J. M. Saiz Jabardo
E. Fockink da Silva
G. Ribatski
and S. F. de Barros
Laboratório de Refrigeração
Departamento de Engenharia Mecânica
Escola de Engenharia de São Carlos
Universidade de São Paulo
Avenida Trabalhador Sãocarlense, 400 Centro
13566-590 São Carlos, SP. Brazil
mjabardo@sc.usp.br

Evaluation of the Rohsenow Correlation Through Experimental Pool Boiling of Halocarbon Refrigerants on Cylindrical Surfaces

This paper reports results from an investigation on the performance of the Rohsenow's type of correlation when applied to the nucleate boiling of halocarbon refrigerants over cylindrical surfaces of different material. Experimental data for refrigerants R-11, R-123, R-12, and R-134a have been raised and fitted according to two different procedures. It has been determined that exponents m and n are weakly affected by the refrigerant, and surface material and finishing. Liquid/surface combinations and surface roughness affect the coefficient C_{sf}. A correlation has been developed for C_{sf} in terms of the liquid/surface combination and surface roughness. The resulting correlation has been evaluated through the experimental data used in the fitting process and results obtained elsewhere. Deviations of correlation with respect to the experimental heat transfer coefficient are within acceptable ranges.
***Keywords**: Nucleate boiling, halocarbon, refrigerant, cylinder*

Introduction

Nucleate boiling has been under intense scrutiny since the early thirties, when pioneering research studies came to light. Ribatski (2002) rightly points out that the number of publications has grown steadily since that time. This interest is justified by the heat transfer enhancement that this mechanism promotes on heated surfaces. Generally speaking, nucleate boiling research has been traditionally focused into the investigation of the physical mechanism and the development of general correlations for the heat transfer coefficient. Physical models tend to reproduce the particular mechanism that prevails under specific operational conditions of the boiling surface such as pressure, liquid subcooling, liquid/surface combination, and geometry. As a result, most of the semi-empirical correlations are strongly dependent upon operational conditions not being amenable to generalizations. The Rohsenow's correlation is one of them, having endure up to present days. Based upon straightforward arguments, Rohsenow (1952) suggested that the heat transfer enhancement under boiling conditions is the result of local liquid circulation in the region close to the heating surface promoted by successive bubble detachments. Given this physical scenario, a locally defined Stanton number could be written in terms of an equally local Reynolds number and the liquid Prandtl number. The local Stanton number was referred to the mass velocity of vapor leaving the surface whereas the Reynolds number was written in terms of the same mass velocity and a characteristic dimension proportional to the bubble detachment diameter. After some manipulation the following equation results:

$$\frac{c_{pl} \cdot \Delta T}{h_{lg}} = C_{sf} \cdot \left\{ \frac{q''}{h_{lg} \cdot \mu_l} \cdot \left[\frac{\sigma}{g \cdot (\rho_l - \rho_g)} \right]^{1/2} \right\}^m \cdot \left(\frac{c_{pl} \cdot \mu_l}{k_l} \right)^n \quad (1)$$

which can be written in a reduced form as:

$$St^* = C_{sf} \cdot \mathrm{Re}_b^m \cdot \mathrm{Pr}_l^n \quad (2)$$

The left hand side of Eq. (1) corresponds to the inverse of Stanton number, St^*, whereas the first term of the right hand side could be considered a Reynolds number referred to the bubble departure diameter. Values of exponents m and n were found to be equal to 0.33 and 1.7 by curve fitting experimental results obtained elsewhere for liquids other than water. Rohsenow suggested to change the exponent of the Prandtl number to 1.0 for water. Furthermore, according to Rohsenow, whereas m is not affected, n might depend upon the surface finishing, attaining values in the range between 0.8 and 2.0. The numerical coefficient, C_{sf}, was related to the effect of liquid/surface combination through the contact angle, θ. Thus for water boiling on a smooth copper surface, Rohsenow determined the value of C_{sf} to be equal to 0.013. Later, Vachon et al. (1968) performed extensive experiments involving several liquid/surface combinations to obtain the associated values of C_{sf} and n. Neither Rohsenow nor Vachon and coworkers performed experiments involving halocarbon refrigerants boiling on cylindrical surfaces which are the main objective of present study. Noteworthy are studies by Sauer et al. (1975), Saiz Jabardo and Silva (1991) and more recently Pioro (1999) who fitted data from experiments involving a limited number of halocarbon refrigerants. Their data shed some light over the behavior of the Rohsenow correlation with respect to the aforementioned refrigerants. Table 1 presents a summary of studies

Paper accepted March, 2004. Technical Editor: Clóvis Raimundo Maliska.

carried out in relation with the Rohsenow correlation. The table includes information regarding the fluid(s), surface material, operational conditions such as the ranges of pool pressures and heat fluxes, and the values of C_{sf}, m, and n each study has come up with by fitting experimental results. Interesting to note in this table is that the few studies that have dealt with halocarbon refrigerants did it with the low pressure ones, such as R-11 and R-113, both of them of the banned family of CFCs.

The present study has been set forth to experimentally investigate nucleate boiling on cylindrical copper, brass and stainless steel surfaces of both low pressure R-11 (CFC) and R-123 (HCFC), and medium pressure halocarbon refrigerants, R-12 (CFC), and R-134a (HFC). Constant parameters of the Rohsenow correlation are evaluated and analyzed based upon data involving this set of refrigerants and over an extensive range of reduced pressures and heat fluxes along with different surface conditions.

Table 1. A summary of research studies related to the determination of the constant parameters of the Rohsenow correlation.

Author /year	Fluid	Surface/ Material	Surface Finish	p_{sat} (kPa)	q'' (kW/m^2)	C_{sf} / n / m
Rohsenow 1952	Water	Platinum	Polished	101-16995	28-530	0.013/1.0/0.33
	Benzene			101-5274	25-600	0.019/1.7/0.33
	n-pentane	Chromium		152-2861	29-440	0.015/1.7/0.33
	Etanol			101-4450	15-800	0.0027/1.7/0.33
Vachon et al (1968)	n-pentane	Copper	Polished	101	12.4-90	0.0154/1.7/0.33
						0.0145/1.7/0.10
	CCl_4				13.2-211	0.0070/1.7/0.33
						0.0063/1.7/0.09
	Water				28-828	0.0128/1.7/0.33
						0.0109/1.7/0.10
Sauer et al (1975)	R-11	Plate** Inconel-600	Mirror finish	---	0-54	0.0096/1.7/0.33
			Half-etched			0.0092/1.7/0.33
			All-etched			0.0090/1.7/0.33
			Glass peened			0.0090/1.7/0.33
			Sand paper			0.080/1.7/0.33
Kartsounes (1975)	R-12	Plate** Copper	Roughness	319	6-220	0.00356/1.7/0.33
			Polished			0.00464/1.7/0.33
Tewari et al (1986)	Water	Plate** Copper	Polished	8-100	15-50	0.021/1.7/0.33
Liaw and Dhir (1993)	Water	Plate*** Copper	Polished	101	250-870	0.0209/1.7/0.33 (14)*
						0.0194/1.7/0.33(38)*
						0.0172/1.7/0.33(90)*
Saiz Jabardo and Silva (1991)	R-11	Tube** Copper	Polished	132	0.8-64	0.0068/1.7/0.33
	R-113			103	0.8-110	0.004 /1.7/0,33
	R-114			112	0.8-110	0.004/1.7/0.33
Pioro (1999)	Water	Tube/ Brass	Polished	101	8-43	0.009/1.1/0.33
		St. Steel	Rq=0.53 µm	101	22-158	0.008/1/0.33
		St. Steel	Rq=3.6 µm	101	37-160	0.007/1/0.33
	Ethanol	Chromium	Polished	90-180	15-800	0.0045/1.47/0.33
	CCl_4	Brass	Polished	101	7,8-43	0.0022/2.1/0.33
	R-12	Copper	---	330-490	1.5-5	0.016/1.7/0.33
	R-11	Plate **	Ra=1.37 µm	98-230	1,4-12	0.0009/3.47/0.33
	R-113	Copper	Ra=1.37 µm	58-270	3.2-21	0.0022/2.25/0.33

* Contact angle, θ; ** horizontal; *** vertical

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_{corr} = correlation heat transfer coefficient [W/m^2.K]
$h_{exp.}$ = experimental heat transfer coefficient [W/m^2.K]
h_{lg} = latent heat of evaporation [J/kg]
k_l = thermal conductivity of liquid [W/m.K]
m,n = exponents of Rohsenow correlation
p_r = reduced pressure
Pr_l = Prandtl number of the liquid
q'' = specific heat flux [W/m^2]
Ra = roughness arithmetic average [µm]
Re_b = Reynolds number referred to the bubble diameter
Rq = roughness root mean square [µm]
St^* = inverse of the Stanton number
T_{sat} = saturation temperature [K]
T_w = wall temperature [K]

Greek Symbols

ΔT = surface superheat (T_w-T_{sat}) [K]
μ_l = dynamic viscosity of the liquid [Pa.s]
θ = contact angle [rad]
ρ_g = vapor density [kg/m^3]
ρ_l = liquid density [kg/m^3]
σ = surface tension [N/m]

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^{o}C and 90^{o}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 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 thermally 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.

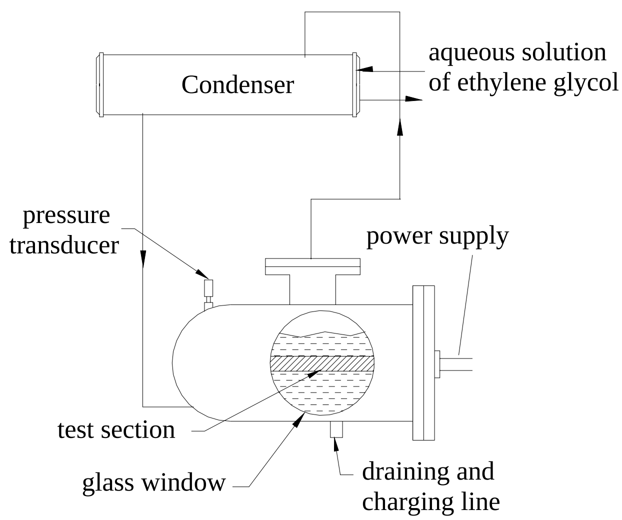


Figure 1. A schematic diagram of the experimental set up showing the main components and equipment.

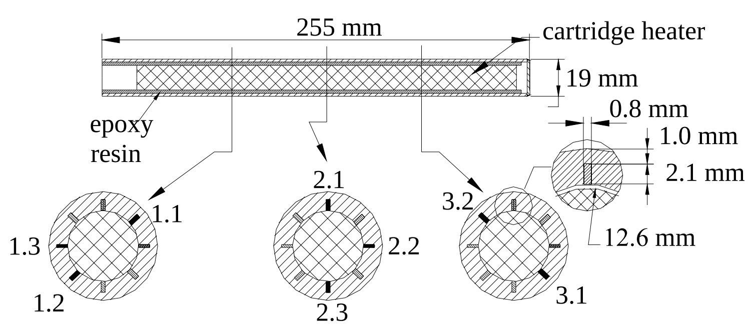


Figure 2. Longitudinal and transverse cut view of the test section showing the location of the surface thermocouples.

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 lathe 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 0.02±0.01 μm and 3.3± 0.4 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.

A Summary of Experimental Results

Tests conducted under the investigation reported herein have raised information regarding the effects on boiling heat transfer caused by the change in refrigerant, pressure and surface material and finishing condition. Though the main objective of the paper is to correlate results according to the form proposed by Rohsenow, a summarized analysis of the obtained data will be presented in such a way to clear up some important effects related the main physical parameters investigated in present research. These effects can clearly be seen in the boiling curves of Figures 3 to 5. Close examination of these figures allows one to draw the following general conclusions:

Table 2. Uncertainty of measured and calculated parameters.

Parameter	*Uncertainty*
minimum heat flux, q"=0.60 kW/m²	$\pm 1.8\%$
maximum heat flux, q"=120 kW/m²	$\pm 0.3\%$
Heat transfer area	$\pm 0.3\%$
wall temperature	$\pm 0.2K$
saturation temperature	$\pm 0.2K$
superheat temperature	$\pm 0.3K$
heat tranfer coefficient, h= 2.27 kW/ (m².K) *R-123,* p_r*=0.011, Ra=0.16μm, copper, q"=114 kW/m²*	$\pm 1.3\%$
heat tranfer coefficient, h= 4.2 kW/ (m².K) *R-134a,* p_r*=0.260, Ra=2.5μm, copper, q"=2.27 kW/m²*	$\pm 19.5\%$

(1) The slopes of boiling curves vary from values close to zero at the incipience of boiling up to an asymptotic level in the high heat flux range. The effect of pressure on the asymptotic slope seems to be of limited extent, especially in the high pressure range (Fig. 3).

(2) The region of the boiling curve where significant variations of the slope occur corresponds to the one known as Partial Nucleate Boiling, Collier and Thome (1994). The extent of this region depends upon the boiling liquid, pressure, and surface roughness. For conditions considered in present study, heat fluxes corresponding to the Partial Nucleate Boiling region are limited to a maximum of 30 kW/m^2.

(3) Pressure affects positively the heat transfer, and so does roughness as the displacement of the boiling curves to the left suggests. This should be an expected result considering effects of both the surface tension and the range of cavity size, which are respectively associated to boiling incipience and density of active cavities. Refrigerants are affected differently by the pressure and especially by the surface roughness. In fact, as shown in Fig. 4(a), the displacement of the boiling curve to the left with *Ra* is more significant for R-11 than for R-123. For the case of medium pressure refrigerants, Fig. 4 (b), R-12 is affected more by surface roughness than R-134a.

(4) Effects of pressure and roughness on the boiling curve are more effective at lower pressures as can clearly be seen in Figs. 3 and 4. This trend confirms a suggestion previously made by Cooper (1984).

(5) Another important nucleate boiling parameter is the heating surface material. As previously suggested, present research involved tests with three materials: copper, brass and stainless steel. Figure 5 shows boiling curves of refrigerants R-123 and R-134a on surfaces made up of the aforementioned materials. The effect of the heating surface material over the boiling curve is strikingly significant, the extent depending upon the particular fluid. It can be noted in Fig. 5(a) for refrigerant R-123 that differences between boiling curves for copper and brass surfaces are minimal as compared to that for stainless steel. On the other hand, in the case of refrigerant R-134a, Fig. 5 (b), boiling curves corresponding to different materials present comparable differences between each other, with copper presenting better performance and stainless the worst.

(6) Results from part 5 suggest the influence of a combined surface/liquid effect instead of an isolated surface material effect, as suggested by some authors. In fact, if this were the case, boiling curves from Fig. 5(a) for copper and brass would present comparable differences between each other as those from Fig. 5(b), opposite to what actually is observed in these figures. This conclusion is in accordance with the proposed Rohsenow surface/liquid effect, characterized through the C_{sf} numerical coefficient.

Correlation of Results

Boiling curves as the ones shown in Figs. 3 to 5 include the following three regions with increasing heat flux: (1) natural convection; (2) partial nucleate boiling; and (3) fully developed nucleate boiling. Data considered for correlation purposes should be only those corresponding to fully developed nucleate boiling. However, in some previous studies experimental data for correlation purposes have been chosen by arbitrarily selecting a minimum heat flux. This heat flux would be one that would guarantee the occurrence of nucleate boiling and, as a result, the elimination of natural convection data. Thus, by adopting this procedure, data for both partial and fully developed nucleate boiling would be included in the set chosen for the fitting procedure. A more rigorous procedure would involve the determination of the onset of fully developed nucleate boiling in such a way that only experimental conditions corresponding to this boiling regime would be considered for fitting purposes. However, it must be recognized that the onset of this regime is not very well established since it depends upon parameters such as surface material and roughness as well as the particular boiling liquid, as clearly displayed in Figs. 3 to 5. Both procedures have been followed in this paper in order to compare results from each one regarding the level of correlation of experimental data. Thus, in the first case, a minimum heat flux was chosen in an "ad hoc" manner so that natural convection related data were not included in the set used for fitting purposes. A preliminary analysis of data allowed us to choose the aforementioned minimum heat flux as being equal to 5 kW/m^2. The second procedure involved a preliminary examination of experimental data along with the proposition of a criterion for the onset of fully developed nucleate boiling, related to the maximum value of the derivative of the boiling curve (q'' vs. ΔT). Initially, the variation of the derivative, $dq''/d(\Delta T)$, of the boiling curves was raised followed by the determination of the onset heat flux and the selection of data points corresponding to fully developed nucleate boiling. The heat flux at the onset of fully developed nucleate boiling varied between 3 and 30 kW/m^2, depending upon the refrigerant, pressure and surface material and roughness.

Curve fitting of experimental results was performed according to the following procedures: (1) by keeping the original values of m and n proposed by Rohsenow, i. e. 0.33 and 1.7, and determining the coefficient C_{sf} for each refrigerant/surface material and roughness combination; (2) by letting C_{sf}, m, and n free.

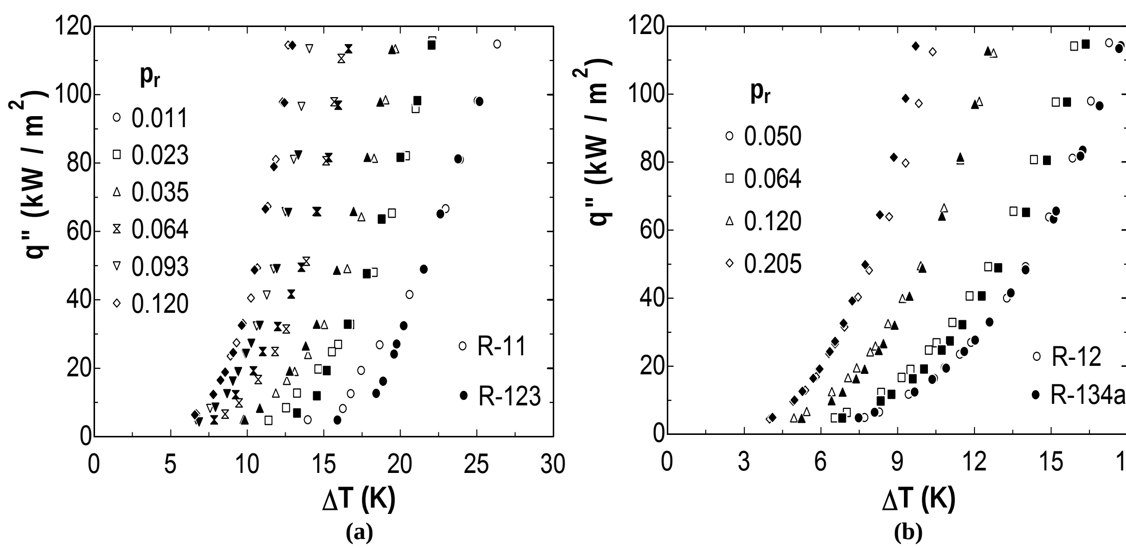


Figure 3. Boiling curves at different reduced pressures. (a) Low pressure refrigerants R-11 and R-123 for an average roughness, *Ra*=0.16 μm; (b) medium pressure refrigerants R-12 and R-134a for an average roughness, *Ra*=0.07 μm. Copper surface. Filled symbols stand for R-123 and the blank ones for R-11.

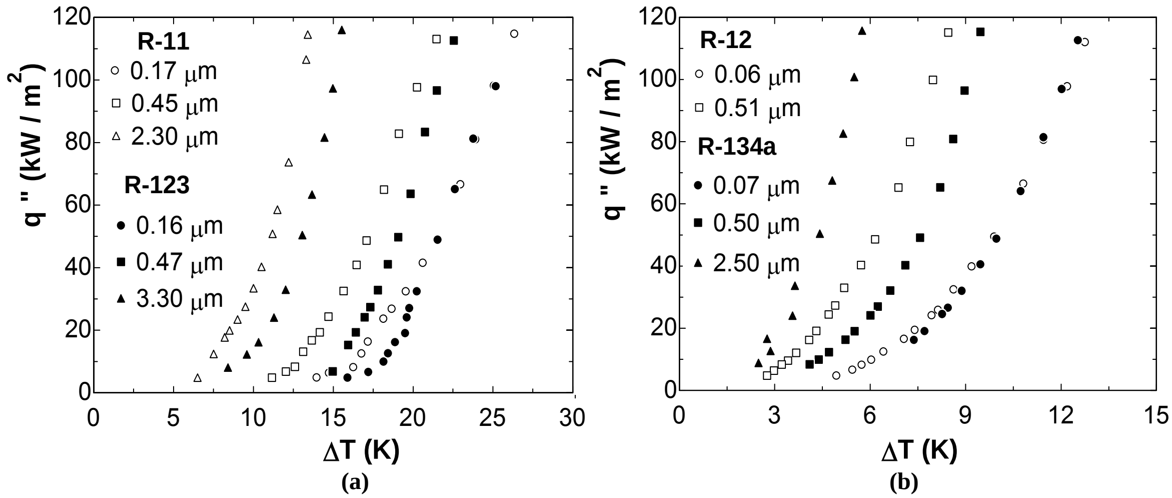


Figure 4. The effect of surface roughness on the boiling curve. (a) Low pressure refrigerants R-11 and R-123 for reduced pressure of 0.011, filled symbols stand for R-123 and the blank ones for R-11; (b) medium pressure refrigerants R-12 and R-134a for reduced pressure of 0.120, filled symbols stand for R-12 and the blank ones for R-134a. Copper surface.

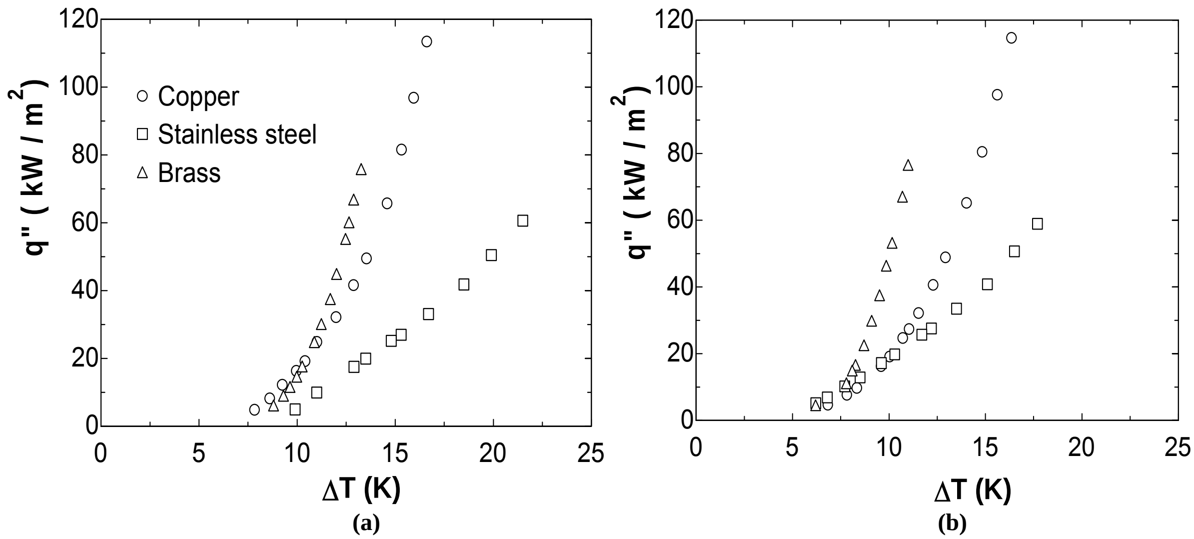


Figure 5. The effect of surface material on the boiling curve. (a) Low pressure refrigerant R-123 for reduced pressure of 0.064 and average roughness of 0.16 μm; (b) medium pressure refrigerant R-134a for reduced pressure of 0.064 and average roughness of 0.07 μm.

C_{sf} Evaluation for m=0.33 and n=1.7

In this case, fitting consisted in determining the coefficient C_{sf} for the refrigerant/surface material and roughness combinations considered in present study. Results are summarized in Table 3 for both $(q")_{min}$=5 kW/m^2 and fully developed nucleate boiling data sets. The following general conclusions can be drawn from this table:

(1) C_{sf} values are not significantly affected by the data set considered in the fitting procedure, except in the case R-11 boiling on the stainless steel surface. However the absolute average deviation is generally higher for the $(q")_{min}$=5 kW/m^2 correlation with respect to its corresponding data set than that for the fully developed nucleate boiling one with respect to its associated data set.

(2) The effect of the liquid/surface material combination over C_{sf}, previously suggested by Rohsenow and others, can clearly be noted. Unfortunately data from other sources are scarce. Thus a detailed comparison with present results is rather questionable since surface material and roughness, and operational conditions are generally not compatible.

A significant effect of the surface roughness *(Ra)* over C_{sf} can be noted in the table, a trend which had not been previously observed. As a general rule, C_{sf} diminishes with the roughness of the surface, a result which is consistent with the observed trends in the boiling curves. It must be noted that the originally proposed dependency upon the surface/liquid combination by the part of C_{sf} is related to the wetting level of the liquid with respect to the heating surface. Thus C_{sf} must keep a closed relationship with the contact angle, which in turn depends upon the surface roughness, as suggested elsewhere, Bikerman (1970), Kandlikar (2001).

Table 3. Values of C_{sf} for different refrigerant/surface material and roughness; m=0.33, n=1.7.

			$(q")_{min}$ = 5 kW/m^2		Fully developed	
Surface material	**Refrigerant**	***Ra* [μm]**	C_{sf}	**Average absolute deviation [%]**	C_{sf}	**Average absolute deviation [%]**
Copper	R-11	0.17	0.0086	15.2	0.0084	12.6
		0.45	0.0066	14.7	0.0065	13.1
		2.40	0.0042	11.8	0.0041	11.0
	R-123	0.16	0.0070	10.2	0.0065	6.4
		0.47	0.0058	12.6	0.0056	10.8
		3.30	0.0036	6.2	0.0036	6.0
	R-12	0.06	0.0100	15.5	0.0100	14.0
		0.51	0.0060	9.9	0.0060	9.8
	R-134a	0.07	0.0073	6.6	0.0072	5.4
		0.50	0.0053	4.0	0.0052	3.4
		2.50	0.0032	3.2	0.0032	3.1
Stainless Steel	R-11	0.16	0.0150	12.3	0.0105	9.8
	R-123	0.16	0.0080	11.5	0.0087	4.3
	R-134a	0.07	0.0080	11.9	0.0083	11.3
Brass	R-11	0.15	0.0080	16.1	0.0083	14.0
	R-123	0.16	0.0070	15.5	0.0063	9.5
	R-12	0.08	0.0090	20.4	0.0090	21.8
	R-134a	0.08	0.0060	10.9	0.0060	0.5

General Procedure

A second and more general fitting procedure has been pursued consisting in the determination of three parameters of the Rohsenow's correlation: m, n and C_{sf}. The adopted procedure has been performed according to the following steps.

• *m* Determination

Initially all data points were plotted in terms of curves St^* vs. Re_b. Values of m for each refrigerant/surface combination have been determined with most of the results varying in a relatively narrow range. This is a clear indication that the refrigerant, surface material and roughness, and pressure do not affect significantly the value of m. The plot of Fig. 6 of all fully developed nucleate boiling data points in terms of St^* vs. Re_b seems to confirm this trend. It can be noted that the cloud of data points is characterized by a common general slope, related to the m value of Eq. (2). It must be stressed that, by doing so, individual trends involving different refrigerants, pressures, and surface material and condition are overviewed. According to Fig. 6, the resultant value of m is 0.21, whereas for data corresponding to $(q")_{min}$=5 kW/m^2, m is equal to 0.18. These results allow one to conclude that the inclusion of partial nucleate boiling data do not affect significantly the value of m.

• *n* and C_{sf} Determination

The characteristic value of n has been determined by plotting data in terms of (St^*/Re_b^m) vs Pr_l, as shown

in Fig. 7 for the fully developed data set. It can be noted that, despite significant dispersion, plotted data follow a common trend characterized by a single slope, illustrated by the superposed straight line in the plot. Given that n is related to this slope, one can immediately conclude that, as a first approximation, its value is not significantly affected either by the refrigerant, surface condition and material or pressure. The resulting value of n is 1.03, for fully developed nucleate boiling data, and 1.15, for data corresponding to $(q")_{min}$=5 kW/m^2. Similarly to m, differences in the value of n associated to the data sets considered in this paper are relatively small.

It is interesting to note at this point that the liquid Prandtl number for refrigerant R-12 presents an odd behavior compared to that of the other three refrigerants in the range of pressures considered in present study, as shown in Fig. 8. It can be noted that whereas Pr_l diminishes with pressure for refrigerants R-11, R-123, and R134a, for refrigerant R-12, Pr_l presents a minimum value at a reduced pressure of the order of 0.1. In addition, the relative variation of liquid refrigerant R-12 Prandtl number in the experimental pressure range (~ 10%) is much smaller than that for the other refrigerants (higher than 25%). Thus, the inclusion of R-12 experimental data in Fig. 7 affects the value of n due to the aforementioned shift in the slope with the reduced pressure though the relative variation of Pr_l for this refrigerant is of limited extent. As an example of this effect, the value of n changes from 1.15 to 1.55 when R-12 data are removed from a plot similar to that of Fig. 7 for the $(q")_{min}$=5 kW/m^2 data set. In present study the value of n was obtained including R-12 data for the sake of generality.

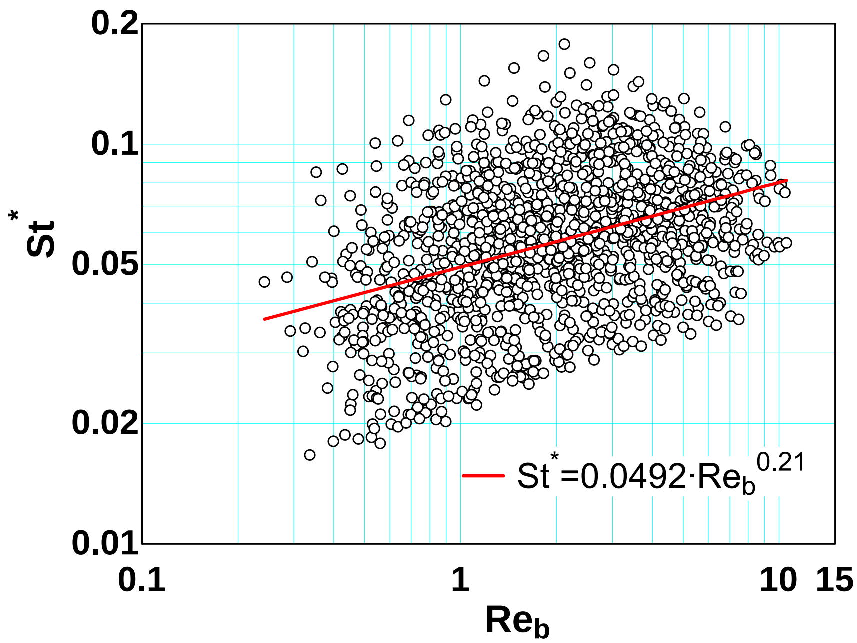


Figure 6. Experimental data in terms of *St* vs. Reb* for the fully developed nucleate boiling set.

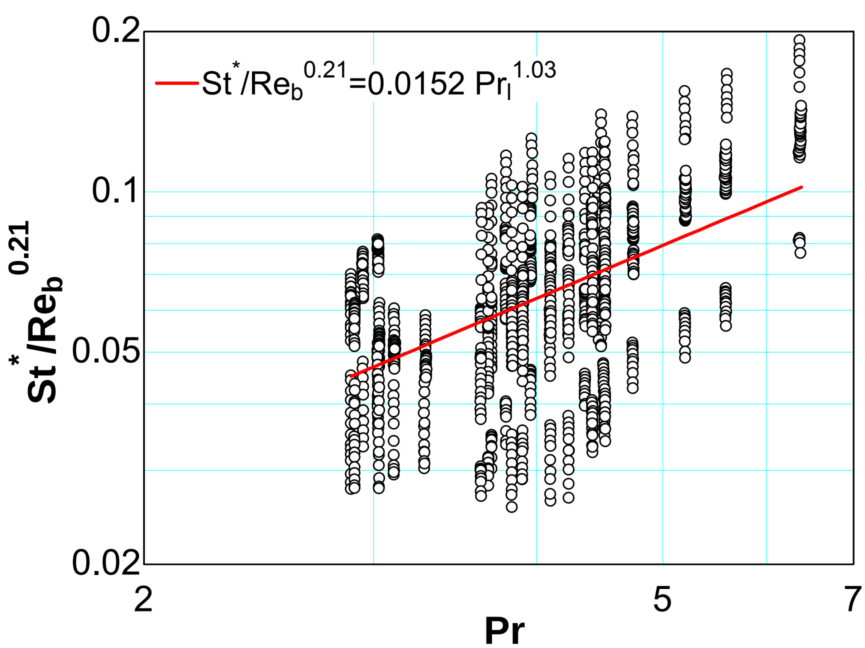


Figure 7. Fully developed nucleate pool boiling data in terms of $St^* / Re_b^{0.21}$ vs. Pr_l.

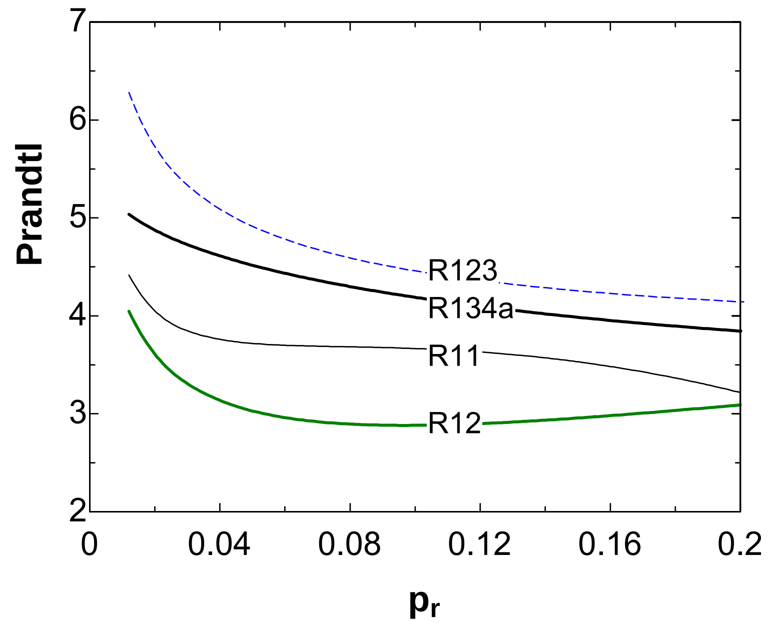
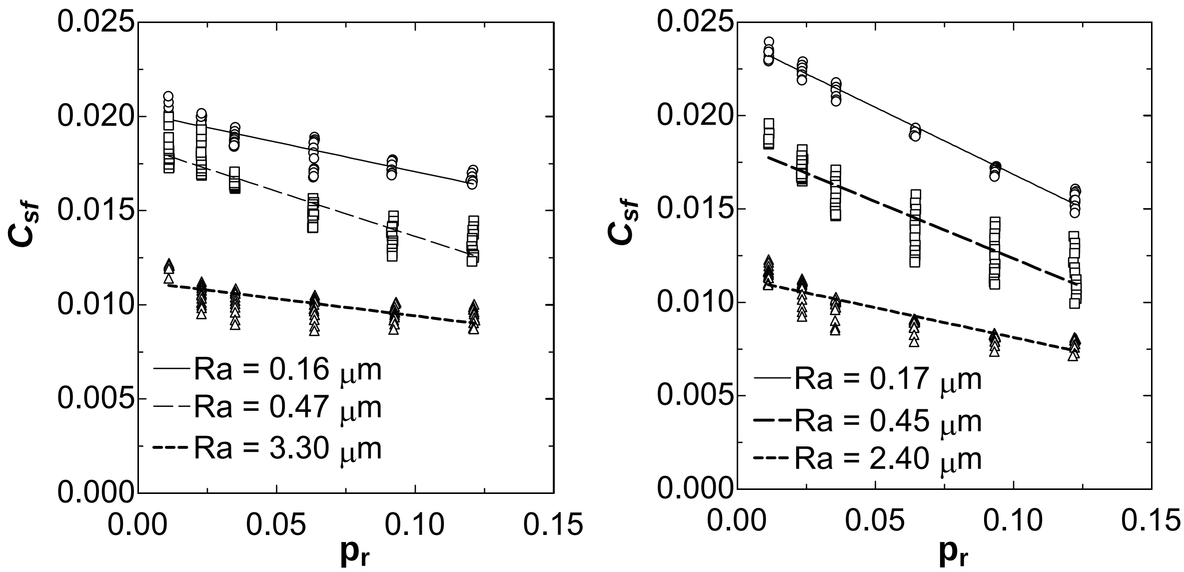


Figure 8. Variation of the liquid Prandtl number with reduced pressure for different refrigerants.

The coefficient C_{sf} of the Rohsenow's correlation has been obtained as the value where the (St^*/Re_b^m) vs Pr_l curve crosses the vertical axis. The dispersion of data in the plot of Fig. 7 is a clear indication that C_{sf} is affected not only by the liquid/surface combination, as previously suggested by Rohsenow and succeeding researchers, but also by the surface roughness, *Ra*, as pointed out in Section 5.1. As a result, data points of the plot of Fig. 7 must be sorted so that the effects of the aforementioned parameters over C_{sf} can quantitatively be determined. An example of the kind of results obtained by this procedure can be seen in Fig. 9, where the variation of C_{sf} with the reduced pressure for different surface conditions and refrigerants R-123 and R-11 boiling over copper surfaces is shown. It can be noted that, as a rule, C_{sf} diminishes with both the reduced pressure and surface roughness. In addition, the higher the roughness of the surface the lesser the effect of pressure.



(a) **(b)**

Figure 9. Variation of C_{sf} with reduced pressure for different surface roughness for refrigerants boiling over a copper surface. (a) R-123; (b) R-11.

Individual C_{sf} curves for each refrigerant and surface material similar to those of Fig. 9 have been obtained. These results have been fitted by a correlation with the following general form:

$$C_{sf} = C \cdot \{[a \cdot \ln(Ra) - b] \cdot p_r - c \cdot \ln(Ra) + d\} \quad (3)$$

valid for the refrigerants and refrigerant/surface combinations considered in this paper. Individual values of coefficients *a* to *d* have been obtained, requiring the use of one equation for each refrigerant. The procedure could be simplified by fitting data extensive to all the refrigerants with a single equation of the same general form as Eq. (3). Results form this general equation correlate data with adequate precision though not being as accurate as the particular ones as should be expected. The general equation has been adopted in this paper, according to it the coefficients *a* to *d* are constant and the refrigerant/surface material combinations are taken by the coefficient *C*. Table 4 presents values of the obtained coefficients from the data sets corresponding to fully developed nucleate boiling and $(q")_{min}$=5 kW/m^2.

Table 4. Coefficients for the C_{sf} correlation, Eq. (3).

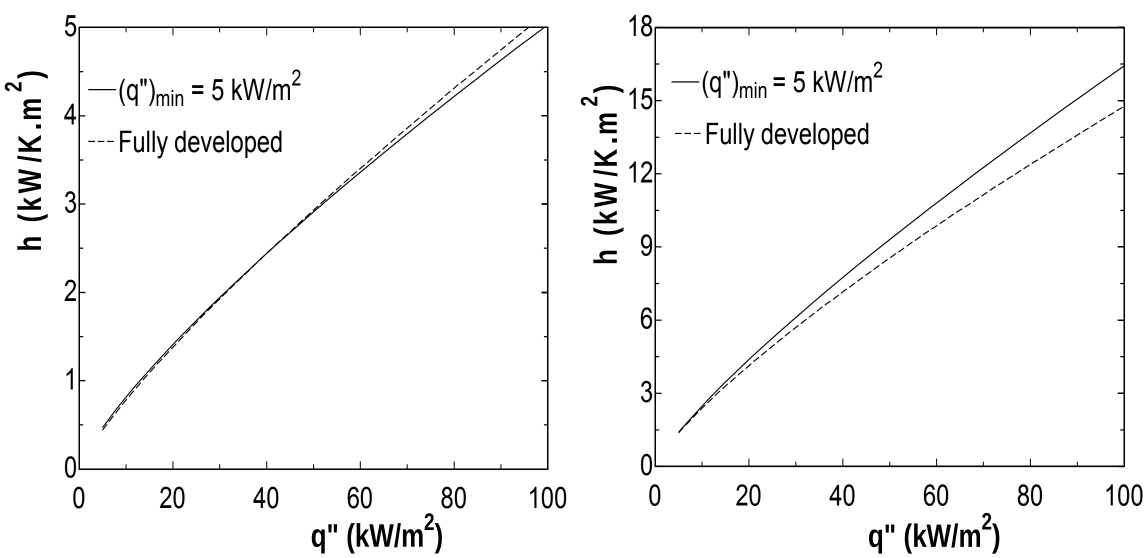
	Fully developed				$(q")_{min}$=5kW/m^2			
	A	***b***	***c***	***d***	***a***	***B***	***c***	***d***
	0.00770	0.0258	0.00360	0.0138	0.0064	0.00188	0.00320	0.0110
R-11/copper	C = 1.00				C = 1.00			
R-11/SS*	C = 1.30				C = 1.20			
R-11 brass	C = 0.90				C = 0.90			
R-123/copper	C = 1.00				C = 1.00			
R-123/ SS	C = 1.30				C = 1.20			
R-123/brass	C = 0.95				C = 0.95			
R-134a/copper	C = 1.00				C = 1.00			
R-134a/SS	C = 1.15				C = 1.10			
R-134a/brass	C = 0.90				C = 0.80			
R-12/copper	C = 1.00				C = 1.00			
R12/ SS	–				–			
R-12/brass	C = 1.00				C = 1.00			

* SS: Stainless steel

Table 4 indicates that differences between the values of C_{sf} resulting from both data sets are minimal. Considering that the differences between exponents *m* and *n* are also small, as previously noted, one can conclude that the proposed correlations are very close to each other as the plots in Figs. 10 (a), (b) clearly display. The correlations are represented in terms of the heat transfer coefficient, *h*, versus the heat flux, *q"*, in these figures. The heat transfer coefficient is determined as

$$h = \frac{q"}{T_w - T_{sat}} = \frac{q"}{\Delta T} \tag{4}$$

The maximum deviation between results from both correlations is of the order of 6.0% for case of Fig. 10 (a), for refrigerant R-11 and low reduced pressure and roughness, p_r=0.023 and 0.1 μm. The case of Fig. 10 (b), for the same refrigerant as in case (a), and p_r=0.1 and *Ra*=2.5 μm, presents a maximum deviation of the order of 11.0%. As expected, differences are minimal between the proposed correlations, a result that could explain why some of the literature correlations developed from data sets involving partial nucleate boiling data produce reasonable results.



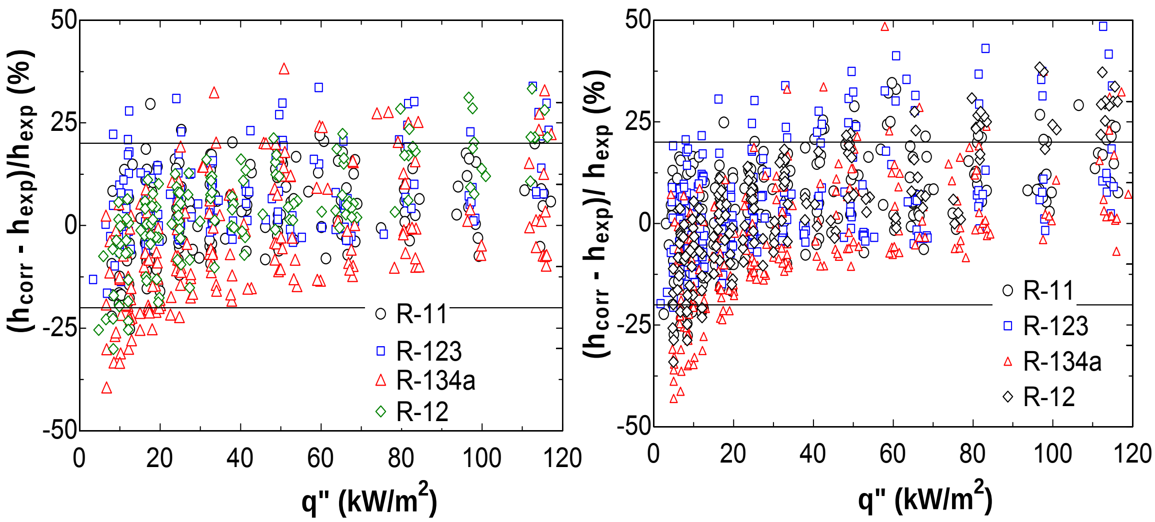
(a) **(b)**

Figure 10. Heat transfer coefficient vs. heat flux according to correlations for fully developed and $(q")_{min}$=5 kW/m^2 nucleate boiling. (a) R-11, p_r=0.023 ; *Ra*=0.1 μm; (b) R-11, *pr*=0.1 ; *Ra*=2.5 μm.

Evaluation of the Proposed Correlation

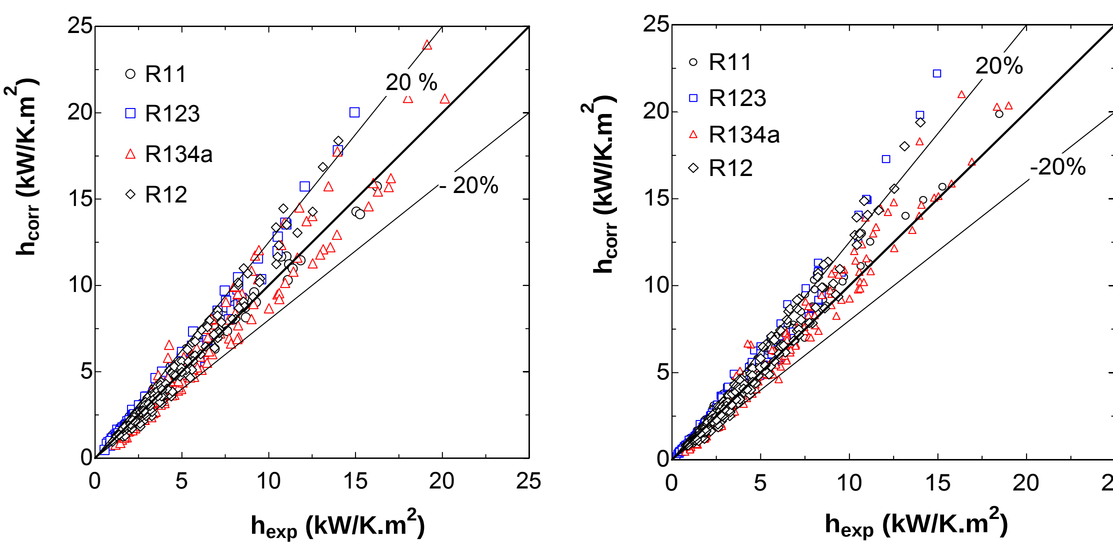
In the previous section the procedure for fitting data was explained in detail leading to a general Rohsenow's correlation. The next step is to evaluate the proposed correlation with respect not only to data obtained as part of the research reported in this paper but also to data raised elsewhere.

In order to evaluate the performance of the proposed correlations with respect to experimental data, the relative deviation between the correlation and the experimental heat transfer coefficients is plotted against the corresponding heat flux. This plot is shown in Figs. 11 (a), (b), respectively for the fully developed nucleate boiling and $(q")_{min}$=5 kW/m^2 data sets. It can be noted that most of the plotted data points fall within the ± 20% range, especially for the fully developed nucleate boiling data. Most of the data outside this range though of limited extent correspond to refrigerants R-123 and R-134a. It can also be noted that, as general rule, in the range of reduced heat fluxes the correlation tends to under predict the heat transfer coefficient, showing the opposite trend for higher heat fluxes. These trends are also discernible in the plots of Figs.12 (a), (b), where the correlation heat transfer coefficient, h_{corr}, is plotted against the experimental, h_{exp}. The absolute average deviation of results from the fully developed nucleate boiling correlation with respect to their experimental counterparts is of the order of 10.1% whereas that relative to the $(q")_{min}$=5 kW/m^2 data set is of the order of 11.2%. These results are clearly noticeable in both figures, Figs. 11 and 12. Results displayed in these figures demonstrate the adequacy of Rohsenow's type of correlation in fitting nucleate boiling of halocarbon refrigerants over cylindrical surfaces.



(a) (b)

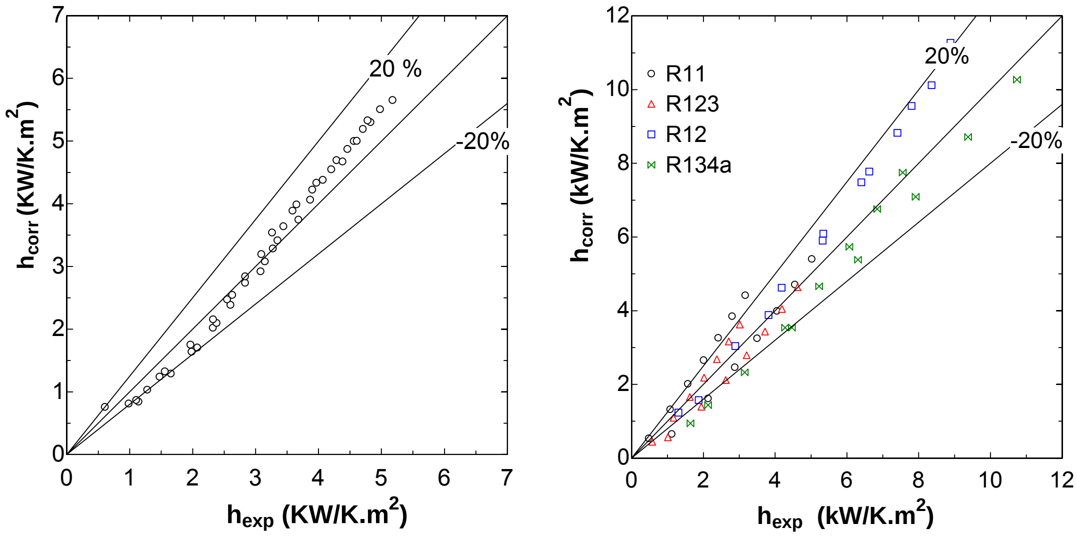
Figure 11. Relative deviation of the correlation with respect to the experimental heat transfer coefficient. (a) fully developed nucleate boiling; (b) *$(q")_{min}$*=5 kW/m^2 data set.



(a) (b)

Figure 12. Correlation versus experimental heat transfer coefficient. (a) fully developed nucleate boiling; (b) *$(q")_{min}$*=5 kW/m^2 data set.

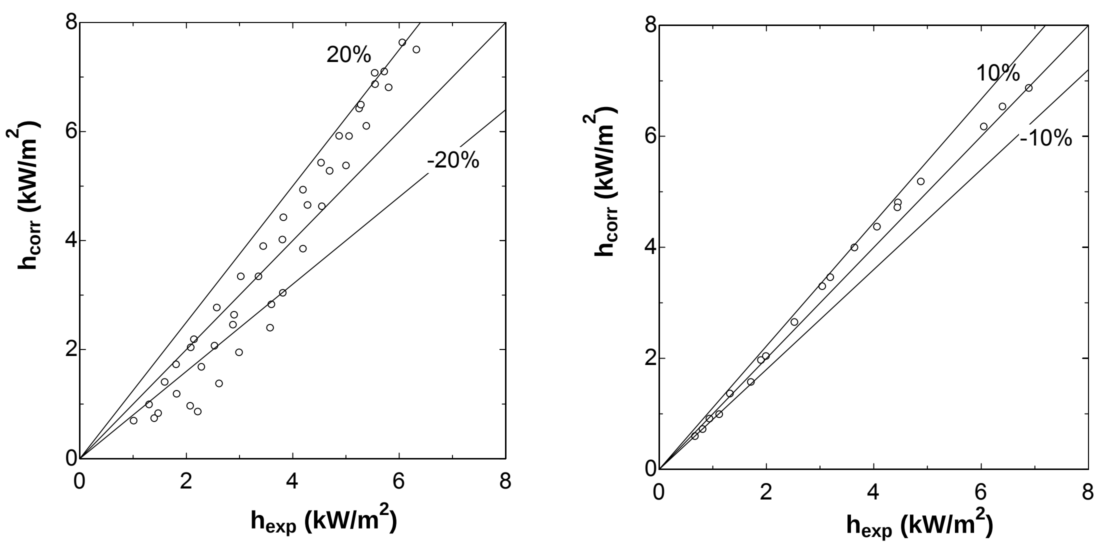
Data from independent sources have been used in the evaluation of the proposed correlation. For refrigerant R-11 boiling on a brass surface, data from Silva (1989) have been used. Data from Webb and Pais (1992) for the same refrigerants considered in present paper boiling over copper surfaces have also been used for comparison purposes with the correlation for $(q")_{min}$=5 kW/m^2. An average roughness, *Ra*, of 0.6 μm has been assumed for the surfaces since the authors only informed that the working surface was a commercial one. The comparison can be seen in Figs. 13 (a) and (b) in h_{corr} vs h_{exp} plots. It can be noted that the proposed correlation fits very well data from both studies, with deviations being well within the ±20% range, a result that can be considered adequate since the only adjustment made in the application of the proposed correlation was the assumption of the surface roughness.



(a) (b)

Figure 13. Comparison of the *(q")$_{min}$*=5 kW/m^2 correlation heat transfer coefficient with experimental data from (a) Silva (1989) for R-11; and (b) Webb and Pais (1992) for refrigerants R-11, R-123, R-12, and R-134a.

Data from Silva (1989), for refrigerant R-113 and a brass surface, and from Jensen (1985), for the same refrigerant and a stainless steel surface, have been fitted using the correlations proposed in the present investigation. The resulting values of the coefficient *C*, Eq. (3), are the following: 0.9 for brass, and 1.5, for stainless steel. The average roughness, *Ra*, of both surfaces has been assumed as being equal to 0.6 μm. Given the uncertainty of the experimental data regarding the roughness of the surfaces, the plots of Figs. 14 (a), (b), in terms of h_{corr} vs h_{exp}, display reasonable results from the correlation. Results from Silva (1989) for a brass surface, Fig,. 14 (a), are not as well correlated as the ones from Jensen (1985), Fig. 14 (b), for a stainless steel surface. In fact, the absolute average deviation of correlation heat transfer coefficient with respect to the experimental ones from Silva (1989) is of the order of 27% whereas with respect to those from Jensen (1985) is 6.2%.



(a) (b)

Figure 14. h_{corr} *(q")$_{min}$*=5 kW/m^2, versus h_{exp}. Refrigerant R-113, data from (a) Silva (1989), brass surface; and (b) Jensen (1985), stainless steel surface.

Conclusions

The research reported herein has been set forth in order to investigate the performance of the Rohsenow type of correlation when applied to nucleate boiling of halocarbon refrigerants over cylindrical surfaces of different material. Two fitting procedures have been tried, including one consisting in keeping the exponents originally proposed by Rohsenow and adjusting the coefficient, C_{sf}. The other procedure, considered as general, fitted the exponents as well as the coefficient. It has been determined that exponents m and n are weakly affected by the refrigerant, and surface material and finishing. Liquid/surface combinations and surface finishing affect the coefficient C_{sf}. A correlation has been developed for C_{sf} in terms of the liquid/surface combination and surface roughness. For the purpose of curve fitting, two data sets have been considered: one arbitrarily chosen to include data corresponding to heat fluxes higher than 5 kW/m^2 whereas the other involved only fully developed nucleate boiling conditions. Though slightly different values of C_{sf}, m and n have resulted from both data sets, differences in results could be considered minimal for all practical purposes. The correlations have been evaluated through the experimental results used in the fitting process and results obtained elsewhere. Deviations between the correlation and the experimental heat transfer coefficient are within acceptable ranges.

Acknowledgements

The authors gratefully acknowledge the support given to the reported research by the Fundação de Amparo à Pesquisa do Estado de São Paulo, FAPESP, and Coordenação de Aperfeiçoamento de Pessoal de Nível Superior, CAPES, Brazil. The technical support given to this investigation by Mr. José Roberto Bogni is also appreciated and recognized.

References

Abernethy, R. B., and Thompson, J. W., 1973, *Handbook, uncertainty in gas turbine measurements*, Arnold Engineering Development Center, Arnold Air Force Station, Tennessee

Bikerman, J. J., 1970, *Physical Surfaces*, Academic Press, Inc, New York.

Collier, J. G., and Thome, J. R., 1994, *Convective Boiling and Condensation*, 3rd Edition, Oxford University Press, Oxford.

Cooper, M. G., 1984, "Heat flow rates in saturated nucleate pool boiling - A wide ranging examination using reduced properties", *Advances in Heat Transfer*, Vol. 16, pp.157-238.

Jensen, M. K., 1985, "Physical Properties Data Tables and Experimental Boiling Data", Personal Communication.

Kandlikar, S. G., 2001, "A Theoretical Model to Predict Pool Boiling CHF Incorporating Effects of Contact Angle And Orientation", *Journal of Heat Transfer*, Vol. 123, pp. 1071-1079.

Kartsounes, G. T., 1975, "A Study of Treatment on Pool Boiling Heat Transfer in Refrigerant 12", *ASHRAE Transactions*, Vol. 18, pp. 320-326.

Liaw, S., and Dhir, V. K., 1993, "Void Fraction Measurements During Saturated Pool Boiling of Water on Partially Wetted Vertical Surfaces", *Journal of Heat Transfer*, Vol. 111, pp.731-738.

Pioro, I. L., 1999, "Experimental Evaluation of Constants for the Rohsenow Pool Boiling Correlation", *Int. J. Heat Mass Transfer*, Vol. 40, pp. 2379-2392.

Ribatski, G., 2002, "Theoretical and Experimental Analysis of Pool Boiling of Halocarbon Refrigerants", Doctoral thesis, Escola de Engenharia de São Carlos, University of São Paulo, Brazil.

Rohsenow, W. M., 1952, "A Method of Correlating Heat Transfer Data for Surface Boiling Liquids", *Transactions of ASME*, Vol.74, pp. 969-976.

Saiz Jabardo, J. M., and Silva, C. L., 1991, "Modeling of the nucleate boiling of refrigerant-oil mixtures", in: *18th International Congress of Refrigeration*, Montreal, Canada.

Sauer, Jr. H. J., Medrow, R. A., and Sinnarwalla, A. M., 1975, "Effects of Surface Condition on Nucleate Boiling of Refrigerant-11", *ASHRAE Transactions*, Vol. 81, part. 2, pp. 274-28.

Silva, C. L., 1989, "*Experimental Investigation of the Nucleate Boiling of Refrigerant-Oil Mixtures"*, Doctoral thesis, Escola Politécnica, University of São Paulo, Brazil.

Tewari, P. K., Verma, R. K., and Ramani, M. P. S, 1986, "Effect of Surface Roughness and Polymeric Additive on Nucleate Pool Boiling at Sub-Atmospheric Pressures", *Int. Comm. Heat mass transfer*, Vol. 13, pp. 503-514.

Vachon, R. I., Nix, G. H., and Tanger, G. E., 1968, "Evaluation of Constants for the Rohsenow Pool-Boiling Correlation", *Journal of Heat Transfer*, Vol. 90, pp. 239-247.

Webb, R. L. and Pais, C., 1992, "Nucleate Pool Boiling Data for Five Refrigerants on Plain, Integral-Fin and Enhanced Tube Geometries", *Int. J. Heat Mass Transfer*, Vol. 35, pp. 1893-1904.