Boiling pure fluids at sub atmospheric pressures

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Abstract— **The study and sizing of sorption machine evaporators are based on the prediction of the heat transfer coefficient at atmospheric pressures, but in the literature we only find correlations modeled from experiments for a wide range of pressure, where the majority of the data are above atmospheric pressure; A review of the experiments of boiling at sub-atmospheric pressures was carried out and compared to four known correlations for three types of fluids, which are water, hydrocarbons and refrigerants; The results obtained showed deviations of the predicted data from the experimental values for three correlations and convincing results for the fourth.**

Keywords— *boiling, correlation, heat transfer coefficient, pressure, sub-atmospheric.*

I. INTRODUCTION (*HEADING 1*)

The heat transfer during pool boiling is used in refrigeration evaporators, air conditioning heat pumps and industrial processes, it is sought after for its heat transfer efficiency for low temperature gradients, on the other hand it is very sensitive to parametric effects.

The needs for cooling and air conditioning are growing, this demand is met by steam compression machines, which are very widespread in the industrial and domestic fields; another type of machine, sorption refrigeration machines have appeared and are increasingly developed, their advantages are that they meet new directives and regulations for the protection of the environment.

The design and manufacture of two-phase equipment, such as the evaporator requires a better knowledge of the phenomenon of boiling at sub-atmospheric pressures ; the modeling of correlations during the pool boiling is relatively well studied, but at low pressures new phenomena appear and the valid correlations for the pool boiling should be checked or readjusted.

Low pressure boiling shows totally different characteristics to known boiling regimes such as nucleate or film boiling as pointed out by Florence Giraud *et al* [1] ; where they detected a new boiling regime, which is characterized by high growth rates, longer waiting times and larges volumes of bubbles at detachment, in addition they observed the non-homogeneity of the pressure and the saturation temperature.

Baki and Aris [2] made the experimental study of the boiling of R141b on a horizontal tube, the results were compared with three known correlations, Baki *et al* [3] and Touhami *et al* [4] studied the impact of the outer diameter of a horizontal tube during pool boiling and have proposed a correlation that can give the coefficient of heat transfer as a function of the diameter and the thermo-physical characteristics of the fluid, Baki [5-7] compared experimental data of the boiling of fluids outside a horizontal tube with known correlations, Baki [8] studied pool boiling and its limits of hydrogen and compared many correlations with experimental data, also analyzed the onset and the critical heat flux.

The objective of this article is to compare the experimental data collected of the heat transfer coefficient from the literature with values predicted by four known correlations of pool boiling at sub-atmospheric pressures, for several pure fluids.

II. REVIEW OF CORRELATIONS AND EXPERIMENTAL DATA

From the literature we have drawn four correlations from known authors [9,12], these relationships have been modeled from experimental data and being able to predict the heat transfer coefficient during pool boiling, they are drawn up in the table 1.

All of these correlations from (1) to (4) make it possible to calculate the heat transfer coefficient directly, or indirectly through the heat flux ; the predicted values are determined as a function of the heat flux, the thermo-physical characteristics of the fluid and the pressure.

Kruzhlin's correlation (1) [9] calculates the heat transfer coefficient as a function of the heat flux and the characteristics of the fluid; The correlation (2) of Mc Nelly [10] determines the heat transfer coefficient from the heat flux of the density ratio of some thermo-physical parameters and the operating pressure; Mostinski's correlation (3) [11] gives the heat transfer coefficient as a function of critical pressure, heat flux and a function of reduced pressure; Labuntsov's correlation (4) [12] determines the heat transfer coefficient as a function of thermo-physical parameters, saturation temperature and heat flux.

Table 2 groups together the experimental data from the literature [13,24], which relate to the pool boiling of pure fluids at sub-atmospheric pressures, totaling 548 points. In this case, the heating element is tube or disc, the absolute pressure varies from 0.3 to 100 kN/m²; The heat flux covers a range of 0.1 to 446 kW/m², the heat transfer coefficient is between 0.2 and 18.6 kW/m².K; grades are stainless steel, brass and copper, the substances used are water, hydrocarbons and refrigerants, the thermo-physical parameters of fluids at saturation are draw from the NIST site (National Institute of Standard and Technology).

Figure 1 shows the relationship between the heat flux and the heat transfer coefficient for all the data points collected from the experiments [13,24], the set of plotted points follows a curve trend except for a group of points of the series [22] which deviate from the whole.

Table 1: Boiling Correlation.

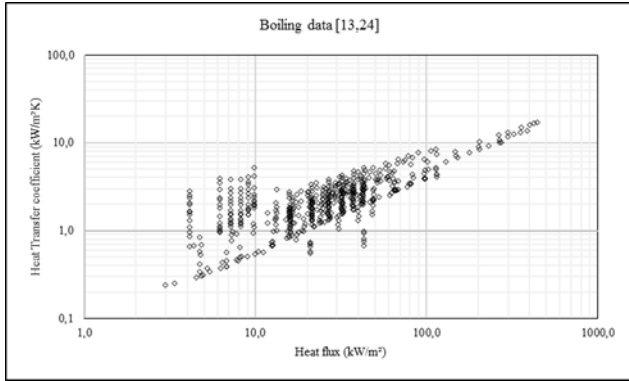| Author, Reference / Year	Correlation	
Kruzhilin, [9] / 1947	$\frac{hl_c}{\lambda} = 0.082 \left(\frac{Lq}{g(T_{Sat}+273.15)\lambda} \frac{\rho_v}{\rho_l-\rho_v} \right)^{0.7} \left(\frac{(T_{sat}+273.15)c_P\sigma\rho_l}{L^2\rho_v^2 l_c} \right)^{0.33} \text{Pr}^{-0.45}$	(1)
Mc Nelly, [10] / 1953	$h = 0.225 \left(\frac{qc_p}{L} \right)^{0.69} \left(\frac{P\lambda}{\sigma} \right)^{0.31} \left(\frac{\rho_l}{\rho_v} - 1 \right)^{0.32}$	(2)
Mostinski, [11] / 1963	$h = 0.106 P_{cr}^{0.69} q^{2/3} F_p$ and $F_p = 1.8(p_r)^{0.17} + 4(p_r)^{1.2} + 10(p_r)^{10}$	(3)
Labuntsov, [12] / 1972	$h = 0.075 \left[1 + 10 \left(\frac{\rho_v}{\rho_l-\rho_v} \right)^{0.67} \right] \left(\frac{\lambda^2}{v\sigma T_{sat}} \right)^{0.33} q^{0.67}$	(4)

Figure 1- Experimental data of boiling

III. COMPARISON FO CORRELATIONS

The comparison of the values predicted by the correlations with the experimental data, is treated statistically by defining the error by equation (5), the mean error (6) and the correlation coefficient (7), the latter measuring the affinity between the two groups of values, the more the coefficient tends towards the unit value and the more the values calculated with the corresponding correlation approach the experimental values and give low mean errors.

$$Error = \left| \frac{h_{cal}-h_{exp}}{h_{cal}} \right| \quad (5)$$

$$Mean\ Error = \sum_{i=1}^{n} \frac{Erreur_i}{n} \quad (6)$$

$$r = \frac{covariance_{h_{exp}h_{cal}}}{variance_{h_{exp}}.variance_{h_{cal}}} \quad (7)$$
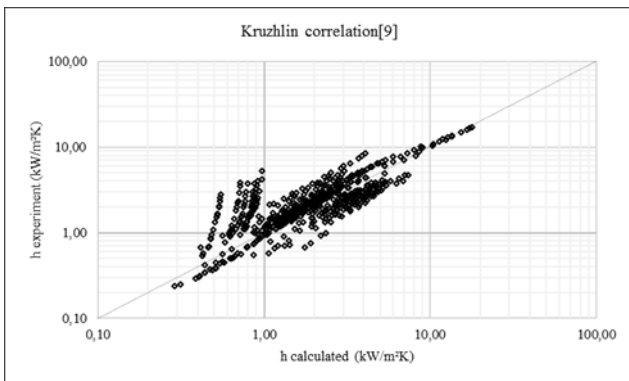

Figure 2. Comparison of data with correlation [9]

Kruzhlin correlation [9]

Figure 2 shows the comparison of the experimental data to that calculated with the Kruzhlin correlation [9], the points are mostly near the median line, except for the series of data

[22] which are increased to the experimental ones, the mean error is 48% and the correlation coefficient is 0.90.

Mc Nelly correlation [10]

Figure 3 indicates that the points obtained are mostly below the median line, the Mc Nelly correlation [10] underestimates the predicted values to those of the experimental values, a series of data relating to water [22] is above the set, the error mean is 40% and the correlation coefficient is 0.91.
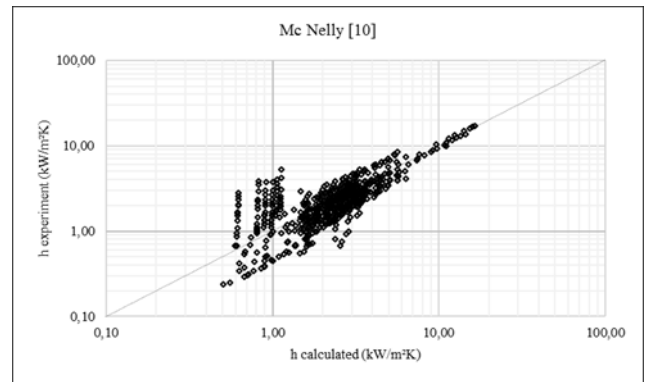

Figure 3. Comparison of data with the correlation [10]

Mostinski correlation [11]

Figure 4 shows a comparison of the heat transfer coefficients of the experimental data with those calculated with Mostinski's correlation [11], one set of points are concentrated above the midline another group of points is below, the average error is of the order of 73% and the correlation coefficient which indicates the affinity of the two types of values is determined and is equal to 0.90.
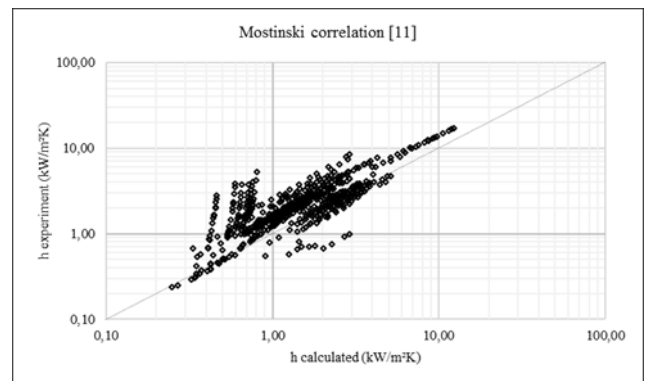

Figure 4. Comparison of data with correlation [11]

Table 2: experimental data of boiling at sub-atmospheric pressures

Reference	Fluid	Heater (mm)	Roughness	Flux kW/m²	h kW/m².K	P	Nr Points
[13] P.K. TEWARI, et al / 1985	Water	Plate d=150, e=3; Copper	Ra= 0.2-0.3 μm Ra= 4-10 μm Ra= 10-20 μm	15,1-68,4	1,3-4,7	10-100 kPa	19 11 21
[14] Varma et al / 1994	Water	Tube Ss /d=14,05/L=240	ND	25-83	3-7	6,67 kN/m²	10
[15] Bhaumik et al / 2004	Water Benzène Toluène	Tube Ss /d=32 / L=150	ND	16-42 16-43 16-43	1,1-3,5 1-2,9 1-1,5	20,01-97,39 kN/m² 23,75-97,13 kN/m² 23,35-96,72 kN/m²	36 36 36
[16] Jabardo et al / 2004	R-11, R-123	Tube Copper d=19/L=210	Ra= 0,16- 2,3μm Ra= 0,16-3,3μm	5-115 5-115	0,3-8,5 0,3-7,4	0,485 bar 0,403 bar	50 45
[17] Prasad et / 2007	Méthanol	Tube Mild steel, copper coated d=32/L=145	ND	15-43 15-43	1,4-3,8 1,7-5,2	27,95-97,23 kN/m² 27,72-97,56 kN/m²	30 30
[18] Lena Schnabel et al /2008	Water	Cylinder Copper d =38, e= 4,5	Ra= 0.169 μm Ra= 5.8 μm	1,7-4,9	0,7-2,2	1-2 kPa	6 9
[19] Saiz Jabardo / 2009	R-123	Tube Brass Copper d=19/L=210	Ra=0,16 μm Ra=0,16 μm	3-77 3-115	0,2-3,2 0,3-4,1	0,403 bar 0,403 bar	17 17
[20] Mark Aaron Chan et al / 2010	Water	Disc d= 30 / t = 27	ND	0,1-446	6-17	2-9 kPa	24
[21] Cieśliński et al / 2011	Water	Tube Ss 10/100	Ra=0,06 μm	13-90	2,9-7,7	10 kPa	9
[22] Yu et al /2015	Water	Tube Copper d=20,8/L=190	ND	4-10	0,7-5,3	1,8-3,5 kPa	77
[23] Tomasz HAŁON et al / 2015	Methanol	Brass circular plate d=77	Ra = 0.05 mm	21-43	0,3-18,6	0.3–18 kPa	11
[24] Kumar et al /2019	Water Benzene	Tube Ss d=70, L=179	ND	13-34 5-25	1,4-3,9 0,5-2,5	35,36-100,07 kN/m² 39,29-98,07 kN/m²	29 25

Labuntsov correlation [12]

Labuntsov's correlation [12] gives results with an error of around 55% and a correlation coefficient of 0.91, two sets of points stand out, one group around the median line and another above and on the right, see figure 5.
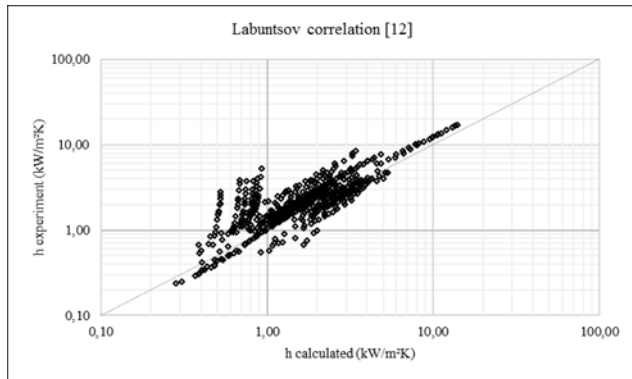

Figure 5. Comparison of data with correlation [12]

IV. CONCLUSION

- Correlations predicting the heat transfer coefficient were drawn from the literature and a review of the experimental data relating to boiling for sub-atmospheric pressures was made.

- An analysis of the experimental data was carried out showing the variability of several parameters influencing the boiling.

- The validation of the correlations with the experimental data gave results with margins of error of 40 to 73%.

- Of the four correlations treated, that of Mc Nelly [10] gave the best results with a minimum of error and a high correlation coefficient.

NOMENCLATURE

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a Thermal diffusivity (m^2/s)
c_p Heat capacity ($J/kg.K$)
F_p Pressure function [10]
g Gravity acceleration (m/s^2)
h Heat transfer Coefficient ($W/m^2.K$)
l_c Capillary length (m)
L Latent heat of vaporization (J/kg)
Nu Nusselt Number
P Pressure (N/m^2)
Pr Prandtl Number
q Heat flux (W/m^2)
r Correlation coefficient
R_a Arithmetic roughness (nm)
Re Reynolds Number
T Temperature (K)

Greek symbols
β Angle contact (*degree*)
Δ Difference
ε Quadratic roughness (μm)
λ Thermal conductivity ($W/m.K$)

μ Dynamic viscosity ($Pa.s$)
v Kinematic viscosity (m^2/s)
ρ Density (Kg/m^3)
σ Surface tension (N/m)

Subscripts
c Critic
cal Calculated
d Departure
exp experimental
l Liquid
v Vapor
w Wall
r Reduced
sat Saturated

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