Proceedings of ENCIT 2016
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16th Brazilian Congress of Thermal Sciences and Engineering
November 07-10th, 2016, Vitória, ES, Brazil

Accuracy of Boiling Correlations on Nucleate Boiling with Ethanol Using a Thin Platinum Wire at Different Pressures

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Abstract: *Nucleate boiling heat transfer has been largely studied in many research centers around the world due to its very high efficiency in cooling hot surfaces. Many conditions, geometries and parameters have been studied and many correlations were proposed to predict heat transfer coefficients and wall temperature. However, the correlations are usually restricted to several conditions, for example geometry, fluid or heater material. If no restriction is applied, it usually has a function or parameter to correct the equation. In the present work, nucleate boiling experiments were performed with ethanol at 4 pressure levels from 1.0 bar to 6.1 bar, with visualization of the phenomenon. Several correlations were tested and one known correlation presented great fit. Rohsenow constants and a slight modification on Gorenflo correlation are also proposed for the experimental conditions studied here. Furthermore, pictures at several heat fluxes for each pressure are presented. It is possible to observe the pressure effect on the boiling heat transfer and the increase in bubble formation with the increase of heat flux until critical heat flux is achieved.*
Keywords: *Nucleate Boiling, Anhydrous Ethanol, Platinum Wire, Boiling Visualization, Boiling Correlations*

1. INTRODUCTION

It is already known how efficient boiling heat transfer is, as well as how much it is studied in many important research centers all over the world. It is investigated since its micro-mechanisms (bubble formation, microlayer structure, nucleation site) until its macro-phenomena (liquid effects, geometry, enhanced convection). Furthermore, there are many studies looking for specific applications, like nuclear engineering, microelectronics, refrigeration, automotive, and others.

The most typical information is the boiling curve, also known as Nukiyama curve (Nukiyama (1966)), where the heated surface temperature is correlated to the heat flux through it. It is common to investigate only the nucleate boiling regime, since it is the condition where high heat fluxes are achieved with relatively low surface temperature. In other words, very high heat transfer coefficients are observed in nucleate boiling regime. Moreover, the Critical Heat Flux (CHF), the maximum heat flux before film boiling is reached, is an important information during heat transfer projects to know the maximum power the heated surface can dissipate.

However, finding the boiling curve can be a difficult task, even more when trying to reproduce the desired application by using the same parts, materials and geometry. Test rigs with simpler geometries are, hence, widely used to provide boiling curves. One method to experimentally reach this information is with a platinum wire immersed in a pool of the test fluid. This is because by measuring only the electrical current and voltage on the wire it is possible to calculate the heat flux (with the power) and the surface temperature (by the calculated wire resistance).

Many correlations have been proposed with several test sections (Rohsenow (1952); Stephan and Abdelsalam (1980); Cooper (1984); Gorenflo (2010), among others). Specifically, Rohsenow (1952) proposed a correlation with platinum wire as test section and water as test fluid, as well as for other surface materials and fluids. However, his correlation is highly empirical by using correction parameters for the heater-fluid interface. Stephan and Abdelsalam (1980) correlation is highly used by many authors for validating experiments (like Inoue *et al.* (2004), who validated platinum wire tests with Stephan-Abdelsalam correlation) or using to further calculate mixture correlations (as in Peyghambarzadeh *et al.* (2009), who tested binary and ternary mixtures). Another remarkable correlation is presented in the VDI Heat Atlas 2010 (Gorenflo (2010)), which considers the most different parameters, like reduced pressure, surface roughness and material properties. In Gorenflo's review (Gorenflo *et al.* (2014)), his correlation is tested with many hydrocarbons, alcohols, refrigerants and other fluids, presenting a mean deviation of only 10% approximately.

The present work presents results of saturate nucleate boiling with anhydrous ethanol using platinum wire as test section at four different system pressures. The results are compared with three known correlations and one proposed modification to find which one fits better. Also, images are presented to observe the bubble formation affected by pressure and heat flux.

2. NOMENCLATURE

Greek Letters

α	Thermal Diffusivity
β	Contact Angle
μ	Dynamic Viscosity
ρ	Density
σ	Surface Tension

Roman Letters

c_p	Specific Heat
C_{sf}	Surface-Liquid Constant
d_b	Bubble Diameter
F	Gorenflo Correction Functions
g	Gravity Acceleration
h_{lg}	Heat of Vaporization
HTC	Heat Transfer Coefficient
I	Electrical Current
k	Thermal Conductivity
n	Prandtl Exponent (Rohsenow Correlation)
$n(p^*)$	Heat Flux Exponent (Gorenflo Correlation)
p	Pressure
p^*	Reduced Pressure ($p^* = p/p_c$)
q	Heat Flux
T	Temperature
V	Voltage

Subscripts

c	Critical Condition
g	Vapor Phase
l	Liquid Phase
nb	Nucleate Boiling
ref	Referential Condition
sat	Saturate Condition
w	Wall

3. EXPERIMENTAL APPARATUS AND PROCEDURE

3.1 Experimental Rig

The experimental apparatus consists of a boiling chamber where about 2.2 liters of fluid is tested. The test section is a horizontal platinum wire and it is powered by a DC electrical current. Each part of the experimental rig will be discussed in the following sections. For a first introduction, it is presented below in Fig. 1.

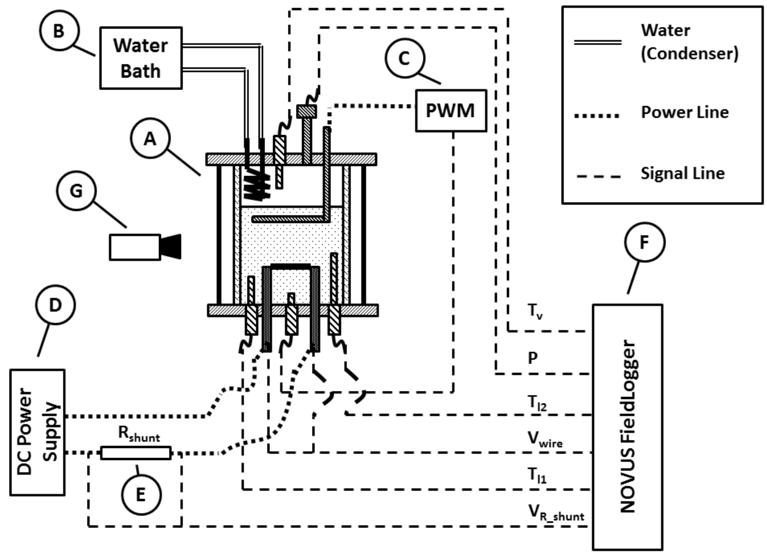

Figura 1: **Complete experimental rig schematic illustration. A) Boiling Test Apparatus; B) Controlled Water Bath; C) PWM Controller; D) DC Power Supply; E) Shunt Resistor; F) Data Acquisition System; G) High-Definition Webcam.**

The boiling test apparatus, shown by the letter (A) in Fig. 1, is where the test effectively occurs. It can be divided in basically two parts: the boiling chamber and the test section. For describing the components in the boiling test apparatus, Fig. 2 will be referred and in the next paragraphs the components' numbers will be cited in parentheses.

The boiling chamber (5) is made of a vertical cylindrical borosilicate glass tube (2) with inner diameter of 152 mm and 9 mm wall thickness. On the upper and bottom sides there are stainless steel lids (3) that are inserted in the glass with o'rings to provide sealing. The borosilicate glass tube (2) is concentrically positioned inside a polycarbonate tube (4), which has the purpose of creating a thermal insulation – with the air trapped within the two tubes – and being a protection in case of the glass failure.

On the upper lid, it can be found: a condenser (6), to condense the vapor during fluid degasification and during the test to maintain the system pressure; a type-T thermocouple (8), placed in the vapor phase to monitor its temperature; a pressure transducer (9), to measure the system pressure; and a bath heater (7), that maintains the fluid at the desired temperature. The bottom lid holds three type-T thermocouples. Two of them (11 and 12) measure the liquid temperature and one (10) is used as feedback for the bath heater controller. Also, it can be found the test section apparatus, which consists of the platinum wire (1) and the conductors (13).

The platinum wire diameter is $0.285\ mm$ (measured using a Micromaster IP54 micrometer), it is $79.15\ mm$ long and its average roughness Ra is 0.3 (measured with a Hommelwerke T8000 profilometer). Platinum is a proper material for this test because of its high melting temperature (about 1770 °C) and its resistivity characteristics, like high sensitivity to temperature and good linearity. For this reason, it is possible to guarantee good accuracy on the temperature by measuring

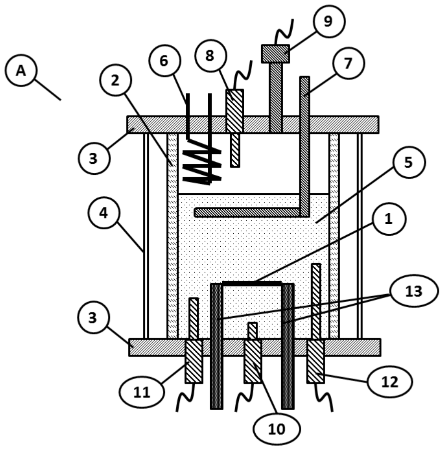

Figura 2: **Boiling Test Apparatus (A). 1) Platinum Wire; 2) Glass Tube; 3) Stainless Steel Lids; 4) Polycarbonate Tube; 5) Boiling Chamber; 6) Condenser; 7) Bath Heater; 8) Thermocouple in Vapor; 9) Pressure Transducer; 10) Thermocouple for Control; 11) Thermocouple 1 in Liquid; 12) Thermocouple 2 in Liquid; 13) Conductors.**

its resistance. Furthermore, since this is a thin wire, it is reasonable to consider its surface temperature equal to its average temperature ($Bi \approx 0.1$).

3.2 Experimental Procedure

The following steps describe the test methodology used for the present study.

1. Ethanol was put into the boiling chamber.
2. To release dissolved non-condensible gases from the fluid, water starts flowing through the condenser and the bath heater and the test section are turned on. They remained on for at least 40 minutes with the fluid at saturation temperature and ambient pressure.
3. The sealing pin that was opened to release the dissolved gases is now closed to begin the test. The PWM control ((C) in Fig. 1) begins to act on the bath heater so the test fluid remains at the desired temperature. The water flow through the condenser is decreased to stabilize the system pressure. This keeps going until the fluid and vapor temperatures stabilize and the pressure read by the transducer is quite constant at the first test pressure.
4. Before starting to cover the boiling curve, the CHF is approximately obtained by slightly increasing the test section power until a rapidly increase of the wire temperature is observed. Afterwards, the test section power is lowered to extinguish film boiling and then again increased to around 80% the CHF.
5. The boiling test in fact starts at this point. The heat flux is decreased to trace the boiling curve during cooling until it shuts down. Subsequently, the heat flux is increased so the boiling curve during heating and the CHF are obtained. This step is repeated several times to verify the test repeatability. The video is recorded at this step (HD Webcam (G) in Fig. 1), however its synchronization is done later during data processing.
6. When the test at the ongoing pressure level is finished, the bath heater is again turned on to increase the fluid temperature and, consequently, the system pressure. It continues until the next test pressure level is achieved. When all the parameters are again stable, the previous two steps are repeated (the CHF finding and boiling test). This step is repeated until all the pressure levels are tested (in this study, it is up to 6.1 bar).
7. The test results acquired by the Data Aquisition System (NOVUS FieldLogger (F) in Fig. 1) are saved and processed to trace the boiling curves. The data is then synchronized with the recorded video so the images could be gathered for each pressure level and heat flux.

3.3 Experimental Uncertainties

For the present work, the experimental uncertainties for tests at 1.0 and 2.0 bar pressures are lower than for 4.1 and 6.1 bar. This is because the bath control (temperature and pressure) for lower pressures are better than for the higher one. For both conditions, the calculated wire temperature has an experimental uncertainty of $1.0\,^{\circ}$C, approximately, and the calculated heat flux uncertainty is not more than 1%.

For tests at 1.0 and 2.0 bar pressure, the pressure uncertainty is 0.05 bar and the bath temperature accuracy is $0.3\,^{\circ}$C. This way, the heat transfer coefficient (HTC, which is calculated by Eq. 1) uncertainty is 13% for heat fluxes lower than $50\ kW/m^2$, 8% when between $50\ kW/m^2$ and $80\ kW/m^2$ and 7% for heat fluxes higher the $80\ kW/m^2$.

On the other hand, for tests at 4.1 and 6.1 bar pressure, the pressure uncertainty is 0.15 bar and the accuracy of the bath temperature is 0.6 °C. Therefore, the HTC uncertainty becomes 17% for heat fluxes lower than $50\ kW/m^2$ and 10% for higher than it.

The HTC equation (Eq. 1) has a correction factor of 0.985 when calculating the power (multiplication of voltage and current). This is because there are resistances in series with the platinum wire that must be taken aside. They correspond to around 1.5% the resistance calculated by Ohm's Law with the voltage and current signals.

$$HTC = \frac{q}{T_w - T_{sat}} = \frac{\frac{0.985.V.I}{A}}{T_w - T_{sat}} \tag{1}$$

4. RESULTS AND DISCUSSION

This topic will be presented in the following order: boiling curves from experimental data for different pressure levels, visual results of the phenomenon for each test pressure, introduction to the pool boiling correlations that will be used in the present work and, eventually, comparison of these correlations with the test results.

4.1 Results with Anhydrous Ethanol

Boiling curves obtained with experimental results at four different pressure levels are presented in Fig. 3. It is possible to see that the heat transfer is higher with the increasing pressure, because the wall superheat is lower at higher pressures. Also, the CHF increases with the increased pressure. This CHF elevation is more significant from 1 bar to 4 bar than from 4 bar to 6 bar pressure. It is known from literature (Gorenflo *et al.* (2014), Hewitt (1998)) that the CHF increase is followed by its decrease with the pressure. Probably if the test was carried out at higher pressures it would be observed the opposite trend (CHF decrease).

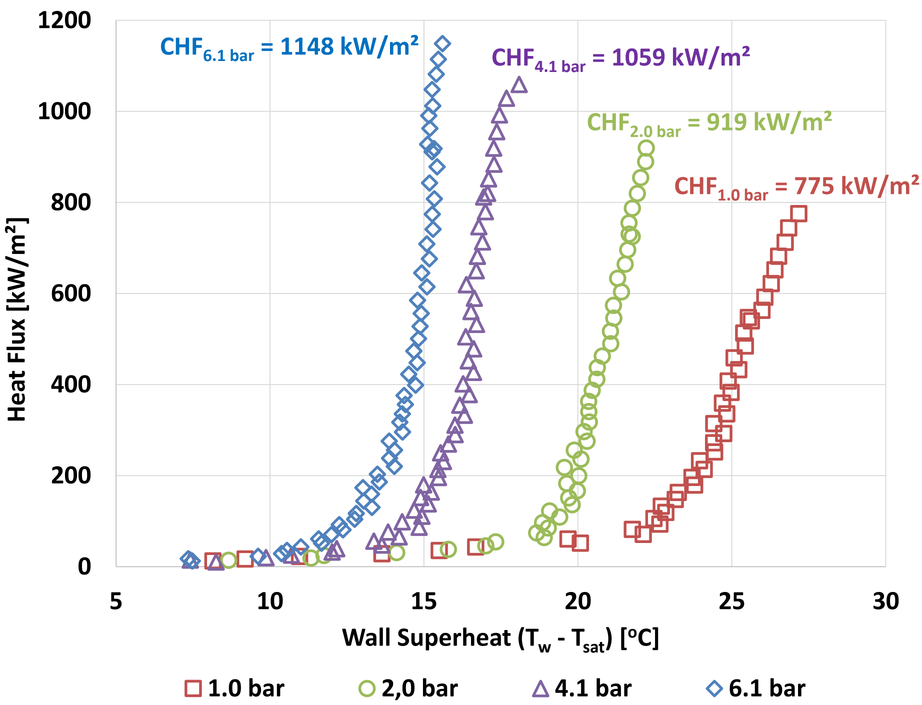

Figura 3: **Boiling curves from experimental results with anhydrous ethanol.**

4.2 Photographic Results

During the tests, a HD Webcam was recording the test section to have images of the boiling phenomenon at different pressures and heat fluxes, which are presented in Fig. 4. Each column contains images at each test pressure, while the rows correspond to the heat fluxes. Therefore, comparing pictures at the same column it is assessed the heat flux effect, while comparing at the same row it is analyzed the pressure effect.

If the heat flux effect is analyzed, it is possible that the higher the heat flux the higher the vapor formation, as expected. This observation can motivate to relate the high performance of boiling heat transfer with latent heat process. When looking at the pressure effect, is observed the decrease of the bubble size with higher pressure levels. This is because the higher the pressure the lower the surface tension (Yaws (2008)), hence the bubble releases earlier during its formation process and, consequently, with smaller size. It is easier to see this effect at higher heat fluxes, like $600\ kW/m^2$, in Fig. 4.

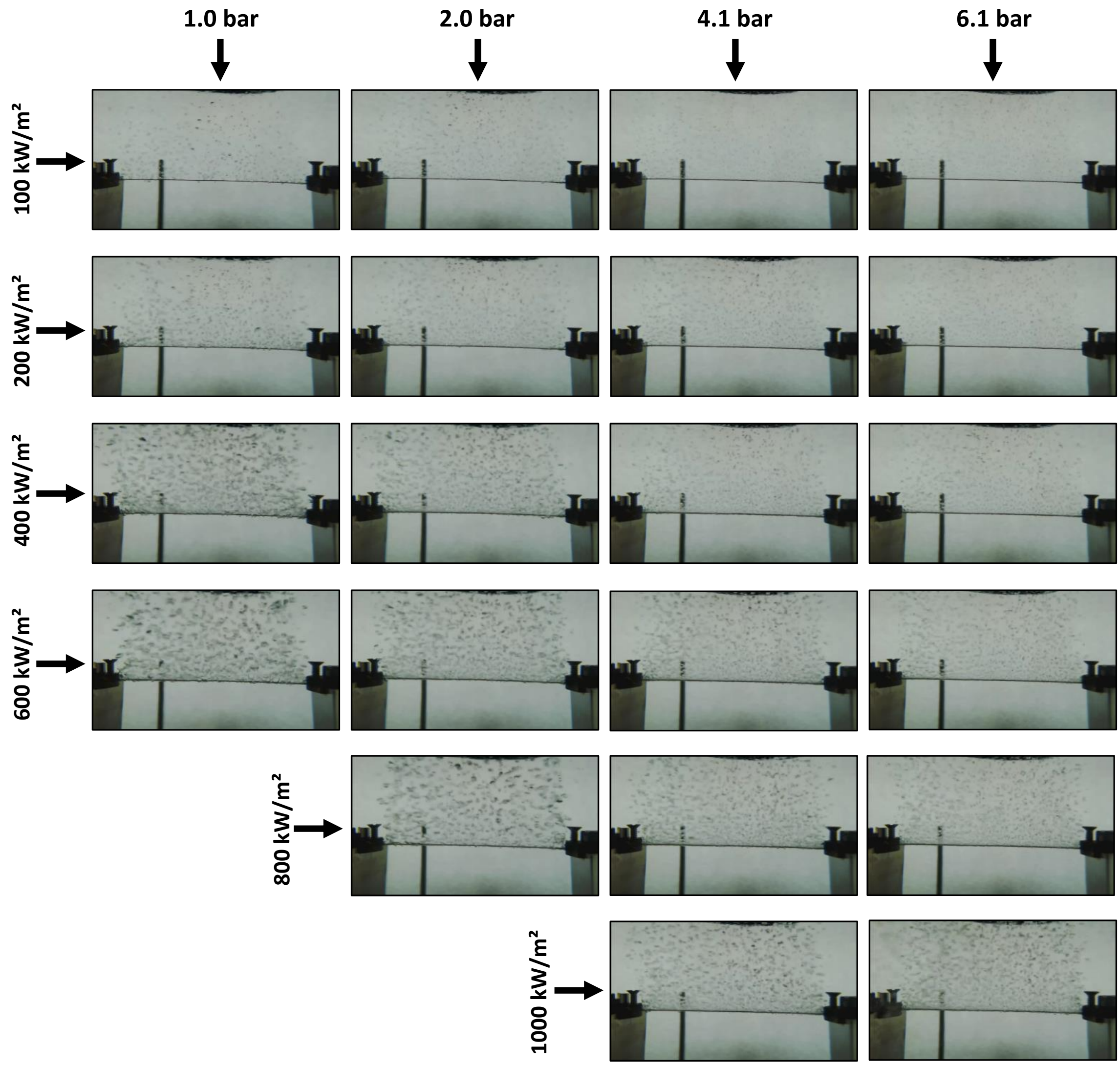

Figura 4: **Images of the test with anhydrous ethanol at different pressures and heat fluxes.**

4.3 Pool Boiling Correlations

For the present study, the following correlations will be compared with new experimental results with ethanol and platinum wire as test section.

- ***Rohsenow (1952)***

  Commonly found in heat transfer textbooks, the Rohsenow pool boiling correlation is one of the first with large acceptance and practical use. Its semi-empirical nature predicts the pool boiling curve only if the liquid-surface coefficient and the respective exponent are known, which are found by experimental results. Nevertheless, this correlation encouraged many researches and it was studied for several decades. It is presented in Eq. (2) as it is in Pioro (1999), whose work presents Rohsenow constants for many liquid-surface conditions.

  Although it is not explicit in Eq. 2 the HTC calculation, it can be obtained by calculating the wall superheat $T_w - T_{sat}$ with the presented correlation and, then, using Eq. 1.

$$\frac{c_p.(T_w - T_{sat})}{h_{fg}} = C_{sf}\left[\frac{q}{\mu.h_{fg}}\sqrt{\frac{\sigma}{g.(\rho_l - \rho_g)}}\right]^{0.33}\left(\frac{c_p.\mu}{k_l}\right)^n \quad (2)$$

- ***Stephan and Abdelsalam (1980)***

  By using multiple regression on thousands of experimental data, Stephan and Abdelsalam (1980) proposed different correlations for four groups of fluids: water, hydrocarbons (organics), cryogenics and refrigerants. Their organic correlation is widely used and is presented in Eq. (3).

$$HTC_{nb} = 0.0546\left(\frac{k_l}{d_b}\right)\left[\left(\frac{\rho_g}{\rho_l}\right)^{1/2}\left(\frac{q.d_b}{k_l.T_{sat}}\right)\right]^{0.67}\left(\frac{\rho_l - \rho_g}{\rho_l}\right)^{-4.33}\left(\frac{h_{lv}.d_b^2}{\alpha_l^2}\right)^{0.248} \quad (3)$$

Where d_b is the bubble diameter and must be estimated. In their original work, the authors recommended the correlation presented in Eq. (4). However, if using this equation, the bubble diameter for ethanol at 1 bar pressure would be around 11 mm, which is not physically representative.

$$d_b = 0.146\beta\left[\frac{2.\sigma}{g(\rho_l - \rho_g)}\right] \tag{4}$$

Other references quote Stephan and Abdelsalam correlation and mentions the bubble diameter equation as in Eq. (5) (examples are Thome (2003) and Peygambarzadeh *et al.* (2014)). This equation decreases in one order the bubble size, which is closer to the reality, and will be used in the present work to evaluate Stephan and Abdelsalam correlation.

$$d_b = 0.0146\beta\left[\frac{2.\sigma}{g(\rho_l - \rho_g)}\right] \tag{5}$$

- ***Gorenflo (2010)***

  Presented in the VDI Heat Atlas 2010 (Gorenflo (2010)), this correlation works by using reduced pressure, non-dimensional parameters and correction functions on a referential condition to find the heat transfer coefficient. The reference is an experimental result with the test fluid at reduced pressure of $p^* = 0.1$, 20 kW/m^2 heat flux and the test section is a horizontal copper tube with $R_a = 0.4\ \mu m$ surface roughness. If the experimental result is unknown, the reference can be estimated with vapor pressure curve of the test fluid (see Gorenflo (2010) or Gorenflo *et al.* (2014)). However it is not the case of the present study because the experimental reference for ethanol is given by the author (Gorenflo *et al.* (2014)).

  The correction functions adjust this referential results according to the real conditions of material, surface finish, pressure and heat flux. Equation (6) presents Gorenflo correlation, while Eq. (7) shows the referential heat transfer coefficient for ethanol and from Eq. (8) to Eq. (11) the correction equations (not valid for water).

$$HTC_{nb} = HTC_{ref}.F(q).F(p^*).F_w \tag{6}$$

Being:

$$HTC_{ref} = 4.35\ kW/m^2 \tag{7}$$

$$F(q) = \left(\frac{q}{q_{ref}}\right)^{n(p^*)} \tag{8}$$

$$n(p^*) = 0.95 - 0.3p^* \tag{9}$$

$$F(p^*) = 0.7p^* + 4p^* + \frac{1.4p^*}{1-p^*} \tag{10}$$

$$F_w = \left(\frac{R_a}{R_{a_{ref}}}\right)^{(2/15)}\left[\frac{(k\rho c_p)_w}{(k\rho c_p)_{ref}}\right]^{0.25} \tag{11}$$

4.4 Comparison with Experimental Results

The experimental results for anhydrous ethanol (previously shown in Fig. 3) are now presented in Fig. 5 together with the calculated correlations. From the first to the forth row there are results for different pressure levels (from 1.0 bar to 6.1 bar, respectively). Meanwhile, the first two columns on the left are results in linear plot and in log-log plot, in this order. It is presented this way so it is possible to see how well the correlations work in high heat fluxes (linear plot) and in low heat fluxes (log-log plot). The third column shows the correlations percentage deviation from the experimental result with the heat flux.

For the Rohsenow correlation, the surface-liquid parameter (C_{sf}) was searched until it was found the smallest overall average deviation with the experimental data. The Prandtl number exponent was kept $n = 1.7$ as originally proposed by the author. With four values for C_{sf} (one for each pressure), the average was taken, giving $C_{sf} = 0.00251$. These parameters were applied for the calculation at all the pressures and is plotted in Fig. 5. It can be seen the difficulty of matching Rohsenow correlation with the entire heat flux range.

All the correlations absolute average deviations are presented in Tab. 1. It can be seen that Gorenflo (2010) correlation describes the best the heat transfer with ethanol on a platinum wire. One possible reason for this better fit could be the use of many correction factors (for example, surface material and referential HTC), that brings the generic calculation to a close-to-real condition.

It is presented as well in Fig. 5 and in Tab. 1 results for a modified Gorenflo correlation. It is a proposal aiming better match with the present condition (ethanol and platinum wire) and pressures up to 6.1 bar. The only slight modification is changing Eq. 9 for Eq. 12. However, it is interesting to see that at 6.1 bar (which corresponds to a reduced pressure of 0.099) the original Gorenflo fits better than the proposed modification, even more when observing that this pressure is close to Gorenflo's referential reduced pressure of 0.1.

$$n(p^*) = 0.974 - 0.3p^* \tag{12}$$

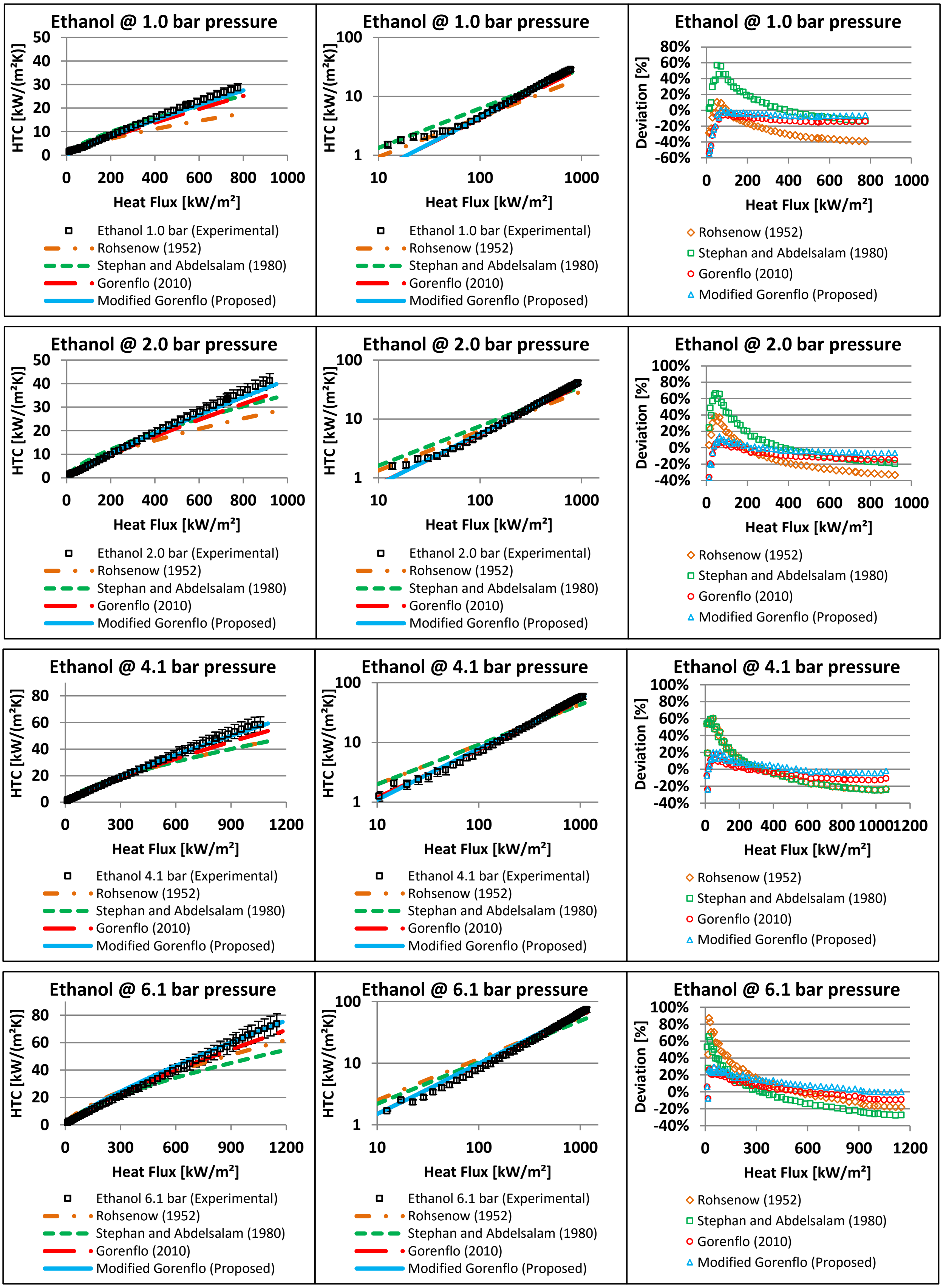

Figura 5: **Experimental results and pool boiling correlations for anhydrous ethanol.**

Tabela 1: **Pool boiling correlations and their absolute average deviation from experimental results**

Pressure	***Rohsenow (1952)***	***Stephan and Abdelsalam (1980)***	***Gorenflo (2010)***	***Modified Gorenflo***
1.0 bar	22.4%	18.2%	15.0%	10.0%
2.0 bar	21.0%	23.6%	9.6%	6.4%
4.1 bar	22.7%	22.7%	8.2%	7.1%
6.1 bar	25.8%	21.8%	10.0%	12.5%

5. CONCLUSION

Experimental results of saturate nucleate boiling for anhydrous ethanol with platinum wire as test section were presented at four different pressures. With the increasing pressure, the heat transfer in enhanced, as well as the CHF, which the increase is more significant from 1.0 bar to 4.1 bar. Visual analysis showed greater bubble formation at higher heat fluxes, as it was expected. Moreover, the bubble size decreases with the increasing pressure because of the surface tension decrease.

A Rohsenow surface-liquid constant for the pressure range between 1.0 bar and 6.1 bar is proposed for ethanol and platinum wire ($C_{sf} = 0.00251$), considering $n = 1.7$. When comparing the test results with known correlations in literature, the Gorenflo method presented the best match. In order to achieve better compliance with the experimental data, a slight modification in Gorenflo correlation was suggested. The use of Eq. 12 instead of Eq. 9 provided better accuracy in the pressure range of the present work. An interesting exception is observed at 6.1 bar, which is very close to Gorenflo referential reduced pressure.

6. ACKNOWLEDGEMENTS

The authors would like to thank to the R&D Department of Magneti Marelli Powertrain in Hortolândia, São Paulo, Brazil. Thanks to the Physical Components Department for aiding the design of the experimental rig and to the Prototyping Laboratory for building it. Thanks to the Vehicle Preparation Laboratory for supplying the test fluid. Special thanks to Mr. Fernando Windlin, Manager of the Physical Components Department, for sponsoring the project and making it happen.

7. REFERENCES

Cooper, M., 1984. "Heat flow rates in saturated nucleate pool boiling-a wide-ranging examination using reduced properties". Elsevier, Vol. 16 of *Advances in Heat Transfer*, pp. 157 – 239.

Gorenflo, D., 2010. *VDI Heat Atlas*, Springer, chapter H2: Pool Boiling.

Gorenflo, D., Baumhögger, E., Herres, G. and Kotthoff, S., 2014. "Prediction methods for pool boiling heat transfer: A state-of-the-art review". *International Journal of Refrigeration*, Vol. 43, pp. 203 – 226.

Hewitt, G.F., 1998. *Handbook of Heat Transfer*, McGraw-Hill, chapter 15. 3rd edition.

Inoue, T., Teruya, Y. and Monde, M., 2004. "Enhancement of pool boiling heat transfer in water and ethanol/water mixtures with surface-active agent". *International Journal of Heat and Mass Transfer*, Vol. 47, No. 25, pp. 5555 – 5563.

Nukiyama, S., 1966. "The maximum and minimum values of the heat Q transmitted from metal to boiling water under atmospheric pressure". *International Journal of Heat and Mass Transfer*, Vol. 9, No. 12, pp. 1419–1433.

Peygambarzadeh, S.M., Hatami, A., Ebrahimi, A. and Fazel, S.A.A., 2014. "Photographic study of bubble departure diameter in saturated pool boiling to electrolyte solutions". *Chemical Industry and Chemical Engineering Quarterly*, Vol. 20, pp. 143 – 153.

Peyghambarzadeh, S., Jamialahmadi, M., Fazel, S.A. and Azizi, S., 2009. "Saturated nucleate boiling to binary and ternary mixtures on horizontal cylinder". *Experimental Thermal and Fluid Science*, Vol. 33, No. 5, pp. 903 – 911.

Pioro, I., 1999. "Experimental evaluation of constants for the rohsenow pool boiling correlation". *International Journal of Heat and Mass Transfer*, Vol. 42, No. 11, pp. 2003 – 2013.

Rohsenow, W.M., 1952. "A method of correlating heat transfer data for surface boiling of liquids". In *Transactions of ASME*. Vol. 74, pp. 969–976.

Stephan, K. and Abdelsalam, M., 1980. "Heat-transfer correlations for natural convection boiling". *International Journal of Heat and Mass Transfer*, Vol. 23, No. 1, pp. 73–87.

Thome, J.R., 2003. *Heat Transfer Handbook*, John Wiley & Sons, chapter 9.

Yaws, C.L., 2008. *Thermophysical Properties of Chemicals and Hydrocarbons*. William Andrew.

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