Evaluation of the cooling performance of individual droplets impinging onto heated targets

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Abstract

The present work reports the experimental evaluation of the cooling performance of individual droplets impinging onto heated targets. The thermal behaviour of the droplets is assessed based on the temporal variation of the surface temperature, within the region of liquid-solid interaction, making use of fast-response thermocouples. A systematic approach considers the variation of several design parameters (e.g. liquid properties, impact velocity and diameter) and boundary conditions to infer on their effect on the thermal and hydrodynamic behaviour of the droplet. The temperature measurements are complemented with the characterization of droplet dynamics and interfacial phenomena, by using high-speed imaging combined with phase Doppler measurements, to provide a better interpretation of the phenomena. Liquid properties are determinant in the cooling performance of the droplet. Particularly, the liquid surface tension and the latent heat of evaporation give rise to relevant morphological modifications of the lamella, which influence the whole heat transfer process. The role of the impact conditions and particularly the impact velocity is secondary, but the use of micro-textured surfaces can be an alternative solution to improve the cooling performance of the impinging droplets. Optimization of the topographical parameters is performed based on the relations between the roughness amplitude and the fundamental wavelength, R_a/λ_R, in a compromising solution of endorsing liquid-solid contact without promoting an excessively intense thermal induced atomization.

Introduction

Interfacial phenomena occurring at liquid-solid contact take place in many practical situations, from coating processes in industrial applications (e.g. development of self cleaning surfaces), to the advance in the alloys for prosthesis and other medical applications (e.g. Gispert [1]) or in the design of cooling systems for electronic parts (e.g. Amon et al. [2]). In the latter, the interfacial phenomena affect both fluid-dynamic and heat transfer processes, thus influencing the performance of the systems. Great emphasis has been put in direct liquid cooling systems such as spray/droplet cooling and particularly in those based on phase change, as they are promising technologies capable of removing high heat fluxes, (e.g. Silk et al. [3]). Therefore, the accurate assessment of the parameters altering the behaviour of the impinging droplets is crucial to improve the performance of such systems. The present study is aimed at the characterization of the cooling performance of individual liquid droplets impacting onto small heated targets. The thermal behviour of the impacting droplets is assessed based on the temporal variation of the surface temperature, within the liquid-solid interaction region, during droplet impaction, following previous work, sparsely reported in the literature (e.g. Labeish [4], Chen and Hsu [5], Pasandideh-Fard et al. [6], Healy et al. [7]). This evaluation includes the estimation of the heat transfer, following previous works (e.g. Labeish [4], Pasandideh-Fard et al. [6]). A parametric study is performed in which several design parameters and boundary conditions are systematically varied to infer on their effect on the thermal and hydrodynamic behaviour of the impacting droplet. The surfaces are heated from room temperature up to over 300ºC, to cover all the boiling regimes, following the classical boiling curve. Under the context of cooling systems for electronic parts, emphasis is put on the temperatures covering the bubble boiling regime, since these systems are upper limited by the Critical Heat Flux, to avoid burn out. On the other hand, recent applications suggest the use of textured surfaces to improve the cooling performance (e.g. Amon et al. [2], Hsieh and Yao [8], Kim [9]). Given this scenario and facing the renewed interest on the potential use of tailored surfaces, several studies have been recently reported in the literature (e.g. Extrand [10], Nakae et al. [11]), although most of them focus on the dynamic behaviour of the droplets impacting onto non-heated targets. In line with this, a systematic study is also performed considering the use of micro-textured surfaces, which were developed to have well defined characteristics in terms of roughness amplitude and fundamental wavelength (rough-

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ness pitch). Main focus is put on the thermal behaviour, as an extension of the work previously reported by the authors (e.g. Moita and Moreira [12]).

Materials and Methods

The experiments reported here encompass the impact of individual droplets of different liquids, including a dielectric fluid, the methoxy-nonafluorobutane, $C_4F_9OCH_3$ (HFE7100), onto heated targets. The impact conditions cover a wide range of the most relevant dimensionless groups, (65<Weber number, We<1314; 170<Reynolds number, Re<8680; Jakob number, 0.1<Ja<1.9). Surface temperatures are varied from room temperature up to 300ºC, thus covering the entire range of boiling regimes. Table 1 summarizes the thermo-physical properties of the working fluids.

Table 1. Thermo-physical properties of the working fluids.

Properties	Surface tension $[Nm^{-1}]x10^3$ (20ºC)	Density $[kgm^{-3}]$ (20ºC)	Kinematic viscosity $[m^2s^{-1}]x10^6$ (20ºC)	Specific heat $[kJkg^{-1}K]$ (25ºC)	Latent heat of evaporation $[kJkg^{-1}]$	Thermal conductivity $[Wm^{-1}K^{-1}]$ $x10^3$	$T_{boiling}$ [ºC]
Water	73.75	998	1.0	4,18	2272	607.1	100
HFE7100	13.6	1430	3.8	1.18	122.6	68.8	61

Different targets are considered, including micro-textured surfaces, with regular roughness profiles, having well defined roughness amplitude, fundamental wavelength and shape of the grooves. The surfaces are characterized by the equilibrium contact angle, θ and by the surface topography. The topography is quantified by the roughness amplitude (mean roughness, R_a, determined according to standard BS 1134 and mean peak-to-valley roughness, R_z, calculated according to standard DIN4768) and by the fundamental wavelength, λ_R when the roughness profile is regular (i.e. for the micro-textured surfaces). The complete characterization of all the target plates and their wetting behaviour with the various liquids used in the experiments (performed at room temperature) is depicted in Moita and Moreira [13], so that only a summary of the main characteristics of the targets used in this study, is provided in Table 2.

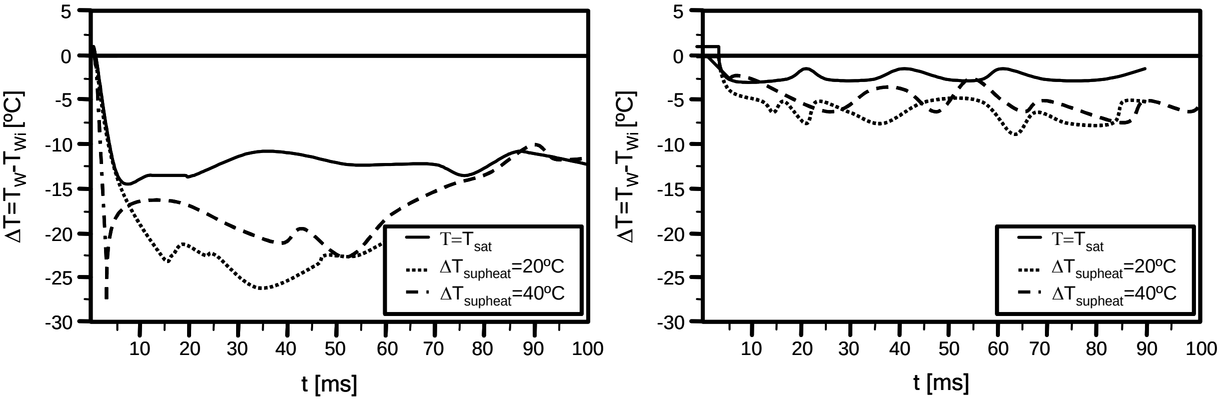
Table 2. Main characteristics of the target plates.

Surface		R_a [μm ± 10%]	R_z [μm]	λ_R [μm]	θ [º]
Glass	Random profile	~ 0	~ 0	-	13.2
Aluminum	Random profile	1.0	13.76	-	75.3
		0.311	2.32	-	-
Stainless steel	Random profile	0.524	9.0	-	94.8
	Regular profile (textured surfaces)	17.1	81.5	210	-
		16.7	92.3	430	-
		42.0	175.3	530	-

Complete wetting ($\theta \approx 0^o$) is observed at room temperature for all surfaces, when wetted by the HFE7100. The targets are accommodated on a copper base inside which a 264W cartridge heater was inserted. The temperature of the targets is monitored by thermocouples type K and controlled by a PMA KS20-I temperature controller. One of the thermocouples is a fast response "Medtherm" eroding-K-type which is embedded at the centre of the impact region of the targets. The signal of the thermocouples is sampled with a National Instruments DAQ board plus a BNC2120 and amplified with a gain of 300 before processing. Droplet morphology is characterized by using two synchronized high-speed cameras (a Kodak Motion Corder Analyser, Series SR 512x420pixels, Model PS-120, with maximum frame rate of 10kfps and a Phantom v4.2 from Vision Research Inc., with 512x512pixels@2100fps, with maximum frame rate of 90kfps). Characterization of the secondary atomization is performed by combining image analysis with phase Doppler measurements, as in Moreira et al. [14]. All the instrumentation is triggered by the same signal, emitted as the passing droplet interrupts a laser beam which is aligned with a photodiode.

Results and Discussion

The effect of various parameters, namely the initial surface temperature, T_{Wi}, the liquid properties and the impact velocity, U_0 on the temporal variation of the surface temperature at the droplet-solid interaction region. is depicted in Figures 1 and 3. The various curves correspond to different initial surface temperatures. Similar superheat degrees were considered for the different liquids.

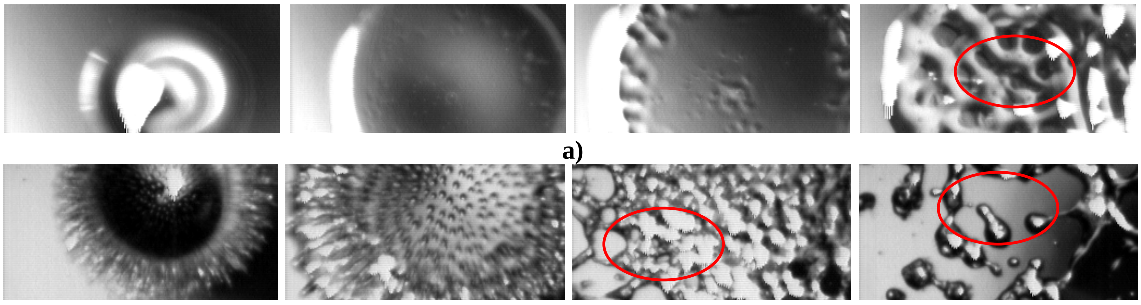


a) **b)**

Figure 1. Surface temperature variation, measured at the point of impact of a droplet impacting onto a smooth stainless steel surface (R_a=0.311μm, R_z=2.32μm) within the bubble boiling regime. a) water droplet (D_0=2.8mm, U_0=1.3ms^{-1}). b) HFE7100 (D_0=2.0mm, U_0=1.3ms^{-1}).

A sudden decrease is observed in the surface temperature, as the droplet contacts the surface and starts to spread, (first 10-20ms after impact) as described in previous works (e.g. Chen and Hsu [5]). Part of the temperature decreases due to the sensitive heat removal from the surface, which can be as high as 30%, which is in accordance to the estimations by Healy et al. [7]. Then, larger amount of heat is removed during phase change. The temperature drop is larger for higher T_{Wi}, but the recovery period depends on the liquid properties. For an application to cooling systems for electronic parts, the results depicted obtained for heat transfer regimes above the Critical Heat Flux temperature are not shown here. Within these regimes and particularly for the film boiling regime, the sudden temperature drop is significant for the water droplets, but the temperature recovery period is quite fast. However, for the HFE7100 droplets, the temperature decay is quite small within the transition and film boiling regimes, which is attributed to the faster liquid evaporation and formation of a thicker vapour cushion, precluding the contact between the droplet and the surface. Surface temperature drop is more significant during the impact of the water droplet, as expected, due to the much larger specific heat and latent heat of evaporation, although there are also particular morphological features of the lamella which further contribute to the differences observed between water and HFE7100. The oscillations observed in the temperature profile within the spreading stage (t>10ms) are attributed to the presence of vapour bubbles. The occurrence of dry regions is not detected here, as it would require a more exhaustive acquisition of the surface temperature along the radius of the lamella, but is clear from visualization of the liquid-solid interface, as performed in Moita and Moreira [15]. The morphology of the HFE7100 droplet is shown as an example in Figure 2, for two different contact temperatures $T_c=(T_l\varepsilon_l+T_W\varepsilon_W)/(\varepsilon_l+\varepsilon_W)$, determined to be comparable to those reported in this work. Here, ε_l and ε_W stand for the thermal effusivities [$\varepsilon=(\rho kCp)^{1/2}$] of the liquid and of the surface, respectively. The Figure shows the formation of cellular structures which lead to dry out regions and consequent disintegration of the lamella, by the rupture of the ligaments between the cells. This behaviour is due to a combined effect of the latent heat of evaporation and the surface tension. Hence, the small surface tension of the HFE7100 promotes the occurrence of cellular structures which contribute to a fast evaporation of the liquid film as well as to the disintegration of the lamella. Given the small latent heat of evaporation, a fast evaporation rate precludes the rewet of the dry regions and will further trigger the secondary atomization to occur sooner (e.g. Moita and Moreira [15]). So, to achieve the same cooling performance with HFE7100, larger flow rates must be used.

In this context, Amon et al. [2] suggest that a water cooling system could eventually be developed for higher cooling demanding systems, although several disadvantages have to be considered, namely the high boiling temperature and non-dielectric properties of this liquid. On the other hand, the boiling temperature of HFE7100 is much closer to the working temperatures of electronic systems, which is an important feature to develop an efficient technique. So, instead of altering the fluid properties, the thermal behaviour of the system may be improved by altering other design parameters such as the impact conditions and the surface properties. In this context, Figure 3 depicts the effect of increasing the impact velocity on the surface temperature. It is not clear from the results that increasing U_0 enhances the temperature drop. The maximum decay is slightly larger, but then, the recovery period is also smaller.



a)

1.0ms 2.0ms 5.0ms 8.5ms

b)

Figure 2. Details of the temporal evolution of the boiling mechanism of HFE7100 droplets (D_0=2.0mm, U_0=1.3ms^{-1}) impacting onto heated transparent substrates within different surface temperatures (Bottom view of the impact region). a) T_c=59ºC. b) T_c=89ºC.

This behaviour is further confirmed when analysing the heat fluxes. At this part of the work and given that the main studied parameters are mostly affecting the contact area of the spreading droplet, the heat transfer is determined based on the model of Pasandideh-Fard et al. [6], (given paper length constrains, the formulation is not developed here) instead of determining the instantaneous surface heat fluxes as in Chen and Hsu [5]. The results depicted in Figure 4 confirm the overall worse cooling performance (for the present configuration) of the dielectric liquid, not only because of its thermal properties, but also due to the boiling morphology which affects the contact area. Furthermore, the heat transfer for the droplet impacting with larger U_0 turns to be overall smaller, for the present experimental conditions. This is in agreement with the observations of Chen and Hsu [5], but contrasts the results reported in Pasandideh-Fard et al. [6]. Interpreting the results based on the dynamic behaviour of the droplet, increasing U_0 leads to an increase of the maximum spreading diameter and therefore to an increase of the contact area. The secondary atomization process is similar to that occurring at smaller impact velocities (in fact the mean diameter of the secondary droplets is actually smaller) but the whole deformation and vaporization process should be faster so that, at the end, the time available for heat transfer may be smaller. So, the temperature difference determined as in Pasandideh-Fard et al. [6] may be overestimated, since the temperature of the droplet can increase significantly during the spreading process. This suggests that adequate temporal and spatial scales are fundamental for an accurate description of the heat transfer processes during droplet impact, because the relative importance of the governing parameters depends on the time available for the occurrence of the phenomena.

Since the impact conditions do not promote a significant improvement of the cooling performance of the impinging droplet, an alternative solution, pointed by many authors, is to consider the use of micro-textured surfaces. Following this argument, a study is also performed to characterize the secondary atomization and thermal behaviour of droplets impacting onto micro-textured surfaces with well defined topographical characteristics (in terms of roughness amplitude and fundamental wavelength), following previous reported work (e.g. Moita and Moreira [12]). The mean size of the secondary droplets, evaluated from phase Doppler measurements, is plotted together with the corresponding surface temperature variation, for water droplets impacting onto these micro-textured surfaces, within the bubble boiling regime. The impact velocity was kept low to avoid the occurrence of prompt splash.

The results do not evidence a straightforward trend, but suggest that both thermal and dynamic behaviour of the impinging droplets depend on the relation $R_a/\ _R$.

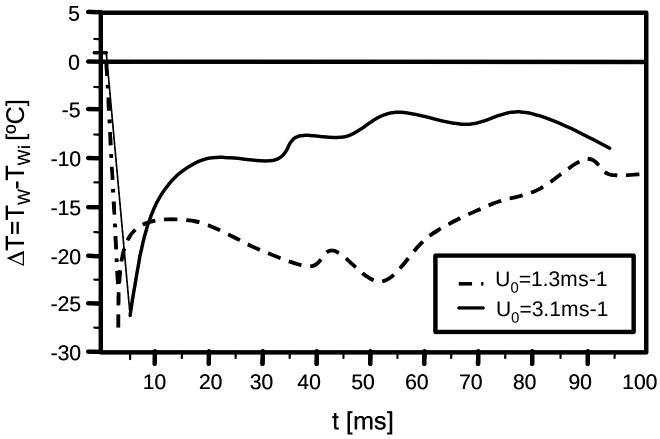


Figure 3. Effect of the impact velocity on the surface temperature variation, measured at the point of impact of a water droplet (D_0=2.8mm) onto a smooth stainless steel surface (R_a=0.311μm, R_z=2.32μm) within the bubble boiling regime ($\Delta T_{Superheat}$=40ºC).

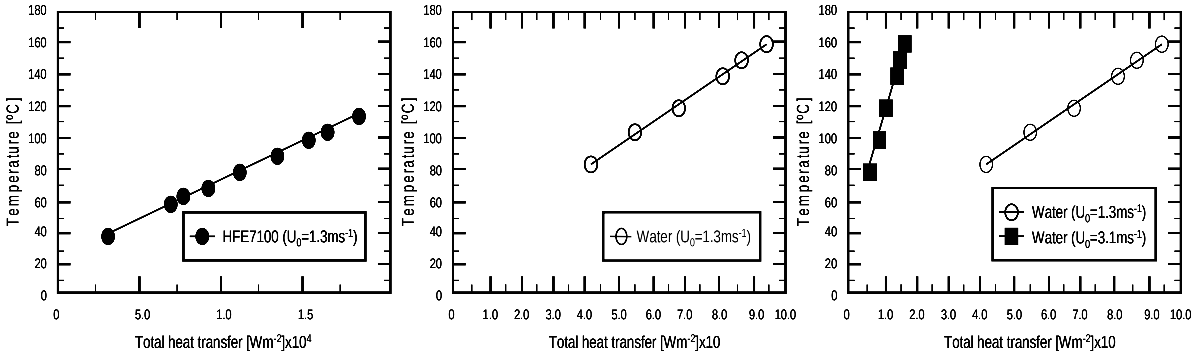
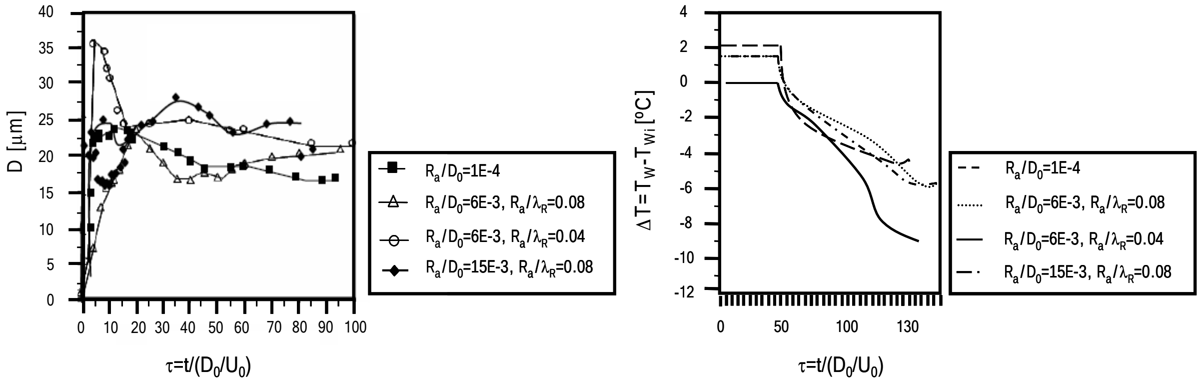


Figure 4. Total heat transferred between the impinging droplet and a smooth stainless steel surface (R_a=0.311μm, R_z=2.32μm). a) Impact of a water droplet (D_0=2.8mm, U_0=1.3ms^{-1}), b) Impact of a HFE7100 droplet (D_0=2.0mm, U_0=1.3ms^{-1}), c) Impact of a water droplet (D_0=2.8mm) at different velocities.

Therefore, secondary atomization is triggered earlier for the textured surface with R_a/λ_R=0.04 and the secondary droplet diameters are generally larger, thus suggesting that this relation enhances liquid/solid contact and promotes nucleation. On the other hand the temperature decay is also larger for this target. These results are interpreted as follows: the larger relation of R_a/λ_R is possibly endorsing a heterogeneous wetting phenomenon onto the heated targets, as it promotes the entrapment of the vapour layer. These modifications in the wetting regime affect the spreading evolution of the lamella and, consequently its thickness, but they will also affect the liquid/surface contact area, thus influencing the heat transfer processes. This hydrophobic behaviour is corroborated as one estimates the critical fundamental wavelength for changing the wetting regime, following the model proposed by Nakae et al. [11].

In summary the use of micro-textured surfaces must be considered with care since some relations between R_a/λ_R can actually degrade the thermal behaviour of the droplet, by promoting a hydrophobic wetting behaviour. Hence, optimization of the topographical parameters is therefore a compromise between the competitive effects of promoting the heat transfer without having a very intense thermal induced atomization.



a) **b)**

Figure 5. The effect of using micro-textured surfaces on the thermal induced atomization and surface temperature variation, measured at the point of impact, for a water droplet (D_0=2.8mm, U_0=1.3ms^{-1}) onto a smooth and textured stainless steel surfaces, within the nucleate boiling regime ($\Delta T_{Superheat}$=40ºC).

Concluding remarks

The work presented here encompasses the experimental evaluation of the cooling performance of individual droplets impinging onto heated targets. The liquid properties are determinant in the cooling performance of the droplet. Particularly, the liquid surface tension and the latent heat of evaporation give rise to relevant morphological modifications of the lamella, which affect the heat transfer process. While the role of the impact conditions and particularly the impact velocity is secondary, the use of micro-textured surfaces can be an alternative solution to improve the cooling performance of the impinging droplets. However this application must be considered with care. Optimization of the topographical parameters can be performed based on the relations between R_a/λ_R, in a compromising solution of endorsing liquid-solid contact without promoting an excessively intense thermal induced atomization. For the present study an optimal relation of R_a/λ_R was found, but it worth to be refined, within a larger range of combinations between R_a/λ_R.

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