An Overview of Surface Roughness Effects on Nucleate Boiling Heat Transfer

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Abstract: The paper aims at an overview of heating surface microstructure effects on nucleate boiling heat transfer. A comprehensive chronological literature survey is presented followed by an analysis of the results of an experimental investigation. Boiling data of refrigerants R-134a and R-123 on 19 mm diameter copper and brass tubes of average surface roughness varying from 0.07 µm to 10.5 µm have been gathered under the present investigation. Though most of the data confirm previous literature trends, according to which the heat transfer coefficient increases with surface roughness, very rough surfaces present a peculiar behavior with respect to that of the smoother surfaces (Ra<3.0 µm). Heat transfer performance of very rough surfaces is superior to the smoother ones at low heat fluxes ($q<20$ kW/m^2). However, decay in their thermal performance is observed in the high heat fluxes range. An in depth analysis of the effect of roughness on the slope, "m" of the h vs q curves has been performed with a general conclusion being that "m" is affected not only by de pressure but also by the surface roughness. Finally, an analysis of the active cavities density is performed using some models from the literature in order to evaluate the effect of surface roughness in cavity activation. The obtained results are generally inconclusive. However, it has been determined that surface microstructure effects must not be neglected in future models.

Keywords: Nucleate boiling, roughness, active cavities.

INTRODUCTION

Nucleate boiling heat transfer is affected by several physical parameters such as surface geometry, finish, cleanness and orientation, type of liquid and its wettability, surface material and its thickness, and gravity. Several studies have found that aging of the heating surface can also affect the nucleate boiling thermal performance [1-3]. The effect of the heating surface microstructure on nucleate boiling heat transfer has called the attention of the scientific community as early as the thirties, when the first pioneering studies were being carried out. The need to understand the effect of the surface condition was apparent in the early models of nucleate boiling and boiling inception [1, 4-7]. This is reasonable since the rate of heat transfer is closely related to the bubble population. Thus raising information related to the activation mechanism of the heating surface cavities seems a reasonable first step in understanding the nucleate boiling phenomenon. The research performed by Corty and Foust [1] in the mid fifties of the last century is one of a long list of experimental investigations aiming at understanding and evaluating the effects of the surface microstructure. However, despite being exhaustively studied, the relation between active cavities and the surface microstructure is one of the key unsolved issues in the prediction of nucleate boiling heat transfer, as pointed out by Dhir [8] and Yagov [9].

The present paper will focus on the analysis of the effect of the surface roughness on nucleate boiling heat transfer. For that purpose, initially a comprehensive review of the literature will be addressed followed by an analysis of experimental results with refrigerants R-123 and R-134a, low and medium pressure refrigerants, boiling on horizontal cylindrical surfaces with average roughness in the range between 0.07 µm and 10.5 µm.

LITERATURE SURVEY

The literature related to the surface structure effects on nucleate boiling heat transfer can be divided into two main approaches: (1) an overall heat transfer analysis focusing on the surface roughness effects; and (2) investigation of the surface microstructure and its relation with the active sites density. The survey preformed herein will focus on the former approach, though references to the second one will be used whenever needed for explanation and/or analysis purposes.

Corty and Foust [1] performed an experimental study of nucleate boiling of refrigerant R-113, diethyl ether, and n-pentane on a horizontal copper surface. Their experiments constitute one of the firsts to evaluate the effect of the surface roughness along with the contact angle, measured through photographs of the boiling surface. These pictures also allowed the counting of the active sites. The rms[1]

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[1] The "Root Mean Square" is defined as the square root of the average of the square of the profile deviation. The average roughness, Ra, is defined as the average deviation of the profile with respect to the average (center) line. The Rp roughness is the deviation of the highest peak of the profile over the sampling length.

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roughness of the heating surface varied in the range between 0.150 μm and 0.575 μm whereas the measured contact angle varied from 45° to 60°. The Corty and Foust results indicate that the heat transfer coefficient increases with the superheating of the wall which in turn affects the number of active centers. It could also be noted a close relationship between the slope shift of the h vs ΔT_{sat} and the N vs ΔT_{sat} correlations. The results of the Corty and Foust investigation regarding the surface roughness effect over the rate of heat transfer can be illustrated by the 86.4 % decrement of the wall superheat when the rms roughness varied from 0.150 μm to 0.575 μm for a constant heat transfer coefficient of 5,675 W/m^2K. It must be noted that the Corty and Foust experiments involved relatively smooth surfaces.

Kurihara and Myers [10] performed thorough boiling experiments on flat horizontal copper surfaces. Experiments were carried out with such liquids as water, acetone, carbon tetrachloride, n-hexane, and carbon disulfide. Roughness of the surfaces varied from 4-0 emery paper to 140-mesh carborundum. The general observed trend was that the rate of heat transfer increases with the surface roughness. Kurihara and Myers [10] suggest that, whereas the slope of the h vs ΔT_{sat} curve increases with roughness, the surface roughness presents a limit on the effect over the rate of heat transfer. The proposed limit is 0.762 μm (30 μinch) rms. Finally, according to Kurihara and Myers, the boiling heat transfer coefficient is approximately proportional to $N^{1/3}$.

In his comprehensive experimental study involving polished surfaces (mirror finish) and different mesh sizes scaled (sand paper treated, E 60, E 320 and lap) surfaces, Berenson [11] suggested that the heat transfer coefficient could be incremented 600% by roughening the heating surface. He claimed that surfaces with higher roughness present higher nucleate boiling heat transfer coefficient due to higher active cavity density.

The well known Rohsenow correlation [12], originally conceived to take into account the liquid-surface combination and the pressure over the rate of heat transfer in nucleate boiling, has the following general expression:

$$\frac{c_{pf}\Delta T_{sat}}{h_{fg}} = C_{sf}\left\{\frac{q}{h_{fg}\cdot\mu_f}\cdot\left[\frac{\sigma}{g\cdot\left(\rho_f-\rho_g\right)}\right]^{1/2}\right\}^{r}\left(Pr_f\right)^{s} \tag{1}$$

Equation (1) is the typical heat convection correlation with the left hand side being the inverse of a local Stanton number, the first term of the right hand side is a "bubble" Reynolds number, and the second, the liquid Prandtl number. C_{sf} is the liquid-surface combination coefficient and the exponents "r" and "s" were supposed to take into account pressure effects. The value proposed by Rohsenow for the exponent "r" was 0.33. The exponent of the liquid Prandtl number, Pr_f, varies in the range between 0.8 and 2.0, though originally Rohsenow attributed to it the value 1.7. Later on, Rohsenow suggested that this value should be changed to 1.0 for water. Vachon *et al.* [13] performed a comprehensive investigation of the so-called 'constants' of the Rohsenow correlation through data from different sources. The investigation involved several liquid-surface combinations and such a surface preparation techniques as: polishing and grinding; chemical etching; artificial scoring and pitting, lapping, and coating. In addition, all the data available to Vachon *et al.* [13] were taken under atmospheric pressure and normal gravity conditions. Vachon *et al.* [13] performed two kind of curve fitting of the available experimental results: (1) determining the liquid-surface coefficient by keeping constant and equal to 0.33 the exponent "r"; and (2) by varying both C_{sf} and "r". Their conclusion was that both, C_{sf} and "r" were affected not only by the liquid-surface combination but by the surface preparation as well. However, this conclusion neither takes into account pressure nor explicit roughness effects. Recently, Saiz Jabardo *et al.* [14] curve fitted their own experimental results of refrigerants R-11, R-123, R-12, and R-134a boiling on cylindrical copper, brass, and stainless steel surfaces at several reduced pressures and surface average roughness, Ra, varying between 0.08 μm and 3.30 μm. Following an analysis similar to that of Vachon *et al.* [13], they obtained the following values for exponents "r" and "s": 0.18 and 1.03. In addition, it was determined that the surface roughness affects the liquid-surface coefficient, C_{sf}, according to the following fitted expression:

$$C_{sf} = C\left\{\left[a\ln\left(Ra\right)-b\right]p_r - c\ln\left(Ra\right)+d\right\} \tag{2}$$

The coefficients "a", "b", "c", and "d" were found to be independent of the fluid and heating surface roughness and material, assuming the following values for data corresponding to heat fluxes higher than 5 kW/m^2: 0.0064; 0.00188; 0.00320; and 0.0110. The coefficient "C" is indeed a surface-liquid combination parameter, with values varying in the range between 0.95 and 1.30 [14].

Kozitskii [15] obtained results from n-butane boiling on electrically heated stainless steel tubes with average roughness varying from 0.03 μm to 1.31 μm. For pressures of 4.9 bar (p_r=0,129) and 12.6 bar (p_r=0,332), Kozitskii observed that the heat transfer coefficient increases up to an average roughness of 0.95 μm, diminishing for Ra equal to 1.31 μm. The relationship between the heat transfer coefficient and the heat flux is generally written as:

$$h = C_1 q^m \tag{3}$$

According to Kozitskii, "m" is slightly affected by the surface roughness, Ra, varying between 0.8 and 0.72 for the range of Ra values of his investigation. Kozitskii [15] assumes "m" constant and equal to 0.7 in his nucleate boiling heat transfer correlation. In addition, based on his own data, Kozitskii [15] suggests the following correlation for the coefficient of Eq. (3) in terms of the surface average roughness:

$$C_1 = C_2 Ra^n \tag{4}$$

Where "n" is given by the following reduced pressure dependent expression:

$$n = 0.13 p_r^{-0.17} \tag{5}$$

Nishikawa *et al.* [16] performed a comprehensive experimental study of boiling of several refrigerants (R-11; R-21; R-113; and R-114) over horizontal/flat copper surfaces of surface roughness, Ra, varying from 0.0088 μm to 1,724 μm (originally, in the paper, Rp roughness varying between 0.022 μm and 4.31 μm). Nishikawa *et al.* argued that rough surfaces present a wider range of cavity radius than smoother ones. This would explain the observed heat transfer coefficient increment with surface roughness. On the other hand, according to these authors, the relative difference in the number of active cavities between rough and smooth surfaces diminishes with pressure. Thus the effect of surface roughness diminishes with pressure, a result that has been confirmed by a subsequent investigations as will be seen further on in this paper. Nishikawa *et al.* [16] suggest that the nucleate boiling heat transfer coefficient varies with the Rp surface roughness according to the following proportionality expression:

$$h \propto Rp^{(1-p_r)/5} \tag{6}$$

Roy Chowdhury and Winterton [17] carried out quenching experiments with water and methanol on copper and aluminium vertical cylindrical surfaces of Ra roughness varying between 0.25 μm and 4.75 μm. The experiments also involved effects of the contact angle, which varied from very small values to values of the order of 70°. Roy Chowdhury and Winterton results confirmed qualitatively results from Nishikawa *et al.* [16], according to which roughness increments the heat transfer coefficient. However, they added that comparisons should be performed only among surfaces submitted to the same treatment, since the procedure could significantly affect the heat transfer coefficient. Based on their results, Chowdhury and Winterton [17] concluded that wetting liquids present better thermal performance.

Benjamin and Balakrishnan [18] conducted experiments with several fluids, including water, n-hexane, acetone, and carbon tetrachloride boiling on aluminium and stainless steel surfaces with average roughness varying form 0.20 μm to 1.17 μm. Benjamin and Balakrishnan [18] also determined the density of active cavities as a function of the wall superheating. Their results displayed an interesting behavior, with the density of active cavities and the heat flux increasing and diminishing with the average roughness of the surface, the extent of this behavior being dependent on the particular fluid. Based on their own results and data from other sources, Benjamin and Balakrishnan [18] proposed the following general correlation for the density of active cavities:

$$N = 218.8\left(Pr_f\right)^{1.63}\left(\frac{1}{\gamma}\right)\Theta^{-0.4}\left(\Delta T_{sat}\right)^{3} \tag{7}$$

Θ is a roughness dimensionless parameter, expressed in terms of the average roughness, the pressure, and the surface tension as follows:

$$\Theta = 14.5 - 4.5\left(\frac{pRa}{\sigma}\right) + 0.4\left(\frac{pRa}{\sigma}\right)^{2} \tag{8}$$

γ is a dimensionless parameter that takes into account the so called surface material-liquid interaction, defined as:

$$\gamma = \sqrt{\frac{\rho_w k_w c_w}{\rho_f k_f cp_f}} \tag{9}$$

Caution must be exercised when using the correlation by Benjamin and Balakrishnan [18], Eq. (**7**), since it has been raised from a data set involving a limited range of physical parameters and fluid-surface combination.

Kang [19] carried out experiments with water at atmospheric pressure on vertical and horizontal cylindrical stainless steel surfaces. Kang tested smooth surfaces with two values of the average roughness: 0.0151 μm (smooth) and 0.0609 μm (rough). As in some of the previous investigations, Kang [19] concluded that the heat transfer coefficient increases with the surface roughness, the increment being more significant for vertical surfaces as compared to the horizontal ones. Sharma and Hara [20] performed an experimental investigation with a 95% ethylene glycol/water solution boiling on shot-peened aluminium horizontal flat surfaces. The obtained results display a significant increment of the heat transfer coefficient with the average roughness up to a value of the order of 6.5 μm, diminishing for higher surface roughness. Hahne and Barthau [21] performed nucleate boiling heat transfer tests on horizontal tubes for R-134a and R-114. They obtained experimental results on a gold plated copper tube (D=15mm, Ra=0.30 μm), on emery ground copper tubes (D=8 and 15mm, Ra=0.52 and 0.40 μm, respectively), and on a stainless steel sandblasted tube (D=15mm, Ra=0.18 μm). Lower heat transfer coefficients on the upper region of the tube were observed with the difference becoming negligible at high reduced pressures. The wall temperature variation along the tube circumference becomes steeper as the tube thermal conductivity is diminished. Such a behavior had also been previously pointed out by Ribatski *et al.* [22] based on their results for R-11 on copper and stainless steel tubes for heat fluxes up to 40 kW/m^2. Ribatski *et al.* [22] noticed an opposite trend at higher heat fluxes, with higher heat transfer coefficients on the upper region of the tube. Hahne and Barthau [21] and Ribatski *et al.* [22] obtained lower heat transfer coefficients for stainless tubes. According to Hahne and Barthau [21], gold-plated and sandblasted copper tubes provided higher heat transfer coefficients than the emery ground copper tube at the reduced pressure of 0.5, while their performance were similar at the reduced pressure of 0.1. Recently, Pioro *et al.* [23] performed an extensive review involving the effect of the heating surface parameters on nucleate boiling heat transfer. They stressed the fact that surface roughness may affect the heat transfer coefficient only in case that the change in the surface roughness is within the range of the diameter of the active bubble centers. Consequently, the creation of larger cavities filled with liquid would not change the heat transfer coefficient as in case of grooves which, according to the authors, are ineffective vapor traps unless they are very poorly wetted. Pioro *et al.* [23] cite a Russian study according to which, the heat transfer coefficient increases with surface roughness up to a maximum. Surface roughness does not affect boiling heat transfer beyond that maximum.

Gorenflo and co-workers have carried out a multi-year research involving several aspects of nucleate boiling, including such effects as the liquid, pressure, material, and surface finishing. Several refrigerants have been tested including such hydrocarbons as propane and butane. The results of the investigation have been published in several papers; two of them will be referred to here [24, 25], along with two by Luke [26, 27]. As expected, their results have shown that the heat transfer coefficient increases with the surface roughness. In addition, they claim that higher differences on surface superheat at the onset of nucleate boiling are related to differences in the maximum cavities size of the surfaces. On the other hand, lesser differences in the minimum cavities size of the tested surfaces correspondingly determine lesser differences in the surface superheating in the high heat flux range, and, as a result, closer heat transfer coefficients for surfaces of different roughness. Luke [26] showed that the standard two-dimensional characterization of the surface is not effective and a complete understanding of the link between the surface microstructure and the evaporating process is needed. This might be accomplished by considering the distribution of cavities using a three-dimensional approach to the surface characterization. Luke [26, 27] combined the stylus technique with the near field acoustic microscopy to characterize the three dimensional microstructure of copper (8 mm diameter) and mild steel (35.8 mm diameter) tubes. The results were used to determine the density of potential active sites. The content of the first paper was enlarged and enhanced in the subsequent paper by Luke [27]. In addition, Luke [26] carried out tests of propane boiling on copper and stainless steel tubes. Emery grounding and fine and rough sand blasting were used to roughen the tubes, obtaining the following average roughness, Ra: 0.20 μm (SS, emery ground); 0.16 μm (SS, fine sand blasted); 1.00 μm (SS, medium sand blasted); 11.6 μm (SS, rough sand blasted); and 0.34 (copper, emery ground). Luke [26] proposed a correlation for the explicit dependency of the heat transfer coefficient on the average surface roughness with the following general form:

$$h \propto Ra^{d-e\ln(p_r)} \tag{10}$$

In addition to include this explicit roughness dependence, Luke [26], as mentioned above, based on experimental data for propane boiling on copper and mild steel tubes of average roughness up to 11.3 μm, suggested that the slope "m" of the h vs q correlation is also affected both by the reduced pressure and the average roughness according to the following general expression:

$$m = a - bp_r^{0.37} + \frac{c}{1 + 200\left(Ra / Rao\right)^{10}} \tag{11}$$

According to DIN 4768, Rao=0.5 μm. The coefficients "a", "b", "c", "d", and "e" must be obtained by curve fitting experimental results.

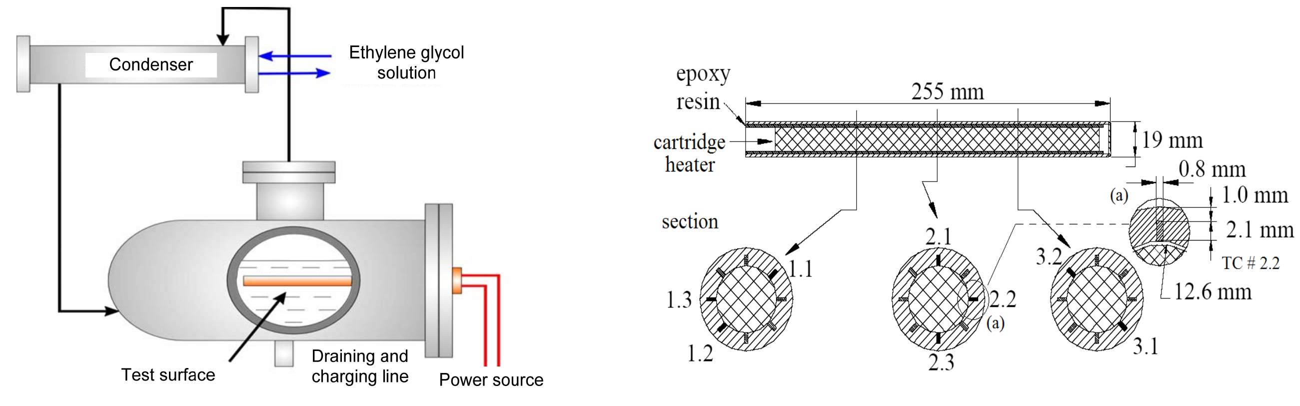
In the preceding paragraphs an overview has been presented of the nucleate boiling heat transfer literature related to the "macro" approach to the effects of the surface roughness. Two general conclusions can be drawn: (1) the surface roughness tends to increment the heat transfer for other parameters kept constant, though there seems to be a limit beyond that, the roughness either does not affect or even tends to diminish heat transfer; (2) despite recent investigations searching for a relationship between macro behavior and the three dimensional microstructure of the surface, results are still sketchy, since parameters such as liquid wettability might play a role as Roy Chowdhury and Winterton [17] and Wang and Dhir [28] suggest. The latter conclusion is strongly related with nucleation and active site density, two aspects that have been intensely investigated in the past but still not well understood [29].

EXPERIMENTAL SET UP

The experimental set up comprises the refrigerant and cooling circuits, as shown in Fig. (**1a**). The charge of refrigerant is basically contained in the boiler in which the liquid is kept at a reasonable level above the test surface (tube) so that the column head does not affect significantly the equilibrium saturation temperature. The cooling circuit is intended to control the equilibrium pressure in the boiler by condensing the refrigerant boiled in the heating surface. The condensing effect is obtained by a 60% solution of ethylene glycol/water that operates as intermediate fluid between the condenser and the cooling system not shown in Fig. (**1a**). The ethylene glycol/water solution is cooled by either a refrigeration circuit or water from a cooling tower, depending on the operating pressure. This solution is intended to operate in the range between –26°C and 90°C.

The boiler is a 40 liters carbon steel container with two lateral circular windows for visualization. It contains the boiling surface in addition to a 1500W/220V electrical cartridge heater, installed at the bottom, and two sheathed type T thermocouples located above and below the test surface. The test (boiling) surface is placed in the middle of the boiler so that the boiling mechanism can easily be visualized through the glass windows. It is made up of a 19.0 mm diameter and 3.1 mm thick tube, a longitudinal cut way view of it is shown in Fig. (**1b**). The test tube is supported by a brass piece which is thread attached to the flanged cover of the boiler. The boiling surface is heated by a 12.6 mm diameter and 210 mm long cartridge electrical heater. The electrical power to the boiling surface is controlled by a manually operated voltage converter and measured by a power transducer. Surface temperature is measured through eight 30 AWG type T thermocouples installed in grooves carved by an electro erosion process in locations indicated in Fig. (**1b**).

The heat transfer coefficient has been evaluated by the Newton's cooling law:



(a) (b)

Fig. (1). (**a**) Schematic diagram of the boiler; (**b**) cut-away view of the test tube and surface thermocouples locations.

$$h = \frac{q}{\Delta T} \qquad (12)$$

where ΔT stands for the surface superheating, that is, $\Delta T = T_W - T_{sat}$. The saturation temperature, T_{sat}, was determined as the average of the readings of the two pool sheathed thermocouples. The average of the pool thermocouples reading should be within 0.2 K of the saturation temperature corresponding to the boiler pressure transducer.

Instruments were calibrated and the uncertainty of measured and calculated parameters evaluated according to the procedure suggested by Abernethy and Thompson [30] with results summarized in Table **1**. Additional information regarding the experimental set-up and procedures can be found in Stelute [2], Ribatski [31], and Saiz Jabardo *et al.* [32].

Table 1. Uncertainty of Measured and Calculated Parameters

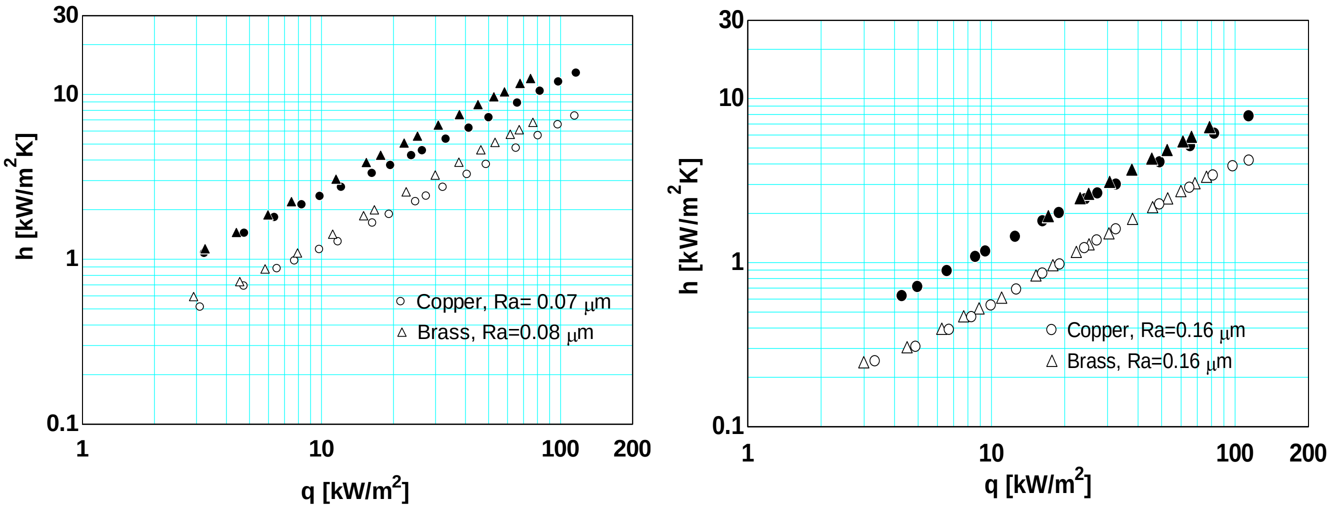
Parameter	**Uncertainty**
Minimum heat flux, q = 0.60 kW/m^2	± 1.8%
Maximum heat flux, q = 120 kW/m^2	± 0.3%
Heat transfer area	± 0.3%
Heating surface temperature	± 0.2K
Saturation temperature (bath)	± 0.2K
Superheating of the heating surface	± 0.3K
Heat transfer coefficient, minimum uncertainty	± 1.3%
Heat transfer coefficient, maximum uncertainty	± 20.3%

EXPERIMENTAL RESULTS AND ANALYSIS

Experiments have been carried out on copper, brass and stainless steel tubes of several diameters, though only data for tubes of 19.0 mm external diameter will be presented. Several refrigerants have been tested under the research program. In this paper only data for refrigerants R-123 (low pressure) and R-134a (medium pressure) will be analysed. The cylindrical surfaces have been treated by several processes in order to obtain different degrees of roughness: polishing (P), scaling with sand paper (SP), and shot peening (SPI) with both controlled size glass beads, up to Ra=3.30 µm, and sand blasting, for the higher values of Ra (4.60 µm and 10.5 µm).

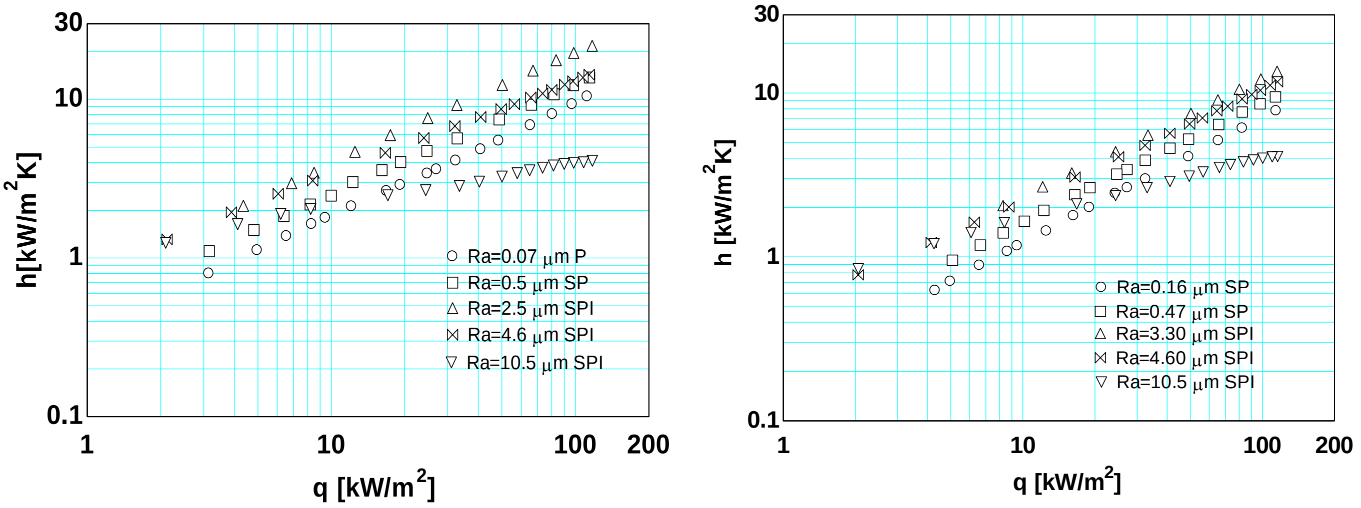
Pressure and liquid effects on nucleate boiling heat transfer are clearly reproduced in Figs. (**2a**) and (**b**) where data from refrigerants R-134a and R-123 boiling on copper and brass tubes are plotted in a h vs q plot. As expected, heat transfer increases with pressure. Differences in heat transfer in the case of refrigerant R-123 boiling on copper and brass tubes are minimal. However, this is not the case for refrigerant R-134a, in which case differences in thermal performance, though small, clearly indicate that brass performs better than copper for the range of pressures (reduced, dimensionless) and relatively small roughness of Figs. (**2a**) and (**b**). It can be noted that copper and brass heat transfer differences increase with the heat flux, reaching values relative to the copper of the order of 30% at the highest heat flux. This result might be related to the different wetting characteristics of the refrigerant R-134a with respect to both heating surface materials.

The roughness effects are clearly shown in Figs. (**3a**) and (**b**), where data corresponding to refrigerants R-134a and R-123 boiling on copper tubes of different average surface roughness, Ra, are plotted on an h vs. q plots. The range of the average surface roughness, Ra, in these plots is relatively wide, since it varies from 0.07 µm for R-134a and 0.16 µm for R-123 to 10.5 µm. The latter roughness corresponds to a rough surface not typical of applications. Large values of Ra have been used to explore the effect of roughness on nucleate boiling heat transfer. The microstructure of the heating surface was evaluated in terms of the two-dimensional profile, the probability distribution density of the profile and its spectrum for average roughness up to 3.30 µm [24]. Microstructure characteristics of the rougher surfaces (Ra=4.6 µm and 10.5 µm) was not determined.



(a) (b)

Fig. (2). Plots of h vs q for boiling on copper and brass tubes. (**a**) Refrigerant R-134a, polished surfaces, p_r=0.063 and 0.260, Ra=0.07 µm and 0.08 µm; (**b**) Refrigerant R-123, scaled surfaces, p_r=0.011 and 0.092, Ra=0.16 µm. Symbols: Blank: lower pressure; blackened: higher pressure.



(a) (b)

Fig. (3). Effect of the surface roughness on a h vs q plot for refrigerants boiling on copper tubes. (**a**) Refrigerant R-134a; p_r=0.177; (**b**) R-123; p_r=0.092.

Trends observed in Figs. (**3a**) and (**b**) agree with those of the literature, at least qualitatively. It can be noted that, in general, the heat transfer coefficient increases with surface roughness up to values of Ra of the order of 3.0 µm (2.5 µm for R-134a and 3.3 µm for R-123). The slope of the h vs q curve diminishes with the average roughness in this range. Beyond that limit, Ra>3.0 µm, the slope diminishes significantly with roughness, reaching a rather low value for Ra=10.5 µm. The slope trends will be discussed further on. As mentioned before, such behavior has already been observed in the literature. Berenson [11] and Nishikawa *et al.* [16] data clearly show that the slope of h vs q curve diminishes with the average roughness of the surface. Kozitskii [15], though having tested surfaces with relatively low values of Ra (Ra≤1.17 µm), observed a limit in the heat transfer increment with surface roughness and a similar trend with the slope. Benjamin and Balakrishnan [18] observed heat transfer increments and reductions as the surface roughness increases. Benjamin and Balakrishnan [18], as in the case of Kozitskii [15], investigated surfaces of a relatively low values of Ra as compared with those considered in the present study. Luke [26] tested tubes with surface roughness up to 11.6 µm, obtaining similar qualitative results as in the present investigation. Luke data presented a clear reduction in the slope of the h vs q curve with the surface roughness, though the heat transfer coefficient increased with Ra even for the highest values of the heat flux, a trend that has not been observed in the present investigation. In fact, as Figs. (**3a**) and (**b**) clearly show, in the range of high heat fluxes, q>10 kW/m^2, the heat transfer coefficient tends to diminish with the average roughness beyond the aforementioned maximum of the order of 3.0 µm.

Nucleate boiling heat transfer increases with the density of active cavities (number of active cavities per unit of area). The number of cavities available for activation tends to increase with the increment of surface roughness what in turn allows for the increment of the active cavities density. However, as suggested by Pioro *et al.* [23], very rough surfaces might present large cavities filled with liquid and, as a result, will not act as active bubble centers. That is certainly the case of the higher average roughness data of the present results displayed in Figs. (**3a**) and (**b**). The characteristics of the surface microstructure must be such that smaller cavities activated at higher heat fluxes (higher wall superheat) are not as numerous as on smoother surfaces, what explains the observed reduced rate of heat transfer. On the other hand, large cavities related to lower heat fluxes are available on the rougher surface in a greater number what causes a higher heat transfer rate than that for the smoother surfaces. Similar arguments have been used by Gorenflo *et al.* [25] to explain the reduction in the slope of the h vs q curve with the surface roughness.

Nucleate boiling heat transfer correlations can generally be expressed by an equation of the type of Eq. (3), where the exponent of the heat flux, "m", is the slope of the h vs q curve. Some characteristics of this slope have been addressed in the preceding paragraphs. One of them is that it depends on the surface roughness as well as the reduced pressure, as expressed by Eq. (11), proposed by Luke [26]. Gorenflo [33] suggests the following expression for the exponent "m" that includes only the effect of the reduced pressure:

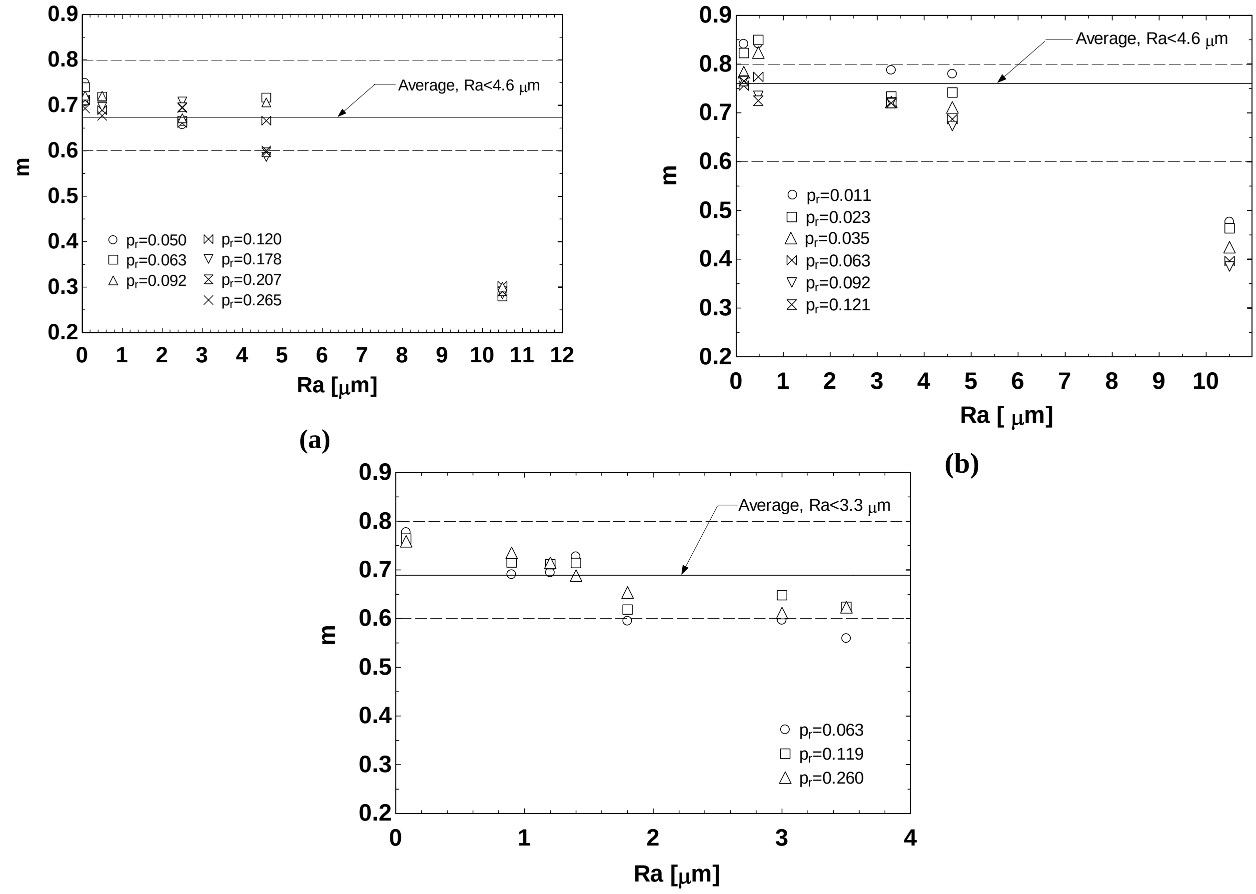
$$m = 0.9 - 0.3 p_r^{0.3} \qquad (13)$$

Ribatski and Saiz Jabardo [34], based on their own experimental results, proposed to substitute the exponent 0.3 of the Gorenflo's correlation by 0.2. As mentioned before, other researchers proposed a constant "m" such as 0.70 by Kozitskii [15], 4/5 by Nishikawa *et al.* [16], and 0.67 by Cooper [35]. In general, the exponent "m" has been attributed values in the range between 0.6 and 0.8.

Data of the investigation reported here in have produced values of the exponent "m" as indicated in Figs. (**4a-c**). The typical literature range has been overlaid in these plots as broken lines along with the continuous line that corresponds to the experimental average "m" for surface roughness lower than 4.6 μm. The following are general conclusions drawn from the plots of Figs. (**4a-c**).

(1) As previously indicated, "m" diminishes with the surface average roughness.

(2) The slope "m" for Refrigerant R-134a boiling on copper surfaces, Fig. (**4a**), are generally lower than those of R-123, Fig. (**4b**).



(a)

(b)

(c)

Fig. (4). Variation of the slope of the h vs q curve, "m", with the average surface roughness, Ra. (**a**) R-134a-copper; (**b**) R-123-copper; (**c**) R-134a-brass.

(3) The average value of "m" for the range of roughness lower than 4.6 μm, Fig. (**4a**) for refrigerant R-134a, is of the order of 0.670, similar to the one proposed by Cooper [35]. The average "m" is of the order of 0.76 in the case of refrigerant R-123.

(4) The range of "m" values is within the literature range (0.6 – 0.8) for surface roughness lower that 4.6 μm. Values of "m" for low surface roughness are slightly higher than the upper limit of the literature range (0.8) for refrigerant R-123.

(5) "m" is significant lower for very rough surfaces, reaching values of the order of 0.3, as in the case of average roughness of 10.5 μm.

(6) The average "m" for R-134a-brass combination, (Fig. **4c**), corresponding to a range of average roughness lower than 3.3 μm, is of the order of 0.689, which is close to the average value of R-134a-copper (0.670).

(7) The range of reduced pressures of the present investigation is generally limited to relatively low values. The general trend of the slope "m" with regard to the reduced pressure effect is shown in Figs. (**5a**) and (**b**), which corresponds to the same data of the plots of Figs. (**4a**) and (**b**). The correlations by Gorenflo [33] and Ribastki and Saiz Jabardo [34] are overlaid in these plots. Generally, "m" tends to diminish with the reduced pressure, a result that confirms trends suggested in the literature. The aforementioned equations for "m" correlate adequately results of the present study at least in the range of low surface average roughness. However, these correlations are not recommended for very rough tubes.

(8) From the preceding paragraphs one can conclude that the surface roughness affects the slope "m". As a result, expressions such as the one proposed by Luke [26], Eq. (11), seem more adequate to correlate the exponent "m".

ACTIVE CAVITIES DENSITY

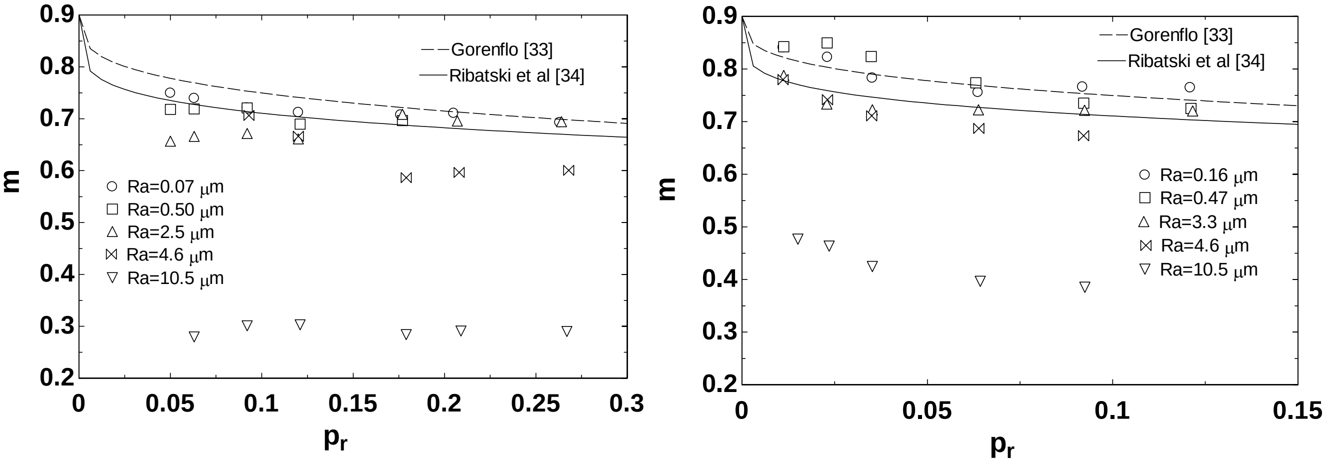
In the preceding paragraphs an analysis of the surface roughness on the nucleate boiling heat transfer was performed. It would be interesting at this point to investigate the relationship between the surface roughness and the density of active cavities provided by models from the literature since in the present investigation a direct count of them has not been performed. The model by Mikic and Rohsenow [36] will be initially considered. The model is based on the assumption that the number of cavities of radius larger than "r" (also designated by "cumulative density") can be approximated by the following expression:

$$N = C_1\left(\frac{r_s}{r}\right)^{m_1} \tag{14}$$

In the present approach it will be assumed that all the heat transferred at the wall is related to the nucleate boiling mechanism (s). Single-phase convection contribution is neglected. As a result, the Mikic and Rohsenow model can be reduced to the following correlation:

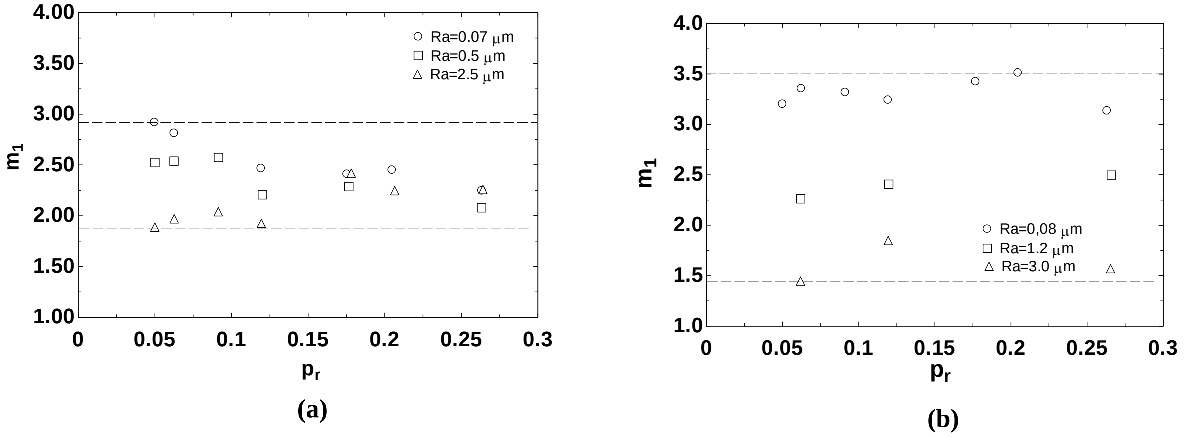
$$\frac{q\sqrt{\dfrac{\sigma}{g\left(\rho_f-\rho_g\right)}}}{\mu_f h_{fg}} = B\left(\varphi\Delta T_{sat}\right)^{m_1+1} \tag{15}$$

"φ" is a complex function of the liquid and vapour transport properties, ΔT_{sat} the superheating of the wall, and B a numerical coefficient. Experimental data can be reduced to the dimensionless parameters of Eq. (15) in such a way to allow for the determination of the exponent "m_1" of Eqs. (14) and (15). The variation of the exponent "m_1" with the reduced pressure for different surface roughness is shown in Figs. (**6a**) and (**b**) for refrigerant R-134a boiling on copper and brass tubes, respectively. The broken lines have been overlaid to indicate the range of variation of the exponent "m_1". It can be noted that, roughly, the range varies between 1.75 and 2.80 for copper and 1.4 and 3.5 for brass. The results displayed in Figs. (**6a**) and (**b**) do not show a clear trend regarding the effect of the reduced pressure over the value of "m_1". However, "m_1" clearly diminishes with the average roughness for both surface materials. Mikic and



(a) (b)

Fig. (5). Data of Figs. 4 (**a**) and (**b**) plotted in terms of the reduced pressure. (**a**) R-134a-copper; (**b**) R-123-copper.



(a)

(b)

Fig. (6). Variation with the reduced pressure of the exponent "m" of the Mikic and Rohsenow [35] model for the density of active cavities for refrigerant R-134a boiling on (**a**) copper; and (**b**) brass tubes.

Rohsenow [36] assumed "m_l" as being equal to 2.5 for water and 3.0 for n-pentane and ethyl alcohol, values which are within the range obtained in the present study. It is straightforward to show that the exponent "m_l" is related to the exponent of the h vs q curve, "m", by the following relationship:

$$m = \frac{m_1}{m_1 + 1} \tag{16}$$

Thus, the range of "m_l" values of Figs. (**6a**) and (**b**) are compatible with the previously introduced values of the exponent "m" of the h vs q relationship.

Wang and Dhir [28], for water at atmospheric pressure boiling on vertical copper surfaces, obtained an active site density correlation similar to Eq. (13), with the exponent "m_l" being equal to 6.0, a value which is significantly higher than those from the present investigation. Wang and Dhir [28] reported tests with contact angles equal to 18°, 35°, and 90°. According to that investigation, no effects of the contact angle on the exponent "m_l" were noticed though it affects the proportionality coefficient.

According to the model proposed by Benjamin and Balakrishnan [18], the active cavity density is proportional to $(\Delta T_{sat})^3$ (see Eq. 7) from which it can be concluded that "m_l" is equal to 3.0. As in the case of the Wang and Dhir model [28], the proportionality coefficient depends on the contact angle in addition to other physical parameters.

Kolev [37] suggested the following correlation for the active site density:

$$N = \frac{4.29}{(2\beta)^2} \lambda_{RT}^2 \left[\frac{h \Delta T_{sat}^{n-1}}{k_f Ja^{1/2}} \right]^4 \tag{17}$$

where

$$\lambda_{RT} = \left[\sigma / g(\rho_f - \rho_g) \right]^{1/2};$$

$$\beta = 25.3 \cos(\theta/2) / \left[(1 + \cos\theta)^2 (2 - \cos\theta) \right];$$

$$Ja = (\rho_f / \rho_v)(c_{pf} \Delta T_{sat} / h_{fg})$$

In the preceding equations, "h" is the heat transfer coefficient as determined form the Newtons's Cooling Law, and "Ja" is the Jakob number referred to the superheat of the wall. Data from the present investigation have been used to plot the active cavities density from the Kolev correlation in terms of the equilibrium cavity radius, defined according to the following expression:

$$r = \frac{2\sigma T_{sat}}{\rho_g h_{fg} \Delta T_{sat}} \tag{18}$$

The plot of Fig. (**7**) illustrates the results for refrigerant R-134a boiling on copper surfaces for all the reduced pressures tested in the present investigation. According to Vadgama and Harris [38], the contact angle, θ, of refrigerant R-134a on copper surfaces is of the order of 6°, a value that has been used in applying the Kolev correlation to the present results. The plot of Fig. (**7**) clearly indicates that the active cavities density increases with the surface roughness. This result should be expected since the data of this plot correspond to surface roughness lower than 3.0 μm. Data points have been fitted by power curves which are overlaid in the plot. The resulting slopes, corresponding to the exponent "m_l", for increasing average roughness are equal to: 6.748; 5.091; 4.609. The observed trend is that the slope "m_l" diminishes with the average roughness. The range of values related to data of Fig. (**7**) is compatible with that of Wang and Dhir [28], though significant higher than the ones from the Mikic and Rohsenow [36] model.

CONCLUSIONS

The present paper has stressed the effects of the surface roughness on the nucleate boiling heat transfer from a "macro" point of view. Data from an experimental investigation with refrigerants R-123 and R-134a boiling on copper

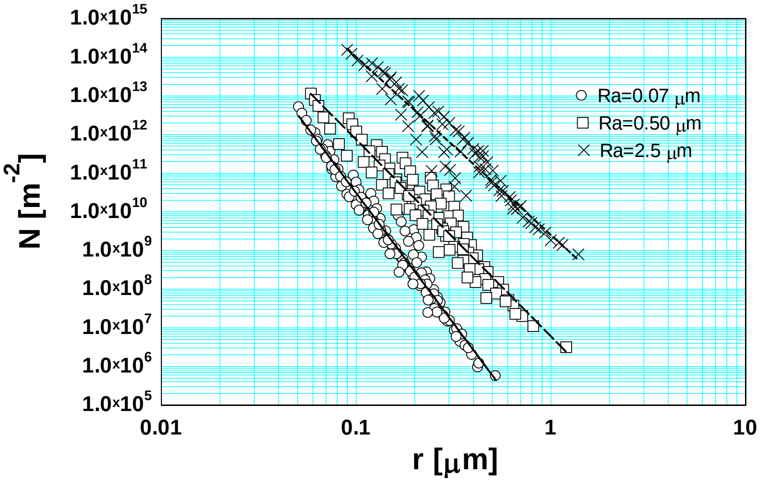


Fig. (7). Active cavity density variation with "r" according to Kolev's model [36]. Refrigerant R-134a; copper tubes; reduced pressures varying from 0.05 to 0.260.

and brass tubes have been used to support arguments in an analysis of the effects of the surface roughness. The literature review revealed common and general qualitative trends regarding the effect of the surface roughness on nucleate boiling heat transfer though an adequate and general correlation is still to be developed. It has been determined that there is a limit in the increment of heat transfer with the surface roughness.

As a closing remark it should be stressed that future research involving the effect of the heating surface condition on boiling heat transfer must focus on two main aspects: (1) characterization of the surface microstructure and its relationship with the treatment procedure; (2) devise a relationship between the surface microstructure and the active cavity density.

NOMENCLATURE

c = Specific heat

c_p = Specific heat at constant pressure

C_{sf} = Fluid-surface coefficient, Rohsenow correlation

g = Gravity acceleration

h = Heat transfer coefficient

h_{fg} = Latent heat of vaporization

Ja = Jakob number as in Kolev correlation

k = Thermal conductivity

N = Active cavity density

Pr = Prandtl number

p_r = Reduced pressure, p / p_c

p_c = Critical pressure

q = Heat flux [W/m^2]

Ra = Average roughness

μ = Dynamic viscosity

ΔT_{sat} = Wall superheating

ρ = Density [kg/m^3]

σ = Surface tension

θ = Contact angle

SUBSCRIPTS

f = Liquid

g = Gás (vapor)

w = Wall

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