NUCLEATE BOILING HEAT TRANSFER

J. M. Saiz Jabardo

Escola Politécnica Superior, Universidade da Coruña,
Mendizabal s/n Esteiro, 15403 Ferrol, Coruña, Spain
mjabardo@cdf.udc.es

ABSTRACT

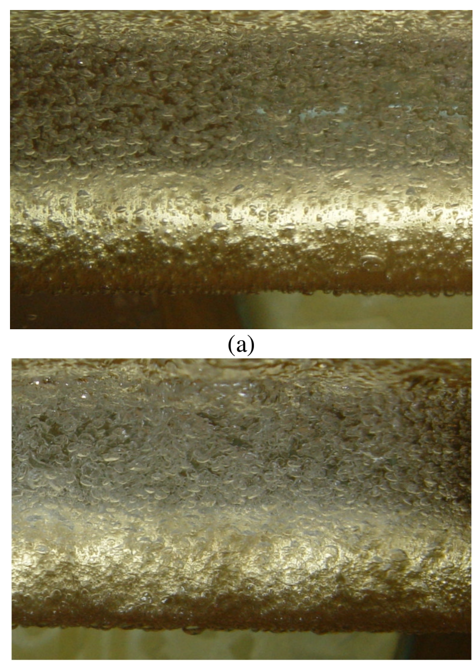
Nucleate boiling heat transfer has been intensely studied during the last 70 years. However boiling remains a science to be understood and equated. In other words, using the definition given by Boulding [2], it is an "insecure science". It would be pretentious of the part of the author to explore all the nuances that the title of the paper suggests in a single conference paper. Instead the paper will focus on one interesting aspect such as the effect of the surface microstructure on nucleate boiling heat transfer. A summary of a chronological literature survey is done followed by an analysis of the results of an experimental investigation of boiling on tubes of different materials and surface roughness. The effect of the surface roughness is performed through data from the boiling of refrigerants R-134a and R-123, medium and low pressure refrigerants, respectively. In order to investigate the extent to which the surface roughness affects boiling heat transfer, very rough surfaces (4.6 μm and 10.5 μm) have been tested. Though most of the data confirm previous literature trends, the very rough surfaces present a peculiar behaviour with respect to that of the smoother surfaces (Ra<3.0 μm).

INTRODUCTION

Nucleate boiling is considered by some as an "old" science due to its exhaustive study during the last eighty years. However, it is still an "insecure" science. This name was used by Wallis [1], citing its original author, Boulding [2], to designate a "field of knowledge for which the available data only cover a small part of the total field and the actual structures and relations in it are extremely complex".

Any text book or paper related to Nucleate Boiling certainly emphasizes the importance of this heat transfer mechanism in a wide range of industrial processes. Thus I will not be repetitive in this paper. However, I would like to briefly comment some of the most important applications related to Nucleate Boiling such as the nuclear industry, probably one of the pioneers in the research and study of Nucleate Boiling (NB). This is reasonable since NB is generally associated to high rates of heat removal from the heated wall for relatively low temperature differences. Using technical wording, NB is characterized by elevated heat transfer coefficients. Other important applications could be mentioned such as the so called flooded evaporators in industrial refrigeration and air conditioning plants where the change of phase of the refrigerant occurs outside a bank of tubes cooling a fluid, generally water, which flows inside the tubes. One of the most recent applications is the cooling of integrated circuits with high power density and heat pipes. Bubbly change of phase also occurs in fluids circulating inside tubes and in thin falling films used in several industrial applications. Figures 1 (a) and (b) display a visual representation of NB of refrigerant R-134a through pictures taken from a single brass tube at different heat fluxes. It can be noted that the population of bubbles clearly increases with the heat flux. In addition, bubbles are noted to be attached to the tube wall and in the bulk of the liquid up to the free surface of the pool.

It would pretentious of my part to develop an in depth analysis of Nucleate Boiling in the available space. Instead I will focus in the analysis of some physical parameters that affect the Nucleate Boiling performance, specifically the wall material and the heating surface finishing. For that purpose, initially an overview of the literature will be addressed followed by an analysis of results obtained in the experimental set up of the Refrigeration Laboratory/EESC, University of São Paulo. Experiments involving boiling of refrigerants R-123 and R-134a, low and medium pressure refrigerants, in horizontal cylindrical surfaces with variable



(a) (b)

Figure 1. Nucleate boiling of refrigerant R-134a on a brass tube. (a) 20 kW/m^2; (b) 40 kW/m^2.

roughness will be considered in the present analysis. Given the short space available, neither the experimental set-up nor the procedure will be described in this paper. A detailed description can be found in the references [3] and [4]. At this point it must be stressed that the results involved macro data with exception of the microstructure of the surface. Given the characteristics of the set-up and the main objectives of the investigation, no efforts have been made to further investigate the micro structure of the surface during the investigation.

LITERATURE REVIEW

Nucleate pool boiling 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 [4], [5] and [6]. 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 of the phenomena 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 [5], [7], [8], [9], [10]. 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 [5] 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 [11] and Yagov [12].

The literature can be divided into two main approaches to the surface structure effects on nucleate boiling heat transfer: (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 in the investigation reported herein will focus on the former approach, though references to the second one will be used whenever needed for explanation purposes.

Corty and Foust [5] performed an experimental study of nucleate boiling on a copper horizontal surface of refrigerant R-113, diethyl ether, and n-pentane. 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] 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^{2}K. It must be noted that the Corty and Foust experiments involved relatively smooth surfaces.

Kurihara and Myers [13] 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 [13] 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 [13] 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 [14] 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 [15], 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:

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

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, and 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 [16] 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 [16] were taken under atmospheric pressure and normal gravity conditions. Vachon et al [16] performed two kind of curve fitting of the available experimental results: (1) determining the liquid-surface

[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 profile over the sampling length. Gorenflo et al […] suggest the following relationship $Ra = 0.4Rp$.

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 [17] curve fitted their own experimental results involving nucleate boiling of refrigerants R-11, R-123, R-12, and R-134a on cylindrical surfaces of copper, brass, and stainless steel 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 [16], for heat fluxes higher than 5 kW/m^2 and the complete data set, they obtained the following values for exponents "r" and "s": 0.18 and 1.03. The surface roughness effects and the liquid-surface combinations were included in the liquid-surface coefficient. Saiz Jabardo et al [17] proposed the following expression for C_{sf}:

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

The coefficients "a", "b", and "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. The values of the coefficient "C" for different liquid-surface combinations can be found in reference [16].

Kozitskii [18] 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 general 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 [18] assumes "m" constant and equal to 0.7 in his nucleate boiling heat transfer correlation. In addition, based on his own data, Kozitskii [18] 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 [19] 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 [19] 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 [20] 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 [19], 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 [20] concluded that wetting liquids present better thermal performance.

Benjamin and Balakrishnan [21] 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. In addition to raising boiling curves, they also raised the density of active cavities as a function of the wall superheating. Their results displayed an interesting behaviour, with the density of active cavities and the heat flux increasing and diminishing with the average roughness of the surface, the extent of this behaviour being dependent on the particular fluid. Based on their own results and data from other sources, Benjamin and Balakrishnan [21] 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 [21], Eq. (7), since it has been raised from a data set involving a limited range of physical parameters and fluid-surface combination.

Kang [22] 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 [22] 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 [23] performed an experimental investigation with a 95% ethylene glycol 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 [24] 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 behaviour had also been previously pointed out by Ribatski et al [25] 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 [25] noticed an opposite trend at higher heat fluxes, with higher heat transfer coefficients on the upper region of the tube. Hahne and Barthau [24] and Ribatski et al [25] obtained lower heat transfer coefficients for stainless tubes. According to Hahne and Barthau [24], 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 [26] 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 [26] cite a Russian study according to which, the heat transfer coefficient increases with surface roughness up to a maximum. Beyond that surface roughness does not affect the boiling heat transfer.

Gorenflo and co-workers have carried out a multi-year research involving several aspects of nucleate boiling, including effects such 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 [27], [28], along with two by Luke [29], [30]. 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 [29] 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 [29], [30] 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 [30]. In addition, Luke [29] 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 [29] 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 [29], 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:

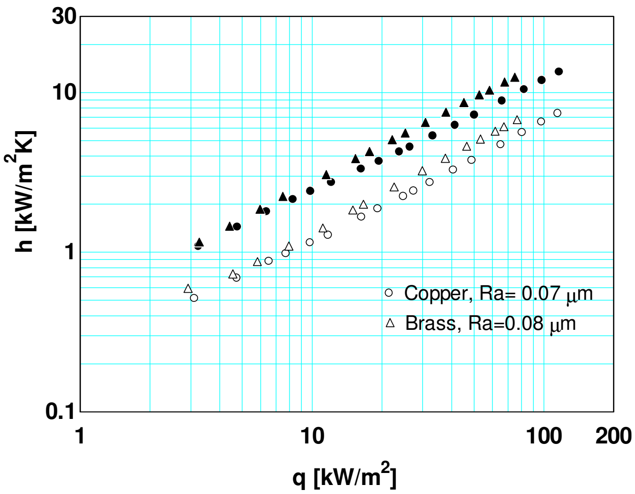
$$m = a - bp_r^{0.37} + \frac{c}{1 + 200\left(Ra / Rao\right)^{10}} \tag{11}$$

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

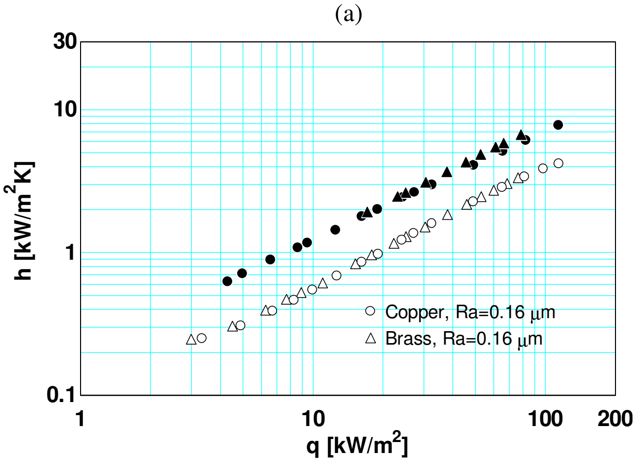
In the preceding paragraphs an overview has been presented of the nucleate boiling literature related to the macro approach to the effects of the surface roughness. Two general conclusions can be drawn: (1) the surface roughness tends to increment the heat transfer for other parameters kept constant, though it 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 behaviour 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 [20] and Wang and Dhir [31] 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 [32].

EXPERIMENTAL RESULTS AND ANALYSIS

The analysis of roughness effects on nucleate boiling will be based on experimental results raised in the Refrigeration Laboratory of the EESC, University of São Paulo, under a comprehensive multi-year research on nucleate boiling of refrigerants. A detailed description of the experimental set up can be found in the references [3], [4], and [17]. Experiments have been carried out with 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 tube 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).



(a)



(b)

Figure 2. h vs q curves 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; Refrigerant R-123, scaled surfaces, p_r=0.011 and 0.092, Ra=0.16 μm. Symbols: Blank: lower pressure; blackened: higher pressure.

The focus of the present analysis will be the effect of the heating surface roughness. A more detailed approach can be found in Saiz Jabardo et al [33].

Pressure and liquid effects on the nucleate boiling are clearly reproduced in Figures 2 (a) and (b) where data of 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 reduced pressures and relatively small roughness of Fig. 2 (a) 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 over the nucleate boiling heat transfer are clearly shown in Figs. 3 (a) 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 a 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. Microstructure characteristics of the rougher surfaces (Ra=4.6 μm and 10.5 μm) was not determined.

Trends observed in Figs. 3 (a) and (b) agree with those of the literature, at least qualitatively. It can be noted that, in general, the heat transfer 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). In addition, 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 behaviour has already been observed in the literature. Berenson [14] and Nishikawa et al [19] data clearly show that the slope of h vs q curve diminishes with the average roughness of the surface. Kozitskii [18], 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 [21] observed heat transfer increments and reductions as the surface roughness increases. Benjamin and Balakrishnan [21], as in the case of Kozitskii [18], investigated surfaces of a relatively low values of Ra as compared with those considered in the present study. Luke [29] 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. 3(a) 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 [26], very rough surfaces might present large cavities that might be 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. 3 (a) 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

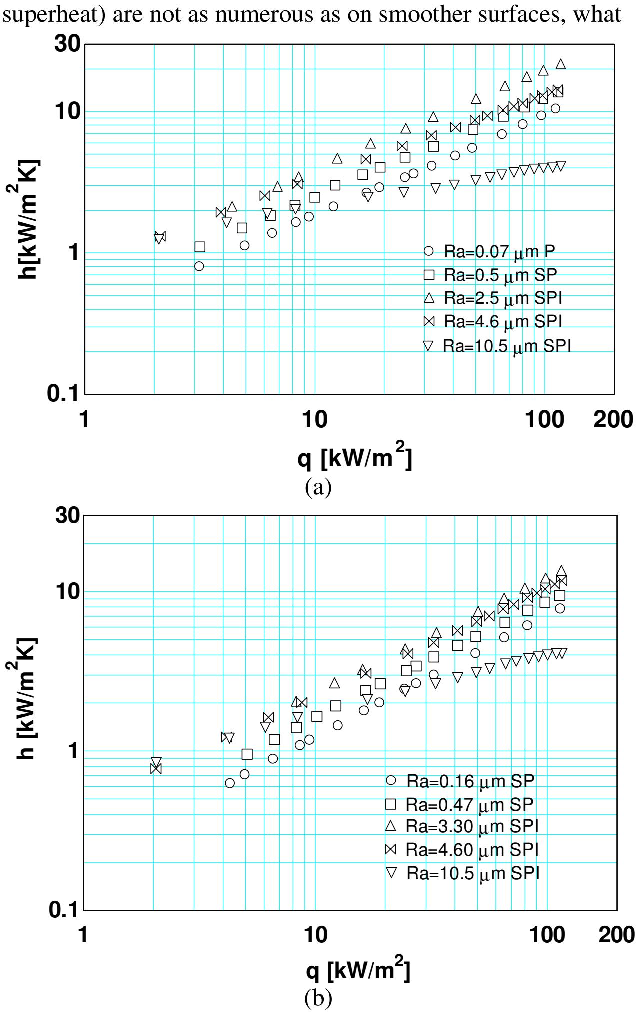


Figure 3. Effect of the surface roughness on a h vs q plot for refrigerants boiling on copper tubes. (a) Refrigerant R-134a; p_r=0.177; (b) R-123; p_r=0.092.

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 [28] to explain the reduction in the slope of the h vs q curve with the surface roughness.

The 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 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 [28]. Gorenflo [34] suggests the following expression for the exponent "m" that includes only the effect of the reduced pressure:

$$m = 0.9 - 0.3p_r^{0.3} \tag{12}$$

Ribatski and Saiz Jabardo [35] 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 [18], 4/5 by Nishikawa et al [19], and 0.67 by Cooper [36]. 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. 4 (a) to (c). The typical literature range has been overlaid in these plots as discontinuous lines. The following are general conclusions drawn from the plots of Figs. 4 (a) to (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. 4 (a), are generally lower than those of R-123, Fig. 4 (b).
(3) The average value of "m" for the range of roughness lower than 4.6 µm, Fig. 4 (a) for refrigerant R-134a, is of the order of 0.670, similar to the one proposed by Cooper [36]. 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. 4 (c), 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. 5 (a) and (b), which corresponds to the same data of the plots of Figs. 4 (a) and (b). The correlations by Gorenflo [34] and Ribastki and Saiz Jabardo [35] 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 use in 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 [29], Eq. (11), seem more adequate to correlate the exponent "m".

In the preceding paragraphs an analysis of the surface roughness on the nucleate boiling heat transfer was performed.

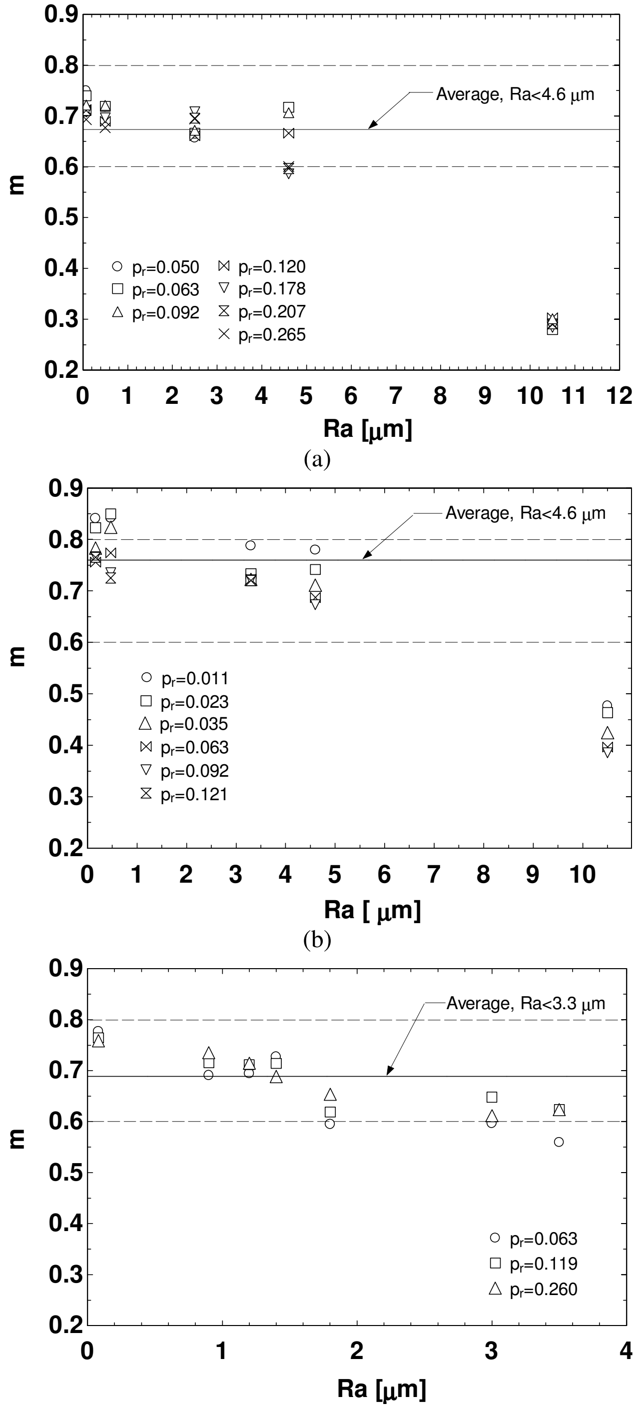


Figure 4. Variation of the slope of the h vs q curve, "m", with the average surface roughness, Ra. (a) R-134a-copper; (b) R-123-copper; (c) R-134a-brass.

It would be interesting at this point to investigate the relationship between the surface roughness and the density of active cavities provided from models from the literature since in the present investigation a direct count of them has not been performed. The model by Mikic and Rohsenow [37] 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:

$$N = C_1 \left(\frac{r_s}{r} \right)^{m_1} \tag{13}$$

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

$$\frac{q \sqrt{\dfrac{\sigma}{g\left(\rho_f - \rho_g\right)}}}{\mu_f h_{fg}} = B\left(\varphi \Delta T_{sat}\right)^{m_1+1} \tag{14}$$

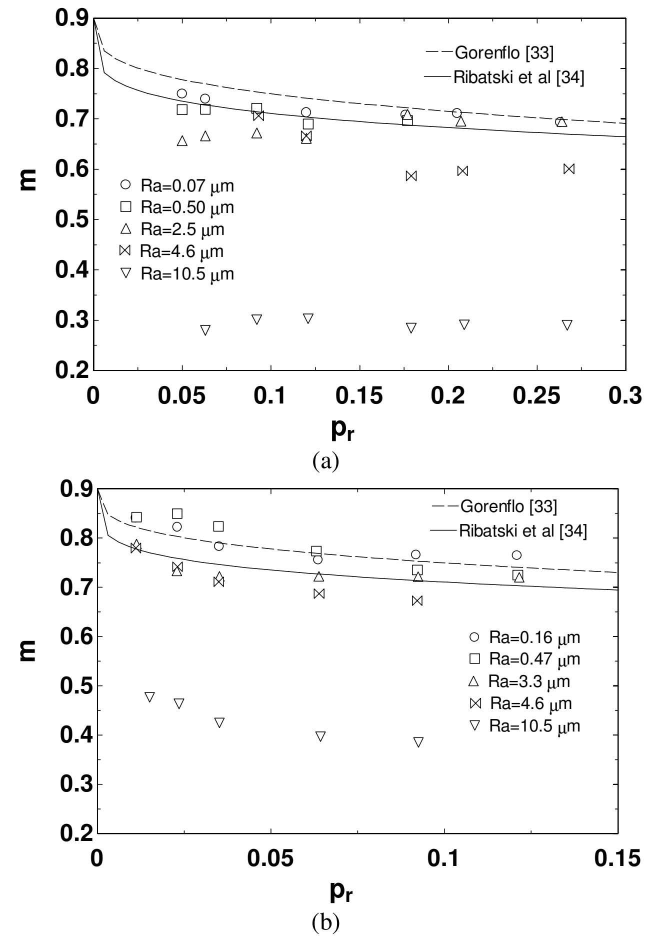
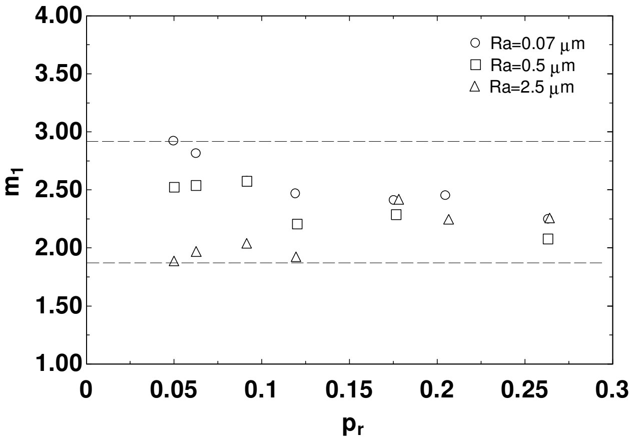


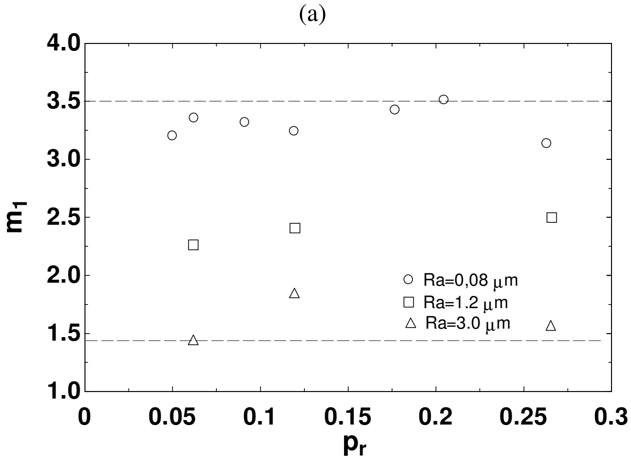
Figure 5. Data of Figs. 4 (a) and (b) plotted in terms of the reduced pressure. (a) R-134a-copper; (b) R-123-copper.

"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. (14) in such a way that the value of the exponent "m_1" of Eqs. (13) and (14) could be determined. The variation of the exponent "m_1" with the reduced pressure for different surface roughness is shown in Figs. 6 (a) and (b) for refrigerant R-134a boiling on copper and brass tubes, respectively. The broken lines 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. 6 (a) 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 Rohsenow [37] assumed "m_1" 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_1" is related to the exponent of the h vs q curve, "m", by the following relationship:

$$m = \frac{m_1}{m_1 + 1} \tag{15}$$



(a)



(b)

Figure 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.

Thus, the range of "m_1" values of Figs. 6 (a) and (b) are compatible with the previously introduced values of the exponent "m" of the h vs q relationship.

Wang and Dhir [31], for water at atmospheric pressure boiling on vertical copper surfaces, obtained an active site density correlation similar to Eq. (13), with the exponent "m_1" being equal to −6.0, a value which is significantly higher than those from the present investigation. Wang and Dhir [31] reported tests with contact angles equal to 18°, 35°, and 90°. No effects of the contact angle on the exponent "m_1" were noticed though it affects the proportionality coefficient.

According to the model proposed by Benjamin and Balakrishnan [21], the active cavity density is proportional to $(\Delta T_{sat})^3$ (see Eq. 7) from which it can be shown that "m_1" is equal to 3.0. As in the case of the Wang and Dhir [31] model, the proportionality coefficient depends on the contact angle in addition to other physical parameters.

Kolev [38] suggested the following correlation for the active site density:

$$N = \frac{4.29}{(2\beta)^2}\lambda_{RT}^2\left[\frac{h\Delta T_{sat}^{n-1}}{k_l Ja^{1/2}}\right]^4 \tag{16}$$

where

$$\lambda_{RT} = \left[\sigma / g(\rho_l - \rho_v)\right]^{1/2};$$
$$\beta = 25.3\cos(\theta/2) / \left[(1+\cos\theta)^2(2-\cos\theta)\right];$$
$$Ja = (\rho_l/\rho_v)(c_{pl}\Delta T_{sat}/h_{fg})$$

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 for refrigerant R134a boiling on copper tubes for all the reduced pressures of the tests have been used in the plot of Fig. 7. The contact angle, θ, has been assumed as being equal to 6° [39]. The cavity radius, "r" has been determined from the equilibrium cavity radius given by the following conventional expression:

$$r = \frac{2\sigma T_{sat}}{\rho_v h_{fg}\Delta T_{sat}} \tag{17}$$

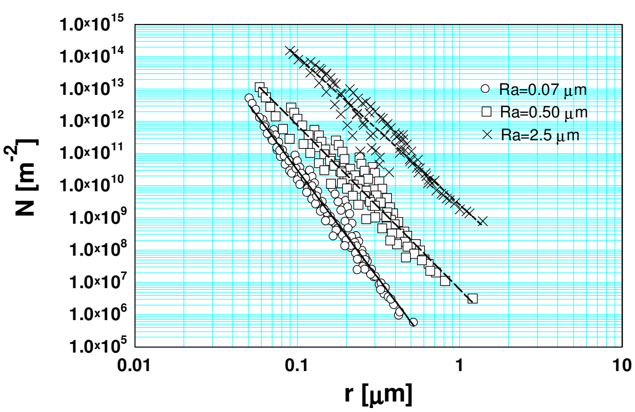


Figure 7. Active cavity density variation with "r". Refrigerant R-134a; copper tubes; all reduced pressures.

The results of Fig. 7 clearly indicate 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_1", for increasing average roughness are equal to: 6.748; 5.091; 4.609. The observed trend is that the slope "m_1" diminishes with the average roughness. The range of values are compatible with those of Wang and Dhir [31], though significant higher than the ones from the Mikic and Rohsenow [37] 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 a couple of refrigerants boiling on copper 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 I would like to stress 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. Regarding the latter aspect, Dhir [32] pointed out that the issue of nucleation might have to be addressed at the molecular level.

NOMENCLATURE

c — specific heat [J/kgK]
cp — specific heat at constant pressure [J/kgK]
C_{sf} — fluid-surface coefficient, Rohsenow correlation
g — gravity acceleration [m/s^2]
h — heat transfer coefficient [W/m^2K]
h_{fg} — latent heat of vaporization [J/kg]
Ja — Jakob number as in Kolev correlation
k — thermal conductivity [W/mK]
N — active cavity density [m^{-2}]
Pr — Prandtl number
p_r — reduced pressure, p / p_c
q — heat flux [W/m^2]
Ra — average roughness [μm]

μ — dynamic viscosity [Pas]
ΔT_{sat} — wall superheating [°C]
ρ — density [kg/m^3]
σ — surface tension [N/m]
θ — contact angle [°]

Subscripts

f — liquid
g — gás (vapor)
w — wall

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