8th World Conference on Experimental Heat
Transfer, Fluid Mechanics, and Thermodynamics
June 16-20, 2013, Lisbon, Portugal

POOL BOILING OVER ENHANCED SURFACES OVER A WIDE RANGE OF WETTABILITY CONDITIONS

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ABSTRACT

The present work addresses the description of the wettability effect in bubble dynamics and in the heat transfer occurring at pool boiling. The wettability is quantified by the equilibrium and dynamic contact angles, θ_e and θ_d, respectively, and by the contact angle hysteresis, $\Delta\theta$. This study covers a range of contact angles, characterizing the wettability of the surfaces, from hydrophilic, to superhydrophobic. Given that the more hydrophilic surfaces offer a larger CHF and have lower performances in terms of the onset of boiling, these surfaces are micro-patterned with artificial sites. The size, depth and distance between the sites are well defined and controlled in order to quantify, quantitatively the effect of the surface topography. The results show that superhydrophobic surface offers the best behaviour for liquids and conditions in which the horizontal coalescence or fluid motion do not destabilize the induced bulk convection. However, if this destabilization occurs, the opposite trend can easily occur. In line with this, a hybrid surface combining hydrophilic and hydrophobic features organized in different locations may not be the most suitable solution, as the results shown here evidence that the pool boiling is mostly dependent on the bubble dynamics process which evolves in time, and as a function of the heat flux. Hence, a more suitable solution may require an adaptable surface with reversing wetting properties changing in time, depending on the boiling stage.

The analysis performed here devises basic relations between bubble dynamics and the heat transfer performance, which will be then used to delineate the basic description of the observed phenomena, towards the development of a model to predict the heat transfer coefficients.

***Keywords**: Superhydrophobic surfaces, pool boiling, heat transfer, bubble dynamics, wettability*

1. INTRODUCTION

Convective heat transfer associated to boiling flows is known to deliver the highest heat transfer coefficients, which are typically one order of magnitude higher than single-phase forced convection and two orders of magnitude higher than single-phase natural convection [1]. Such high heat transfer rates are required in many industrial processes, for instance in cooling systems for metallurgy, electronics cooling or even in food processing. Hence, a wide diversity of strategies have been studied to enhance boiling heat transfer, many of them requiring particular modification of the wetting properties of the surfaces over which boiling occurs. Several authors have used coating and or micro-and-nano-structuring to create superhydrophilic and superhydrophobic surfaces (e.g. [2, 3]) sustaining for their particular working conditions, many of them in pool boiling studies, the enhancement of the heat transfer rates.

Indeed, the wettability is one of the most important factors governing liquid-vapour phase change phenomena. However, quite dissimilar wetting characteristics are reported to be required at different stages of the boiling process, depending on the heat fluxes involved: at lower heat fluxes it requires hydrophobicity to promote nucleation and at higher heat fluxes it requires hydrophilicity to maintain the liquid transport to the heated surface in the regime of slugs and columns, thus extending the Critical Heat Flux (CHF) [4]. In the attempt of devising the optimum surface to enhance pool boiling heat transfer, several authors tried different hybrid hydrophilic/hydrophobic combinations (*e.g.* [4,5]). However, these authors still report several difficulties; namely hydrophilic surfaces patterned with hydrophobic sites do not offer fine pool boiling heat transfer at low heat fluxes, while and hydrophobic surfaces patterned with hydrophilic sites cannot achieve good performance at high heat fluxes [4,5]. Additionally, these authors do not quantify the effect of the surface topography, which is extremely relevant, even at very low roughness amplitudes (e.g. [6]). On the other hand it is not yet clear how the surface wettability is related to the pool boiling mechanisms.

In line with this, the present paper addresses the description of the wettability effect, in bubble dynamics and in the heat transfer, occurring at pool boiling. The wettability is quantified by the equilibrium and dynamic contact angles, θ_e and θ_d, respectively, and by the contact angle hysteresis, $\Delta\theta$. The present study covers a range of contact angles, characterizing the wettability of the surfaces, from hydrophilic, to superhydrophobic. Given that the more hydrophilic surfaces offer a larger CHF and have lower performances in terms of the onset of boiling, these surfaces are micro-patterned with artificial sites. The size, depth and distance between the sites are well defined and controlled in order to quantify, quantitatively, the effect of the surface topography.

The analysis performed here devises basic relations between bubble dynamics and the heat transfer performance, which will be then used to delineate the basic description of the observed phenomena, towards the development of a model to predict the heat transfer coefficients.

2. EXPERIMENTAL METHODOLOGY

The experiments encompass the characterization of bubble dynamics and quantification of the heat fluxes and heat transfer coefficients, for pool boiling over surfaces which cover a wide range of wetting properties.

Three liquids are used, namely water, ethanol and the dielectric fluid HFE7000, to account for the influence of their thermophysical properties in the observed phenomena. It is worth noting that the contact angles are varying also using the different fluids, and that the superhydrophobic condition can be reached with water only. Nevertheless, significantly diverse properties are expected with the hydrophobic surfaces when using other fluids. The most relevant thermophysical properties of the working fluids are summarized in Table 1.

Table 1 Thermophysical properties of the liquids used in the present study, taken at saturation, at 1.013x10^5Pa.

Property	Ethanol	Water	HFE7000
T_{sat} [°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_l [N/m]x10^3	17	58	12.4

Diverse techniques are used to makeup the surfaces: hydrophilic surfaces are made from silicon wafers and are micro-structured and characterized (in terms of topography and wettability) as detailed in [7, 8]; the superhydrophobic surfaces are prepared using a grafting technique on a aluminum substrate (confidential information).

In the attempt to overcome the limitation of the hydrophilic surfaces in establishing a stable boiling onset, these surfaces are micro-patterned with arrays of square cavities with cross section with side length a=52 µm and depth h_R=20µm. The distance between the centers of the cavities S is mainly the only variable, ranging between 300µm<S<1200µm. Table 2 depicts the main topographical characteristics of the surfaces used in this study.

The Table includes the average values of the static contact angle, which were measured as described in [9].

The surface SHS can be considered as a superhydrophobic surface as it shows an equilibrium contact angle θ_e= 167º (i.e. higher than 150ºC) and a very low hysteresis, $\Delta\theta$, defined as the difference between the advancing and the receding contact angles. Here $\Delta\theta$<8º.

Table 2 Main range of the topographical characteristics of the micro-patterned surfaces. θ_e is the average static contact angle measured with water at room temperature.

Material	**Reference**	a **[µm]**	h_R **[µm]**	S **[µm]**	θ_e **[º]**
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
Aluminum	SHS	-	-	.	167

2.1 Measurement procedures

Heat flux and heat transfer coefficients obtained from thermocouple measurements (see [7]) are determined for the various liquid/surface pairs and related to the bubble dynamics characterized by combining high-speed visualization with PIV measurements.

Several studies in the literature confirm the potential of using PIV to measure bubble velocity inside a flowing fluid, as for example reported by [10] and [11]. However, 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.* [11]).

The PIV system uses a CCD camera Kodak Megaplus, Model 1.0, with an image resolution of 1018x1008 pixel. The bubbles are illuminated via a dual Nd:YAG Litron laser. The PIV set-up and the coordinate system considered in the measurements are shown in Figures 1 and 2, respectively.

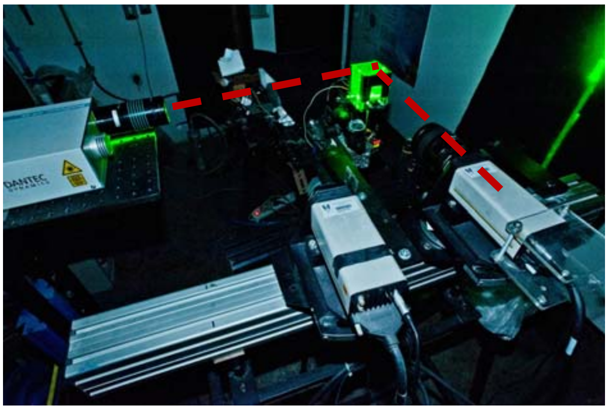


Figure 1 PIV arrangement.

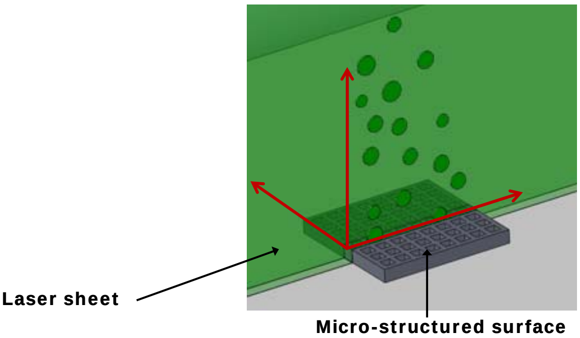
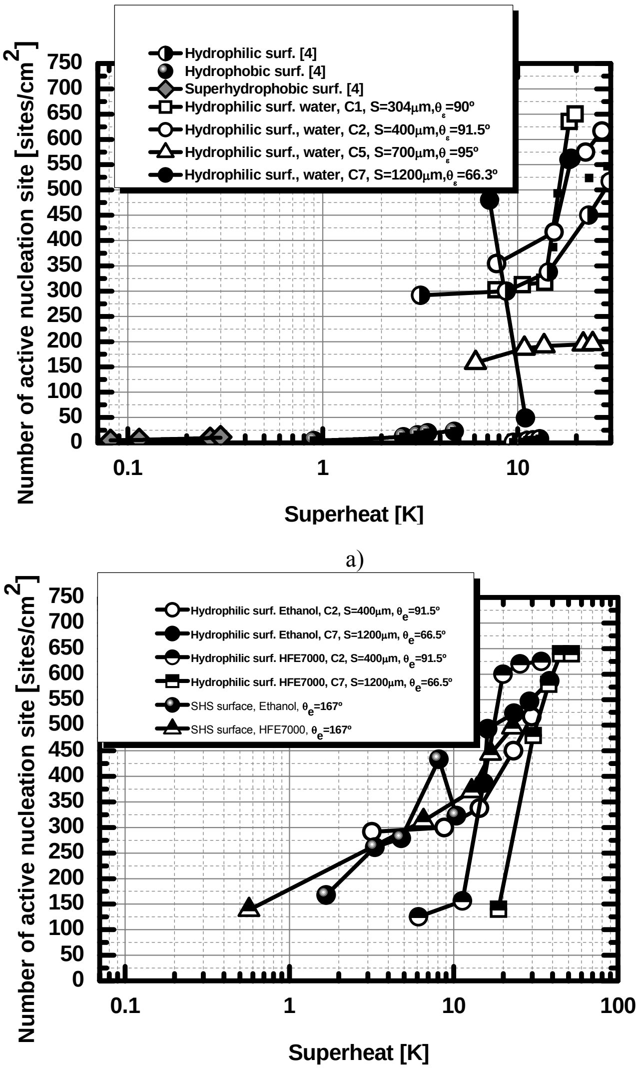


Figure 2 Coordinate system considered for the PIV measurements.

The time delay between laser pulses is varied ($1<\Delta t<8$ms) depending on the imposed heat flux: the time between pulses is smaller for higher imposed heat fluxes. Furthermore, the interrogation area and the overlap are also varied for the various imposed heat flux conditions, in an optimization process, to assure that the chosen values are adequate to obtain accurate measurements. Hence, the selected interrogation area was varied between 16 and 64 pixels (1pixel/58μm) to assure that at least five bubbles are inside. An overlap of 50% is chosen by analyzing two consecutive frames and evaluating the average displacement of the bubbles. The most appropriate approach for this kind of flow is using a recursive cross correlation or the average correlation algorithms (*e.g.* [11]). In the present work, after analyzing extensively both approaches, the cross correlation was considered to be the most appropriate. The measurements performed using PIV are compared with extensive image post-processing, within quite good agreement.

3. RESULTS AND DISCUSSION

In a recent work, Moita *et al.* [7] suggest that the pool boiling of liquids such as water, with high latent heat of evaporation h_{fg} and high surface tension σ_{lv}, have a slow boiling onset. It was considereda mechanistic approach, which is quite valid at low heat fluxes, in which bubble departure is governed by the competition between the surface tension forces ($\sim\sigma_{lv}D_b^2$) and the buoyancy forces ($\sim g(\rho_l-\rho_v)$). On the other hand, liquids like HFE7000, which have low h_{fg} and low σ_{lv} will give rise to a very fast boiling process, in which the maximum number of nucleation sites is achieved (the value of the number of active nucleation sites stabilizes around a maximum value), although small bubbles are formed. This behavior is clearly observed in Figure 3, which depicts the measured density of active nucleation sites for the pool boiling of water, ethanol and HFE7000 over smooth and micro-patterned surfaces with different wetting properties. Here the experimental results of Betz *et al.* [4] are also included for comparative purposes. Indeed, the number of active nucleation sites is the largest, independently of the surface used,it is also clear that the micro-patterns do not increase significantly the number of active nucleation sites for well wetting liquids such as HFE7000 and ethanol. However it is worth noting the positive effect of the micro-patterning in the promotion of the active nucleation sites for water boiling: the hydrophilic surfaces used here generate a number of active nucleation sites which is 2 orders of magnitude higher than that reported in [4] even for their best performing hydrophobic and biphilic (hybrid hydrophilic surfaces with hydrophobic spots) surfaces, at lower superheats. The very fast onset of boiling for low superheats observed for our SHS is in agreement with the reports in [4] and in [5]. This is actually the best performing surface in terms of active nucleation sites for all the fluids tested, even in comparison to other surfaces reported in the literature (e.g. [7]), which is attributed to its high roughness amplitude.

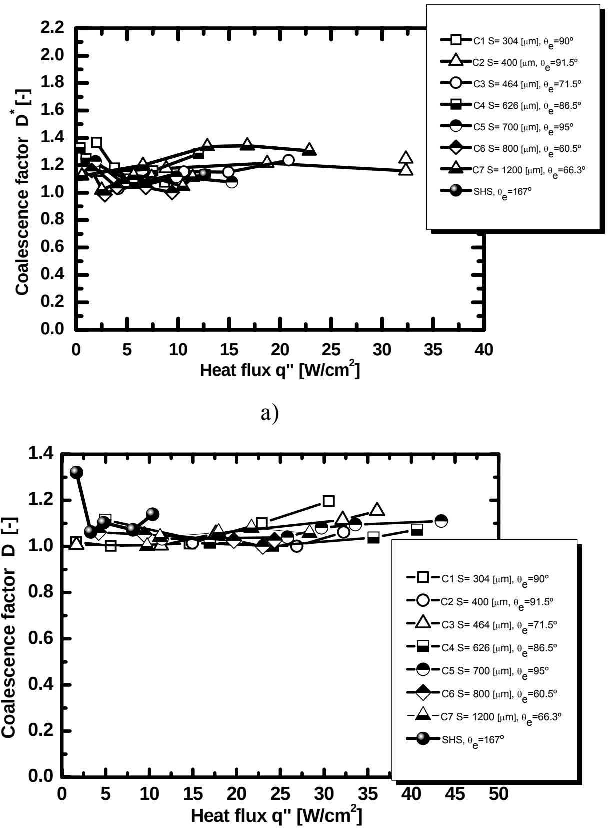


a)

b)

Figure 3 Measured density of active nucleation sites for: a)water pool boiling over smooth and micro-patterned surfaces with different wetting properties, b) for ethanol and HFE7000 for micro-patterned and SHS surfaces

Nevertheless, a high number of active nucleation sites do not assure the best pool boiling heat transfer, as the flow and bubble dynamics may significantly affect the overall heat transfer coefficient. In fact, as also reported in [7] the liquid and/or surface properties promoting the formation of large bubbles are strongly affected by horizontal coalescence (the coalescence factor, as introduced in [7] $D^*=D_b/D_{nc}>>1.0$, where D_b is the averaged bubble diameter and D_{nc} is the diameter as the bubble exits the cavity, i.e. with no coalescence), which may generate large vapor blankets over the surface, thus leading to a steep deterioration of the heat transfer coefficient *h*. This effect is quite evident for the water boiling over most of the micro-patterned hydrophilic surfaces, but is rather well controlled in both hydrophilic and SHS surfaces for HFE7000 and ethanol, as can be inferred from the results depicted in Figure 4. The size of the bubbles over the SHS is not significantly large when compared to the other surfaces, although the onset of boiling occurs much earlier. Also, this surface is not promoting a significant coalescence among the bubbles, despite promoting a vigorous boiling.



a)

b)

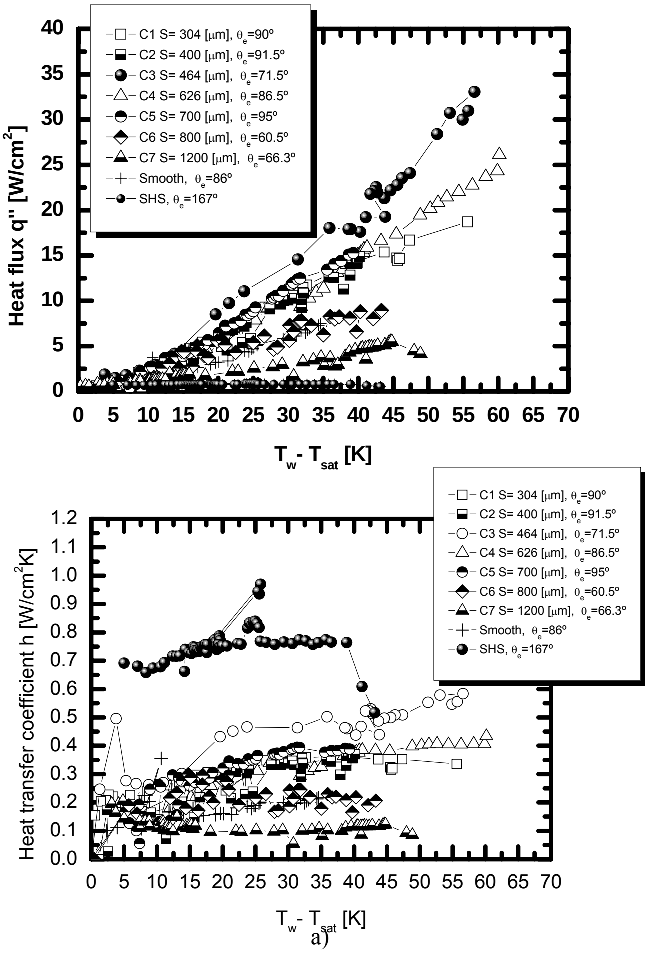
Figure 4 Coalescence factor vs heat flux for pool boiling over hydrophilic micro-patterned surfaces and superhydrophobic surfaces of a) HFE7000, b) ethanol.

It is worth mentioning that the wetting effects of surface SHS cannot be accurately defined as those of a real superhydrophobic surface, as the contact angle obtained with HFE7000 and ethanol is much lower than that obtained with water. Nevertheless such angle is higher than that obtained with any of these liquids with all the other surfaces. It is also noticeable a slipping effect of the bubbles as they are formed over the surface SHS, which can be related to a superhydrophobic behaviour. The accurate description of this sliding phenomenon and clarification of its effect on the pool boiling heat transfer requires further investigation, but serves already as a qualitative proof of "hydrophobic" behaviour of the surface SHS.

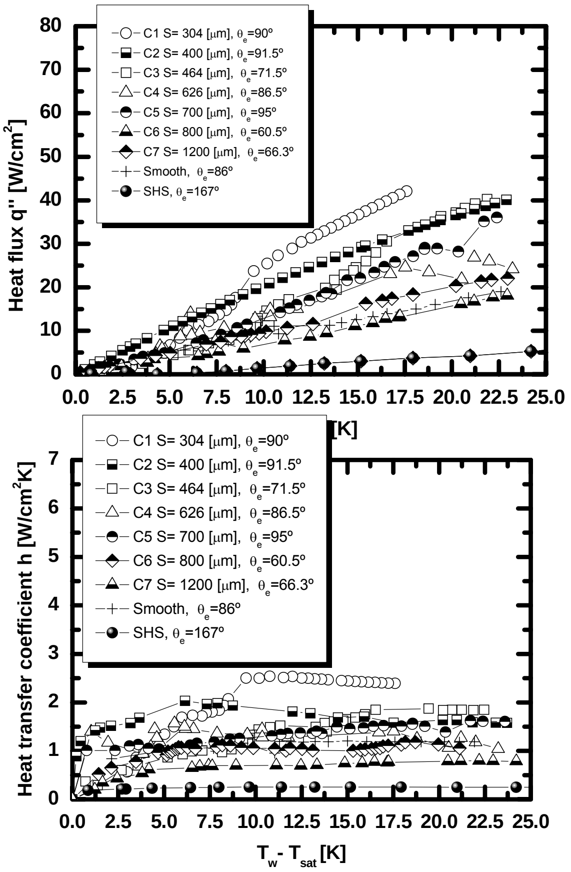
In line with this description and in agreement with the previous findings of [4,5 and 7] the pool boiling heat transfer behaviour of our SHS surface is the best, when compared to that of the hydrophilic surfaces, for HFE7000, as shown in Figure 5a. The heat transfer coefficient obtained with the SHS increases very fast, following later a constant trend, as the large number of vapour bubbles quickly limits the number of active nucleation sites. Also, contrarily to the micro-patterned hydrophilic surfaces, for which CHF is not reached, for the SHS surface, one clearly reaches the heat fluxes required to the formation of the "mushroom" bubbles region, typically observed as one approaches the CHF.

This is in agreement with the superhydrophobic behaviour reported by [4] and by [5] with water, thus confirming that a similar behaviour is obtained for this surface with HFE7000. Given the low surface tension of such liquid, one must relate this behaviour to the topographical properties of the surface.

A different trend is however observed for the pool boiling of ethanol, as the SHS is actually the worst performing surface (Figure 5b).



a)



b)

Figure 5 Boiling curves and heat transfer coefficients over hydrophilic micro-patterned surfaces and superhydrophobic surfaces of a) HFE7000, b) ethanol.

Although deeper investigation is yet required, one may explain this as follows: the pool boiling heat transfer results from the sum of 3 parcels, namely the natural convection, the evaporation and the induced bulk convection. While the large heat transfer coefficients associated to the water pool boiling are perfectly understandable, given the well known larger order of magnitude of the evaporative parcel in comparison to the natural convection (*e.g.* [12]), for liquids with lower values of h_{fg}, such as HFE7000 and ethanol, the analysis presented in [7] suggests a dominant role of the induced bulk convection. The relative importance of each parcel was investigated in the present study and, although the results cannot be depicted in this paper, due to length constrains, they confirm the dominance of the parcel of the induced bulk convection. Hence, one reason for the bad performance of the SHS surface is that it promotes a less significant (when compared to water) but not negligible coalescence effect very close to the surface, which decreases the parcel of the induced bulk convection. On the other hand these bubbles, as well as other associated effects may be destabilizing the flow. A destabilization was observed by Moita *et al.* [13] for micro-textured surfaces.

In summary, a hybrid surface combining hydrophilic and hydrophobic features organized in different locations may not be the most suitable solution, as the results shown here evidence that the pool boiling is mostly dependent on the bubble dynamics process which evolves in time, and as a function of the heat flux. Hence, a more suitable solution may require an adaptable surface with reversing wetting properties changing in time, depending on the boiling stage.

In terms of the description of the heat transfer process, taking as a starting point the micro-convection model of Mikic and Rohsenow [14], the heat transfer coefficient can be estimated as in [4]:

$$h = 2\,(\pi k_l \rho_l C_{pl})^{1/2}\,\eta_a\,D_d^2 f_d^{1/2}$$

where k_l, ρ_l and C_{pl} represent the thermal conductivity, the specific mass and the specific heat of the liquid phase, respectively. η_a, D_d and f_d are the density of active nucleation sites, the bubble departure diameter and the departure frequency. The experimental value of the number of active nucleation sites is a very sensitive measure to obtain, although it can be easily related to a property that is known a priori for the micro-patterned surfaces S, given that $\eta_a \propto S^{-a}$. On the other hand, besides being theoretically related with the characteristic length $Lc=(\sigma_{lv}/(\rho_l-\rho_v))^{1/2}$ which results from the equilibrium between surface tension and buoyancy forces, governing bubble detachment, Dd is suggested to be related to the contact angle, as suggested by [5]. This relation clearly needs to be refined, as shown in Figure 6, as the correlation between the wetting angle and the contact angle of the departure bubbles is not trivial. Nevertheless, the approach is suggested here and after refinement, it should be validated through the wide range of wettability, as presented here.

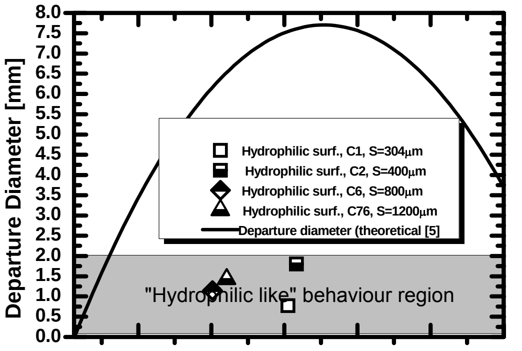


Figure 6 Comparison between the model of bubble growth and departure, as a function of the contact angle according to [4] and experimental data. The hydrophilic surfaces used here are micro-patterned with square cavities of size 20μm and depth 20μm. The distance between cavities *S* is the variable. The measurements were performed for low superheat values 5.1<ΔT<10K.

SUMMARY

The present work addresses the description of the effect of the wettability, in bubble dynamics and in the heat transfer occurring at pool boiling. The wettability is quantified by the equilibrium and dynamic contact angles, θ_e and θ_d, respectively, and by the contact angle hysteresis, $\Delta\theta$. This study covers a range of contact angles, characterizing the wettability of the surfaces, from hydrophilic, to superhydrophobic. Given that the more hydrophilic surfaces offer a larger CHF and have lower performances in terms of the onset of boiling, these surfaces are micro-patterned with artificial sites. The size, depth and distance between the sites are well defined and controlled in order to quantify, quantitatively the effect of the surface topography. The results clearly confirm the benefic effect of micro-patterning the hydrophilic surfaces, in promoting the increase of active nucleation sites. However, this is not enough to assure a good heat transfer performance, as the flow and bubble dynamics may significantly affect the overall heat transfer coefficient. In agreement with this, the superhydrophobic surface offers the best behaviour for liquids and conditions in which the horizontal coalescence or fluid motion do not destabilize the induced bulk convection. However, if this destabilization occurs, the opposite trend can easily occur. In line with this, a hybrid surface combining hydrophilic and hydrophobic features organized in different locations may not be the most suitable solution, as the results shown here evidence that the pool boiling is mostly dependent on the bubble dynamics process which evolves in time, and as a function of the heat flux. Hence, a more suitable solution may require an adaptable surface with reversing wetting properties changing in time, depending on the boiling stage.

ACKNOWLEDGEMENTS

The authors are grateful to Fundação para a Ciência e a Tecnologia (FCT) for partially financing the research under the framework of project PTDC/EME-MFE/109933/2009 and for supporting A.S. Moita with a Fellowship (Ref.:SFRH/BPD/63788/2009).

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