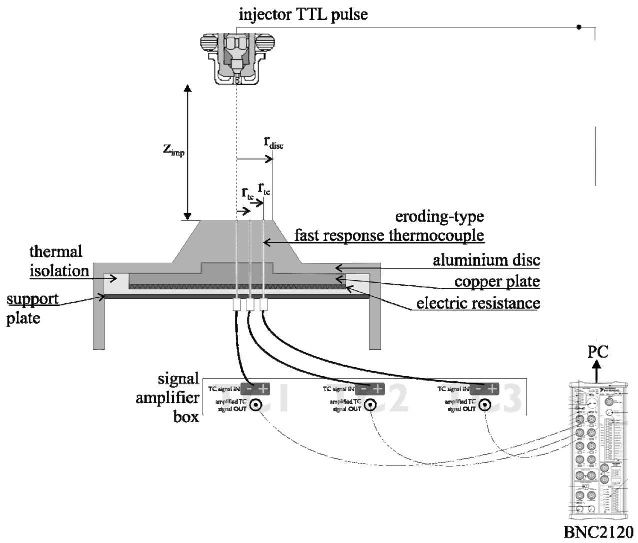

Fig. 1 Experimental setup

The injection frequency, pulse duration and number of injections are software controlled by a NI5411 arbitrary function generator from National Instruments. In these experiments the pulse duration is kept constant and equal to 5 ms. The pressure of injection is 3 bar and the impingement distance (Z_{imp}) is 50 mm. Two liquids were used in this experiment: acetone and gasoline. 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 acetone' properties with temperature follow Reid *et al.* (1986), and those of gasoline follow Lefebvre (1989).

Local time-resolved measurements of droplet size and velocity are simultaneously made at 3 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 70º for minimizing the system's sensitivity to changes in the refractive index, and a 58N10 Covariance processor.

Table 1 Fluids thermophysical properties

Fluid	**ρ (kg/m^3)**	**μ (kg/m/s)**	**σ (mN·m)**	**c_p (J/kg°C)**	**T_b (°C)**	**h_{fg} (kJ/kg)**
Acetone	790	3.2×10^{-4}	23.7	2161	56.3	534
Gasoline	758	4.66×10^{-4}	19.4	2037	60	346

The number and mass fluxes depend on the effective cross-section area of the PDA measurement volume, which is calculated according to Roisman and Tropea (2001) and Panão and Moreira (2005). Error propagation analysis showed that errors are smaller than 10% for all phase-averaged flux quantities.

3. Heat transfer data processing

PDA and thermocouple measurement are both triggered by the electronic pulse used to trigger fuel injection. In order to study the effect of injection frequency groups of seven injections are performed during which PDA and temperature data series are acquired and then reconstructed in order to obtain simultaneous data. The electrical heating system is switched off during data acquisition to avoid any contamination of the data by electric noise. The number of seven injections was chosen so that the temperature decay is always smaller than 10% and each injection interacts with the surface at the same heat transfer mechanism. For the same reason, the first injection is always rejected. The procedure is repeated to average the groups of seven injections and stop after achieving sampling sizes large enough for the resulting processed measurements to be statistically independent. The method is detailed in Moreira et al. (2006).

However, a brief summary of the devised algorithm to obtain phase average values of surface temperature decays, θ_w, wall heat flux, $\dot{q}''$, and heat transfer coefficient, h_w, is given in the following steps:

1. each injection in the group of seven is individualized and the initial temperature, $T_{w,(t=0)}^{i^{th} inj}$, calculated as an averaged obtained from data acquired 1 ms before the electronic trigger has been received;
2. surface temperature decays are calculated ($\theta_w = T_w - T_{w,(t=0)}$), and normalized by the initial superheating degree (ΔT_{wb}), according to:
$$\theta^*(t) = \frac{T_w^{ith\ inj}(t) - T_w^{ith\ inj}(0)}{T_w^{ith\ inj}(0) - T_b} = \frac{\theta_w(t)}{\Delta T_{wb}} \qquad (1);$$
3. normalized decays, $\theta^*(t)$, are chosen from the average series of N_{inj} injections to guarantee that all follow a similar transient behavior;
4. from the injections chosen in step 3, the final phase-average temperature decays are calculated: $\langle\theta_w(t)\rangle$;
5. from $\langle\theta_w(t)\rangle$ the instantaneous heat flux ($\dot{q}''$) is computed according to:
$$\dot{q}''_w(t_n) = \frac{2\beta}{\sqrt{\pi \cdot \delta t}} \sum_{i=1}^{n} \frac{\langle\theta(t_i)\rangle - \langle\theta(t_{i-1})\rangle}{\sqrt{n-i} + \sqrt{n-i-1}} \qquad (2)$$
where $\beta = \sqrt{(\rho k c_p)}$ is the thermocouple effusivity and δt is the time step between two consecutive temperature measurements;
6. the heat transfer coefficient (h_w) is further calculated from $\dot{q}''$.

Error propagation analysis applied to $\langle\theta_w(t)\rangle$, $\dot{q}''$ and h_w results in errors of less than 1% in all experiments, except the case of 108.9ºC±1.9% with 30 Hz, where it is less than 2%.

4. Results and discussion

The results presented in this paper are aimed at discussing the effect of injection frequency (f_{inj}) and initial surface temperature ($T_{w,(t=0)}$) on the intermittent spray characteristics, and consequent heat transfer processes upon spray impact. While section 4.1 addresses the influence of these two parameters on the spray before impact, in section 4.2, a phase-average analysis is performed with simultaneous data on the intermittent characteristics of the spray and surface thermal behavior. In these sections, the analysis is based on two initial surface temperatures ($T_{w,(t=0)}$ of 72.3ºC±0.9% and 108.9ºC±1.9%ºC), two frequencies of injection (10 and 30 Hz) and also acetone is compared with gasoline at the highest surface temperature case with f_{inj} = 10, 30 Hz, in order to evaluate the effect of different fluids on heat transfer. Finally, some considerations are made about the impact of single and multiple injections.

4.1. Effect of injection frequency and initial surface temperature on the spray before impact

The hydrodynamics of droplet deformation upon impact on a solid surface depends on several parameters, but two of the most important are the size and axial velocity (normal to the impact surface) of drops at the instant of impact. This impact hydrodynamics further determines the duration of thermal contact between the impinging liquid and the wall, which is directly related with the heat transfer process. Considering this, any change in the spray dynamics would influence the surface thermal behavior. On one hand, for Diesel injectors, Özdemir and Whitelaw (1993), and Arcoumanis and Chang (1993), reported that higher injection frequencies corresponded to higher drop velocities. On the other hand, the thermal plume emanating from a heated wall was found by Gonzalez and Black (1997) to decelerate impinging droplets with lower Reynolds numbers ($Re = U_d D_d / \nu_d$) around 800, and by Özdemir and Whitelaw (1993) to decrease their size, and increase the number density, where this thermal plume is described as a *«strain field of the continuous phase within the impingement region* [deforming] *the inflowing droplets so that the surface tension is reduced by heat transfer from the wall* […] *and breakup occurs until the surface tension can balance the strain».*

However, the distributions depicted in Figures 2 and 3 for the size and axial velocity of impinging droplets show no significant changes with either the frequency of injection (f_{inj}), nor with the initial surface temperature ($T_{w,(t=0)}$). This means that the Reynolds values of impinging droplets are higher than those of droplets prone to decelerate by a thermal plume; that surface temperatures used in this experiment are not sufficient to generate a strain field capable of inducing secondary breakups to reduce the size of droplets before impact; and that the spray dynamics is quite independent of the frequency of injection, which is consistent with measurements previously reported in Moreira and Panão (2006) for the region near the injector nozzle.

It is noteworthy that the characteristics of the gasoline spray are also independent of injection frequency and initial surface temperature, but despite the similar properties between acetone and gasoline, their differences, however slight, are enough to differentiate the sprays produced by both fluids. Namely, the fact that the surface tension is 20% higher, and that the dynamic viscosity is 30% lower for acetone leads to larger and faster drops, than those of gasoline.

Given the spray unchangeable characteristics as observed above, the differences in the *magnitude* of the heat transfer coefficient (h_w) depicted for acetone in fig. 4, can only by attributed to a combined effect of f_{inj} and $T_{w,(t=0)}$. However, an accurate evaluation of the several parameters acting on the transient nature of the heat transfer process during an injection cycle requires simultaneous measurements of drop size, axial velocity and surface temperature. This is the subject of the following section.

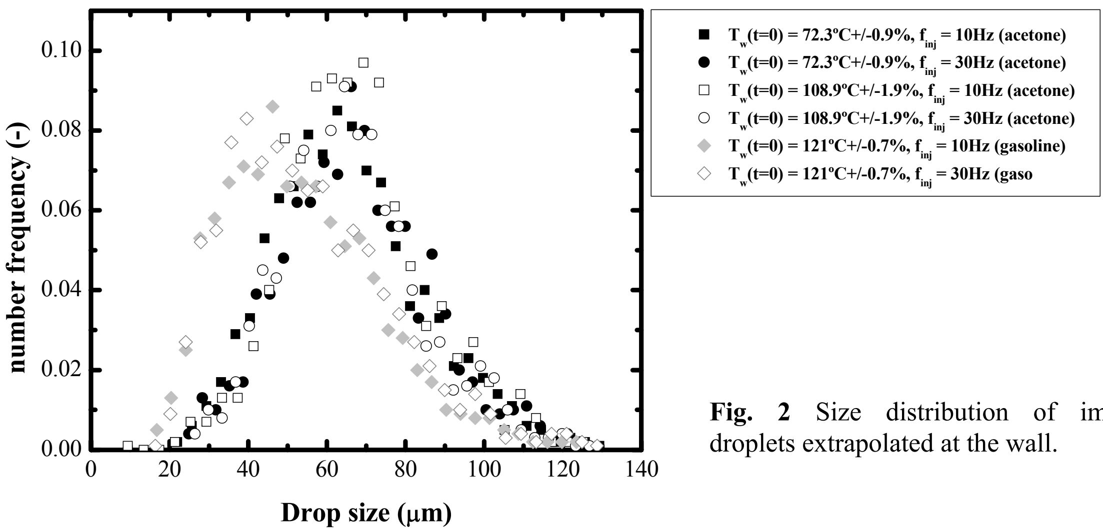

Fig. 2 Size distribution of impinging droplets extrapolated at the wall.

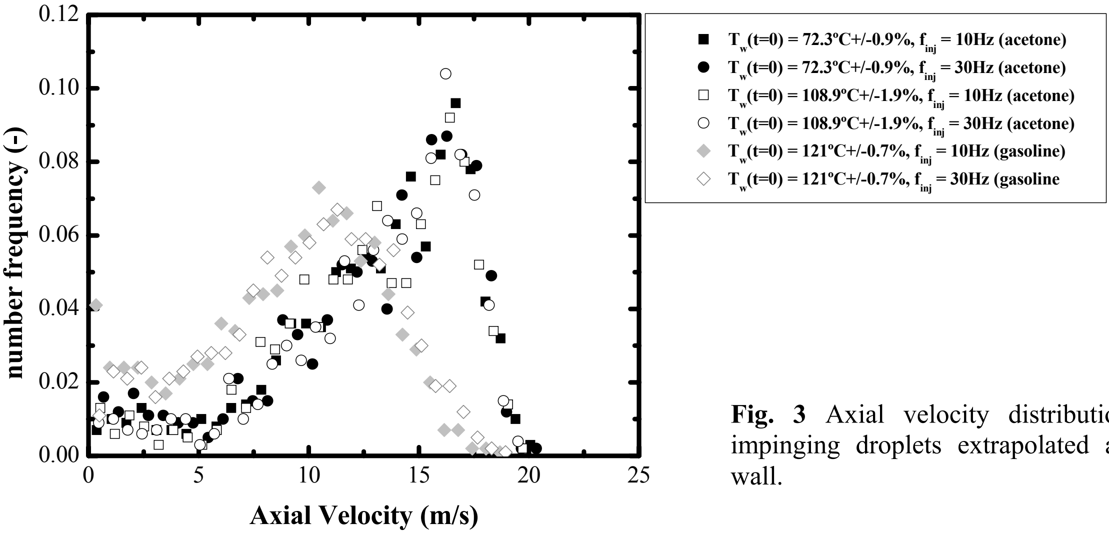

Fig. 3 Axial velocity distribution of impinging droplets extrapolated at the wall.

4.2. Simultaneous measurements of spray characteristics and surface thermal behavior - phase-average analysis

The main concern in this section is to provide further insight into the following research question: which parameter(s) play the dominant role in the heat transfer of multiple-intermittent sprays? The most known parameters affecting spray cooling, already mentioned in this paper' introduction, are:

- droplet axial velocity, U;
- number flux of impinging drops, $\dot{n}''$;
- volumetric or mass flux, $\dot{V}'', \dot{m}''$;
- Weber number, We = $\rho U^2 D/\sigma$;
- initial wall superheat, $\Delta T_{wb,(t=0)} = T_{w,(t=0)} - T_b$;

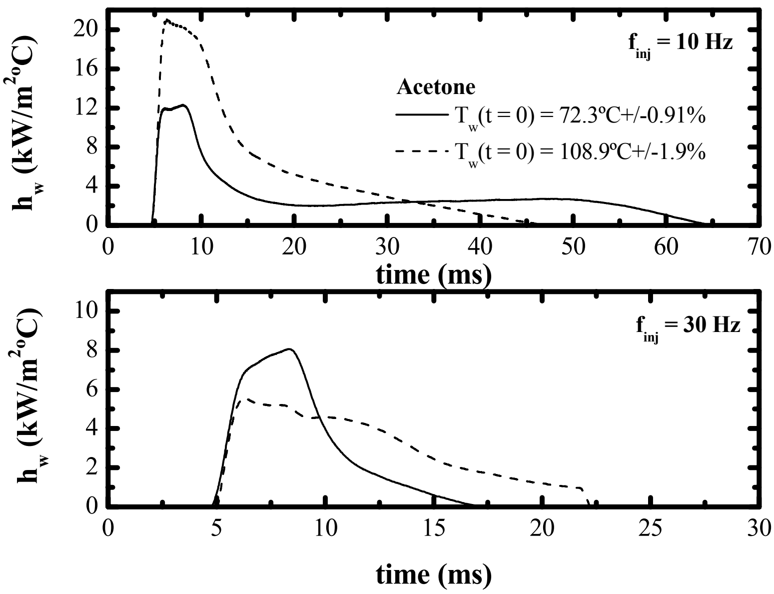

Fig. 4 Heat transfer coefficient transient behavior with f_{inj} and $T_{w,(t=0)}$ for acetone.

The importance of each is evaluated in sub-section 4.2.1, followed by an analysis on the effect of the latent heat of vaporization through the comparison of acetone with gasoline.

4.2.1. Heat transfer governing parameters

Fig. 5 depicts the results obtained for two of the parameters mentioned above ($\dot{n}''_d, U_d$), normalized by their maximum value (see Table 2) on the impact of a multiple-intermittent spray. It appears that the density of droplets arriving at the wall ($\dot{n}''$) dominates the transient behavior of the heat transfer process until the injector closes. This appreas similar to continuous dense sprays, where Yao and Choi (1987) and Estes and Mudawar (1995) have identified the liquid flux impinging on the wall as a parameter of much greater significance to characterize spray heat transfer, while droplet size and velocity have insignificant effects. However, from the injector closing onward (t > 8 ms), drops loose most of their kinetic energy provided by pressure forces at the exit of the injector nozzle, and the decrease observed in h_w, thereafter, follows the same pattern as the axial velocity (right side of Fig. 5).

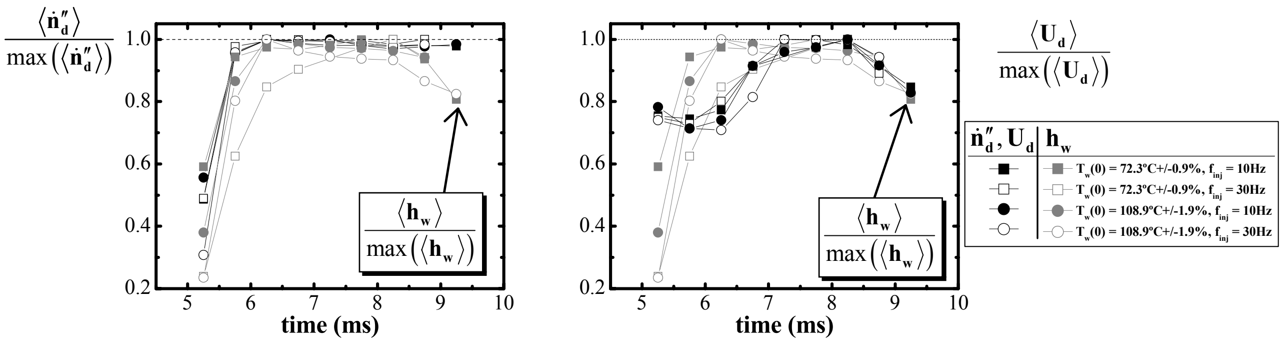

Fig. 5 Phase-average results for the spray characteristics and surface thermal transient behaviors.

This means that in the first period until the injector closes, the density of multiple drop impacts, where the hydrodynamics associated with single impacts is negligible toward an increasingly importance of the interaction phenomena between neighboring droplets, is the main factor affecting heat transfer. However, after the injector closing, the spray dynamics prior to impact becomes the dominant parameter influencing heat transfer.

Table 2 Maximum phase-average values in h_w, U_d and $\dot{n}''_d$

	$\max(\langle h_w \rangle)$ in kW/m^{2}ºC	**$\max(\langle U_d \rangle)$ in m/s**	**$\max(\langle \dot{n}''_d \rangle)$ in #/m^2/s**
■ *72.3ºC ± 0.9%, f_{inj} = 10Hz*	12.215	16.978	19617.5
□ *72.3ºC ± 0.9%, f_{inj} = 30Hz*	8.047	17.135	13.307.1
● *108.9ºC ± 1.9%, f_{inj} = 10Hz*	20.932	17.134	16566.4
○ *108.9ºC ± 1.9%, f_{inj} = 30Hz*	5.522	16.982	12156.6

4.2.2 Effect of latent heat of vaporization

The characteristic advantage of spray cooling systems resides in the use phase-change as a more efficient mechanism to cool a given surface, which is strictly related with the latent heat of vaporization (h_{fg}). The thermal properties of gasoline are similar to those of acetone, except for the latent heat of vaporization, which is 1.54 times larger for acetone. For this reason, considering that the size and axial velocity of impinging gasoline droplets has the same order of magnitude as those of acetone, the main differences in heat transfer can be attributed to the latent heat of vaporization. Fig. 6 compares the instantaneous heat transfer coefficient (h_w) between acetone and gasoline as a function of the Jacob number ($Ja = c_p(T_{w,t} - T_b)/h_{fg}$) and an interesting results is that the effect of h_{fg} is only important if there is not enough interaction between consecutive injection cycles, as in the case of f_{inj} = 10 Hz, where the potential of the spray cooling system is enhanced.

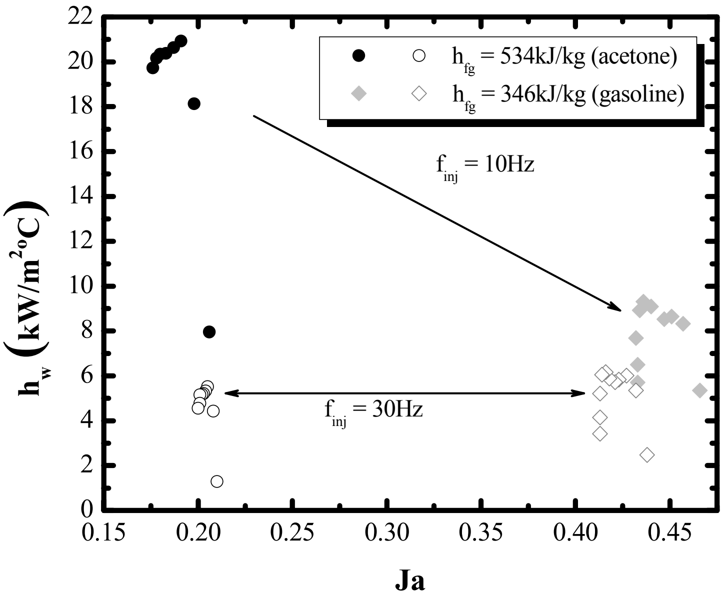

Fig. 6 Heat transfer coefficient as a function of Jacob number comparing acetone with gasoline at the initial reference temperature of $T_{w,(t=0)}$ = 125ºC.

4.3. Single versus multiple pulses

Ultimately, if we continue to increase the injection frequency, it eventually means that the number of injections used in the experiments (7 in our case) is merged into one single pulse. Fig. 7 shows that the spray characteristics do not change with a longer pulse.

Therefore, to evaluate the implications of this merging in the local time-average heat flux removed by the spray, a 35 ms pulse is compared with the number of 5 ms injections performed at 10 and 30 Hz within that period. Each case is identified by its duty cycle (DC = pulse duration × injection frequency in %) according to the scheme depicted in fig. 8. For DC = 15%, N_{inj} = 2 injections were performed and with DC = 5%, only one (N_{inj} = 1) is performed.

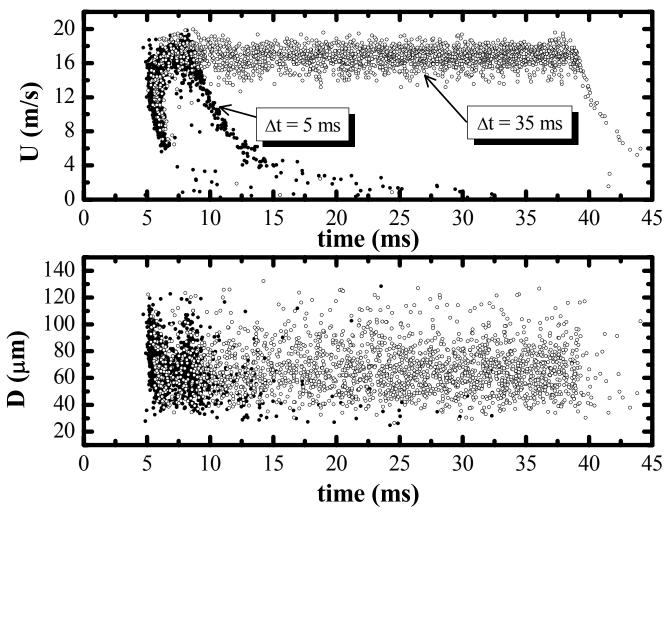

Fig. 7 Drop size and axial velocity of droplets in a 5 ms pulse compared to a 35 ms.

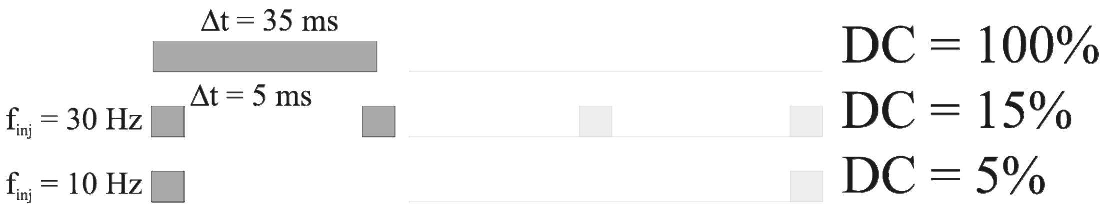

Fig. 8 Schematic of single versus multiple pulses through the duty cycle.

The local time-average heat flux is based of the instantaneous heat flux data measured for each frequency and computed according to

$$\overline{\dot{q}''} = N_{inj} \cdot f_{inj} \int_0^{T_{cyc}} \dot{q}''(t)\,dt \quad (3)$$

where f_{inj} is equal to 1 for the single pulse and T_{cyc} is the cycle period. Fig. 9 shows for both initial surface temperatures of 80ºC and 125ºC that a higher injection frequency leads to an increase in the local amount of heat extracted as a direct consequence of a larger flow rate, but the most significant result is denoting that the injection merging process into a single pulse means less cooling potential.

In fact, heat transfer with short, intermittent pulses occurs according to a thin film evaporation mechanism, which enables a more efficient vapor removal and enhances heat transfer through the piercing and mixing of the liquid film by the impinging droplets (Moreira and Panão, 2006). The use of a longer single pulse, instead of multiple-intermittent, eventually leads to thicker liquid films over the impact surface and single-phase convection becomes dominant over phase-change.

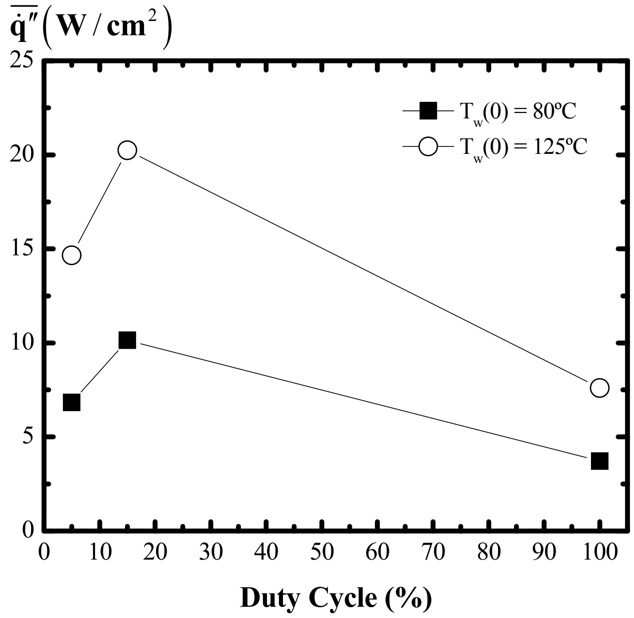

Fig. 9 Local time-average heat flux as function of the duty cycle for different surface temperatures.

5. Concluding remarks

Spray cooling systems are provided with the enormous potential of removing heat from a surface through the latent heat of vaporization, using phase-change as the dominant mechanism for energy transfer. However, this requires a precise control of the liquid supplied for cooling and the removal of vapor, meanwhile, produced. The main advantage of using multiple-intermittent sprays is to contribute in this achievement by proper matching the frequency and duration of injection.

In this paper, simultaneous measurements of the spray characteristics (drop size and axial velocity) and surface thermal behavior provide the empirical background for discussing the governing parameters that play the dominant role in heat transfer processes on the impact of a multiple-intermittent spray.

The main concluding remarks are summarized as follow:

1. the frequency of injection and the surface temperature do not influence the spray characteristics prior impact, only the magnitude of heat transfer;
2. in multiple-intermittent sprays, several parameters govern heat transfer processes during an injection cycle, namely:
    a. density flux of droplets until the closing of the injector;
    b. axial velocity from the injector closing afterwards;
3. increasing the injection frequency corresponds to an increase in the flow rate, consequently increasing heat transfer, however, a comparison between acetone and gasoline has shown that a higher interaction between injection cycles hinders phase-change, and jeopardizes energy exchanges between the impinging spray and the wall;
4. multiple pulses avoid thicker films, and enhance vapor removal between consecutive injections, providing further control over the spray cooling system, increasing its potential for fast response in the cooling of dynamic power dissipation devices.

Further studies will include the variation of more parameters, such as pulse duration, pressure of injection and impingement distance, providing enough information to develop a more accurate spray/wall interaction correlation for two-phase cooling with multiple-intermittent sprays.

Acknowledgements

The authors acknowledge the financial contribution of the National Foundation of Science and Technology at the Ministry for Science and Technology through project POCTI/EME/57944/2004. The author M. R. O. Panão is also provided with financial support through PhD grant SFRH/BD/18669/2004.

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