The Effect of the Surface Condition on Nucleate Pool Boiling of Refrigerant R-11 on Cylindrical Copper Surfaces

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An experimental investigation of nucleate pool boiling of refrigerant R-11 on cylindrical copper surfaces has been performed. In order to investigate surface condition effects, five surfaces with different finishing have been tested. Boiling curves have been raised for heat fluxes up to a maximum of 120 kW/m^2 whereas the pool reduced pressure varied in the range between 0.011 and 0.12. It has been determined that the heat transfer coefficient increases with the average surface roughness (Ra) up to a maximum, decreasing for higher values of Ra, in what could be considered an unexpected trend. Experimental data have been compared with those from correlations from the literature that include a surface condition parameter, such as the ones proposed by Cooper (1984), Gorenflo et al (1994), Ribatski (2002), and Silva (2002). The correlations given in terms of the average surface roughness, Ra, compare reasonably well with experimental data for most of the surface conditions tested in the present investigation, with few exceptions discussed in the paper related to the choice of the surface finishing parameter.

Keywords. *nucleate boiling, refrigerants, roughness*

1.Introduction

Nucleate boiling heat transfer occurs in numerous industrial applications. In the refrigeration industry, nucleate boiling is the heat transfer mechanism that prevails in flooded evaporators and those with liquid recirculation, both of them used in liquid cooling operations. The rate of heat transfer, ϕ, in nucleate boiling depends on several physical parameters, the most significant being the type of boiling fluid, the pressure, and the surface material and condition.

Surface condition, characterized by its roughness, is one of the physical parameters that affect most the heat transfer under nucleate boiling conditions. In fact, in an experimental study on nucleate boiling of refrigerant R-11 on cylindrical copper surfaces, Silva (2002) has shown that the heat transfer coefficient almost doubles when the average roughness of the surface, Ra, varies from 0.17 μm to 2.30 μm. Anderson and Mudawar (1989), working with FC-72 at atmospheric pressure on surfaces treated through different processes in order to vary the surface condition, concluded that surface roughness increments reduce the boiling inception superheating and improve the rate of heat transfer. In addition, the critical heat flux is slightly reduced by roughening the surface. Sauer et al (1975) arrived to similar conclusions by boiling refrigerant R-11 on inconel surfaces of different roughness.

In different type of experiments, Chowdhury and Medrow (1985) studied nucleate boiling at atmospheric pressure of water and ethanol on aluminum and copper surfaces submitted to different finishing. Some of the surfaces were anodized after the roughening procedure, without altering the surface roughness. As expected, they found an increment in the rate of heat transfer on the straight roughened surfaces with respect to the smoother ones. However, on the anodized surfaces, roughening did not cause any significant effect on the rate of heat transfer. Detailed microphotography analysis revealed that the anodized surfaces were uniformly covered of pits of size of the order of 1 μm, whereas on the non-anodized ones, the cavities were larger and non-uniformly distributed, though larger than the former. Berenson (1962) concluded that roughness does not affect the nucleate boiling rate of heat transfer for anodized surfaces. Rather he found out that nucleate boiling performance varies when surfaces submitted to the same mesh size scale have their respective roughness being produced by movements of the scale in different directions. On the other hand, Dhir (1991), based on a study carried out by Bier (1968), suggests that the nucleate boiling heat transfer coefficient varies with the surface roughness according to the following general expression: $h \approx R_p^C$. However, based on the aforementioned studies, it is not clear that the rate of heat transfer depends exclusively on the surface roughness, as suggested by Dhir (1991). Instead the rate of heat transfer certainly is proportional to the density of active cavities on the heating surface. Summing up, results from the literature tend to agree with the increment in the rate of heat transfer with the surface roughness. In addition, this trend seems to be related to the corresponding increment in the density of active cavities. It is interesting to note that smoother surfaces are more sensitive to average roughness increments. Silva (2002) has found out that the rate of heat transfer increases in a logarithmic fashion with the average roughness of the surface, Ra, reaching an asymptotic maximum for a given value of Ra, a trend that had already been mentioned by Kurihara (1956).

Regarding the nucleate boiling heat transfer correlations, some take into account the effect of the surface roughness, among them, the ones by Cooper (1984), Gorenflo (2002), and Ribatski (2002) could be mentioned. Recently, Silva (2002) proposed a correlation based on the one by Rohsenow, where the surface/liquid coefficient, C_{sf}, is given by a closed form expression involving the combined effect of surface average roughness, Ra, and the reduced pressure, p_r. For reader information purposes, these correlations along with the pertinent range of reduced pressures are shown in Table 1.

Table 1. List of some correlations that include the effect of the surface roughness along with their pertinent range of surface roughness.

Author / Year	Correlation	Range of Ra or Rp (µm)
Cooper (1984)	$\frac{h}{(\phi)^{0.67}} = 55 p_r^{0.12-0.2\log R_p} \left(-\log p_r\right)^{-0.55} M^{-0.5}$	0.02 – 4.3
Gorenflo et al (1994)	$\left(\frac{h}{h_o}\right) = \left(1.2 p_r^{0.27} + \left(2.5 + \frac{1}{1-p_r}\right) p_r\right) \left(\frac{\phi}{\phi_o}\right)^{0.9-0.3.p_r^{0.30}} \left(\frac{Ra}{Rao}\right)^{0.133} \left(\frac{s}{s_o}\right)^{0.5}$	0.16 – 10.8
Rohsenow modificada por Silva (2002)	$\frac{c_{pl}\Delta T}{h_{lv}} = C_{sf} \left(\frac{\phi}{\mu_l h_{fg}} \sqrt{\frac{\sigma}{g(\rho_l - \rho_v)}}\right)^{0.28} \left(\frac{c_{pl}\mu_l}{k_l}\right)^{1.55}$ $C_{sf} = (\ln(Ra)^{0.0077.p_r - 0.0026} - 0.0224.p_r + 0.0077)$	0.17 – 2.3
Ribatski (2002)	$\frac{h}{\phi^{0.9-0.3\cdot p_r^{0.2}}} = 100 p_r^{0.45} \left[-\log(p_r)\right]^{-0.8} Ra^{0.2} M^{-0.5}$	0.02 – 3.3

The main purpose of the present paper is to report results from an experimental study involving the investigation of effects of the surface condition in nucleate boiling heat transfer. In particular, results for refrigerant R-11 boiling on cylindrical copper surfaces will be considered. The reduced pressures covered by the investigation varied in the range between 0.011 and 0.12 whereas the average roughness of the heating surface varied from 0.17 µm to 4.6 µm.

2. Experimental set up

The experimental set up comprises the refrigerant and cooling circuits, as shown in Fig. 1. 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. 1. The ethylene glycol/water solution is cooled by either a refrigeration circuit or water from a cooling tower, depending upon the operating pressure. This solution is intended to operate in the range between –26°C and 90°C.

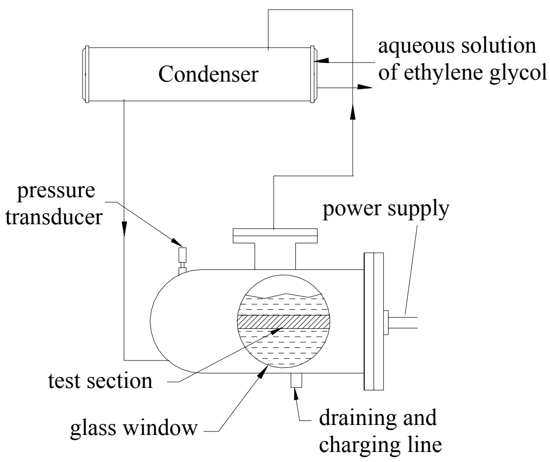

Figure 1. A schematic diagram of the experimental set up showing the main components and equipment.

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 heater, installed at the bottom, and two sheathed type T thermocouples. The boiler is also fitted with openings for connections to a pressure transducer, a safety valve, and vapor and liquid return copper lines, as shown in Fig. 1. The sheathed thermocouples are installed in such a way to measure and monitor the temperature of the liquid pool and the vapor in equilibrium with it. Under normal operating conditions these thermocouples indicate temperatures which are very close to each other and to the saturation temperature at the boiler internal pressure measured by the pressure transducer.

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 copper tube, a cut way view of it is shown in Fig 2. 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. 2. Thermocouples are kept in place by a thermal conductive epoxy resin. Electrical signals from the transducers are processed by a data acquisition system which includes two 12 bit A/D converter boards with 16 channels each, and three connection panels. Two of these panels are dedicated to thermocouple connections.

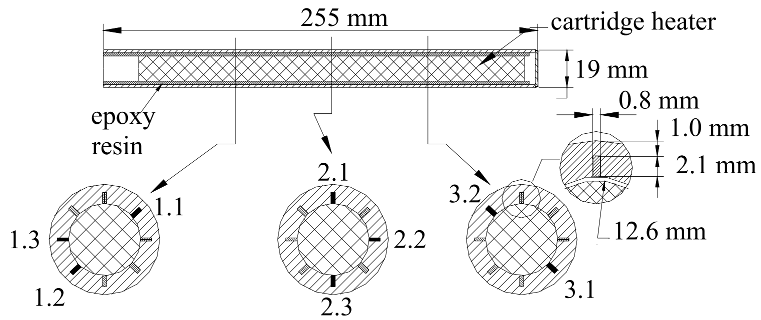

Figure 2. Longitudinal and transversal cut view of the test section showing the location of the surface thermocouples

3. Experimental procedure

The boiling surface used to be treated prior to the beginning of the tests. Sandpaper scales with mesh size varying in the range from 220 to 1,200 were used to obtain the final surface roughness and applied through a regular late machine run at 1,200 rpm. Experiments were also conducted with a polished surface, which required a special treatment, and a sand blast surface. After treatment, the boiling surface used to be thoroughly cleaned with a solvent (normally refrigerant R-11) and the roughness measured at 10 randomly selected regions before attaching it to the boiler. After testing the boiling surface, 10 randomly selected regions were again taken for roughness measurement so that conditions of the surface before and after the tests could be compared. The roughness was measured in terms of the CLA arithmetic average, *Ra.* The treatment suggested above allowed experiments to be run in the range of surface roughness, *Ra*, between 0.17 ± 0.01 μm and 4.6 ± 0.5 μm.

The internal surface of the boiler used to be cleaned and kept under a vacuum of less than 2 kPa during a period of 12 hours before the attachment of the boiling surface and the introduction of the test refrigerant. Tests were conducted under saturated conditions of the refrigerant. This condition was continuously monitored and adjusted as needed. The datum point would only be logged if the readings of the sheathed thermocouples were close enough (within 0.2 K) to each other and to the saturation temperature inside the boiler obtained from the pressure transducer reading. For analysis purposes, the saturation temperature of the pool was determined as the average of the readings of the sheathed thermocouples. Tests were conducted by gradually increasing the heat flux up to its predicted maximum. Once the maximum was attained, the heat flux was gradually reduced down to zero. Only downward heat flux data were considered for analysis purposes. Several procedures were tried to check for possible effects on the results. Two of such procedures consisted in keeping the boiling surface active for some time before logging data and starting directly from the maximum heat flux.

In measuring the surface temperature care was exercised in evaluating the thermal resistance of the copper wall between the couple location and the actual boiling surface. In addition, axially located thermocouples helped in evaluating axial heat conduction. It has been determined that in the location corresponding to section 2 of the test tube, Fig. 2, the axial heat flux was negligibly small. A thorough discussion of surface temperature measurement can be found in Ribatski (2002). The temperature considered for analysis purposes was the one from the thermocouple located midway between those at top and bottom of the heating surface at section 2 (Fig. 2). The temperature indicated by this thermocouple is equivalent to the average of the readings of the three section 2 thermocouples.

Instruments were calibrated and the uncertainty of measured parameters evaluated according to the procedure suggested by Abernethy and Thompson (1973) with results summarized in Table 2.

Table 2. Uncertainty of measured and calculated parameters

Parameter	Uncertainty
minimum heat flux, ϕ=0.60 kW/m^2	± 1.8%
maximum heat flux, ϕ=120 kW/m^2	± 0.3%
heat transfer area	± 0.3%
wall temperature	± 0.2K
saturation temperature	± 0.2K
superheat temperature	± 0.3K
heat transfer coefficient, minimum uncertainty	± 1.3%
heat transfer coefficient maximum uncertainty	± 20.3%

4. A summary of experimental results

Boiling curves of refrigerant R-11 on copper surfaces of different average roughness are shown in Figs. 3(a) and (b). The reduced pressure corresponding to data of Fig. 3(a) is 0.011 whereas that of Fig. 3 (b) is 0.092. In order to abbreviate the analysis, just a summary of the conclusions drawn based on the data plotted in these figures will be presented in what follows. More details can be found in Silva (2002).

a) The rate of heat transfer, ϕ, increases with the reduced pressure, an expected trend which can clearly be noted when comparing Fig 3 (a) with Fig. 3 (b) for the same average roughness. This trend is characterized by steeper boiling curves.

b) It can clearly be noted in both figures that the roughness effect is more significant in the range of lower values of Ra, confirming the asymptotic trend toward a maximum noted by Silva (2002). In fact, the displacement of the boiling curves with Ra is more pronounced at lower values of this surface parameter, as one can observe in these figures.

c) It is interesting to note that when the average roughness varies from 2.30 µm to 4.60 µm, the boiling curves become less steep, pointing toward a reduction in the rate of heat transfer. This is a striking result, though an expected one given the asymptotic trend proposed by Silva (2002). This trend clearly suggests that there is a maximum on the rate of heat transfer that can be achieved by increasing the surface roughness. Increasing the roughness beyond the value corresponding to that maximum, the rate of heat transfer diminishes. This behavior could be related to the presence of cavities of large size on surfaces with elevated values of roughness. These larger cavities eventually are not activated, reducing the rate of heat transfer as observed in the results of Figs. 3(a) and (b). This trend seems to confirm results reported by Kurihara (1956) almost 50 years ago.

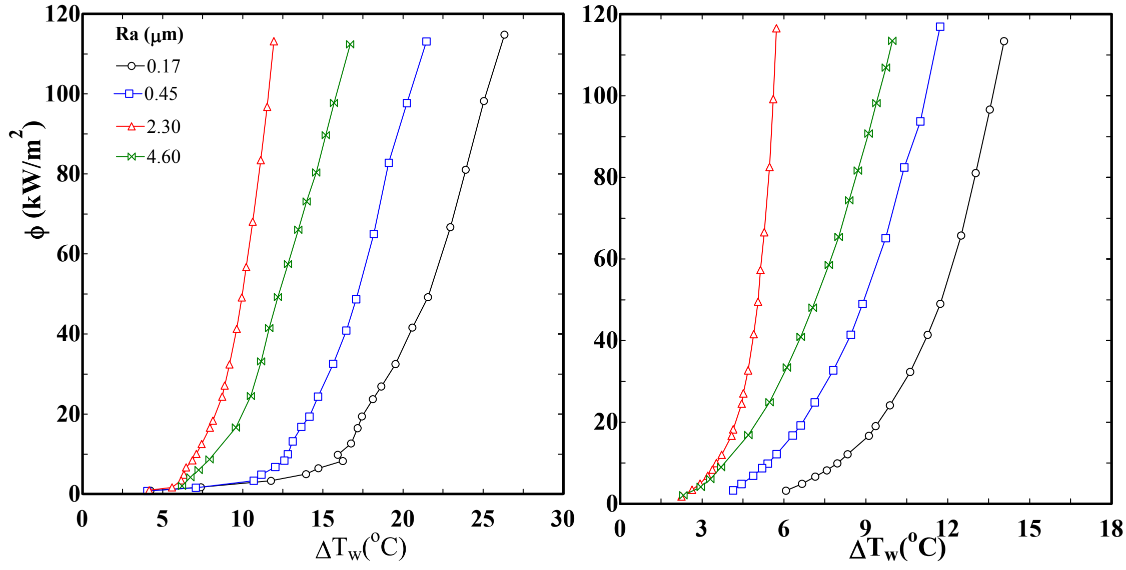

Figure 3. Boiling curves of refrigerant R-11 on copper surfaces. (a) p_r= 0.011; (b) p_r= 0.092.

5. Comparison with correlations

The correlations considered for comparison are those listed in Table 1. It must be noted that in the Cooper's correlation, instead of the average roughness, Ra, Rp characterizes the surface condition. The latter roughness parameter is defined as the average distance between peaks and valleys of a typical printout of a roughness meter. For comparison purposes, the value of Rp in the Cooper's correlation will be assumed as equal to Ra, though it must be recognized that there is no such a relationship between these roughness parameters.

The heat transfer coefficient from each of the considered correlations is plotted against the average roughness of the surface, Ra, for different operational conditions in Figs. 4(a) to (d). For comparison purposes, experimental data corresponding to these conditions have also been included in these figures. A glance at these figures allows one to immediately conclude that all the correlations present similar qualitative behavior, according to which, the heat transfer coefficient increases with the surface roughness. However, from the quantitative point of view, results from correlations are significantly different from each other and from experimental data. It is also apparent that the correlations do not capture the trend displayed by the experimental heat transfer coefficient, which clearly reaches a maximum in the range of average roughness considered in the figures.

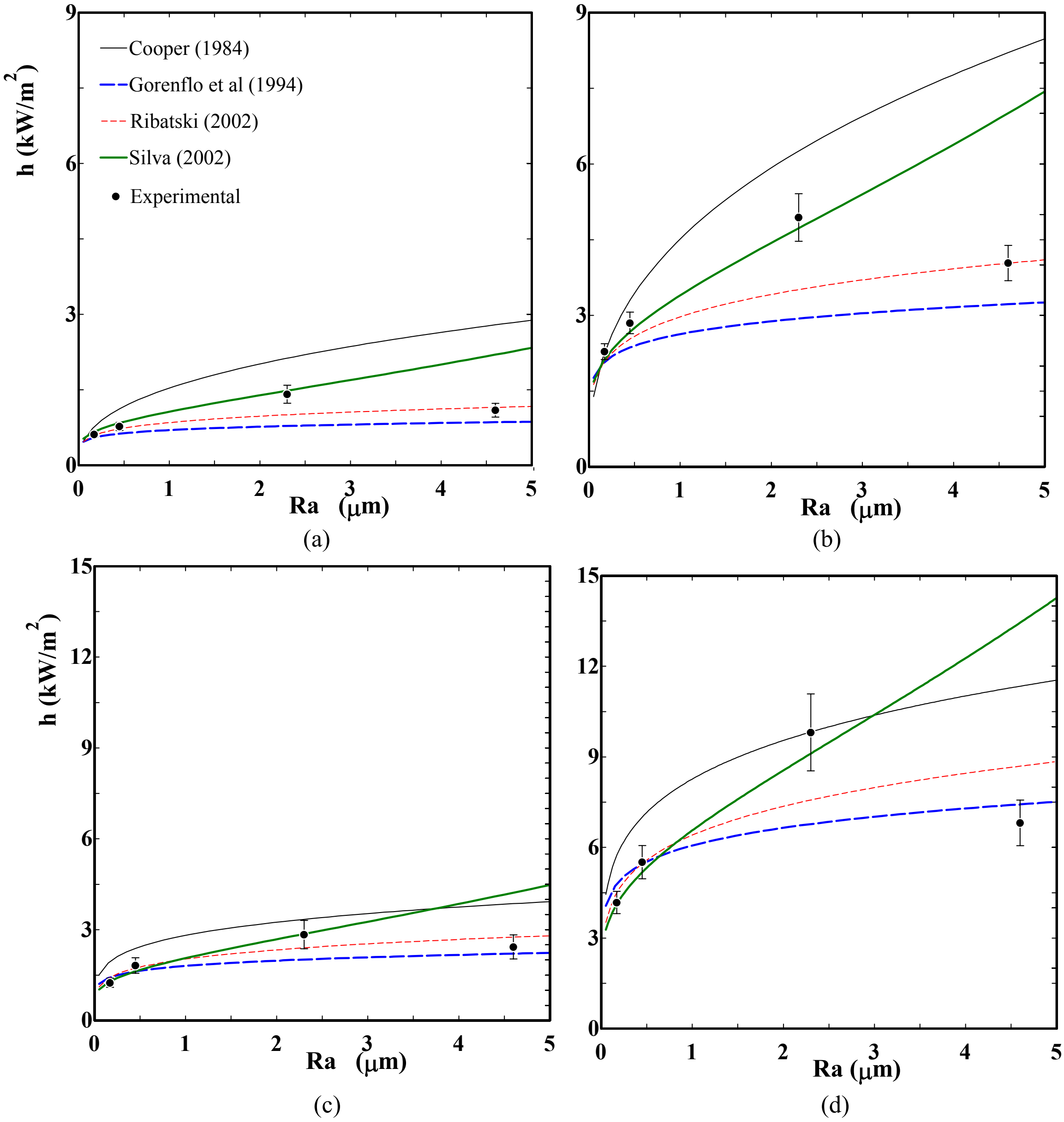

Figure 4. Heat transfer coefficient variation with surface roughness for nucleate boiling of refrigerant R-11 on copper surfaces. (a) p_r=0.011 and ϕ=10 kW/m^2; (b) p_r=0.011 and ϕ=50 kW/m^2; (c) p_r=0.092 and ϕ=10 kW/m^2; (d) p_r=0.0921 and ϕ=50 kW/m^2.

The calculated versus the experimental heat transfer coefficient for the surface average roughness values considered in this investigation is shown in the plots of Figs. 5 (a) to (d). Each correlation considered for comparison has been included in each plot. The data points in each plot are the ones corresponding to the indicated roughness, covering the whole range of reduced pressures considered in the investigation. Trends from these figures can also be assessed in Table 3, where the values of the average absolute relative deviation, ε, of the calculated with respect to the experimental heat transfer coefficient are presented for both each value of Ra and the overall data set. The average absolute relative deviation, ε, is defined as

$$\varepsilon = \frac{\sum_{i=1}^{n} \left| \frac{h_{\exp} - h_{calc}}{h_{\exp}} \right|}{n} \tag{1}$$

Table 3. Average absolute relative deviation of experimental with respect to calculated heat transfer coefficient.

Ra [μm]	**Cooper (1984)**	**Gorenflo et al (1994)**	**Ribatski (2002)**	**Silva (2002)**
	ε (%)	**ε (%)**	**ε (%)**	**ε (%)**
0.17	27.42	8.11	7.06	5.17
0.45	25.62	13.07	6.48	7.47
2.3	20.52	37.04	24.75	5.56
4.6	82.17	14.30	14.10	83.63
OVERALL	**37.93**	**18.76**	**13.47**	**24.25**

It can be noted that, for lower values of Ra, Figs. 5 (a) and (b), all correlations compare reasonably well with the experimental data, falling within the ±20% range. The Coopper's correlation tends to over-predict experimental data, see also Table 3, though falling closely in that range. For higher values of Ra, the correlations tend to deviate more from the experimental data. In the case of Ra=2.3 μm, Cooper's and specially Silva's correlations present better performance than the other two, which tend to under-predict experimental data. Surface roughness increment from 2.3 μm to 4.6 μm, as previously noted, causes a reduction in the heat transfer coefficient, a trend that is not captured by none of the correlations. Thus, the better performance by the Gorenflo's correlation at the elevated surface roughness (4.6 μm) could be considered as the result of a fortunate extrapolation of surface roughness effects by this correlation. Regarding the overall data set, the correlation proposed by Ribatski is the one that compares better with experimental data, followed closely by the one by Gorenflo. Silva's correlation, as should be expected, predicts very well experimental data in the lower range of surface roughness, Ra ≤ 2.3 μm. The significant performance degradation displayed by this correlation at the surface roughness of 4.6 μm could be attributed to its "curve fitting" nature. In fact, this correlation has been developed by a curve fitting present data covering the surface roughness range from 0.17 μm to 2.3 μm. Thus, given the odd trend displayed by experimental data, extrapolation of this correlation to higher surface roughness would not be adequate.

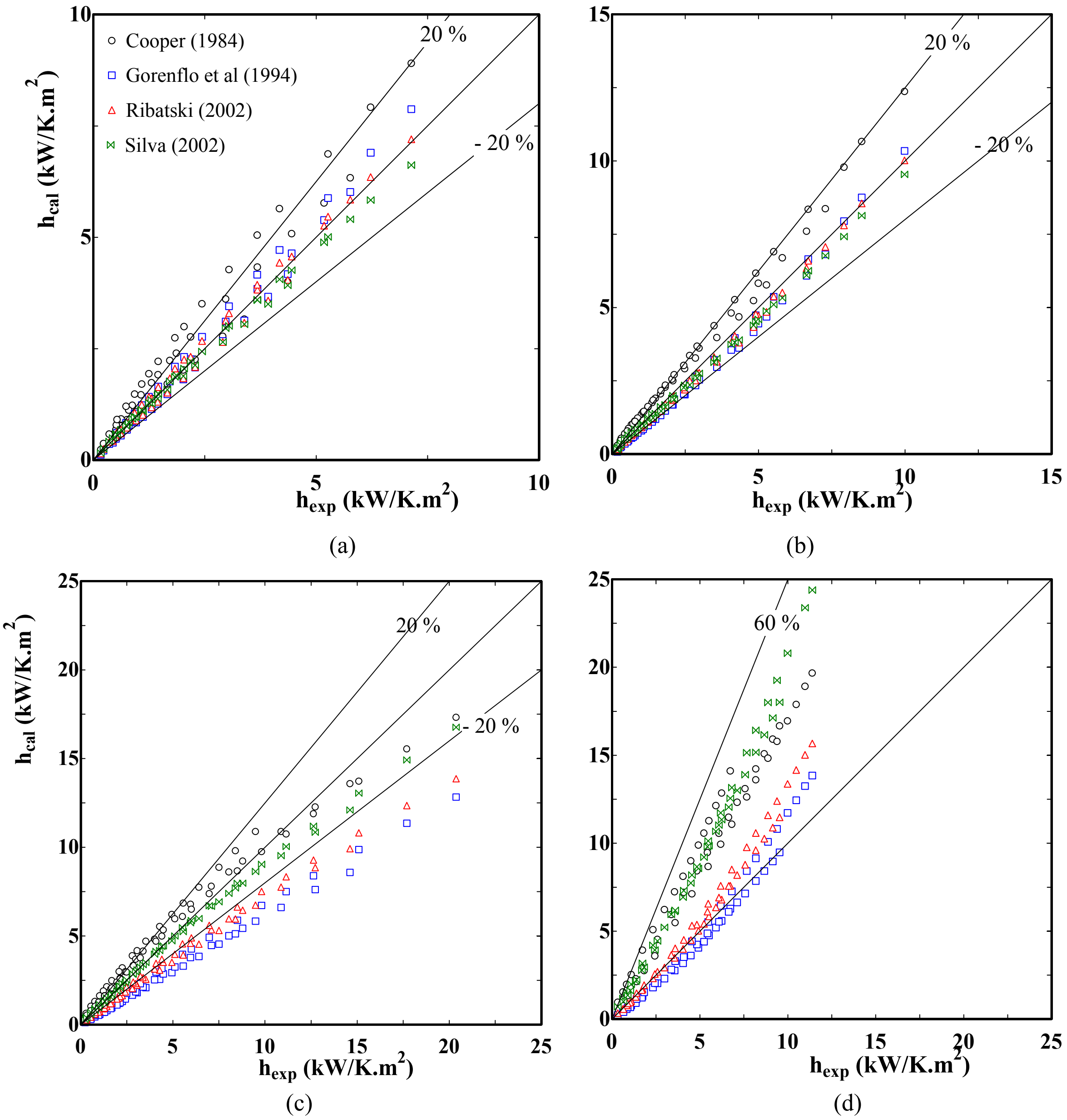

Figure 5. Calculated versus experimental heat transfer coefficient. (a) Ra=0.17 μm; (b) 0.45 μm; (c) 2.3 μm; (d) 4.6 μm.

6. Conclusions

The present paper reports a summary of results from an investigation involving nucleate boiling heat transfer of R-11 on cylindrical copper surfaces of different roughness. Effects of the surface roughness have been the focus of this paper with the following general conclusions having been drawn:

(1) As a general rule, the rate of heat transfer increases with the heating surface average roughness up to a certain value. The available nucleate boiling heat transfer correlations follow this trend at least in a qualitative manner.

(2) However, above a certain value of the average roughness, the rate of heat transfer diminishes, a trend that is not captured by the correlations.

(3) In the lower range of the heating surface roughness, Ra, varying between 0.17 μm and 2.30 μm, Silva's correlations compares better with experimental results. However, for the uppermost average roughness, 4.60 μm, the nucleate boiling heat transfer coefficient from this correlation presents the highest average deviation from the experimental one.

(4) Gorenflo's correlation is the one with better performance at the highest average roughness. Regarding the overall data set, the correlation proposed by Ribatski is the one that presents the least average deviation with respect to experimental data.

7. Acknowledgements

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8. Nomenclature

C_{sf}	-	Surface/liquid parameter of the Rohsenow correlation
c_{pl}	-	Specific heat of the liquid [J/kg K]
g	-	Gravitational acceleration [m/s^2]
h	-	Heat transfer coefficient [W/m^2 K]
h_0	-	Reference heat transfer coefficient [W/m^2 K]
h_{cal}	-	Calculated heat transfer coefficient [W/m^2 K]
h_{exp}	-	Experimental heat transfer coefficient [W/m^2 K]
h_{fg}	-	Latent heat of vaporization [J/kg]
k_l	-	Thermal conductivity of liquid [W/m K]
m, n	-	Exponents of Rohsenow correlation
M	-	Molecular mass [kg/kmol]
p_r	-	Reduced pressure
Ra	-	Roughness arithmetic average [µm]
Ra_0	-	Reference roughness arithmetic average [µm]
Rp	-	Peak to peak average roughness [µm]
s	-	Penetration parameter - $\sqrt{k\rho c_p}$
s_0	-	Reference penetration parameter
T_{sat}	-	Saturation temperature [^{o}C]
T_w	-	Heating surface (wall) temperature [^{o}C]
ΔT_w	-	Surface superheat [^{o}C]
ϕ	-	Heat flux [W/m^2]
ϕ_0	-	Reference heat flux [W/m^2]
μ_l	-	Dynamic viscosity of the liquid [Pa s]
ρ_l	-	Liquid density [kg/m^3]
ρ_v	-	Vapor density [kg/m^3]
σ	-	Surface tension [N/m]

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