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COOLING PLATES BY POOL BOILING OF R-113

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Abstract. This work presents experimental results concerning the boiling heat transfer of R-113 on two flat stainless steel plates, one with aluminum powder deposition and the other without. The tests were carried out in natural convection and nucleate pool boiling regimes, at atmospheric pressure and at low to moderate heat fluxes (< 45 kW/m^2), with bulk temperatures between 20 and 45ºC. The effect of surface type was investigated. For heated surfaces facing downwards, the results show that the boiling heat transfer coefficient, for the plate with deposition, is higher than that for the one without deposition.

Keywords: *nucleate boiling, heat transfer, enhanced pool boiling, roughness*

1. Introduction

The search for the development of compact heat exchangers has led us to operation conditions characterized by high heat fluxes and, consequently, to the need to operate these devices under conditions of high pool boiling heat transfer coefficients (as, for example, in the plate-type heat exchangers and in evaporators with microfinned tubes), see Shah and Sekulic (1998). Among the different passive techniques utilized to enhance the boiling heat transfer coefficient we can consider the enhancement of the surface roughness, the increasing of the heat transfer surface area by fins, microfins and grooves (Passos and Reinaldo, 2000) and the deposition of a porous layer, (Webb, 1994 and Thome, 1990).

Jakob and Fritz, see Stephan (1992), were the first researchers to show the increase in the boiling heat transfer coefficient with an increase in surface roughness, Carey (1992). Corty and Foust (1955), observed that the decrease in the wall superheating caused by the increase in the roughness is due to an increase in the number of nucleation sites. Hübner and Künstler (1997), have shown the effect of the machining process of finned tubes on the enhancement of heat transfer, in nucleate boiling.

Golobic and Ferjancic (1999), analyzed the effect of surface roughness on the heat flux limit for nucleate pool boiling, known as critical heat flux or dryout depending on the quality, for FC-72, at atmospheric pressure. The heated surfaces were of titanium and stainless steel 1010 with varying thickness and roughness produced by sandpaper and by sulfuric acid attack. For surfaces with roughnesses R_a of 0.25 µm and 1.5 µm the critical heat flux increased 6 % and 12 %, respectively, when compared with a smooth surface. For R_a=0.20 µm, obtained by sulfuric acid attack, the critical heat flux was 29 % higher than in the case of the smooth surface.

The high flux surface is a commercially enhanced surface protected by patents, Webb (1994). Gottzmamm et al. (1973) presented experimental results with this kind of surface consisting of a sintered coating of copper with a thickness of aproximately 0.3 mm. The particles of this layer had sizes of up to 44 µm and the pores bound the heated surface to the cooling fluid. These authors showed, for a constant heat flux, a superheating, $\Delta T = T_w - T_{sat}$, of up to ten times less than the ΔT for a smooth or plain surface. This surface was tested in real situations in evaporators and the boiling remained stable for a long period of time.

Chang and You (1996), studied FC-72 saturated boiling at micro-porous surfaces prepared with copper and aluminum particles. They concluded that the micro-porous surfaces gave a high heat transfer coefficient with a low superheating in nucleate boiling. This effect is attributed to the creation of micro-porous structures in the heated surface which increase, significantly, the number of active nucleation sites.

This work presents experimental results and their uncertainties for atmospheric R-113 pool boiling on flat stainless steel plates with and without deposition of an aluminum layer, as a function of the liquid temperature and the orientation of the plate in relation to the gravity vector.

2. Experiment apparatus

The tests were carried out in a pool of R-113, inside a glass container, as shown in Fig. (1), see Rocha (2001), with a 230 mm external diameter and 270 mm height. The glass container is pressed between the two bases consisting of two stainless steel disks. Holes present in the upper disk function as feedthroughs for the thermocouple, fluxmeter cables and electrical supply cables and also for the output vapor and input condensate. A water serpentine covers the outside wall of the container and allows the control of the pool temperature (or the bulk temperature) by a Lauda cryostat, between 5^{o}C and 75^{o}C.

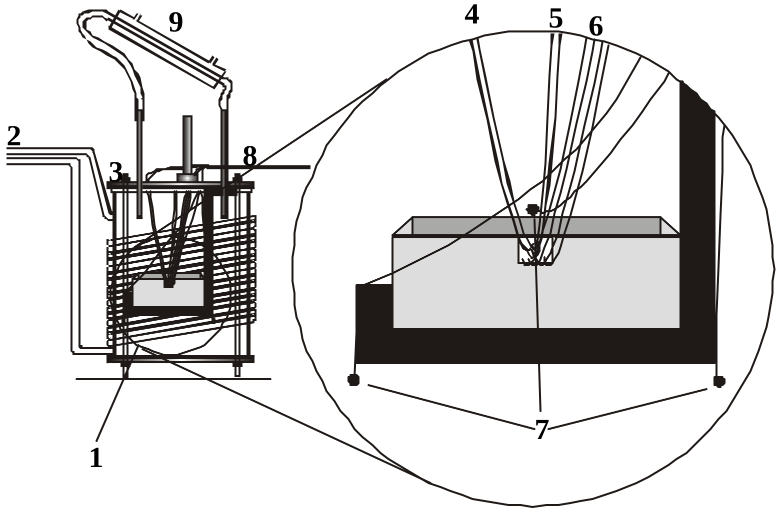


Figure 1 – Experimental apparatus.

Figure (1) shows the following components: 1- Test section, 2- Water coil, 3- Stainless steel disk, 4- Electrical resistance cables, 5- Fluxmeter cables, 6- Thermocouples of the plate, 7- Thermocouples of the pool, 8- Data acquisition system cables, 9- Condenser.

Figure (2) shows a three-dimensional view of the test section. The sequence of components is PVC plate, fluxmeter, electrical resistor and stainless steel plate (without aluminum deposition) assembled from bottom to top, respectively.

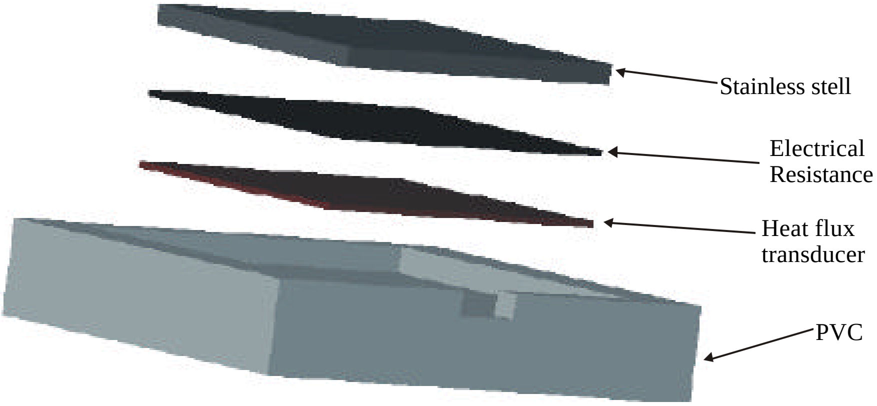


Figure 2 – Components of the test sections.

The test sections studied in this work are two flat stainless steel plates AISI 1040, one with a deposition of aluminum and the other without this deposition. The dimensions of the plates are 50x50x3.2 mm (in the case of the plate without deposition) and 50x50x4.1 mm (in the case of the plate with deposition). The deposition of the aluminum layer was obtained by the process of thermal aspersion and its thickness is 900 µm.

Each plate is equipped with four type E thermocouples formed by OMEGA wires of 0.125 mm diameter and attached by means of an epoxy resin dried for 24 h, in the position indicated in Fig. (3), in holes of 1 mm diameter and 1 mm depth.

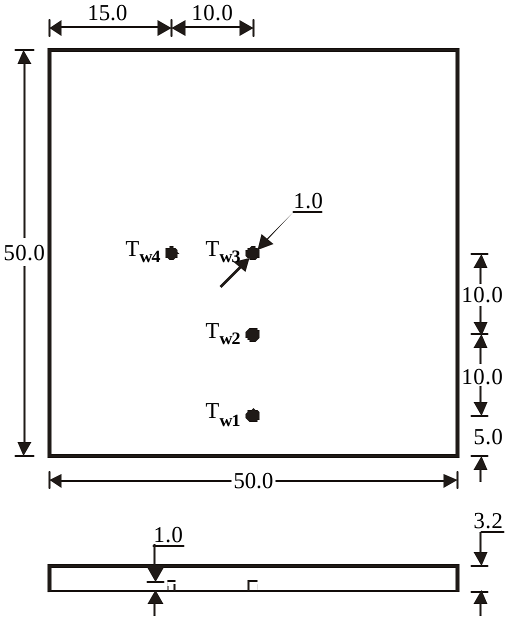
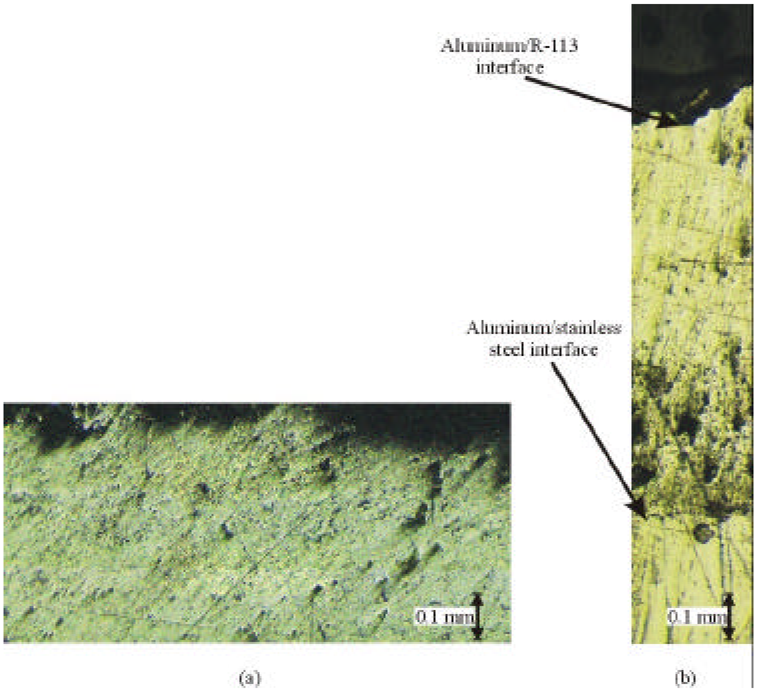


Figure 3. Thermocouple locations on the stainless steel plate. Dimensions in millimeters.

2.1. Plate characteristics

In Figs. (4.a,b), the structure of the aluminum deposition layer is visualized. The dark regions in these figures represent the regions where the working fluid is present. This visualization was obtained utilizing a JVC electronic microscope, Olympus pme3-cvt model, in the LMPT/UFSC. It can be seen in these figures, that the pores are not connected to the external edge of the layer which is in contact with the working fluid; and the pores, therefore, don't play an important role in the boiling process.

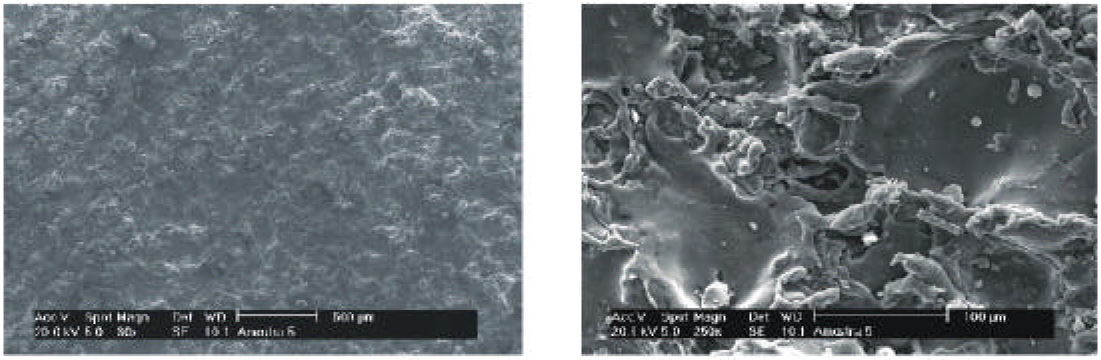
At the beginning of the present study, Rocha (2001), we expected to measure porosity of the aluminum layer. However, as shown in Figs. (4.a,b) the technique of thermal aspersion of aluminum powder was not adapted to create a layer with pore connections. Because this layer is not percolant the determination of its porosity is not of interest to this study. On the other hand, the superficial layer that is in contact with the working fluid has regions where the existence of a great number of nucleation sites is evident and its thickness is aproximately 100 µm and it may play an important role in the boiling enhancement.



(a) (b)

Figure 4 – View of the aluminum layer: (a) pore distribution inside the aluminum layer; (b) interfaces between the aluminum layer and R-113 (in black) and the aluminum layer and the stainless steel. Dimensions in millimeters.

In Figs. (5.a, b) two photographs of the overhead view of the stainless steel plate with aluminum deposition, used in the present work, are presented. These photographs were obtained with a Philipps electronic microscope, in the LABMAT/UFSC. The magnification was 30 times, Figure (5.a), and 250 times, Figure (5.b).



(a) (b)

Figure 5 – Overhead view of the aluminum layer. (a) the magnification is 30 times and (b) the magnification is 250 times.

Fig. (5.b) shows a photograph of the aluminum deposition showing various, well distributed, irregular geometrical patterns, characteristic of the topography of all layers tested in the present work. As can be observed in this figure, the surface with aluminum deposition is sufficiently irregular, presenting a great number of cavities that would make possible the intensification of the boiling and great valleys with low roughness or very smooth surfaces. These irregularities justify the consideration of a superficial aluminum layer providing a porous and rough surface. The roughness of the deposited layer was measured with a Perthen rugosimeter and Perthometer S8P 4.51 model, in the GRUCON/UFSC and the value of the depth of average roughness, R_p, is 75.4 µm, according to the DIN 4762 standard. The conclusion is that this macroscopic roughness masks the microscopic heat transfer mechanisms.

The average roughness R_p of the plate without deposition was 2.0 µm, see Fig. (6), which was measured by a Mitutoyo rugosimeter, Surfest-III model, according to the DIN 4762 standard.

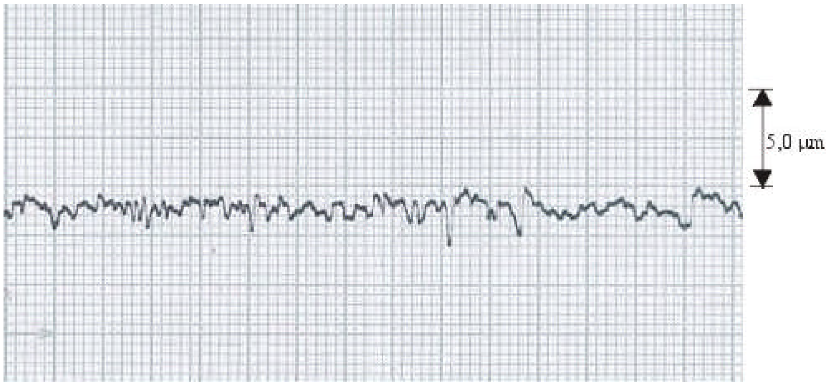


Figure 6 – Profile of the surface roughness of the plate without deposition of aluminum.

2.2. Metodology

Each test section was assembled in the upper base and immersed in the R-113 bath, with a volume of around 4 liters. The R-113 was then heated close to the temperature of saturation (T_{sat}=47.6°C) for around one hour in order to eliminate the dissolved air.

The tests were carried out through of a range of heat fluxes between 0 and 45 kW/m^2 allowing the stabilization of the process, in successive regimes of natural convection and nucleate boiling, for a constant heat flux. The bulk temperatures tested were close to 22 and 44°C. The plates were mounted in the horizontal, at a 0° inclination, with the heated surface facing upwards, and at a 180° inclination, with the heated surface facing downwards. In Tab. (1) the list of tests carried out for each combination of orientation of the heated surface and bulk temperature is presented.

Table 1 – List of tests for each combination of orientation and bulk temperature.

Test	Power (W)
1	5 to 10
2	15 to 20
3	25 to 30
4	35 to 40
5	45 to 50
6	55 to 60
7	65 to 70
8	75 to 80
9	85 to 90
10	95 to 100
11	105 to 110
12	115 to 120

In order to keep a constant bulk temperature, each test had a maximum duration of 260 s and there was a minimum interval of 5 min between two successive tests. Data was collected at intervals of 1.3 s and each test acquired 279 data points for readings of temperature, heat flux and electrical resistance.

The determination of the temperature of the heated surface, T_w, in contact with the working fluid is a key point in a practical study of boiling. By means of the temperatures T_{w1}, T_{w2}, T_{w3} and T_{w4}, whose locations are indicated in Fig. (3), and using Fourier's law in the normal direction to the plate, the averaged value of T_w was computed and details are given in Rocha (2001). The heat loss on the opposite side of the heated plate was computed, considering losses through natural convection, and, for selected cases, the computational procedure was validated by comparison with experimental results using a fluxmeter placed downward of the electrical resistance, as shown Fig. (2). The temperature distribution in the plate showed that the insulation on the sides of the plate is enough to consider negligible the loss across the sides. The percentage of the heat delivered by the resistance that is lost across the PVC is 4.9 and 1.7 % for a power of 4.3 and 105.5 W, respectively.

3. Results

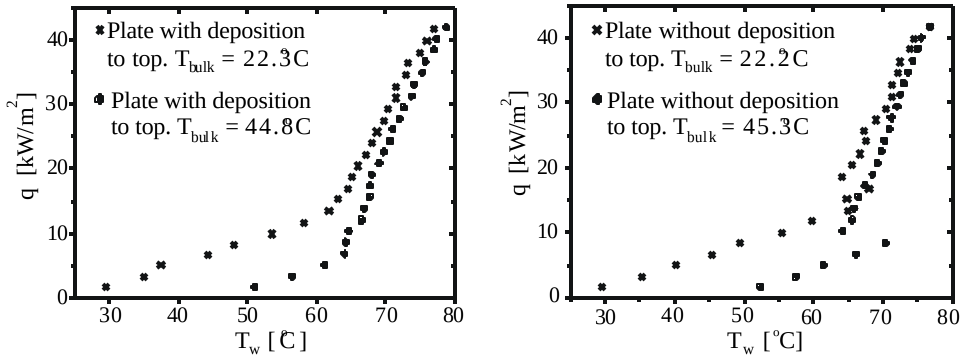
In this section the analysis of the experimental uncertainties, the experimental results concerning the effect of the liquid temperature and the orientation of the heated side of the horizontal plates are presented.

3.1. Experimental uncertainties

The experimental uncertainties of the heat transfer coefficient, h, for the plate without aluminum deposition and at a bulk temperature of 23.2°C, were 7.4 % and 6.4 %, for heat fluxes of 15.3 kW/m^2 and 41.8 kW/m^2, respectively. For a bulk temperature of 45.2°C the experimental uncertainties of h were 6.9 % and 6.1 %, for heat fluxes of 15.3 kW/m^2 and 41.8 kW/m^2, respectively. The average uncertainty of h is 7.1 %. The uncertainties for the plate with aluminum deposition were similar to those of the plate without deposition.

3.2. Bulk temperature effect

In Fig. (7.a) the curve of the R-113 boiling, for two bulk temperatures is presented. Considering that the saturation temperature of R-113, at atmospheric pressure, is 47.6°C, the sub-cooling of the liquid, for these two test conditions in Fig. (7.a), is 25.3°C (T_{bulk} = 22.3°C) and 2.8°C (T_{bulk} = 44.8°C). For a heat flux of aproximately 15.5 kW/m^2 the difference in wall temperatures for these two test conditions is 4.3°C, while the temperature difference between the bulk temperatures of the working fluid is 22.5°C. For higher heat fluxes, the experimental results show, as a trend, the relatively small effect of the bulk temperature on the nucleate boiling heat transfer. These results agree with the results presented by Carey (1992), Reinaldo (1999) and Passos and Reinaldo (2000).



(a) (b)

Figure 7 – Effect of bulk temperature on the boiling curve: (a) with deposition; (b) without deposition.

Figure (7.b) shows the effect of bulk temperature on the nucleate boiling curve for a plate without deposition. For a heat flux of 19 kW/m^2, the difference between the wall temperatures is 4.4°C whereas the boiling curves become very close for a heat flux higher than 28 kW/m^2, confirming the same trend indicated above, for the tests shown in Fig. (7.a).

A comparison of the curves shown in Figs. (7.a,b) at the transition from natural convection to nucleate boiling, reveals that this transition, is clearly more smooth for the plates with deposition, whereas for plates without deposition this occurs with a higher superheating of the wall. Moreover, the nucleation occurs for heat fluxes that decrease with an increase in the bulk temperature and at lower heat flux in the case of plates with deposition. This enhancement of the nucleation is interpreted as a consequence of an increase in the number of nucleation sites, in the case of the plate with deposition.

3.3. Effect of surface type

In the Fig. (8) results are presented for the plates, with and without aluminum deposition, oriented to 180° (with the heated side facing downwards) for bulk temperatures close to 44°C.

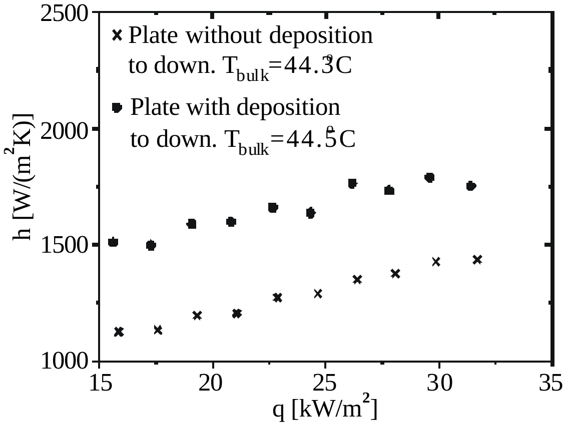


Figure 8 – Effect of surface type on the heat transfer coefficient.

The results presented in Fig. (8) indicate an enhanced boiling heat transfer for the plate with deposition. The visualization for these tests showed the existence of large bubbles under the plate with deposition indicating a more efficient vaporization of the supeheating liquid in the thermal boundary layer. These results agree with the results of Nishikawa et al. (1984).

4. Conclusions

In this work, the nucleate boiling heat transfer of R-113 was analysed on two stainless steel plates, one with aluminum deposition and the other without deposition. The main conclusions can be outlined as follows:

- In the plate with aluminum deposition, a smooth transition from natural convection to nucleate boiling was observed, which characterizes a lower superheating of the surface before the beginning of nucleate boiling. Probably, the existence of a greater number of nucleation sites, in the case of the plate with deposition, is the cause of this phenomenon.
- As seen in Figs. (7.a,b), the beginning of nucleate boiling demanded a higher superheating when the bulk temperature was increased. In a nucleate boiling regime, when the heat flux increased the influence of bulk temperature decreased.
- For the plates with a horizontal orientation and with the heated surface facing downwards, the heat transfer was enhanced for the plate with deposition, compared with the plate without deposition, and this was accompanied by the formation of large bubbles.

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