# CONFINED NUCLEATE BOILING OF FC-72 ON A DOWNWARD OR UPWARD FACING COPPER DISC

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***Abstract.*** *This paper presents new experimental results for saturated nucleated boiling of FC-72 on a horizontal copper disc, at atmospheric pressure, for different degrees of confinement, s, in the range of 0.1 to 13mm, and with two kinds of confinement element, for low and moderated heat fluxes (≤40kW/m²), on both a downward and an upward facing heating surface. The results show the enhancement of boiling heat transfer for the downward facing heating surface and with a decreasing distance s between the copper disc and an unheated surface. The experimental heat transfer coefficients for unconfined boiling, s=13mm, are compared with three empirical correlations.*

***Keywords:*** *nucleate boiling, confined boiling, Bond number, dryout heat flux, heat transfer.*

## 1. Introduction

It is well known that nucleate boiling is one of the most efficient forms of heat transfer. It has been used extensively in many technological applications where the main requirement is high heat transfer coefficients, allowing the transference of high heat fluxes from the surface to be cooled while keeping the temperature some degrees over the saturation temperature. This characteristic allows the design of compact and lightweight equipment. Boiling can be applied, for instance, in the thermal control of satellites, in the cooling of electronic components by immersion in a dielectric fluid pool, and several other applications that include the use of compact evaporators and devices as heat pipes and thermosyphons.

The heat transfer coefficient can be modified by the confinement of the system using, for example, an unheated surface. The characteristic most observed in the results of previous studies is that the heat transfer coefficient increases when the distance between the heated and unheated surfaces decreases (the confinement increases) for moderate heat fluxes (Passos *et al*., 2004). For relatively high heat fluxes, this enhancement effect disappears and the heat transfer coefficient decreases with increasing confinement and the dryout heat flux (DHF) limit can be attained as shown by Katto *et al*. (1977).

The effect of the confinement on the bubbles can be characterized by a dimensionless parameter known as the Bond number, *Bo*, defined as the ratio of the characteristic length to the confined space, *s*, and the capillary length, *L*. The latter is proportional to the detachment diameter of the vapor bubble in a pool and defined as (Carey, 1992):

$$L = \sqrt{\frac{\sigma}{g(\rho_l - \rho_v)}} \tag{1}$$

where $\sigma$, $g$, $\rho_l$ e $\rho_v$ represent the surface tension, the acceleration due to gravity, the liquid density and the vapor density, respectively. Thus, the Bond number $Bo = s/L$. In general, when $Bo<1$ the effect of the confinement is important and the bubbles tend to be coalesced and deformed, while for $Bo>1$, the bubbles become isolated (Ishibashi and Nishikawa, 1969).

The increase in the heat transfer coefficient when $Bo<1$ is explained by the evaporation of a thin liquid film, which is present between the heated surface and the base of the deformed bubble (Ishibashi and Nishikawa, 1969). For a low Bond number, as consequence of the coalescence phenomenon, the bubble becomes large and deformed allowing an increase in the bubble area pressed against the heated wall and the vaporization process to take place as proposed by Passos *et al*. (2004). According to Straub (1994), at the base of the bubble a thin liquid film called the microlayer is attached to the surface by intermolecular attractive forces between the liquid and the surface, known as the London-van-der-Waals dispersion forces. Because of these forces the film, which has a thickness of a few nanometers, does not evaporate completely. Only a sufficiently high superheating will break the molecules of the microlayer, with a dry area then forming and the heat transfer coefficient slowly decreasing. Therefore, the maximum heat flux, represented by the critical heat flux (CHF) or dryout, depends on the confinement and its tendency is to decrease with a decrease in *s* (Bonjour and Lallemand, 1997).

The gravitational acceleration can also influence the boiling mechanism. Under microgravity the bubble lifetime is longer and in consequence the vapor bubbles are larger compared to those under terrestrial gravity as reported by Straub

(1994). Under microgravity, the heat transport depends on the thermocapillary flow, called Marangoni convection, and is induced by the temperature gradient in the thermal layer that leads to a surface tension gradient on the bubble surface (Straub, 1994; Carey, 1992).

Nishikawa *et al*. (1984) have studied the effect of the orientation of the heated surface and its influence on several aspects of water nucleated boiling, at atmospheric pressure, such as, release, growth and detachment of the bubbles, movement of the bubble and the liquid over the surface, among others. Their results indicated that for low heat flux values and inclination angles lower than 120°, the heat transfer is controlled by the agitation of isolated vapor bubbles. Nevertheless, for angles higher than 150°, the heat transfer is controlled by the removal of the superheated thermal layer when the vapor bubble slides over the surface and by the heat of vaporization due to the liquid film vaporization under the vapor bubble when it covers the surface. For high heat fluxes, the mechanisms associated with the movement of the vapor bubble are not influenced by orientation of the surface and the vaporization of the liquid film becomes the dominant mode of heat transfer.

Moissis and Berenson (1969) presented a semi-empirical model for the transition from an isolated bubble regime (low and moderate heat flux) to that with slugs and columns (high heat flux), the heat flux corresponding to this transition being given by:

$$q_{MB} = 0.11\rho_v h_{lv}\theta^{0.5}\left(\frac{\sigma g}{\rho_l - \rho_v}\right)^{\frac{1}{4}} \tag{2}$$

where $\theta$ is the contact angle and $h_{lv}$ is the latent heat of vaporization. Lienhard (1985), *apud* Carey (1992), showed that the data of Nishikawa *et al*. (1984) suggested a transition whose heat flux agrees with the value calculated by Eq. (4) when $\theta$ lies between 35° and 85°.

Passos *et al.* (2005) performed a visualization study, by means of still photographs, of FC-72 confined and unconfined nucleate boiling on a downward facing disc and showed for s=0.2mm (Bo=0.3) and 0.5mm (Bo=0.7) few small bubbles and some coalesced and deformed bubbles were formed whereas for s=1mm (Bo=1.4) and 13mm (Bo=18) the heating copper disc was covered with small bubbles with a trend towards large coalesced bubbles.

The objective of this paper is to analyze FC-72 nucleated boiling, under saturated temperature and atmospheric pressure conditions, for different degrees of confinement (s=0.1, 0.2, 0.3, 0.4, 0.5, 1 and 13mm), on a downward facing surface (DF) and upward facing surface (UF). The experimental data of this work represent partially the results obtained by Cardoso (2005). The aim of this study is to obtain results of interest to the industry for new refrigeration system components, air conditioning and cooling of electronic components for thermal control of machines, where the heat fluxes to be removed are high.

## 2. Empirical correlations for nucleate boiling

The heat transfer coefficient, in boiling heat transfer, is defined by: $h=q(T_w-T_{sat})^{-1}$, where, $q$, $T_w$ and $T_{sat}$ represent the heat flux, the temperature of the heating surface in contact with the working fluid and the saturation temperature.

Among the great number of existing empirical and semi-empirical correlations to calculate $h$, for the nucleate boiling regime developed, those of Cooper (1984), Rohsenow (1952) and Stephan and Abdelsalam (1980) continue to be employed by several research groups and are presented as follows (see Carey, 1992).

Correlation of Cooper (1984):

$$h_{cooper} = 55 p_r{}^{b}\left(-0.4343\ln p_r\right)^{-0.55} M^{-0.5} q^{0.67} \tag{3}$$

where $b=0.12 - 0.2\log R_p$, and $p_r$, $M$ and $Rp$ represent the reduced pressure, the molecular weight and the surface roughness.

Correlation of Rohsenow (1952):

$$h_{Rohsenow} = \mu_l h_{lv}\left(\frac{g(\rho_l - \rho_v)}{\sigma}\right)^{0.5}\left(\frac{c_{pl}}{C_{sf} h_{lv} P_r{}^{s}}\right)^{3}\Delta T_p{}^{2} \tag{4}$$

where $\rho_l$, $c_{pl}$, $Pr_l$ represent the viscosity, the specific heat and the Prandtl number of the liquid. $\Delta T_w$ represents the superheating of the heating wall, $\Delta T_w=(T_w-T_{sat})$, and $C_{sf}$ is dependent on the material of the heating wall, the surface roughness and the working fluid and $r$=0.333 e $s$=1.7 (Carey,1992).

Correlation of Stephan and Abdelsalam (1980):

$$h_{sa} = 207\left(\frac{k_l}{d_b}\right)\left(\frac{q d_b}{k_l T_{sat}}\right)^{0.745}\left(\frac{\rho_l}{\rho_v}\right)^{0.581}\Pr_l^{0.533} R_p^{0.133} \tag{5}$$

where $k_l$ represents the thermal conductivity of the liquid. The detachment diameter of the bubble is calculated by:

$$d_b = 0.0149\theta\left(\frac{2\sigma}{g(\rho_l - \rho_v)}\right)^{0.5} \tag{6}$$

## 3. Experiment

The test section consists of a copper disc with a 12mm diameter and 1mm thickness, with three type-E thermocouples of 0.15mm diameter, set in the disc close to its center. The copper disc is heated by an 11.8Ω electrical resistance skin heater fixed by Araldite® epoxy resin to the upper side of the disc and is fixed to a piece of PVC beveled to an angle of 45° with an outside diameter of 20mm. For the case where the test section is mounted, horizontally, with a downward facing heating surface, the PVC support is mounted onto the end of an aluminum tube with 200mm height and 20mm diameter, which the thermocouples cables pass through. This ensemble is mounted inside a boiling vessel, consisting of a glass tube with a 50mm inside diameter and 180mm height. The boiling vessel is mounted inside a second vessel, 160x160x186mm, as shown in Figs.1 and 2, whose lateral walls are transparent plexy-glass plates, allowing the lateral visualization of the boiling space, and the upper and lower bases consist of two aluminum plates, 180x180x10mm. Mounted in the lower aluminum base there is a rectangular transparent plexy-glass window, 70x70mm, allowing the visualization of the boiling phenomenon on the copper disc. The boiling vessel is filled with 150ml of a 3M® dielectric fluid, FC-72 ($C_6F_{14}$), at atmospheric pressure. Two other type-E thermocouples are placed inside the boiling vessel, at two heights, in order to measure the liquid and the vapor temperatures. The surface of the copper disc, which is in contact with the working fluid, was polished using emery paper #600, corresponding to a roughness, $R_p$, of 1.1µm. The distance between the copper disc and the plexy-glass window is adjustable by turning the aluminum tube and is controlled by means of a dial. For a downward facing heating disc the geometric factor of the confinement element is the PVC support of the copper disc, 45° beveled, and this configuration of the test section will be noted as DF45º. The working fluid is heated up to the saturation temperature ($T_{sat}$=56.6°C) by water flowing in a second chamber, whose temperature is controlled by a cryostat LAUDA RK20 KP. One type-E thermocouple is inside the water bath.

For the case where the test section is mounted, horizontally, with an upward facing heating surface the confinement of the boiling space was imposed by two types of PVC elements, with 20mm outside diameter, mounted on the end of the aluminum tube, where the distance from the copper disc is controlled as in the downward facing case.

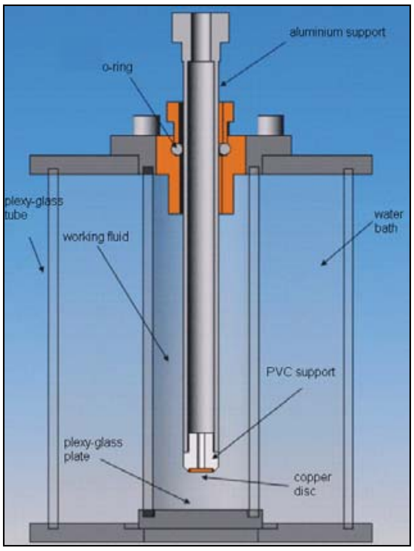


Figure 1. Scheme of the experimental setup (DF45°).

Figure 2. Photograph of the experimental setup (DF45°).

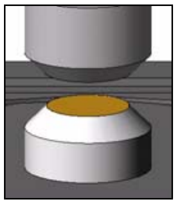

Figure 3a. Scheme of the PVC confinement element and the test section (UF45°).

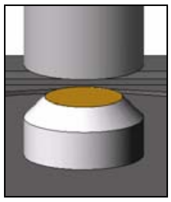

Figure 3b. Scheme of the PVC confinement element and the test section (UF90°).

One PVC confinement element was beveled to an angle of 45°, as shown in Fig.3a (UF45°), and the other, was without beveling, as shown in Fig.3b (UF90°). Only a lateral visualization of the boiling space is allowed for the configurations UF45° and UF90°.

The thin gap between the periphery of the copper disc and the PVC support is filled with Araldite® epoxy resin but this is not enough to avoid the presence of natural parasite sites at the periphery of the copper disc. Moreover the polishing treatment of the copper surface, after the boiling tests, can contribute to creating new parasite nucleation sites. This can adversely affect the quality of the experimental results, particularly for the configuration UF90º.

The DC power supply, HP6030A, is connected to the skin heater and controlled by a PC using LABVIEW. The acquisition and previous treatment of the data are carried out with an HP34970A system. The heating of the copper disc is controlled by increasing the heat flux.

The temperature uncertainty was ±0.6ºC. The experimental uncertainty for the heat flux was 2%, and those for the heat transfer coefficients were 23%, for the DF45° configuration, and 17% for the UF45° configuration, when the heat flux was $1kW/m^2$. For high heat fluxes, the experimental uncertainty was less than 5%.

In the next section, the experimental results for FC-72 confined nucleated boiling in a pool will be presented and discussed for heat fluxes less than $40kW/m^2$, for three configurations: downward facing heating surface (DF45°), upward facing heating surface with a confinement element beveled to an angle of 45° (UF45°) and upward facing heating surface without beveling (UF90°). The confinement distances of 0.1, 0.2, 0.3, 0.4, 0.5, 1 and 13mm were analyzed.

## 4. Results

Figure 4 shows the partial boiling curves for s=0.1, 0.3, 0.4, 0.5, 1 and 13mm, for a downward facing heating surface, DF45º, see Figs.1 and 2. For s=0.1mm and heat fluxes lower than $25kW/m^2$, the experimental points are shifted to the left compared with the case of s=13mm, characterizing an enhancement in the heat transfer for the confined case. However, for a heat flux higher than $20kW/m^2$ the wall temperature increases and even for a heat flux of $30kW/m^2$ the wall superheating is close to 25°C, indicating that the liquid is drying on the surface. Due to this very thin gap, corresponding to a Bond number of 0.15, the bubbles are deformed and the frequency of bubble detachment is not enough to cool the heating surface. A similar trend can be observed for s=0.3 and 0.4mm in comparison with s≥1mm, but the dryout heat fluxes are higher than when s=0.1mm. In synthesis, we can consider that there is a range of moderate heat flux where an increase in the confinement allows an increase in the heat transfer coefficient. For s=0.5mm, *h* was higher than it was for s=1 and 13mm. For s=1mm the wall temperatures are close to those for s=13mm, for q≤$20kW/m^2$, with an increase that leads to consider the possibility of reaching the DFH earlier than in the case with s=13mm. Passos *et al*. (2005) have reported visualization results showing the coexistence of large bubbles, not so deformed, with isolated bubbles for s=1 and 13mm. For the cases with a very high level of confinement, s≤0.5mm, the enhanced boiling is a consequence of the deformed bubbles which increase the area of the liquid film between the vapor bubble and the wall, allowing an efficient heat transfer, as explained also by Katto (1977) and Ishibashi and Nishikawa (1969).

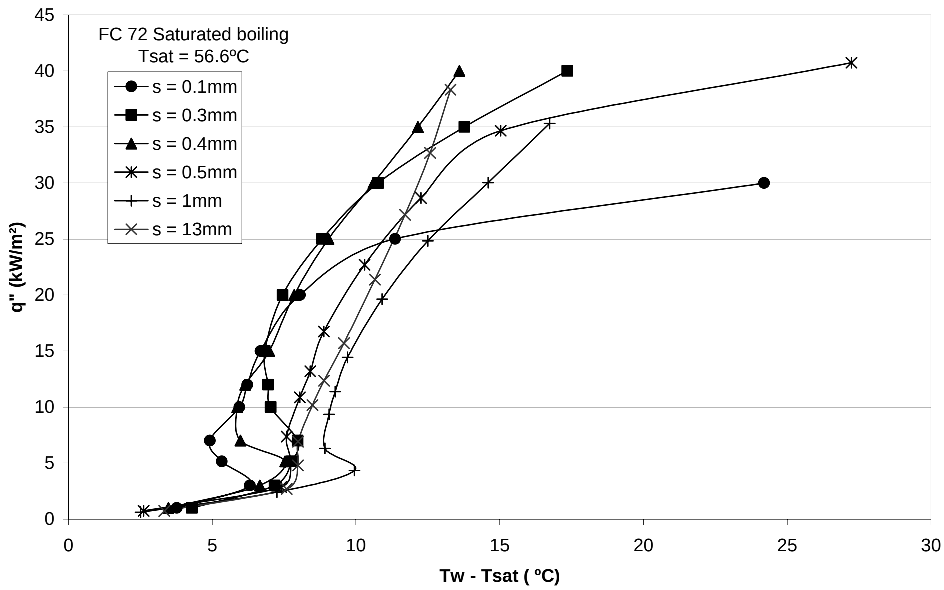


Figure 4. Partial FC-72 boiling curves, as a function of *s*, for DF45°.

Figure 5 shows partial boiling curves for s=0.1, 0.2, 0.3, 0.4, 0.5, 1 and 13mm, for upward facing heating surface, UF45º, see Fig.3a. When q≤$25kW/m^2$, there is an enhancement of boiling when s decreases and the data can be divided into three sets: the first including data for s=0.1 and 0.2mm, where the $\Delta T$ values are very close and lower than those for s=0.3, 0.4 and 0.5mm, which make up the second set and where the $\Delta T$ values are also very close, and a final set with data for s=1 and s=13mm. The decrease in DHF follows the tendency of previous results published by different authors that showed a decrease in the DHF with a decrease in *s*. However, in these tests the differences in $\Delta T$ values were not enough to characterize a gradual enhancement effect with a decrease on *s*.

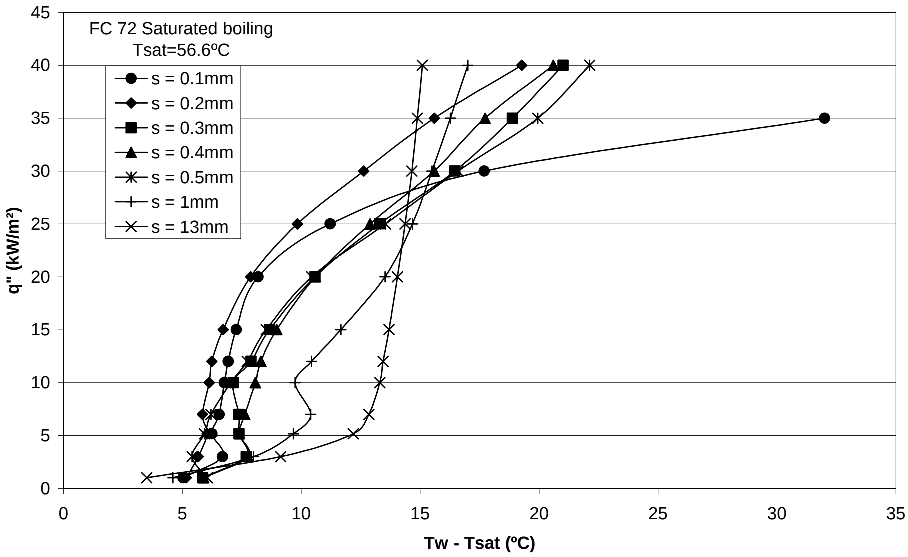


Figure 5. Partial boiling curves in function of *s*, for UF45°.

Figure 6 shows partial boiling curves for s=0.1, 0.2, 0.3, 0.4, 0.5, 1 and 13mm, for another upward facing heating surface, with a confinement element without beveling, UF90º, see Fig.3b. In comparison with the conditions in Fig.5, with UF45°, there is now the additional effect of an increase in the residence time of the bubbles. For s=0.1mm and s=0.2mm the curves are almost together, however, for heat fluxes higher than 25kW/m$^2$ the decrease in the heat transfer for s=0.1mm becomes clear, due to the rapid dryout of the surface. The confinements s=0.3mm and s=0.4mm have the same behavior, where for heat fluxes lower than 35kW/m$^2$ the superheating is lower than for s=13mm and consequently, the heat transfer is better. However, the better performance for s=0.3 and 0.4mm up to 40kW/m$^2$, compared with the cases of Fig.5, was not expected because for UF90° the residence time is higher than for UF45° and the cooling of the heating surface appears to be inhibited. For s=0.5mm and s=1mm the same tendency of the experimental points can be observed, noting that for fluxes lower than 35kW/m$^2$ the heat transfer is better for s=0.5mm.

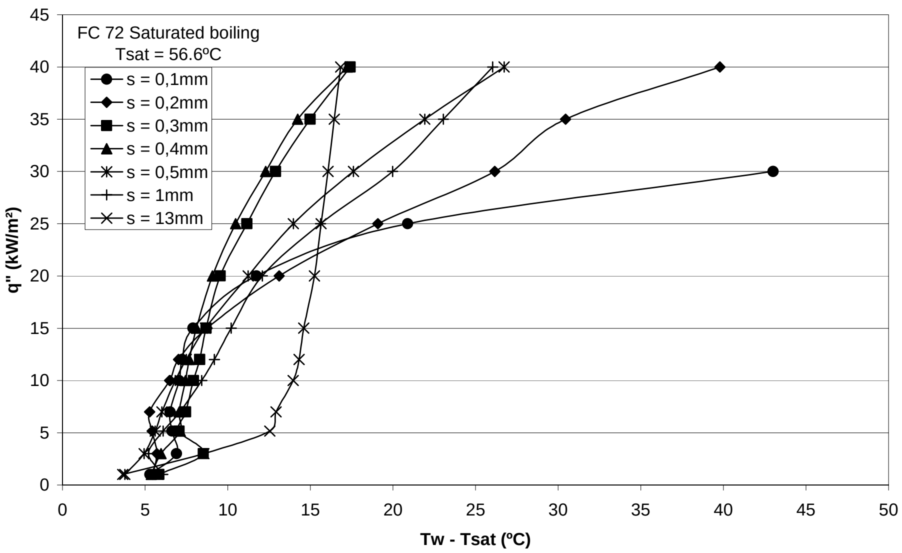


Figure 6. Partial boiling curves for FC-72, as a function of *s*, for UF90°.

An analysis of the configuration (DF45°, UF45° and UF90°) effect on the heat transfer coefficient was carried out for each distance *s*. Figs.7 and 8 show these effect for the more confined case, s=0.1mm, and for the unconfined case, s=13mm, respectively. In Fig.7, when q<20kW/m$^2$, the best heat transfer coefficient is for the downward facing configuration (DF45°). For q≥20kW/m$^2$, for the configurations DF45° and UF45°, *h* decreases, indicating that the dryout phenomenon is in progress. For configurations and tests discussed here we can consider 20kW/m$^2$ as the value representative of the DHF. For UF90° and q<15kW/m$^2$ the heat transfer coefficients are very close to the results for the UF45° configuration and the DHF is 15kW/m$^2$. The decrease in the DHF for the UF90° configuration, compared to the other two cases, is caused by the additional effect of confinement with an element without beveling, that increases the residence time of the bubbles on the heated wall and inhibits the cooling effect caused by the liquid front after departure of a bubble, as reported by Passos *et al.* (2004, 2005).

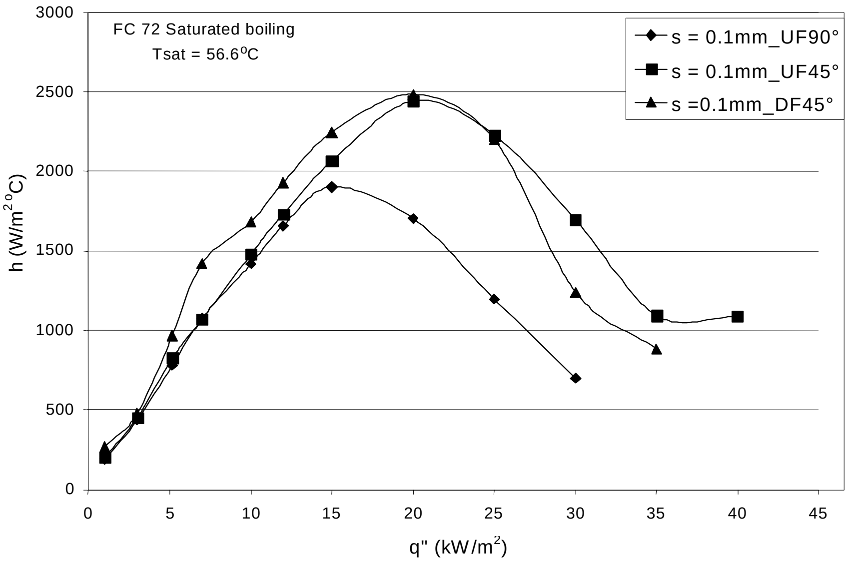


Figure 7. Configuration effects on the heat transfer coefficient against the heat flux, for s=0.1mm.

Figure 8 shows the results of *h* against *q*, for the cases without confinement, s=13mm. The heat transfer coefficient for DF45° is the best, followed by UF45°. This trend is consistent with the heat flux characterizing the transition between the isolated regime and the regime developed in nucleate boiling. Using the FC-72 properties and contact angle $\theta$ of 35° and 85° the heat flux calculated by Eq.(4) is 70 and 109kW/m$^2$, respectively, higher than that of the maximum heat flux in this experimental work. For DF45°, the thickness of the thermal layer is greater than for the other two configurations and the nucleation site density is higher. As reviewed in the introduction, for an orientation angle of 0° (upward facing heating surface) the generation of bubbles is practically periodic and is characterized by isolated bubbles, therefore, the heat transfer is controlled by the agitation caused by the bubble departure into the liquid. For an orientation of 180° (downward facing heating surface), the bubbles are larger because they remain longer on the surface, but not long enough to cause the dryout phenomenon, and the heat transfer mechanism is controlled by the heat transport due to the removal of the superheated thermal layer (when the vapor bubble slides over the surface), and by the latent heat transport that occurs through the evaporation of the thin liquid layer under the vapor bubble, as also explained in the analysis of Nishikawa *et al*. (1984).

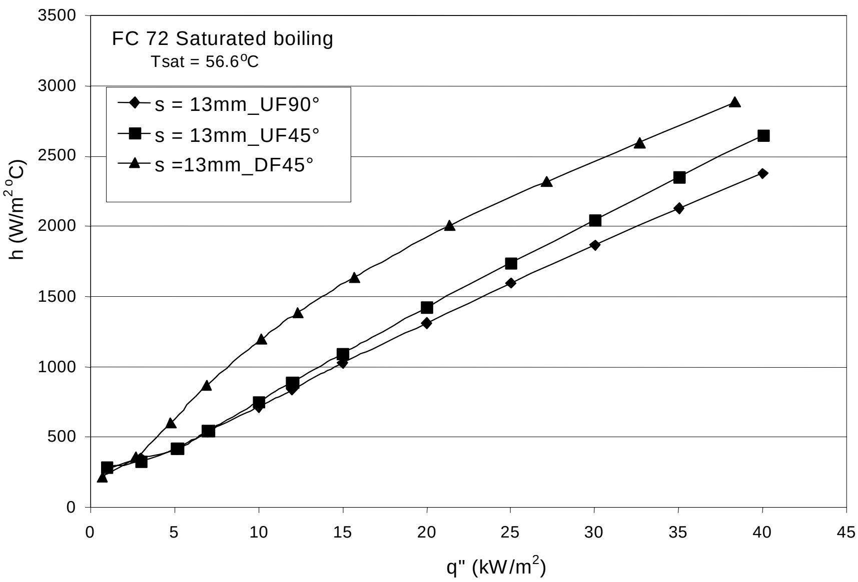


Figure 8. Configuration effects on the heat transfer coefficient against the heat flux, for s=13mm.

Figure 9 shows the values for the heat transfer coefficient as a function of the orientation of the surface for the unconfined case, s=13mm, and four values of heat flux, 15≤q≤40kW/m$^2$. The difference between the $h$ values for the orientations of 0° (UF45°) and 180° (DF45°) decreases when the heat flux increase, which is consistent with the tendency of results reported by Nishikawa *et al.* (1984). These experimental results show that the partial boiling curves presented in this paper are not in the developed nucleate boiling region.

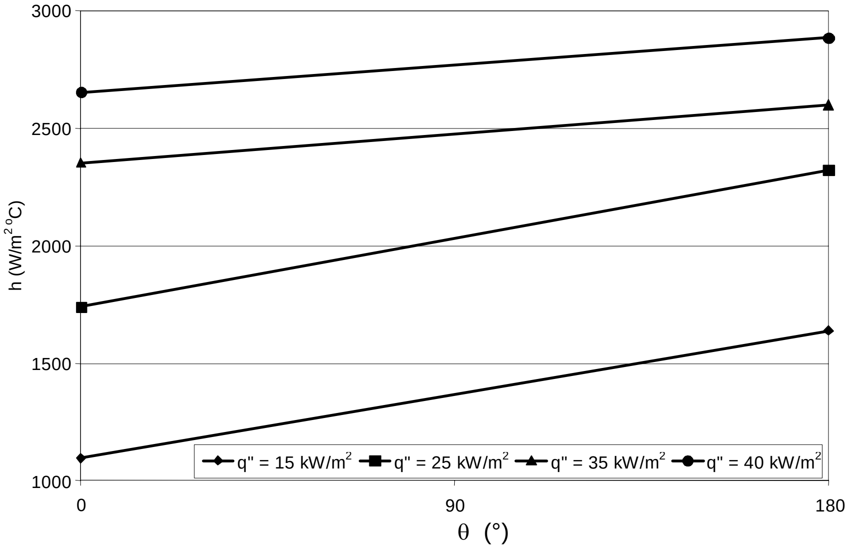


Figure 9. Effect of the orientation of the surface for FC-72, with s=13mm, as a function of the heat flux.

Figures 10 and 11 show the comparison of experimental heat transfer coefficients, for s=13mm, for DF45° and UF90° configurations with the values of $h$ calculated by Eqs.(3-6), corresponding to the empirical correlations of Rohsenow (1952), Stephan and Abdelsalam (1980) and Cooper (1984). Figure 10 shows that the values of $h$, for the DF45° configuration, are close to those calculated by the correlation of Stephan and Abdelsalam and the Rohsenow correlation with $C_{sf}$=0.0047 and an average deviation of 5.3%. For the correlation of Cooper the average deviation was of 23.3%.

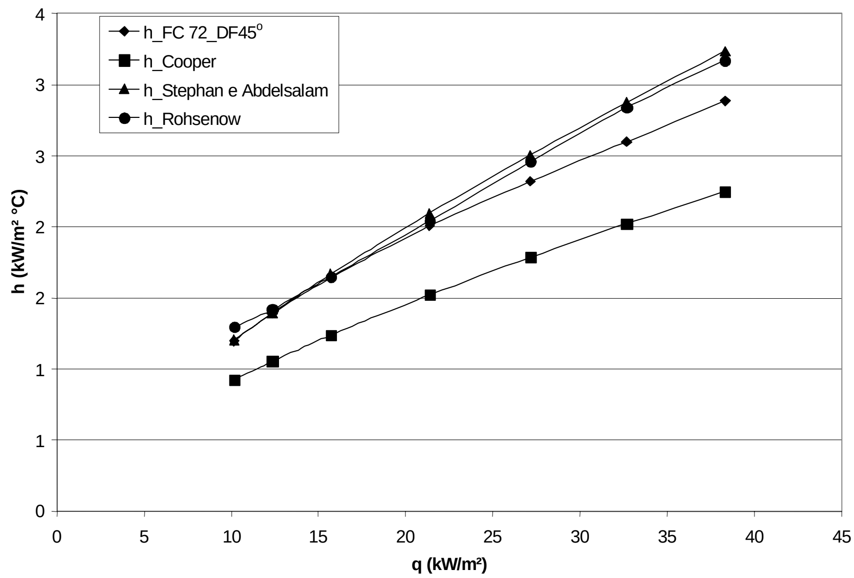


Figure 10. Comparison of experimental heat transfer coefficient with the correlations, for s=13mm and DF45°.

Figure 11, for the UF45° configuration, the experimental values of $h$ present an average deviation of 10.2% from those calculated by the Cooper correlation. For the Rohsenow correlation, with $C_{sf}$=0.0064, an average deviation of 30,9% was observed. In the same figure the values computed with $C_{sf}$=0.0047, correlated with the experimental data for the case DF45°, are presented where the values are very high because of the double effect of the enhancement boiling observed for DF45° and the higher $\Delta T$ values for the UF45º. Therefore, it is possible to conclude that the coefficient $C_{sf}$ in the Rohsenow correlation is dependent on the orientation of the surface for this zone of moderated heat flux.

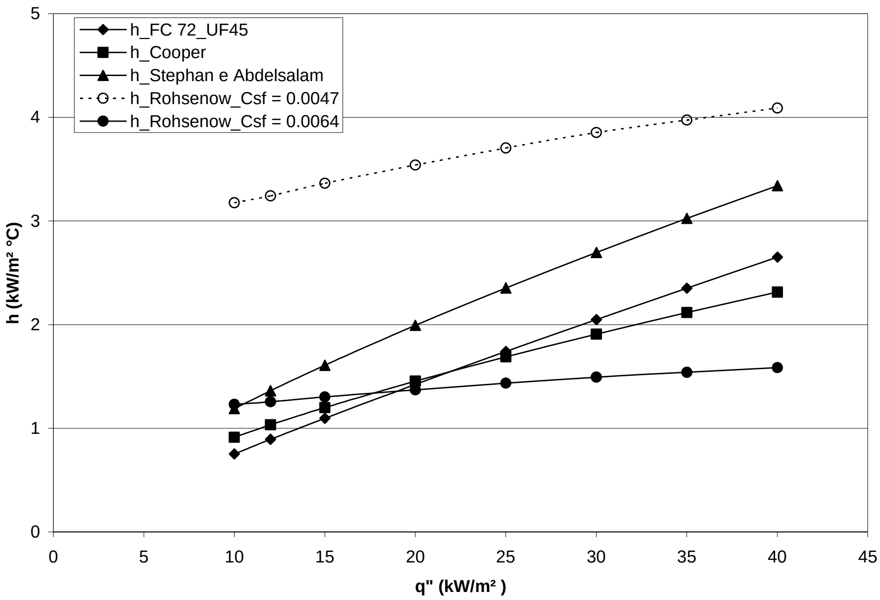


Figure 11. Comparison of experimental heat transfer coefficient with the correlations, for s=13mm and UF45°.

## 5. Conclusions

An experimental analysis was here presented on the effect of confinement on the partial FC-72 saturated boiling curves on a copper disc of diameter 12mm, for a downward and upward facing heating surface. Two types of element of confinement were used. As a general tendency the heat transfer coefficient increases when the confinement increases, corresponding to the decrease in the distance between the copper disc and a second horizontal wall. The effect of orientation is to modify the boiling mechanisms and for the downward configuration (DF45°) the heat transfer coefficients are higher than those for the upward configurations (UF45° and UF90°) both for a high level of confinement, s=0.1mm, and for the unconfined case (s=13mm), but the highest effect was obtained for the unconfined case. For the very confined boiling, s=0.1mm, an increase in the residence time (UF90°) for deformed and coalesced bubbles on the heating surface promotes the beginning of the dryout phenomenon for a heat flux lower than this for the cases with a beveled element of confinement (DF45° and UF45°).

Comparing the correlations for the nucleate boiling it was observed that the experimental values for the DF45° practically overlaps the correlation values of Stephan and Abdelsalam. However, the experimental values for UF45° have the same tendency as the Cooper correlation values. For the Rohsenow correlation, the value of $C_{sf}$ was calculated through an approximation of experimental data, so its value changes according to the surface orientation, because the nucleate boiling regime is not developed.

## 6. Acknowledgements

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