Empirical Correlations Between Bubble Dynamics and Heat Transfer Coefficient for Pool Boiling Over Micro-Textured Surfaces

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Abstract This paper proposes correlations to predict the pool boiling heat transfer over micro-patterned silicon wafer surfaces. Two different approaches are followed. The first consists in the development of a modified Rohsenow correlation, which includes a geometrical parameter that can accurately describe the typology of the surfaces. In an alternative approach, an original correlation was devised based on a dimensional analysis. The independent data required for validation of the proposed relations were collected coupling high-speed camera visualization, Particle Image Velocimetry and heat flux/surface temperature measurements. Additional data was also taken from the literature, for comparison purposes.

The modified Rohsenow correlation was able to predict the pool boiling heat transfer coefficients for all the liquid/surface combinations tested (which were gathered with additional data reported in the literature) within an error of ±20%. The final correlation obtained by dimensional analysis was able to predict the heat transfer coefficient within an error of ±30%. In addition, this correlation could predict the behaviour of fluids with significantly different thermo physical properties. Hence, despite this is still a preliminary work, the results are encouraging to evaluate the devised correlation within a wider range of conditions.

1. Introduction

In the context of cooling techniques for electronic components, direct immersion in a boiling dielectric fluid is extremely efficient in removing large amount of heat at low values of superheat of the component. The liquid, used for this application, has to be dielectric and with a low value of saturation temperature to assure that boiling occurs at low values of the component temperature. This kind of characteristics of the fluid are usually related with poor thermo physical properties (e.g. latent heat of vaporization and specific heat) when compared with other common liquids (e.g. ethanol or water). Hence to tackle this issue one can enhance the cooling performance by micro-structuring the surface. Silicon surfaces are usually used to simulate electronic components. Several different geometry arrangements are proposed the literature (e.g. Anderson and Mudawar, 1989, Honda et al., 2002). Etched cavities on the surface have been found to be efficient in increasing the pool boiling heat transfer. For instance, Yu et al. (2006) report an increment of the heat transfer coefficient of around (150%) for boiling of FC 72 over surfaces micro-patterned with circular cavities with diameters ranging from 50 to 200 µm and depth between 110 and 200µm. The authors also varied the distance between cavities from 100 to 400 µm. Nitesh et al. (2006) also showed an increment of the heat transfer coefficient around (50%) for the pool boiling of FC72 over surfaces micro-patterned with pyramidal cavities of mouth dimension of 40 µm and base dimension of 240 µm. The spacing between the cavities was varied between 500 and 1000µm. Recognizing the need to fix the geometry of the cavities and after some preliminary work, Moita et al. (2012) and Teodori et al. (2013) studied the boiling of water, ethanol and HFE7000 over micro-patterned surfaces with square cavities of fixed dimensions (length of the side was 52 µm and the depth of the cavities was 20µm). They only varied the distance between cavities from 300 to 1200µm. The authors observed an increment of the heat transfer of the order of (150 %) and discussed the relevance of the role of the distance between cavities in such enhancement. In fact, the enhancement achieved in terms of the heat transfer in pool boiling over micro-patterned surfaces results from the combined effect of the surface augmentation (increase of the contact area) and the promotion of the heterogeneous nucleation process by means of the etched cavities. However, it would be extremely simplistic to consider that these two parameters affect linearly the heat transfer coefficient. In fact, it has been noticed by the authors cited above (Yu et al., 2006, Nitesh et al., 2006, Moita et al., 2012 and Teodori et al., 2013) that changing the spacing between cavities can lead to interaction mechanisms which affect the boiling performance. In this context, a number of authors (e.g. Chekanov, 1977, Calka and Judd, 1985, Judd, 1988 and Zhang and Shoji, 2003), highlighted that the distance between cavities and the bubble departure diameter are characteristic parameters for the definition of the different interaction mechanisms involved in the boiling process. Furthermore, Chai et al. (2002) actually stress the definition of a characteristic length scale which
can be correlated with the interaction mechanisms occurring in pool boiling and thus with the resulting heat transfer coefficient. Hence, an accurate theoretical prediction of the heat flux and/or heat transfer coefficients for pool boiling over micro-patterned surfaces must account with all of these parameters.

1. Existing models and correlations

Several attempts have been made in the past to predict the pool boiling heat flux and heat transfer coefficients. Two main approaches are mainly followed: one is based on modelling of the phenomena (e.g. Tien, 1962, Gerardi et al., 2009) and the other is based on the development of empirical correlations (e.g. Vachon et al., 1968, Jabardo et al., 1991). Modelling of nucleate boiling is approached in different ways by various researchers. A well known model is based on the heat flux partitioning, which considers that the pool boiling heat flux is the result of three governing concurring mechanisms:

i) Natural convection: in the region of the surface not influenced by the presence of the bubbles;  
ii) Evaporation: occurring during the growing period of the bubble;  
iii) Quenching: due to the inflow of cold fluid on the heating surface and subsequent thermal boundary layer reformation after bubble departure.

Despite one must recognize that this kind of approach is one of the most representative in terms of the physics of the observed phenomena, the formulations expressing the different mechanisms of heat transfer are usually strongly related with experimental data such as bubble departure frequency, bubble departure diameter, nucleation site density, among others. This leads to the fact that these models have a strong empirical nature and depend from the availability and the accuracy of the existing experimental data, which is not trivial to obtain. To contour this issue several authors propose modelling of the nucleate boiling through dimensional analysis. Examples of this method are the correlations reported in Kruzhlin (1949), Rohsenow (1952), Borishansky et al., (1961), Borishansky (1969), Stephan and Abdelsalam (1980).

Despite these efforts, after some analysis of the existing correlations, it becomes clear that they are not adequate to use for pool boiling over micro-patterned surfaces, given that, apart from the Rohsenow correlation (1952), these correlations usually do not take into account the effect of the surface/liquid combination and the surface microstructure, or include it considering an average surface roughness, which is not a characteristic parameter for studies addressing micro-patterned surfaces. Thus, this brief review highlights the need to devise more tailored models and correlations, which include data obtained in similar experimental conditions as those reported when micro-patterned surfaces with regular profiles are used (e.g. in Nitesh et al., 2006, Moita et al., 2012 and Teodori et al., 2013).

In this context, the present paper proposes two approaches to define a correlation for the specific case study of pool boiling over surfaces micro-structured surfaces with a regular pattern of cavities.

The first approach consists in evaluating the performance of a Rohsenow’s type correlation and the following determination of the fitting parameters, as proposed in Vachon et al., (1968), Sauer et al. (1975), Jabardo et al. (1991), Pioro (1999) and Jabardo et al. (2004). Based on this analysis a modified Rosenhow ‘s correlation is proposed, which has, nevertheless the aforementioned empirical nature.

In the second approach, an original correlation is devised based on the dimensional analysis of the phenomena, which is strongly related with the effect of the surface geometry.

The independent data required for validation of the proposed relations are collected coupling high speed camera visualization, PIV (Particle Image Velocimetry) and heat flux/surface temperature measurements, following the approach considered in Teodori et al. (2013).

2. Experimental Approach

2.1. Experimental Set-Up
The experimental data required for the validation of the devised correlations was obtained as in Moita et al. (2012) and in Teodori et al. (2013), for the pool boiling of the dielectric fluid HFE 7000, ethanol and water. In addition, the results reported by Yu et al. (2006) and by Nitesh et al. (2006) for the pool boiling of FC 72 are also presented for comparative purposes, due to experimental conditions considered in these studies, which are very similar to those considered here. The relevant thermo physical properties of the fluids are reported in Table 1. The description of the experimental set-up, experimental procedure and sample results are here only briefly presented. A more detailed description can be found in Moita et al. (2012) and in Teodori et al. (2013).

Table 1. Thermo physical properties of the liquids used here, in Yu et al. (2006), in Nitesh et al. (2006), in Moita et al. (2012) and in Teodori et al. (2013). The properties of FC72 are taken from Mudawar and Anderson (1990). Here $T_{sat}$ is the saturation temperature of the liquids. $\rho$ is the density, $\mu$ the dynamic viscosity, $C_p$ the specific heat, $k$, the thermal conductivity, $h_{fg}$ the latent heat of vaporization and $\sigma_{lv}$ the liquid surface tension. L and v stand for liquid and vapour phases, respectively.

<table>
<thead>
<tr>
<th>Liquid</th>
<th>$T_{sat}$ [°C]</th>
<th>$\rho_l$ [kg/m$^3$]</th>
<th>$\rho_v$ [kg/m$^3$]</th>
<th>$\mu_l$ [mN/m/s$^2$]</th>
<th>$c_{pl}$ [J/kgK]</th>
<th>$k$ [W/mK]</th>
<th>$h_{fg}$ [kJ/kg]</th>
<th>$\sigma_{lv}$ [N/m]$x10^3$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water</td>
<td>100</td>
<td>957.8</td>
<td>0.596</td>
<td>0.003</td>
<td>4217</td>
<td>0.68</td>
<td>2257</td>
<td>58</td>
</tr>
<tr>
<td>Ethanol</td>
<td>78.4</td>
<td>736.4</td>
<td>1.647</td>
<td>0.004</td>
<td>3185</td>
<td>0.165</td>
<td>849.9</td>
<td>17</td>
</tr>
<tr>
<td>FC 72</td>
<td>56</td>
<td>1620</td>
<td>13.01</td>
<td>0.004</td>
<td>1096</td>
<td>0.0583</td>
<td>84.73</td>
<td>9.5</td>
</tr>
<tr>
<td>HFE 7000</td>
<td>34</td>
<td>1374</td>
<td>4.01</td>
<td>0.003</td>
<td>1352.5</td>
<td>0.07</td>
<td>142</td>
<td>12.4</td>
</tr>
</tbody>
</table>

The structured surfaces used here are custom made from silicon wafers. The surfaces are micro-structured with regular arrays of squared cavities, with fixed size length $a=52$ µm and fixed depth $h=20$µm. The distance between the centers of the cavities, $S$ is mainly the only variable distance, ranging between 300µm$<S<1200$µm. The parameters characterizing the micro-patterns are schematically defined in Fig. 1, together with a photo of one of the surfaces. Slight rounding of the edges of the square cavities may occur, but the apparent round shape of the cavities in Fig. 1 is an optical distortion caused by the positioning of the camera. The surfaces were characterized by their surface topography, from roughness profiles, measured with a profile meter, (Dektak 3, by Veeco with a vertical resolution of 200Angstroms) and by the wettability quantified by the static contact angle $\theta$, using an optical tensiometer THETA from Attesion, with One-Attesion v1.8 software, with an accuracy of $\pm 1^\circ$, according to the manufacturer. The measurements are performed at room temperature, for all the liquids and surfaces used in this study. Each value is averaged from at least five measurements taken at different regions of the surface. The detailed measurement procedure is described in Moita and Moreira (2012). The contact angles obtained with ethanol and HFE7000 in contact with all the surfaces are close to zero.

![Image](image1.png)

**Fig. 1** a) Identification of the main parameters quantifying the micro-patterns. b) Sample of one of the micro-structured surfaces.

Table 2 depicts the main topographical characteristics of the surfaces used in this study.

Table 2. Main range of the topographical characteristics of the micro-patterned surfaces. $\theta$ is the average static contact angle measured with water at room temperature. $\theta=0^\circ$ for all the surfaces in contact with
ethanol and HFE7000.

<table>
<thead>
<tr>
<th>Material</th>
<th>Reference</th>
<th>$a$ [µm]</th>
<th>$h_R$ [µm]</th>
<th>$S$ [µm]</th>
<th>$\theta$ [°]</th>
<th>$Aen/\text{Asmooth}$ [-]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Silicon Wafer</td>
<td>Smooth</td>
<td>$\approx 0$</td>
<td>$\approx 0$</td>
<td>$\approx 0$</td>
<td>86.0</td>
<td>1</td>
</tr>
<tr>
<td>C1</td>
<td></td>
<td>52</td>
<td>20</td>
<td>304</td>
<td>90.0</td>
<td>1.0675</td>
</tr>
<tr>
<td>C2</td>
<td></td>
<td>52</td>
<td>20</td>
<td>400</td>
<td>91.5</td>
<td>1.0392</td>
</tr>
<tr>
<td>C3</td>
<td></td>
<td>52</td>
<td>20</td>
<td>464</td>
<td>71.5</td>
<td>1.0275</td>
</tr>
<tr>
<td>C4</td>
<td></td>
<td>52</td>
<td>20</td>
<td>626</td>
<td>86.5</td>
<td>1.0159</td>
</tr>
<tr>
<td>C5</td>
<td></td>
<td>52</td>
<td>20</td>
<td>700</td>
<td>95.0</td>
<td>1.0122</td>
</tr>
<tr>
<td>C6</td>
<td></td>
<td>52</td>
<td>20</td>
<td>800</td>
<td>60.5</td>
<td>1.0089</td>
</tr>
<tr>
<td>C7</td>
<td></td>
<td>52</td>
<td>20</td>
<td>1200</td>
<td>66.3</td>
<td>1.0039</td>
</tr>
</tbody>
</table>

The experimental arrangement is composed by a power supply, a pool boiling test section (Fig 2a), a high-speed camera (Phantom v4.2 from Vision Research Inc., with 512x512pixels@2100fps and a maximum frame rate of 90kfps), a DAQ acquisition system (Fig 2b) and a PIV system. The temperatures are sampled using type K thermocouples. The signal is acquired and amplified with a National Instruments DAQ board plus a BNC2120. The acquisition frequency is 100Hz and the temperature is monitored for 20 seconds after reaching a stable condition (constant temperature variation which does not exceed ±0.5°C). The entire heating section of the pool boiling test section is isolated with Teflon. The liquid is pre-heated and degassed in a pre-chamber. The refilling and the entire measurement processes are automatically controlled using two valves. The system responds based on the information provided by a pressure transducer (OMEGA DYNE Inc). The control system reacts to pressure variations in the order of 5mbar. Heaters disposed on the sides of the pool boiling chamber are controlled by a PID controller to assure that the liquid remains inside the chamber at saturation temperature.

2.2. Experimental Procedure and Measurement Uncertainties

The boiling curves are presented for each liquid and each heating surface by manually varying the imposed heat flux in discrete steps. Each curve is obtained from the average of four experiments, as illustrated in Fig.3. It is worth mentioning that the entire curve is not represented here, but only the part which is relevant for our results.
The main uncertainties of the quantities related to the heat transfer measurements are summarized in Table 3.

<table>
<thead>
<tr>
<th>Measured parameter</th>
<th>Maximum combined uncertainty</th>
<th>Evaluation method</th>
</tr>
</thead>
</table>
| Heat flux q'' [W/cm²]         | ±22.5%                      | \[
\frac{\Delta q''}{q''} = \left[ \left( \frac{\Delta L}{L} \right)^2 + \left( \frac{\Delta T}{T} \right)^2 \right]^{1/2}
\]
| (fully developed nucleate boiling of HFE7000) |                                                                           |
| Temperature T [°C]             | ±1.2 °C                     | \[unc_T = \left[ B^2 + t_{95}\sigma^2 \right]^{1/2}\]
|                               |                             | B is the bias limit, t_{95} is the confidence level and \(\sigma\) is the standard deviation |
| Heat transfer coefficient h [W/cm²K] | ±22.5%                     | \[
\frac{\Delta h}{h} = \left[ \left( \frac{\Delta q''}{q''} \right)^2 + \left( \frac{\Delta T}{T} \right)^2 \right]^{1/2}
\]
| (fully developed nucleate boiling of HFE7000) |                                                                           |

2.2.1. PIV – Particle Image Velocimetry Measurements

As suggested by Cheng et al. (2005), seeding is not used, but instead the bubbles are tracked. Bubbles' diameter is in the range of 500-800µm, measured by image post-processing. These dimensions and the low characteristic velocities of the bubbles (1-10 cm/s) require a careful analysis of all the parameters which have to be selected in the PIV configuration. The PIV system uses a CCD camera Kodak Megaplus, Model 1.0, with an image resolution of 1018x1008 pixel². The bubbles are illuminated via a dual Nd:YAG Litron laser. The time delay between laser pulses is varied (1<Δt<8ms) depending on the imposed heat flux: the time between pulses is smaller for higher imposed heat fluxes. 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. After detailed analysis, the cross correlation was considered to be the most appropriate approach to process the data. The measurements performed using PIV are compared with extensive image post-processing, within quite good agreement. The PIV data were processed with the software Flow manager 4.2. Comprehensive description of the entire procedure and configurations used is provided in Teodori et al. (2013).
3. Results and Discussion

Pool boiling curves for the three liquids tested (water, ethanol and HFE7000) are obtained over the micro-structured surfaces. The results, reported in Fig.4, highlight that the water pool boiling is generally characterized by higher values of the heat transfer coefficient, due to the higher thermo physical properties of this fluid.

The surface topography is dramatically influencing the heat transfer process. Decreasing the distance between cavities, thus increasing the number of cavities, leads to an increase of the heat transfer coefficient, due to the augmentation of the contact area and to the promotion of heterogeneous nucleation sites. This is a straightforward trend for liquids with low surface tension such as HFE 7000 and ethanol. On the other hand, for liquids with higher surface tension, like water, the larger bubbles and the slower departure of the bubbles (due to the high surface tension and latent heat of vaporization), strong horizontal coalescence can occur, which for surfaces with a high number of cavities may actually lead to a deterioration of the heat transfer coefficient, as previously reported by Nitesh et al. (2004) and by Moita and Moreira (2012).

A practical representation of the combined effect of surface topography and liquid properties on the pool boiling heat transfer can be obtained with the curve reported in Fig.5. In this figure, the ratio between the average heat transfer coefficient of the structured surface over that of the smooth surface (h_s/h_smooth) is plotted versus a distance parameter S/L_c. h_s/h_smooth expresses the relative enhancement in terms of heat transfer coefficient obtained by micro-structuring the surfaces, while surface S/L_c relates a characteristic parameter of the surface geometry (the single dimension that is being varied, S) with a characteristic length L_c which is proportional to the bubble departure diameter:

\[ L_c = \sqrt{\frac{g}{\rho_1 - \rho_v}} \]  

(1)

The distance parameter S/L_c has been widely used in literature (e.g. Chekanov, 1977, Calka and Judd, 1985, Judd, 1988 and Zhang and Shoji, 2003) to define different regions of interaction between cavities. In this context, it was considered useful to express the performance of the pair liquid/surface, which is strongly related to the aforementioned interaction (e.g. coalescence) mechanisms.

![Fig.4 Heat transfer coefficient vs Wall Superheat for the three liquids studied over micro-structured surfaces. (a) Water (b) Ethanol (c) HFE7000.](image-url)
Fig. 5: Heat transfer ratio vs dimensionless distance for water, ethanol and HFE 7000 in the range of patterns studied.

As previously inferred from Fig. 4, it can be noticed that for low wetting fluids such as water, decreasing $S/L_c$ is only advantageous until a maximum value of $S$, for which the coalescence factor is too high (this value corresponds to surface C1 $S=304\mu$m). For such values of $S$ the negative effects of bubble interaction becomes dominant and leads to a deterioration of the heat transfer coefficient, so that $h_{av}/h_{smooth}$ decreases. This behaviour is not observed instead in fluid with lower surface tension, as the interaction mechanisms play a secondary role (e.g. Moita et al., 2012, Teodori et al., 2013).

A deeper analysis to the heat flux, partitioned by the terms of natural convection, evaporation and induced bulk convection or quenching (e.g. Gerardi et al., 2009) as explained in the Introduction, was performed in a previous work (Teodori et al., 2014) and allowed to identify an important role of the induced bulk convection term, which is associated to the additional heat that is removed by the flow induced by bubble departure. This term was particularly important for the highly wetting liquids. The mechanism of the bulk induced convection is naturally dependent on the bubble parameters which become very high for the boiling of such low wetting liquids over enhanced surfaces (e.g. bubble departure frequency), but looking at the fluid dynamics it is also associated to the bubble detachment and to the induced bubble flow, which in turn should be related to the bubble vertical velocity. Taking into account that most of the existing correlations (including Rohsenow’s equation) are a function of Reynolds and Prandtl numbers and address the pool boiling heat transfer as a special kind of forced convection flow, the vertical velocity of the departure bubbles was evaluated for the boiling fluids, in order to understand if the surface typology could affect this induced convective flow. The average vertical bubbles’ velocity (average of the velocity profile for a fixed value of $H/D$) was evaluated along the vertical dimensionless distance $H/D$, using the PIV technique, as described in sub-section 2.2.1. Here, $H$ 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 are presented for the surfaces with the smallest and the largest distance between cavities in Fig. 6, for illustrative purposes. The velocity profiles are only shown for ethanol, but a similar trend was observed for HFE7000. Overall, the plots show that bubbles are ejected with larger average velocity, as the imposed heat flux is higher. Surfaces with closer cavities (C2 $S=400\mu$m) present more uniform and stable profile when compared to those with sparser cavities (C7 $S=1200\mu$m), for which the velocity profiles can be very disturbed, particularly at higher heat fluxes. Hence, the cavities, for these fluids, seem to act as stabilization factor to the vertical velocities. This is in agreement with our previous findings (Teodori et al., 2013).
After confirming the relevance of the induced bulk convective term, it is legitimate to consider an approach based on the principles considered by Rohsenow.

3.1. Development of the Correlations - 1st Approach: Modified Rohsenow Correlation

According to Rohsenow, the heat transfer enhancement under boiling conditions is the result of local liquid circulation in the region close to the heating surface promoted by successive bubble detachments. After some manipulation, the correlation can be presented as follows:

\[
\frac{cp_i \cdot \Delta T}{h_{fs}} = C_{sf} \left[ \frac{q''}{\mu_i h_{fg}} \cdot \sqrt{\frac{\sigma_i}{g \cdot (\rho_i - \rho_v)}} \right]^m \cdot Pr_i^n \tag{2}
\]

or

\[
St^* = C_{sf} \cdot Re_b^m \cdot Pr_i^n \tag{3}
\]

The left hand side of the equation (2) corresponds to the inverse of Stanton number, $St^*$, whereas the first term of the right hand side could be considered a Reynolds number referred to the bubble departure diameter. Values of exponent $m$ and $n$ were found to be equal to 0.33 and 1.7 or 1.0 for water. According to Rohsenow, whereas $m$ is not affected by the surface, $n$ might depend upon the surface finishing, attaining values in the range between 0.8 and 2.0. The numerical coefficient, $C_{sf}$, was related to the effect of liquid/surface combination through the contact angle, $\theta$.

In the evaluation of the Rohsenow’s correlation, only the data corresponding to fully developed nucleate boiling was considered, and in particular, in the region of the boiling curve for which all the cavities acted as active nucleation sites. The fitting procedure reported here is similar to that proposed in Jabardo et al. (2004).

3.1.1. First Fitting (Rohsenow’s $n(1-1.7), m(0.33)$ - $C_{sf}$ Evaluated)

The first fitting process consists in maintaining the original exponents of the Rohsenow’s equation and determine $C_{sf}$ for the different surfaces/fluids combination. To accomplish with this, eq. (2) was linearized and re-arranged in terms of logarithms:
\[ \ln St^* = a_1 + m \cdot \ln Re_b + n \cdot \ln Pr \]  
with \( a_1 = \log C_{sf} \)

and the data is then processed through regression analyses.

To take into account the combined effect of cavity spacing and surface augmentation, a new geometric parameter is now introduced \( \left( \frac{L_c}{S} \right) \cdot \left( \frac{A_{en}}{A_{smooth}} \right) \), in which, \( \frac{A_{en}}{A_{smooth}} \) is the ratio between the wetted area of the structured surface and the wetted area of the smooth surface, while \( \frac{L_c}{S} \) is the distance parameter, as previously introduced. The first fitting procedure confirms some conclusions reported by Jabardo et al. (2004): the values of \( C_{sf} \) obtained during the fitting procedure are strongly dependent from the surface topography. This dependence is clearly shown in Fig. 7, in which it is evident that values of \( C_{sf} \) decrease as the geometric parameter increases.

![Fig.7. Evaluated values of \( C_{sf} \) versus the geometry parameter \( \left( \frac{L_c}{S} \right) \cdot \left( \frac{A_{en}}{A_{smooth}} \right) \) for water, Ethanol, HFE7000 and FC 72.](image)

The results presented in Fig.7 were fitted by a correlation with the general form:

\[ C_{sf} = a \cdot \ln \left( \frac{L_c}{S} \cdot \frac{A_{en}}{A_{smooth}} \right) + b \]  
(5)

The coefficients \( a \) and \( b \) are correlated with the different liquids as reported in Table 4.

The heat transfer coefficients resulting from this first fitting procedure are further reported in Fig. 8.

It can be noted that most of the data points fall in the range of ±20% indicated by the two straight continuous lines. A strong approximation error is noted only for the data from Yu et al. (2006), but one cannot assure the exact similarity in the experimental conditions used by those authors, when compared to the rest of the data. Overall, the agreement between the correlation and the data is rather good, which encouraged to perform a more abstract and general fitting, to pursue a more universal relation.

<table>
<thead>
<tr>
<th>Tested fluid</th>
<th>( a )</th>
<th>( b )</th>
<th>( R^2 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water</td>
<td>0.027706</td>
<td>-0.01002</td>
<td>0.89</td>
</tr>
<tr>
<td>Ethanol</td>
<td>0.002343</td>
<td>-0.00361</td>
<td>0.84</td>
</tr>
<tr>
<td>FC72</td>
<td>0.003944</td>
<td>-0.00019</td>
<td>0.78</td>
</tr>
<tr>
<td>HFE7000</td>
<td>0.011271</td>
<td>-0.00299</td>
<td>0.91</td>
</tr>
</tbody>
</table>
Fig. 8. Evaluation of the first fitting process for water, ethanol, HFE7000 and FC 72.

3.1.2. Second Fitting (n, m and Csf Evaluated)

Assessment of m

All data points for the different fluids were plotted in terms of curves ln St* vs. ln Re b. Values of m for each liquid/surface-geometry were determined as:

\[ \ln St^* = m \cdot Re_b + C \]  \hspace{1cm} (6)

The values of m have been found to be dependent from the liquid tested from the surface geometry, as shown in Fig. 9. It is worth mentioning that the cloud of data points for each fluid is characterized by a common general slope for all the surface/liquid combination under investigation. Such trend is also in agreement with the analysis performed by Jabardo et al. (2004).

Fig. 9. Determination of m for the Rohsenow’s type correlation for water, ethanol, HFE7000 and FC 72.

Assessment of Csf,n

To assess the remaining fitting parameters of the Rohsenow equation, the following assumptions were made:
i) $C_{st}$ is considered a function of the geometry parameter $[\left(\frac{L_c}{S}\right) \cdot \left(\frac{A_{en}}{A_{smooth}}\right)]$. This dependency was identified in the first fitting procedure.

ii) $n$ is not determined as a variable dependent from pressure (as for instance in Jabardo et al., 2004), but instead, similarly to $C_{st}$ is considered to be a function of $[\left(\frac{L_c}{S}\right) \cdot \left(\frac{A_{en}}{A_{smooth}}\right)]$. Although not proven, this hypothesis is also raised by Vachon et al. (1968), who argue that $n$ could indeed be a function of the different surface/liquid combinations. Through their work, Jabardo et al. (2004) also consider this fact.

Following the aforementioned assumptions, the Rohsenow correlation assumes a new form, in which the effect of the surface topography is predominant. The final correlation in the logarithm form is here proposed as:

$$\ln S + m \cdot \ln Re_p = a1 \cdot \ln \left[\frac{L_c}{S} \cdot \frac{A_{en}}{A_{smooth}}\right] + a2 \cdot \left[\frac{L_c}{S} \cdot \frac{A_{en}}{A_{smooth}}\right] \cdot \ln Pr + C \quad (7)$$

The parameters $a1,a2$ and the constant $C$, determined through regression analysis are summarized in Table 5.

<table>
<thead>
<tr>
<th>Tested fluid</th>
<th>$a1$</th>
<th>$a2$</th>
<th>$C$</th>
<th>$R^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water</td>
<td>-2.57031</td>
<td>0.68038</td>
<td>-1.93375</td>
<td>0.91</td>
</tr>
<tr>
<td>Ethanol</td>
<td>-0.17176</td>
<td>-0.08928</td>
<td>-1.93375</td>
<td>0.82</td>
</tr>
<tr>
<td>FC72</td>
<td>-0.83221</td>
<td>0.05696</td>
<td>-1.93375</td>
<td>0.75</td>
</tr>
<tr>
<td>HFE7000</td>
<td>-2.10861</td>
<td>0.37261</td>
<td>-1.93375</td>
<td>0.89</td>
</tr>
</tbody>
</table>

The resulting heat transfer coefficient evaluated based on this new correlation is depicted in Fig. 10. With most of the data falling in the range of ±20% also this modified Rohsenow correlation proposed here appears to be suitable for prediction purposes. Furthermore, this correlation is in fairly good agreement with the experimental data reported by other authors (Yu et al. 2006, Nitesh et al., 2006).

![Fig. 10. Evaluation of the modified Rohsenow correlation for water, ethanol, HFE7000 and FC 72.](image-url)

The procedure followed up to now was a first attempt to include the combined effect of the distance between cavities and the surface augmentation in the boiling process, thanks to the geometry parameter introduced in the modified Rohsenow correlation. Despite being reasonably successful, this approach has a strong empirical nature, thus requiring different fitting parameters and, consequently losing its generality.

In this context, a new correlation will be proposed, based on a dimensional analysis, as described in the following paragraphs.
3.2. Development of the Correlations - 2\textsuperscript{nd} Approach: Dimensional Analysis

The proposed correlation is based on the Buckingham (pi) theorem to formulate the independent variables chosen to represent the dependent parameters. It is widely known that the pool boiling heat transfer can be related with:

i) The physical properties of the liquid, namely the latent heat of vaporization, the thermal conductivity, the specific heat and the saturation temperature;

ii) The operating conditions of the boiling process, expressed here as the heat flux;

iii) The combined effect of surface augmentation and cavity spacing, here represented by the geometric parameter already introduced in the previous section;

iv) The characteristic dimension \( L_{c} = \sqrt[3]{\frac{g}{g\cdot(\rho_{l}-\rho_{v})}} \) is widely recognized to be proportional to the bubble departure diameter and to the dimension of the thermal boundary layer.

In the assessment of the required criteria for pi-grouping, the following considerations have been taken into account:

i) The pool boiling heat transfer coefficient is widely expressed in terms of Nusselt number, which represents the ratio between the heat transferred by convection and the heat transferred by conduction. Thus the first pi group is:

\[
\frac{h \cdot L_{c}}{k_{1}}
\]

(8)

Surface augmentation and cavities spacing strongly affect the pool boiling heat transfer, thus the previously introduced geometric parameter is the second pi group:

\[
\frac{L_{c}}{S} \cdot \frac{A_{en}}{A_{smooth}}
\]

(9)

On the other hand, the parcel of heat transfer removed by quenching during the reformation of the thermal boundary layer is one of the predominant mechanisms of heat transfer in the region of the pool boiling curve studied here. Thus the third pi group tries to account for the percentage of heat removed by this mechanism and can be expressed as:

\[
\frac{q'' \cdot L_{c}}{k_{1} \cdot T_{sat}}
\]

(10)

Thermal and dynamic phenomena interact in a complex way in the pool boiling process. The proposed modified Stanton number is related with the ratio of heat transferred into the fluid to the thermal capacity of the fluid. This number is widely used to describe processes that involve the concurrence of static and dynamic heat transfer. Taking this into account, the fourth pi group can be expressed as:

\[
\frac{h_{fg}}{Cp_{l} \cdot T_{sat}}
\]

(11)

Once all the pi groups are identified, new correlation proposed here for the pool boiling heat transfer can be rearranged in the form:

\[
\frac{h \cdot L_{c}}{k_{1}} = C \cdot \left[ \frac{L_{c}}{S} \cdot \frac{A_{en}}{A_{smooth}} \right]^{a_{1}} \cdot \left[ \frac{q'' \cdot L_{c}}{k_{1} \cdot T_{sat}} \right]^{a_{2}} \cdot \left[ \frac{h_{fg}}{Cp_{l} \cdot T_{sat}} \right]^{a_{3}}
\]

(12)
After regression analysis, the final formulation is given by:

\[
\frac{h \cdot L_c}{k_i} = 19.3467 \cdot \left( \frac{L_c \cdot A_{en}}{S \cdot A_{smooth}} \right)^{0.33088} \cdot \left( \frac{q'' \cdot L_c}{k_i \cdot T_{sat}} \right)^{0.75583} \cdot \left( \frac{h_{fg}}{C_{p1} \cdot T_{sat}} \right)^{0.25136}
\] (13)

Fig.11 depicts the heat transfer coefficients evaluated with this correlation. Most of the data are in good agreement with the relation, within an error of ±30%. This is quite surprising taking into account the fact that in total, 30 surface liquid/combination are reported in the experimental data, including results from other authors. Furthermore, the various liquid tested have significant differences in terms of their thermo physical properties, which are in fact well captured by the correlation. Hence, from these encouraging results one can infer that the dimensional analysis preformed here is indeed a suitable way to determine a more general correlation, which can incorporate several different boiling configurations. Nevertheless, it is worth noting that this was a preliminary approach, which requires a deeper research, within a wider range of conditions.

![Fig.11. Evaluation of the dimensional based correlation for Water, Ethanol, HFE7000 and FC 72.](image)

4. Conclusions

The present paper proposes correlations to predict the pool boiling heat transfer coefficient for the pool boiling of various fluids over micro-patterned silicon wafer surfaces, following two approaches. The first consists in determining a modified Rohsenow correlation. Emphasis was given to the introduction of a geometric parameter, which could accurately describe the typology of surfaces used in the experiments. The correlation devised was able to predict the pool boiling heat transfer coefficient for various liquid surface combinations tested, including additional data reported in the literature, within an error of ±20%.

In a second approach, an original relation was devised based on dimensional analysis. The final relation proposed in this approach was able to predict the pool boiling heat transfer coefficient for the various liquid surface combinations (and also the data reported in the literature) within an error of ±30%. Furthermore, this final correlation could predict the behaviour of fluids with significantly different thermo physical properties. Hence, despite this is still a preliminary work, the results are encouraging to evaluate the devised correlation within a wider range of conditions.

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References


