

THERMAL AND FLUID DYNAMIC PROCESSES OCCURRING AT LIQUID BOILING OVER MICRO-AND-NANO ENHANCED SURFACES

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ABSTRACT

This paper addresses the basic nucleation and bubble dynamics mechanisms, focusing on the effect of enhancing the surface. The consequences at the heat transfer mechanisms are also discussed. The review performed here stresses the need to accurately describe the effect of surface topography and wettability, as this is a critical step to lessen the strong empirical nature that is present in most of the theoretical predictions.

This accurate description also requires adequate diagnostic techniques. Combining Particle Image Velocimetry – PIV with high speed imaging and thermography has been recently reported in the literature to render precise measurements of several quantities such as bubble departure diameters and frequencies, and even thickness of the micro layer, which are of major importance to validate theoretical correlations.

The experimental analysis performed here also highlights the important role of the interaction mechanisms in bubble dynamics and consequently in the heat transfer mechanisms.

INTRODUCTION

Several strategies for surface modification have been addressed within the last decades to enhance heat transfer between liquids and solid surfaces. Particular emphasis is given to boiling processes, due to the high heat transfer coefficients involved which are required in many industrial applications at diverse spatial scales, such as electronics cooling, boilers, nuclear and chemical reactors, refrigeration systems, thermal generation of electricity, metallurgy or food processing (*e.g.* [1,2]).

The fast advance of micro-and-nano technologies provided the researchers with a wide range of solutions to alter the surface and/or the liquid properties to enhance boiling heat transfer. Surface modifications focus on changing the surface topography, making use of micro-patterning, nanostructuring and microporous (*e.g.* [3,4]), while modifications of surface

chemistry are based on nanocoatings that change the surface wettability (*e.g.* [5]). Regarding the working fluids, the most popular strategies to alter their properties address the use of nanofluids (*e.g.* [6]) and the addition of surfactants (*e.g.* [7]). These strategies have been proposed to enhance pool boiling heat transfer, which mainly act on two distinct regimes: i) at low heat fluxes, in partial nucleate boiling, for which the heat transfer coefficient can be enhanced by promoting nucleation [8] and ii) at high heat fluxes, in the fully developed nucleate boiling regime, in which the main objective, besides having high heat transfer coefficient, h is to delay the occurrence of the Critical Heat Flux CHF [9].

Despite the study of the nucleation and heat transfer processes occurring at pool has been intensively performed during the last half of the twentieth century and particularly since the early thirties, deeper understanding and an accurate description of the physical mechanisms governing the observed phenomena have not been achieved yet, particularly when dealing with enhanced liquids and/or surfaces. The difficulty of this task is explained by the intricate relation between the various relevant parameters, which are difficult to assess quantitatively and depend on the thermophysical properties of the boiling liquid and of the surface material (thermal conductivity and thermal absorption), interactions between the solid surface, liquid and vapor (wettability, adhesion, adsorption) and surface microgeometry (dimensions and shape of cracks and pores) (*e.g.* [10]). An additional difficulty arises in characterizing the boiling processes occurring over enhanced surfaces due to the fact that many of the strategies alter simultaneously the surface chemistry and its topography so it is difficult to assess their isolated effects in the wettability, and in turn define the role of the wettability in a more precise manner. Although the complex relation between wettability and surface topography has been extensively debated since the classical theories of Wenzel [11] and of Cassie and Baxter [12] it is still a hot topic for discussion, as recently revisited by Marmur [13].

BUBBLE DYNAMICS AND HEAT TRANSFER PROCESSES

Nucleation and bubble dynamics

The heterogeneous nucleation mechanism is usually considered in pool boiling studies. In this mechanism, microscopic cavities or crevices of the surface trap vapour/gas, acting as nuclei of bubbles. Once the nucleus is formed, it will only subsist if its internal temperature equals the saturation temperature for the pressure of the vapour phase, determined from the Young-Laplace equation. Assuming ideal gas behaviour for the vapour and that the specific volume of the liquid compared to that of the vapour is negligible, the Clausius-Clapeyron equation can be applied and expressions can be devised which relate the temperature required to activate a vapour nucleus and the minimum radius of the cavity (*e.g.* [18]). This critical radius is obviously related to the wettability of the surface, as early suggested for instance by Lorenz *et al.* [19,20], but several modifications were later proposed to the relations proposed in [19,20], which are associated with the definition of the most appropriate contact angle (static or dynamic) to consider. Recently, Bourdon *et al.* [16,17] showed that the wettability affects the inception of boiling even at very smooth surfaces: increasing the dynamic contact angle usually favours the onset of boiling to start at lower degrees of superheat.

Detailed review on the nucleation mechanisms is presented by Dhir [21]. Generally, one may argue that surface topography has a major role to increase the number of nucleation sites. These sites must, nonetheless, satisfy particular geometric and energetic minimal conditions to become active. The wettability acts directly as the balance of the interfacial forces at the nucleation sites. So, lower wettability (larger contact angles) endorses the onset of heterogeneous boiling and consequently increases the nucleation sites density.

Subsequently to the onset of boiling, attention must be naturally paid to bubble dynamics, which for a single bubble can be followed by monitoring three main quantities: bubble growth, bubble departure diameter and bubble departure frequency. These are relevant parameters since they provide vital information to relate the heat transfer (*e.g.* heat removed from the surface during bubble formation and growth and further re-heating, which in turn is related to the time available between succeeding bubbles).

From the fundamental point of view, the bubble growth is initially dominated by heat transfer (*e.g.* Fritz and Ende [22]). The source of this energy that is transferred by heat to the bubble is still debated. Hence, while for instance Mikic *et al.* [23] argue that a bubble grows from the evaporation of the interface all around itself, other authors such as Snyder and Edwards [24] and more recently Stephan *et al.* [25] stand for the existence of a micro-layer at the bubble base between the vapour-liquid interface and the heater surface, which is promoted by high heat wall and bulk temperatures. Experimental results reported for instance by [26,27] and more recently by [28] are consistent with the micro-layer theory. Good reviews on this subject are presented for instance by Dhir [21] and by Hutter, [29].

The effect of surface topography and wettability are recognized to act at different levels, but the need to perform chemical and topographical modifications to the surface separately has been only recently raised by Bourdon *et al.* [14,15]. Hence, much experimental and theoretical work should be performed to define the accurate role of surface topography and chemistry in both nucleation and heat transfer processes occurring at pool boiling. In this context, the present paper revises the basic nucleation and bubble dynamics mechanisms focusing on the effect of the aforementioned surface modifications. The efforts in obtaining theoretical relations to quantify the heat flux and the heat transfer coefficients are briefly revised in the following subsection. Such review will evidence the importance of obtaining accurate experimental data, which requires adequate diagnostic techniques. These techniques will be afterwards in a small subsection. Finally, some experimental data obtained with these techniques are depicted and explored in the final subsection. Particular emphasis is given here to the interaction mechanisms, whose relevance in the pool boiling heat transfer over micro-patterned surfaces has been reported in our most recent work [16,17].

NOMENCLATURE

a	[μm]	Side length of the square cavities
A	[m^2]	Area of the heater
C_p	[J/kgK]	Specific heat
C_{sf}	[-]	Fitting coefficient associated to surface properties
D_b	[mm]	Bubble departure diameter
f	[s^{-1}]	Bubble departure frequency
h	[$\text{W/cm}^2\text{K}$]	Heat transfer coefficient
h_{lg}	[kJ/kg]	Latent heat of vaporization
h_R	[μm]	Depth of the square cavities
k	[W/m.K]	Thermal conductivity
m	[-]	Fitting parameter
n	[-]	Fitting parameter
N	[-]	Number of cavities
Pr	[-]	Prandtl number
q''	[W/cm^2]	Heat flux
R_a	[μm]	Average surface roughness
Re	[-]	Reynolds number
R_z	[μm]	Average peak-to-valley roughness
S	[μm]	Distance between the centers of the cavities
St	[-]	Stanton number
T	[$^{\circ}\text{C}$]	Temperature
t	[s]	time
V	[m/s]	Velocity

Special characters

μ	[mN m/s^2]	Dynamic viscosity
ϕ	[$^{\circ}$]	Angle formed between the surface and the bubble interface
θ	[$^{\circ}$]	Equilibrium contact angle
ρ	[kg/m^3]	Density
σ	[N/m]	Surface tension

Subscripts

B	Bubble
g	Gas
l	Liquid
s	Surface
v	Vapour

Bubble growth is not only controlled by heat flow to the bubble surface, but it is also affected by the forces acting on the bubbles. Therefore, the evaluation of the bubble departure diameter, which is probably the most used parameter to characterize bubble dynamics, is often discussed based on a force balance, as proposed by Fritz [32], from the force balance $\sigma_{lv} \pi D \sin \phi = (\rho_l - \rho_g) \cdot g \cdot \pi \cdot (2 + 3 \cos \phi - \cos^3 \phi) / 24 D_b^3$ where D_b is the diameter of the spherical bubble and ϕ is the angle formed between the surface and the bubble interface. So, bubble departure is considered to be mainly controlled by the balance between buoyancy ($\sim g(\rho_l - \rho_g)$) and surface tension forces ($\sim \sigma_{lg} D_b^2$).

Despite being regularly evaluated and discussed in both experimental and theoretical approaches, the bubble departure diameter is actually quite difficult to measure accurately (e.g. McHale and Garimella [30]), so analytical and/or empirical relations seem to be the safest alternative when quantifying bubbles' departure diameter (e.g. [31-36]). Nevertheless, care must be taken given the empirical nature of many of those relations. In fact, they are often contradictory and may strongly disagree with other experimental data, different from those used to devise the relations. To illustrate this, various relations reported in the literature to predict the bubble departure diameter are plotted together with our experimental data in Figure 1. Here, Ja is the Jakob number defined as $(T_w - T_{sat}) \cdot c_{p,l} \cdot \rho_l / (\rho_g \cdot h_{lg})$, where C_{pl} is the specific heat of the liquid, h_{lg} is the latent heat of vaporization and ρ_l and ρ_g are the densities of the liquid and of the vapor, respectively. These correlations are plotted together with our experimental data obtained for the pool boiling of water and ethanol over micro-patterned surfaces. The patterns are composed by regular arrays of squared cavities, with fixed size length $a=52\mu\text{m}$ and fixed depth $h_R=20\mu\text{m}$. The distance between the centers of the cavities, S is the only geometric quantity that was varied. The schematic representations of these quantities and of the patterning are detailed in Figure 3.

Apart from the aforementioned empirical nature of these correlations, which makes them sensitive to the particular mechanisms that prevail under the specific working conditions for which the experimental data is obtained, there are few other reasons explaining the lack of universality of the existing correlations and the disagreement with our experimental results. Indeed, Matkovic and Koncar [37] argue that the uncertainty of these correlations is in part related with the fact that not all the relevant forces are included in the force balance. For instance, the shear lift and the quasi-static drag force have a non-negligible role in this balance, adding to the buoyancy effect. Also, the stochastic nature of the roughness of many of the surfaces used in these studies also disables establishing an accurate relation between the processes of bubble formation and departure and the geometry of the cavities, so that the empirical nature of the relations cannot be cancelled. This is a relevant argument of McHale and Garimella [30]. Additionally, it is worth noting that the role of wettability is very simplified in these expressions. Hence, describing the phenomena occurring at the interface formed

between the bubble and the surface is still a task vital to accomplish. Only afterwards, one can accurately describe the effect of the contact angle ϕ , which has also not yet been completely achieved (interesting approach was followed for instance in [38]). This is indirectly highlighted in the results of Matkovic and Koncar [37] that show how this kind of relations is very sensitive to variations in the values of ϕ . Finally, another effect that is not being considered in the aforementioned relations, as they were derived for a single bubble, are the interaction and coalescence mechanisms. Such mechanisms can have a significant effect in both bubble dynamics and heat transfer processes, as recently reported in our work [16,17]. This issue will be considered in detail later on in this paper, as one will propose some parameters to include the interaction mechanisms in the description of the basic bubble dynamics.

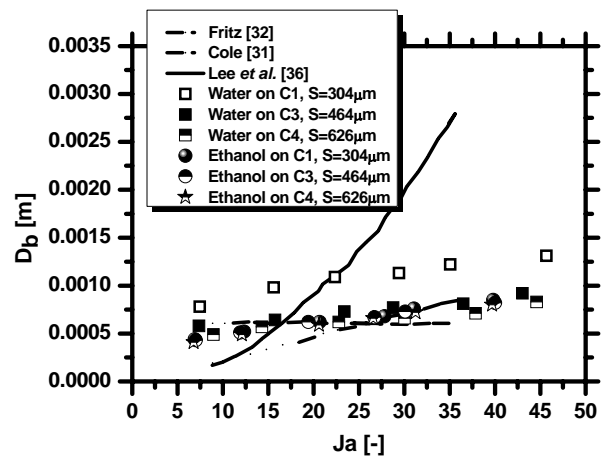


Figure 1. Bubble diameter at departure, as a function of the Jakob number, for boiling over micro-structured surfaces: comparison between the experimental data and the correlations reported in the literature.

The difficulty in obtaining good measurements of the bubble parameters is even more evident when analysing the departure frequency and the nucleation sites density. This is due to the fact that these measurements are often obtained from semi-automatic image post-processing methods, which can be affected by significant uncertainties (over 20%). In this context, it is not surprising that the comparison between the experimental data and the existing correlations shows substantial disagreement, as reported for instance by McHale and Garimella [30].

The aforementioned limitations in the description of bubble dynamics will naturally affect the theoretical prediction of the pool boiling heat transfer, as revised in the following paragraphs.

Theoretical predictions of pool boiling heat transfer

The relations devised in pool boiling heat transfer over enhanced surfaces are usually focused on 3 items: i) the overall

heat transferred between the surface and the liquid and its relation with the surface properties, ii) the relation between the surface micro-structures and the active nucleation sites [39] and iii) the effect of the surface modifications on the Critical Heat Flux.

Pioneering work of Corty and Foust [18] can be included in item ii). The authors discussed the effect of the surface roughness (relatively smooth surfaces with stochastic roughness profiles were used) in the number of active nucleation sites N vs the wall superheat and in the heat transfer coefficient also vs the wall superheat. Main conclusions highlight the significant decrease of the wall superheat for similar heat fluxes when the surface roughness was increases, which was related to the proliferation of the number of active nucleation sites. Similar approaches were later followed for instance by Nishikawa *et al.* [40], who related the heat transfer coefficient with the peak to valley roughness R_z according to the expression $h\alpha R_z^{(1-Pr)^5}$, being Pr the Prandtl number, $Pr=C_p\mu_l/k_l$, where μ_l is the liquid dynamic viscosity and k_l is the liquid thermal conductivity. Also here, stochastic roughness was considered. Benjamim and Balakrishnan [41] related the active nucleation sites density with a dimensionless roughness parameter, function of the average roughness R_a , of the pressure and of the liquid surface tension. As highlighted by [39] the relation of Benjamim and Balakrishnan [41] must be used with particular care, as it was devised based on a limited range of physical parameters and fluid-surface combinations.

Regarding the prediction of the heat transfer, one of the most popular correlations was proposed by Rohsenow [42]:

$$q_s'' = \mu_l h_{fg} \left(\frac{g(\rho_l - \rho_g)}{\sigma_{lg}} \right)^{1/2} \left(\frac{C_{pl} \Delta T}{C_{sf} h_{fg} Pr_l^n} \right)^3 \quad (1)$$

Here, σ_{lv} is the liquid surface tension. Surface properties (material and roughness) are included in the parameter C_{sf} , which also accounts for the differences in the wettability associated to the use of different liquid/surface combinations. However, this constant was simply determined from empirical fitting to experimental data, so that several inconsistencies were observed. Hence, significantly contradictory reports can be found in the literature: the heat flux determined according to eq. (1) can be quite acceptable when fitting to experimental data, as reported for instance by [43] or can be up to 100% inaccurate, as discussed in [44]. Another limitation that may also contribute to these contradictions is the fact that Rohsenow's correlation does not consider pressure effects [39].

More recently Gerardi *et al.* [45] propose an estimation of the heat transfer, dividing the heat flux in different terms, namely the term of latent heat of evaporation, the term of heat convection and the term of the so-called quenching heat flux, following the approach earlier suggested by Han and Griffith [46]. Despite its empirical nature, there is a significant effort in this mechanistic approach to include the governing physics in the heat transfer process, considering the various mechanisms and including the effects of bubble dynamics.

Finally, considering the prediction of the CHF, Two main theories can be identified, which explain CHF enhancement. One is the fairly accepted hydrodynamic instability mechanism, developed by Zuber [47] and later modified by Polezhaev and Kovalev [48]. The second is the surface liquid replenishment of dryout hotspots [49-52]. Zuber's theory stands for the argument that CHF will take place once the hydrodynamic instability limit has been reached. By reducing vapor/liquid counter flow and/or separating adjacent vapor/liquid columns, it can delay the onset of hydrodynamic instability, and in turn inhibit the onset of CHF.

As for the theory of a replenishment limit, it states that if the hydrodynamic instability has not happened yet, the CHF may still occur once the liquid replenishing of the dryout hotspots has reached its limit.

Although widely accepted, Zuber's theory does not successfully predict the CHF values for nanofluid boiling or the boiling on porous surfaces. One of the main reasons, as pointed by Kim *et al.* [53] can be due to the aforementioned fact that the surface characteristics and wettability are not considered in Zuber's theory. Based on a force balance to bubble formation [54] also proposes a relation to predict the CHF, which explicitly includes the effect of the wettability quantified by the contact angle. However, this correlation is not valid for complete wetting fluids, so [55] slightly modified it.

DIAGNOSTIC TECHNIQUES TO CHARACTERIZE POOL BOILING OVER ENHANCED SURFACES

Characterization of bubble dynamics

Qualitative and quantitative description of the quantities characterizing bubble dynamics is a fundamental step through the understanding of the pool boiling heat transfer over enhanced surfaces. As mentioned in the previous subsection, the most relevant quantities used in the description of bubble dynamics are related to the bubble size (*e.g.* growing rate, departure diameter), departure frequency and nucleation sites. The most used technique to characterize bubble dynamics is high-speed visualization. On one hand, it provides one of the most trustable ways to actually observe the phenomena. However, there may be significant accuracy issues related to insufficient $\mu\text{m}/\text{pixel}$ resolution. Also, post-processing procedures are mainly semi-automatic and while measurements of bubble diameters can be fairly obtained based on edge detection algorithms, the measurements of departure frequencies and nucleation sites density are usually dependent on the subjectivity of a visual confirmation and personal decision. In addition, any significant information can be obtained solely from high-speed imaging to quantify characteristic bubble velocities. In order to solve many of these limitations, Duan *et al.* [28] proposed an integrated Particle Image Velocimetry (PIV) combined with infrared thermometry for high resolution measurements in pool boiling. Despite the innumerable difficulties in accurately using PIV (*e.g.* associated to the tracers and to the reflective problems that may compromise the measurements performed very close to the surfaces), Duan *et al.* [28] were able to obtain very detailed qualitative and quantitative information on bubble formation

and growth, including velocity and temperature distributions around individual bubbles. Precise measurements of bubble diameter and frequency and even thickness of the micro-layer have also been reported from the same research group not only in [28], but also for instance in the study of Gerardi *et al.* [56], who used infrared thermography to characterize the pool boiling of nanofluids.

One year later, Teodori *et al.* [17] proposed the combined use of PIV and high-speed imaging to evaluate bubble dynamics on pool boiling of water and ethanol over micro-structured surfaces. Keeping as the main focus that PIV was only used to quantify bubbles velocity and being aware that the results obtained from this technique are very sensitive to the characteristics of the flow and to the parameters used during the visualization and the post-processing of the images (*e.g.* [57, 9]), Teodori *et al.* [17] did not use tracers but followed the bubbles instead as suggested in [57]. Bubbles diameter was in the range of 500-800 μm , measured by image post-processing. Very careful parametric analysis was performed and both recursive cross correlation and average correlation were extensively analysed to assure accurate measurements [58]. The coordinate system considered in the measurements is shown in Figure 2. Detailed description of the PIV system and configurations used can be found in [17].

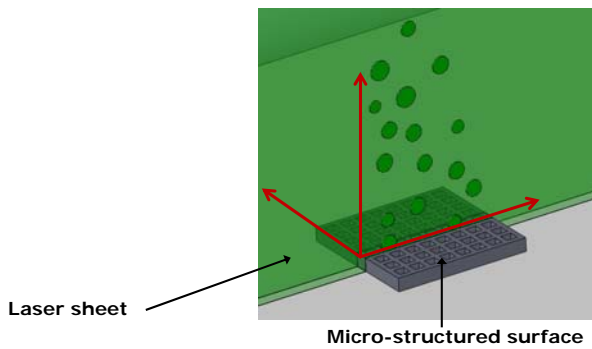


Figure 2. Coordinate system considered for the PIV measurements.

Heat transfer measurements

The most usual approach followed in heat transfer measurements is to evaluate the heat fluxes and temperatures based on thermocouple measurements. Important limitations in this technique are the contact thermal resistances associated to the thermocouples positioning, which may include relevant uncertainties in the measurements (over 20%). To avoid this problem, Bourdon *et al.* [14,15] propose the use of very accurate heat flux sensors. The heat flux measurements are far more precise, but still the authors need several thermocouples to control the temperature of the liquid and of the surface.

Surfaces modification and characterization

There are numerous techniques to enhance the surface which, as revised in the introduction, mainly address mechanical or electromechanical processes that alter the

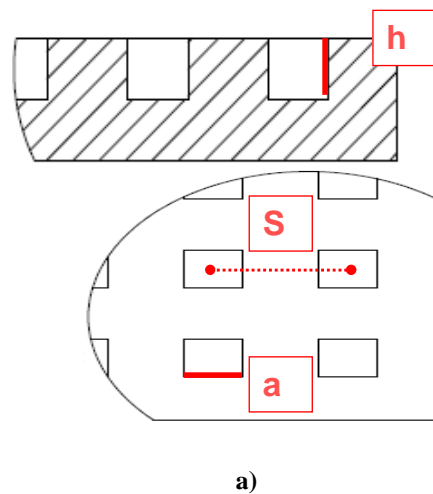
topography of the surface, or concern the use of numerous coating methods (some preparations, for instance to produce superhydrophobic surfaces actually must involve both mechanical treatments and coatings, *e.g.* [59,60]). The review of these techniques is a theme for an entire new paper, so it will not be addressed here.

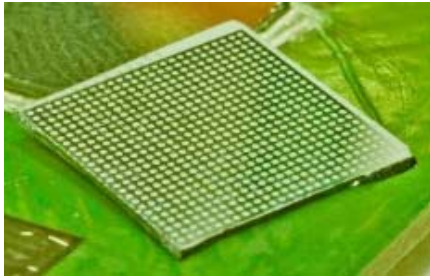
After the surfaces are produced, their characterization is required. This often involves SEM (Scanning Electron Microscopy) analysis, combined with topographical measurements to determine the roughness amplitude (*e.g.* average roughness R_a) using profilometers (*e.g.* [14,15,40,41]). Complementary information is then provided by the measurement of the static, quasi-static and dynamic contact angles (*e.g.* [14-17]). Following the discussion presented so far, accurate characterization of surface topography and wettability are vital steps.

It is worth mentioning that although the role of surface wettability has been recognized for many years (*e.g.* [22,31,42]) information on the contact angles is often not included in the experimental characterization of the surfaces.

For illustrative purposes, the micro-structured surfaces that were used to obtain the results presented in Figure 1 and additional data, which will be analysed in the next subsection, are briefly described and characterized as follows.

The surfaces are custom made from silicon wafers, combining wet etching with plasma etching. Roughness profiles were measured using a Dektak 3 profile meter (Veeco) with a vertical resolution of 200Angstroms. Wettability was also characterized, being quantified by the static contact angle θ , using an optical tensiometer THETA from Attesion, with One-Attesion v1.8 software. Accuracy of the measures of the contact angle is $\pm 1^\circ$, according to the manufacturer. The surfaces are micro-structured with regular arrays of squared cavities, with fixed size length $a=52 \mu\text{m}$ and fixed depth $h_R=20\mu\text{m}$. The distance between the centers of the cavities, S is mainly our optimization variable, ranging between $300\mu\text{m} < S < 1200\mu\text{m}$. The parameters characterizing the micro-patterns are schematically defined in Figure 3, together with a photo of one of the surfaces.





b)

Figure 3. a) Identification of the main parameters quantifying the micro-patterns. b) Sample of one of the micro-structured surfaces.

Table 1 depicts the main topographical characteristics of the surfaces used in this study. The table includes the average values of the static contact angles, which were measured with water. For the other fluids used to produce the experimental data that is explored in the present paper, namely ethanol and a dielectric fluid HFE7000, the contact angles obtained with all the surfaces are close to zero.

Table 1. Main range of the topographical characteristics of the micro-patterned surfaces. θ is the average static contact angle measured with water at room temperature. $\theta \approx 0^\circ$ for all the surfaces in contact with ethanol and HFE7000.

Material	Reference	a [μm]	h_R [μm]	S [μm]	θ [$^\circ$]
Silicon Wafer	Smooth	≈ 0	≈ 0	≈ 0	86.0
	C1	52	20	304	90.0
	C2	52	20	400	91.5
	C3	52	20	464	71.5
	C4	52	20	626	86.5
	C5	52	20	700	95.0
	C6	52	20	800	60.5
	C7	52	20	1200	66.3

EFFECT OF SURFACE ENHANCEMENT IN THE BUBBLE DYNAMICS AND POOL BOILING HEAT TRANSFER: THE RELEVANCE OF INTERACTION MECHANISMS

Analysis of the bubble dynamics nucleation mechanisms for water, ethanol and HFE7000, allows deepening the understanding of the coupled effect of liquid properties and surface topography. These fluids are chosen as they allow a systematic variation of the relevant thermophysical properties, which are relevant for pool boiling heat transfer, as summarized in Table 2.

Differences between the boiling of these 3 fluids is evidenced in Figure 4, which depicts the bubble departure diameter, departure frequency and nucleation sites density for the boiling of several micro-structured surfaces, which were

prepared and characterized as described in the previous paragraphs. From a simple mechanistic approach, by considering that bubble departure depends on the balance between surface tension forces ($\sim \sigma_{lv} D_b^2$) and the buoyancy forces ($\sim g(\rho_l - \rho_v)$), the largest bubbles are expected in water boiling, which is confirmed in the figure. Due to the lowest dimensions of the bubbles and to the more homogeneously distributed boiling process, HFE7000 gives rise to the highest value of nucleation sites on top of the structured surfaces (Figure 4b). Also, the boiling of this fluid resulted in the highest relative increase of the number of nucleation sites, when compared to the number of cavities etched in the surface, i.e. the relation number of active nucleation sites/number of cavities is the highest. The lowest relation is observed for the boiling of water.

Table 2. Thermophysical properties of the liquids used in the present study, taken at saturation, at $1.013 \times 10^5 \text{ Pa}$.

Property	Ethanol	Water	HFE7000
T_{sat} [$^\circ\text{C}$]	78.4	100	34
ρ_l [kg/m^3]	736.4	957.8	1374.7
ρ_v [kg/m^3]	1.647	0.5956	4.01
μ_l [mN m/s^2]	0.448	0.279	0.3437
C_{pl} [J/kgK]	3185	4217	1352.5
k_l [W/mK]	0.165	0.68	0.07
h_{fg} [kJ/kg]	849.9	2257	142
σ_{lv} [N/m] $\times 10^3$	17	58	12.4

This is a non-intuitive result, since the highest value of surface tension of the water should promote more unwetted cavities, thus facilitating the formation of bubbles. Nevertheless one must keep in mind that the largest dimensions of the bubbles avoids simultaneous presence of all the active nucleation sites on top of the surface, thus the actual nucleation sites are lowered. These bubbles also stay at sites on top of the surface, thus the actual nucleation sites are lowered. These bubbles also stay attached to the surface for longer periods of time, thus allowing stronger interaction mechanisms such as horizontal coalescence. As a result, the bubble departure frequency for the boiling of water is declined for higher values of the heat fluxes, where typically the interactions mechanisms are stronger (Figure 1c). The opposite effects are observed in the boiling of HFE7000, which depicts the highest bubble departure frequency.

This brief analysis highlights the relevance of the interaction mechanisms and how they can be promoted in a non-systematic way, as one alters the surface properties, particularly the topography. However, studies reported in the literature concerning the interaction mechanisms are still relatively sparse. In fact, after the pioneering work of Pioneering work of Chekanov [61] and of Judd *et al.* [62-64] very little work has been reported on this topic. These authors spaced and identified diverse regions of interaction among nucleation sites (artificially created) and categorized those

regions as a function of the dimensionless cavity spacing S/\overline{D}_d , where S is the distance between two cavity centres (thus the distance among nucleation sites) and \overline{D}_d is the mean bubble departure diameter. Comparing the results obtained by the various authors one finds no agreement between the reported conclusions, probably due to some differences in the experimental conditions, but also to the lack of consistency in the identification of the various mechanisms which may occur. A consensual interpretation was later tried by Zhang and Shoji [65], who proposed an alternative set of interaction regions,

also as a function of S/\overline{D}_d , based on the dominance of different effects. More recently, few authors (*e.g.* [66,67]) focused on the effect of the spacing between arrays of cavities with different shapes. Both reported the degradation of the heat transfer coefficient at high imposed heat fluxes, which was attributed to bubble interaction mechanisms, but again, different optimum values of the spacing between the cavities are recommended.

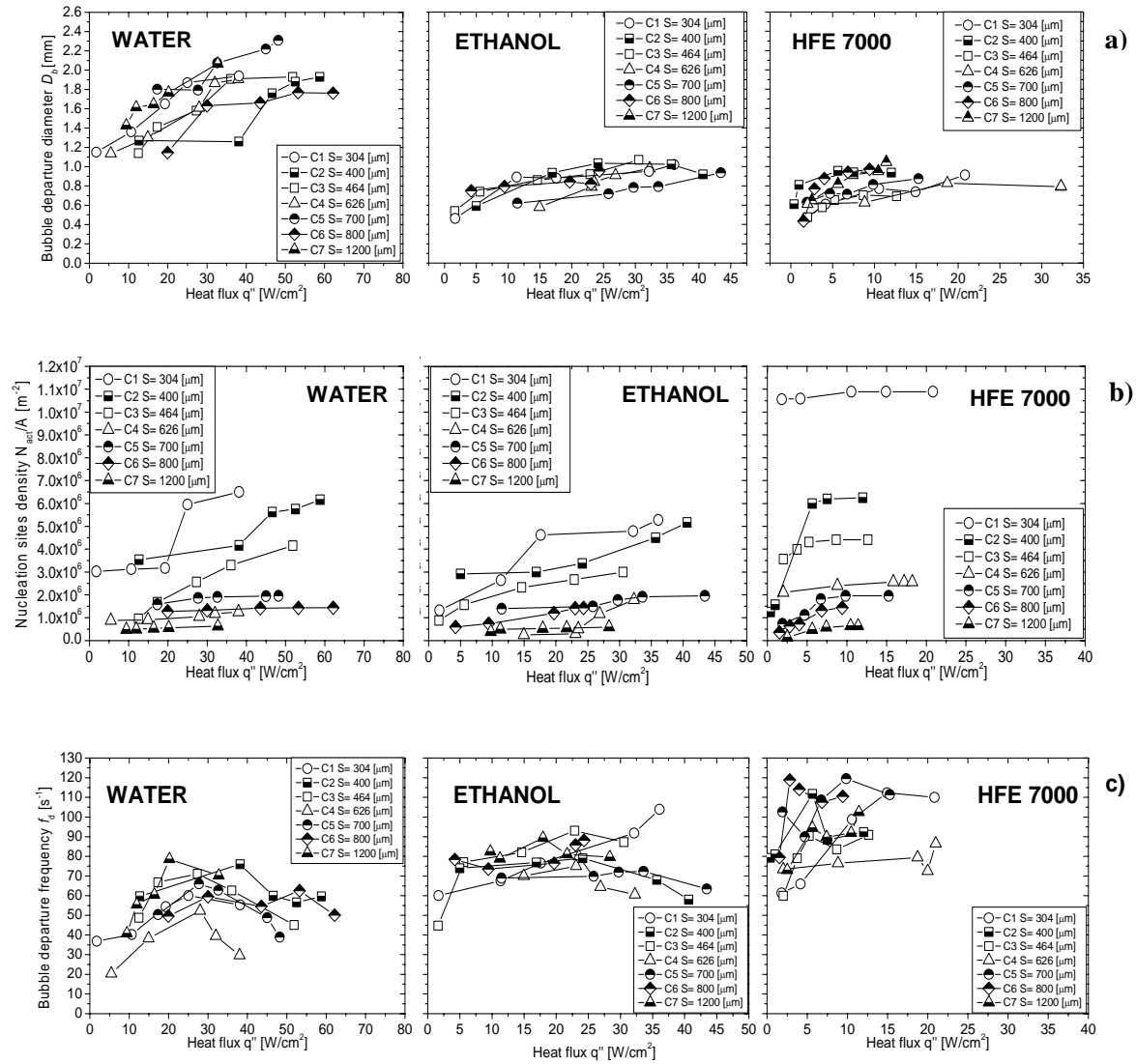


Figure 4. Bubble dynamics in pool boiling of water, ethanol and HFE700 over micro-structured surfaces: **a)** bubble departure diameter, **b)** nucleation sites density, **c)** bubble departure frequency.

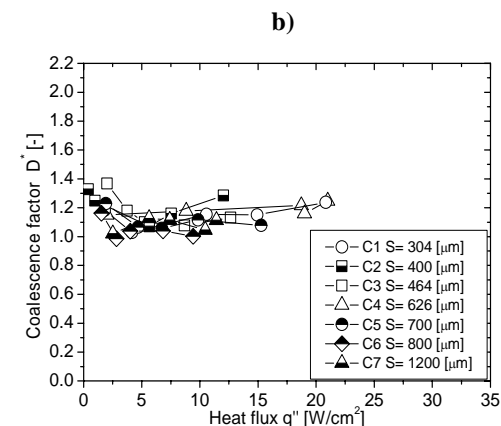
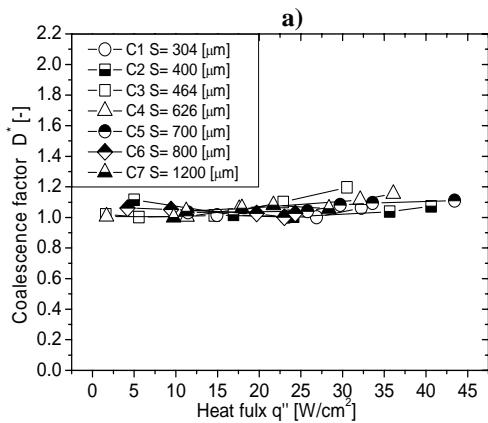
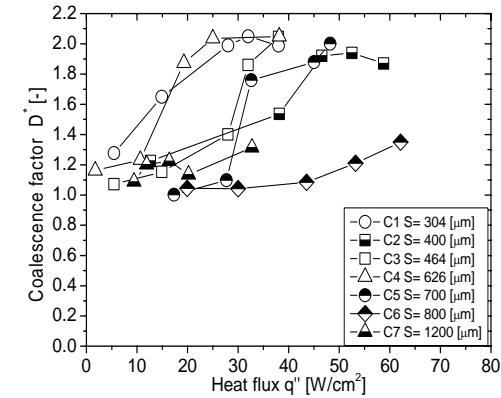


Figure 5. Coalescence factor versus heat flux for the boiling of a) water, b) ethanol and c) HFE 7000.

Revisiting the interaction mechanisms, Moita *et al.* [16] identified a relevant role of the horizontal coalescence: the bubble parameters and particularly the departure diameters of liquids with high surface tension (such as water), were varying with the distance between cavities S in a non-linear manner. Hence, they proposed a new parameter to quantify the horizontal coalescence, the so-called coalescence factor D_b/D , where D_b is the departure diameter including coalescence and D

is the diameter without coalescence. According to this definition, $D_b > 1$ reveals the presence of horizontal coalescence. The coalescence factor vs the heat flux is presented in Figure 5 for water, ethanol and HFE700 boiling over the micro-structured surfaces. The results shown here clearly evidence the highest values of the coalescence factor, obtained for water boiling, thus confirming the strong influence of horizontal coalescence for this fluid. Contrary, for ethanol and HFE 7000, the coalescence factor is always close to 1, which is associated to low horizontal coalescence phenomena.

These results also highlight the need to include parameters to quantify these interaction mechanisms.

In agreement with this, the boiling curves and the heat transfer coefficients reported in Teodori *et al.* [68] show that ethanol and HFE 7000 present a more homogenous and vigorous boiling, with limited interaction mechanisms, so there is a monotonic raise of the heat transfer coefficient for the micro-patterned surfaces, as the distance between cavities S decreases, i.e. the number of nucleation cavities increases. Given that the coalescence mechanisms are lessened for these fluids, as S decreases and therefore there are more cavities in the surfaces, the active nucleation sites density can effectively increase in line with the larger number of cavities, thus improving the pool boiling heat transfer. On the other hand, the strong horizontal coalescence phenomena characterizing water boiling on surfaces with very small distance between the cavities, as for instance surface C1 ($S=304 \mu\text{m}$), leads to a steep deterioration of the heat transfer coefficient.

Hence, the coalescence effects were empirically related to the distance S , since this distance between cavities is directly acting on the coalescence mechanisms which occur close to the surface. This should also be well related to the force balance describing the bubble detachment, as proposed by Fritz [32]: $L_c = (\sigma_{lv} / (g \cdot (\rho_l - \rho_v)))^{1/2}$. This empirical relation, earlier suggested in [16] is extended for ethanol and HFE7100 pool boiling as depicted in Figure 6.

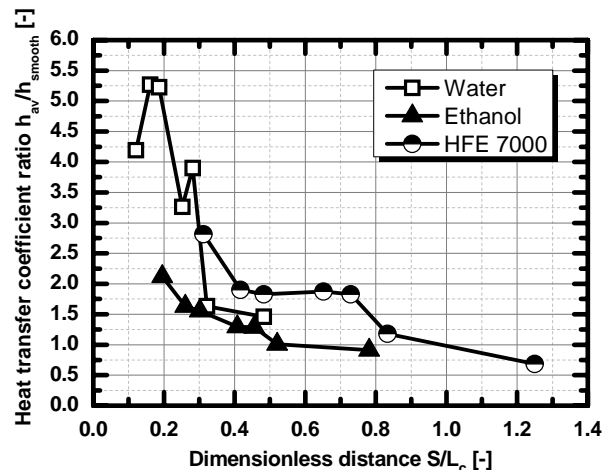


Figure 6. Heat transfer ratio vs dimensionless distance for water, ethanol and HFE 7000 in the range of the studied micro-structures.

It is nevertheless worth noting that the values of the heat transfer coefficient represented in Figure 6 include various terms of the heat transfer. Following the approach of [46], which was recently used by [45], the heat transfer is divided in 3 main terms, namely the natural convection $q''_{nat\ conv}$, the evaporation q''_{ev} and the induced convection $q''_{ind\ conv}$, which are respectively given by:

$$q''_{nat\ conv} = \left[1 - \frac{\pi}{4A} \sum_{n=1}^{N_T} (D_{b,n})^2 \right] h_{nat\ conv} (T_w - T_{sat}) \quad (2)$$

$$q''_{ev} = \frac{\pi}{6A} \rho_v h_{fg} \sum_{n=1}^{N_T} (f_n \cdot D_{b,n}^3) \quad (3)$$

$$q''_{ind\ conv} \propto f_b N_{ac} = q''_{tot} - q''_{nat\ conv} - q''_{ev} \quad (4)$$

where, A is the area of the heater, N_T is the total number of nucleation sites and N_{ac} is the number of active nucleation sites.

The resulting terms of latent heat and induced convection are shown in Figure 7. Emphasis is put on these two terms as the high latent heat of evaporation of liquids such as the water is expected to be dominant over other terms. However, extremely diverse boiling behaviour has been reported for water when compared to other fluids with much lower latent heat of evaporation and also much lower surface tension. Hence, it is worth to explore whether such different behaviour is reflected on different relative importance of each of the terms. Being less affected by coalescence, the fluids with lower latent heat of evaporation may compensate this fact with a larger departure frequency. This is more evident for boiling over the structured surfaces with smaller S (e.g. for C2 $S=400\mu\text{m}$), for which there is a strong effect of the coalescence in generating large vapour bubbles, which lessen the departure frequency and block the convection of liquid near the surface. Hence, in this case the evaporative term obtained for the boiling of this fluid is similar or even smaller than that evaluated for ethanol and for HFE7000.

These plots also highlight the importance of the induced convection term for the liquids with lower values of the latent heat of evaporation. This term is associated to the bubble detachment and to the induced bubble flow, which in turn should be related to the bubble vertical velocity.

To infer on this possible relation, bubbles' vertical velocity was evaluated by PIV measurements, following the procedure introduced in Teodori *et al.* [17].

The average vertical bubble velocity (average of the velocity profile for a fixed value of H/D), along the vertical dimensionless distance H/D , where H is the vertical distance from the top face of the surface in (mm) and D is the bubble departure diameter (also in mm), for different heating conditions and different micro-patterns.

The velocity profiles were recently presented for the boiling of ethanol and HFE7000 over several micro-structured surfaces

in Teodori *et al.* [69]. As a general trend, the results reported in [69] show that surfaces with closer cavities (C2 $S=400\mu\text{m}$) present more uniform and stable profile when compared to those with sparser cavities (C7 $S=1200\mu\text{m}$), so the cavities, for these fluids, seem to act as stabilization factor to the vertical velocities. As a complement to this information, Figure 8 illustrates the global heat transfer coefficients as a function of the average bubbles' vertical velocities for ethanol and HFE7000 boiling over the micro-structured surfaces with smallest and largest S . It is now clear that the bubbles' vertical velocity is larger for HFE7000 than for ethanol, particularly for the boiling over the surfaces with smaller S . Also, the heat transfer coefficient follows a more stable increase with the bubble's characteristic velocity for this surface, when compared to that of ethanol. Considering the important weight of the induced bulk convection in these fluids, the highest heat transfer coefficient that was obtained for the boiling over the surface with smaller S cannot be solely attributed to the increase of nucleation sites, but should also be related to the flow and to the stabilization effect of the micro-patterns. The heat transfer coefficient for ethanol pool boiling is less sensitive than that obtained for HFE7000 to the characteristic bubble velocity, as this fluid still has quite a high value of the latent heat of evaporation and the term of bubble evaporation is definitely quite relevant.

However, one may argue that the term of induced bulk convection is quite important for both ethanol and HFE7000. Consistently, the heat transfer coefficient seems to be well related to the characteristic bubbles' velocity.

To infer on how well this correlation could be established, some preliminary parametric studies were performed. One can re-write eq. (1) in its reduced form:

$$St^* = C_{sf} Re_b^m \cdot Pr_l^n \quad (5)$$

St^* is the inverse of the Stanton number $St=h/(\rho V_{carat} \cdot c_p)$, Pr_l is the liquid Prandtl number and Re_b is the Reynolds number associated to bubbles' departure diameter. m and C_{sf} are fitting parameters being the later classically related to surface properties. However instead of using the superficial velocity of the liquid and $(\sigma_{lv}/(g \cdot (\rho_l - \rho_v)))^{1/2}$ as the characteristic length scale, we considered the experimental values of D_b (which were related to the heat flux in [68]) and the characteristic bubbles velocity. This velocity, weighted by the ratios of the vapor and the liquid densities, to account for the buoyancy effect, was also used to compute a modified Stanton number St' . Details in the development of the proposed correlation are provided in [69]. Additional work is still required to refine the relation and to take out as much as possible its empirical nature, which is still much present. Nevertheless, preliminary results, as depicted in Figure 9 show good agreement between the experimental data and this relation, which takes into account bubble dynamics and the interaction mechanisms. This also encourages a serious mechanistic approach which will consider the role of these mechanisms in agreement with the discussion presented here.

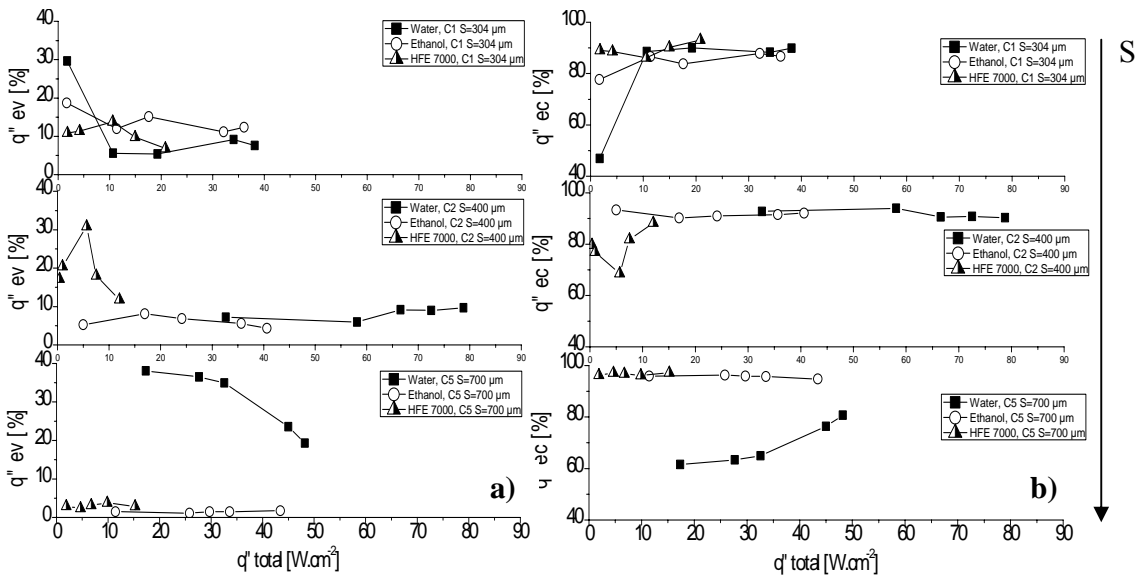


Figure 7. Term of latent heat (left) and enhanced convection (right) for water, ethanol and HFE7000 on micro-structured surfaces (the distance between cavities, S , is increasing from top to the bottom).

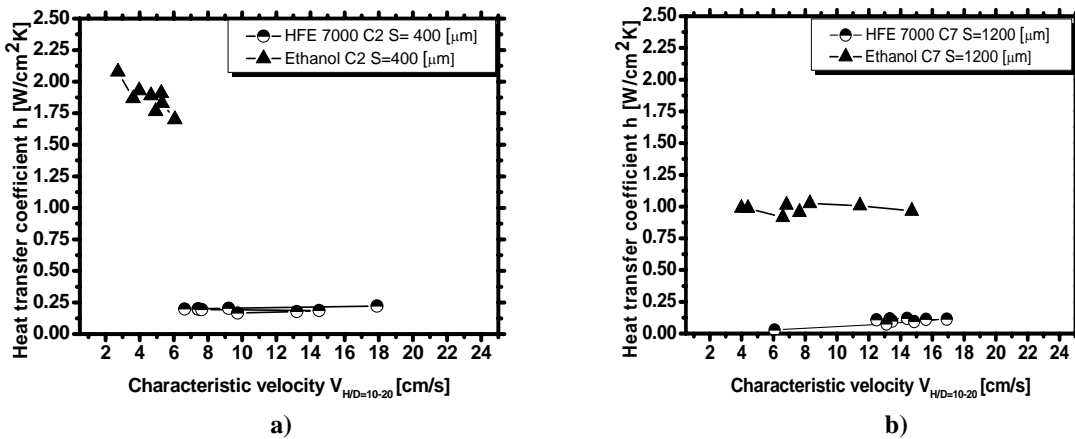


Figure 8. Heat transfer coefficient as a function of the characteristic velocity $V_{H/D}$ for ethanol and HFE 7000 boiling over: **a)** Surface C2 ($S=400\mu\text{m}$) and **b)** Surface C7 ($S=1200\mu\text{m}$).

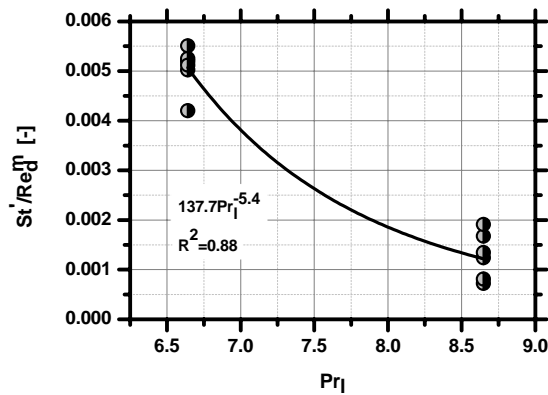


Figure 9. Correlation between the experimental data and our empirical modified Rohsenow equation.

FINAL REMARKS

The present paper revises the basic nucleation and bubble dynamics mechanisms focusing on the effect of enhancing the surface. The consequences at the heat transfer mechanisms are then discussed. The review performed here stresses the fact that despite of the fast advance of the micro-and-nano technologies which allowed the researchers to try numerous surface modifications, the study of the physical processes governing the observed phenomena were taken to a secondary place, as quick trial and error approaches would reach to good results. However, such fundamental study is vital to accurately describe the effect of surface topography and wettability, as this is a critical step to lessen the strong empirical nature that is present in most of the theoretical predictions.

This accurate description also requires adequate diagnostic techniques. Combining Particle Image Velocimetry – PIV with high speed imaging and thermography has been recently reported in the literature to render precise measurements of several quantities such as bubble departure diameters and frequencies, and even thickness of the micro layer, which are of major importance to validate theoretical correlations.

The experimental analysis performed here also highlights the important role of the interaction mechanisms in bubble dynamics and consequently in the heat transfer mechanisms.

Finally, preliminary analysis proposed here, based on combined high-speed imaging with PIV allows a deeper understanding of the relation between bubble dynamics and the heat transfer, encouraging the pursuit of a mechanistic approach, as followed by previous authors, complemented with the appropriate integration of the missing parameters (wettability and surface topography, the latter related to the interaction mechanisms).

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