EXPERIMENTAL EVALUATION OF THE HEAT TRANSFER COEFFICIENT DURING FLOW BOILING OF DI-WATER IN A STAINLESS STEEL TUBE COATED WITH SIO_2 NANOPARTICLES

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Abstract. *The present paper reports experimental results for the heat transfer coefficient during flow boiling of DI-water in a stainless steel (AISI-304) tube with internal diameter of 1.1 mm. The internal surface of the channel was coated through a boiling process using nanofluids composed of DI-water and* SiO_2*. Nanofluids were prepared using two sizes of spherical* SiO_2 *nanoparticles, corresponding to diameters of 15 nm and 80 nm. Tubes were nanocoated using nanofluids with volumetric concentrations of 0.001, 0.01 and 0.1% for each nanoparticle size. Flow boiling results were also obtained for DI-water in a surface without coating. For nanoparticles with diameter of 15 nm, the experimental data reveal that the nanocoating causes a reduction of the heat transfer coefficient. It was also observed that the heat transfer coefficient reduction is intensified by increasing the volumetric concentration of nanoparticles used for the deposition process. On other hand, for nanoparticles of 80 nm, the heat transfer coefficient was almost unaffected by the* SiO_2 *nanocoating.*

Keywords*: heat transfer coefficient, flow boiling, coated surface, nanoparticles, nanofluids, microchannels*

1. NOMENCLATURE

ABN – Surface coated with nanofluids
BBN – Surface without deposition
G – Mass velocity, kg/m^2s
ID – Internal diameter
h – Heat transfer coefficient, $W/m^2{}^\circ C$
q – Heat flux, W/m^2
T_{wall} – Temperature of the internal tube wall, °C
T_{bulk} – Fluid bulk temperature, °C

2. INTRODUCTION

Since Choi and Eastman (1995) introduced the term “nanofluid” to nominate the addition of nanoparticles to a base fluid in order to improve its thermal conductivity and, consequently, the heat transfer coefficient in convective heat transfer processes, several research paths were opened concerning this new research area. Studies were performed focusing on characterizing the properties of these fluids, principally the viscosity and conductivity, obtaining the stabilization of these suspensions and investigating the heat transfer coefficient and pressure drop provided by this fluids for single-phase convection and flow and pool boiling.

It is consensus in the literature that for pool and flow boiling heat transfer the main consequence of adding nanoparticles to a base fluid is the deposition of nanoparticles on the heated wall (Wen et al., 2011; Diao et al., 2013; Valfei and Borca-Tasciuc, 2014; Souza et al., 2014; Fang et al., 2015), modifying the surface structure, the surface-liquid interactions and the size of the cavities on the surface. These modifications can promote either augmentation or reduction of the active site density implying on variations on the heat transfer coefficient. The relative effect of the nanoparticle deposition on the heat transfer coefficient seems related to the combination of surface roughness and nanoparticle size, as pointed out by Souza et al. (2014) and Wen et al. (2011).

In the present study, the effect of nanoparticle deposition on the surface into the heat transfer coefficient during flow boiling of DI-water in a 1.1 ID stainless steel AISI-304 tube was investigated. The nanoparticle deposition was obtained by performing previously to the tests with DI-water, flow boiling experiments with spherical SiO_2 nanoparticles with diameters of 15 and 80 nm and volumetric concentrations of 0.001, 0.01 and 0.1%

3. EXPERIMENTAL APPARATUS AND PROCEDURE

3.1 Experimental facility

Figure 1 illustrates the experimental apparatus and details of the test section. In the facility, the test fluid is driven from the reservoir through the circuit by a gear pump (Micropump GA-T23). The mass flow rate is estimated from single-phase pressure drop measurements through a 2.0 mm ID, 100 mm long quartz tube using a differential pressure transducer (Endress+Hauser PMD75) with a measurement span of 0-3 kPa. Calibration curves were previously adjusted correlating the pressure drop and mass flow rate using as reference the mass deposition in a digital analytical balance (precision 0.01 g). During these testes, the test facility was run as an open circuit. Such procedure was implemented to avoid possible effects on the flow rate measurements of nanoparticles deposition on the internal parts of commercial and non-internally inpectable flow meters. The error associated with the mass flow meter was found equal to as 4.6% of the measured value with reliability of 95.4%.

A pre-heater consisting of a tube-in-tube heat exchanger is used to impose the inlet temperature of the test fluid at the test section. This heat exchanger uses as heating source a thermal fluid (capable of working at temperatures up to 317°C) whose temperature is controlled by a thermal bath. Needle valves located upstream and downstream of the test section are used to minimize two-phase flow oscillations due to the confined bubble formation. At the test section entrance, measurements of bulk temperature, using a thermocouple positioned within the flow, and absolute pressure, using a pressure transducer (Endress+Hauser PMP131 for 0-400 kPa) were performed. The differential pressure along the test section was measured with a differential pressure transducer (Endress+Hauser PMD75 for 0-300 kPa). The outlet temperature was measured through a thermocouple positioned within the flow. The wall temperature was measured with thermocouples fixed on the external wall of the test section at the top and bottom of each section. Wall temperatures were measured at 5 cross-sections distributed along the heated length of the test tube.

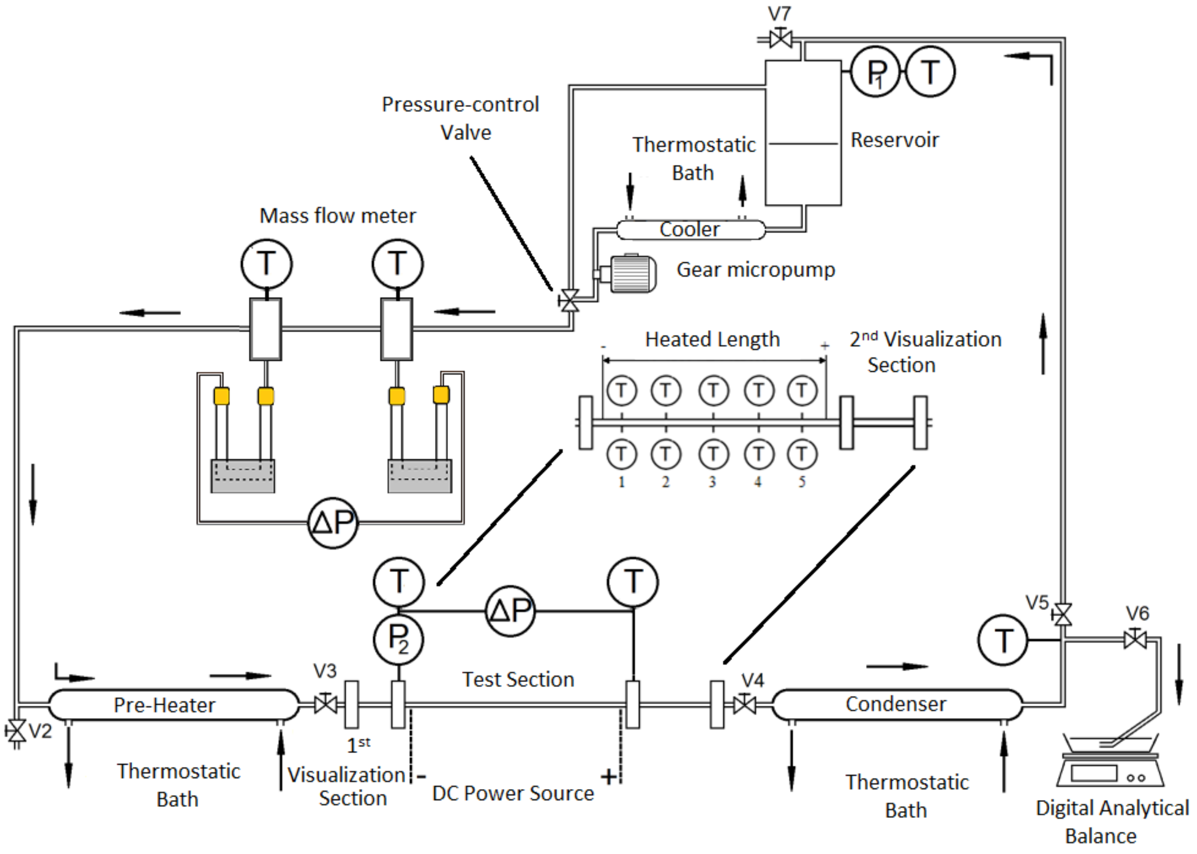


Figure 1. Illustration of the test facility.

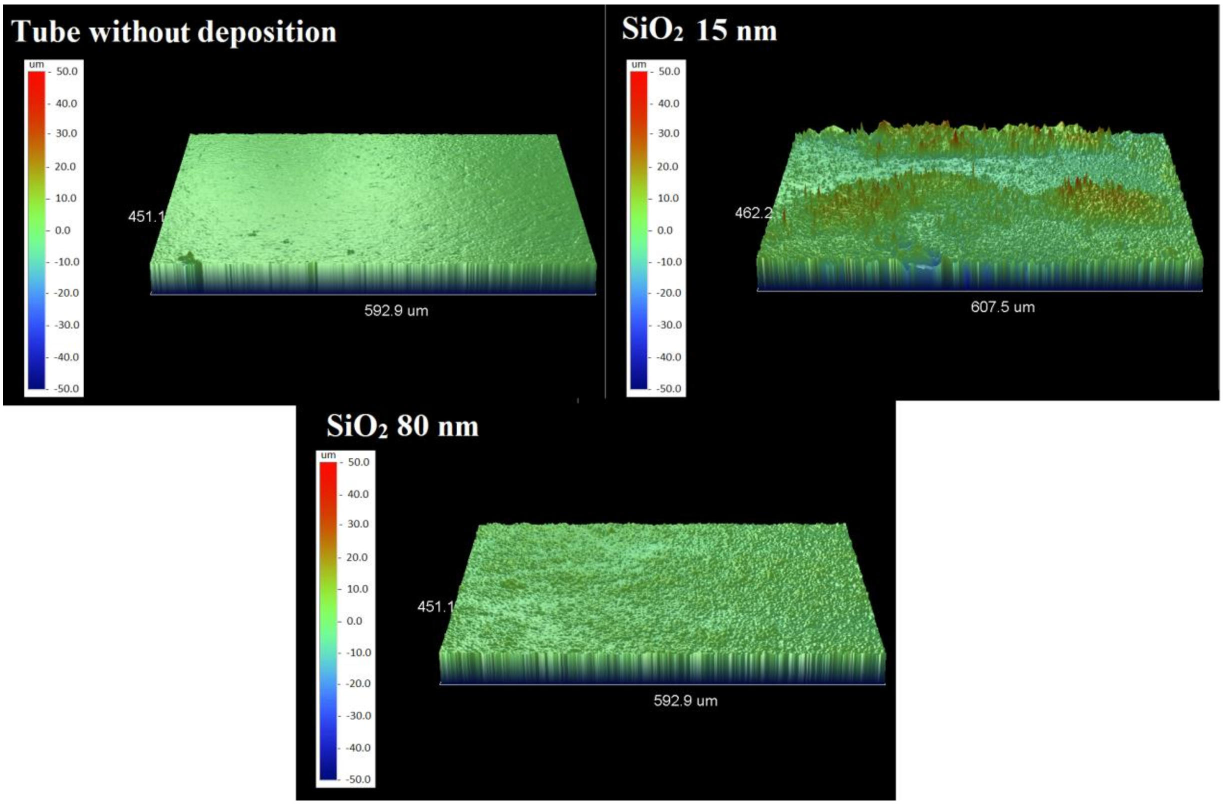
The test section is a stainless steel tube (AISI-304) with internal diameter of 1.1 mm and 200 mm long. The heating effect of the test section was obtained by supplying electrical current from a DC power source (TDK-Lambda GEN 20V-76A) directly to the test surface. All temperatures were measured with K-type thermocouples with hot junction diameters of 0.152 mm. Just downstream the test section is a 1.0 mm ID and 100 mm long quarts tube, installed in order to allow two-phase flow visualizations with a high-speed camera. Downstream the transparent tube is a heat exchanger (condenser) responsible for condensing and subcool the test fluid by rejecting heat to a secondary fluid which temperature is controlled by a second thermal bath. The condenser, the pre-heater, the flow meter and the reservoir are made of borosilicate glass, allowing the evaluation of deposition of nanoparticles along the circuit. To record the data and to monitor and control the experimental apparatus, a LabView program was used with a National Instruments data acquisition system (SCXI-1000 with SCXI-1102 thermocouples module).

The test facility and the data regression procedure were validated through comparisons of heat transfer and pressure drop experimental results for single-phase flow and well-established predictive methods from literature (see Moreira et al., 2015).

3.2 Experimental procedures

3.2.1 Coating of the surfaces

The coating of the surface was obtained by boiling nanofluids with volumetric concentrations of 0.001, 0.01 and 0.1% on the test tube surface. For the coating (deposition), the different nanofluids were inserted on the experimental apparatus, boiled on the test tube, and then withdrawn. Figure 2 presents images obtained with a Vecco Wiko NT1100 optical profiler of the test tube surface as received from the manufacturer, deposited with SiO_2 15 nm and SiO_2 80 nm nanoparticles. The images were obtained for depositions performed with nanoparticles volumetric concentration of 0.1%. It is important to highlight that a new tube was used for each experimental condition characterized by nanofluid volumetric concentration and nanoparticles dimension.



Tube without deposition

SiO_2 15 nm

SiO_2 80 nm

Figure 2. Images of the internal surface obtained with an optical profiler (10x magnification).

3.2.2 Experimental campaign and analysis

Heat transfer coefficient results were obtained for the following conditions: (i) DI-water for the tube surface as received from the manufacturer (BBN); DI-water on the coated surface for depositions obtained with nanoparticles volumetric concentration of (ii) 0.001% (ABN 0.001%); (iii) 0.01% (ABN 0.01%); and (iv) 0.1% (ABN 0.1%).

Before been charged in the circuit, the DI-water (working fluid) was boiled for a period of 30 minutes in order of eliminating non-condensable gases. The experimental circuit was firstly evacuated down to an absolute pressure of 10 kPa, and then charged with DI-water. The tests were performed for a saturation temperature at the test section outlet of 102 ± 3°C, subcooling at the test section inlet of 25°C, heat fluxes ranging from 100-350 kW/m^2, vapor quality at the test section outlet from 0.01 to 0.5 and mass velocities of 200, 400 and 600 kg/m^2s.

The local heat transfer coefficient, h, was estimated according to the Newton's cooling law, as follows:

$$h = \frac{q}{(T_{wall} - T_{bulk})} \tag{1}$$

The temperature at each one of the five cross-sections with thermocouples was estimated by averaging the measurements at the top and bottom of the tube external surface. Based on this value for each cross section, the wall temperature of the inner surface, T_{wall}, was estimated by solving the heat diffusion equation assuming one-dimensional heat conduction through the wall, uniform heat generation by joule effect and adiabatic external surface. To estimate the fluid bulk temperature, T_{bulk}, firstly, based on the heat flux and the measured temperature and pressure at the test section inlet, the subcooled region length, the single-phase pressure drop over its length, and the saturation temperature at the beginning of the saturated region were calculated by solving simultaneously an equation of state relating saturation temperature and pressure plus single-phase pressure drop and a local energy balance. The overall pressure drop over the saturated region was then determined by subtracting the single-phase pressure drop from the measured total pressure drop. After that, a constant pressure drop gradient, given as the ratio of the overall pressure drop over the saturated region and the corresponding length, was assumed from the beginning of the saturated region until the end of the test section. Then, the saturation temperature was calculated from the estimated local pressure. The heat flux, q, was calculated as the ratio between the electrical power supplied to the test section and its internal area based on the heated length. The electrical power was calculated as the product between the electrical current and the voltage supplied by the DC power source. The local vapor quality was estimated based on determined by an energy balances over the corresponding heated lengths.

Temperature measurements were calibrated and the temperature uncertainty was evaluated according to the procedure suggested by Abernethy and Thompson (1973). Accounting for all instrument errors, uncertainties for the calculated parameter were estimated using the method of sequential perturbation according to Taylor and Kuyatt (1994). The experimental heat transfer coefficient error was always lower than 20%. The heat transfer coefficient average error was 10.6%.

3.2.3 Manufacturing procedure of the nanofluids

The nanofluids were prepared according to the two-steps method, which consists of adding nanoparticles, (SiO_2 nanoparticles with 80 nm or 15 nm diameter) weighed through a digital analytical balance, to a base fluid (DI-water) and dispersing them through ultrasonication during a period of 30 minutes (Coleparmer CP505). Once prepared, the nanofluid was loaded to the test facility following the procedure above cited (item 3.2).

4. RESULTS

Figure 3 illustrates the heat transfer coefficient behavior with varying vapor quality for flow boiling of DI-water on nanoparticles coated tubes. This figure reveals different behaviors according to the nanoparticle size. In general, the heat transfer coefficient is lower for the surface covered with 15 nm nanoparticles compared to the tube as commercially available. On the other hand, distinct behaviors according to the mass velocity range are observed for the heat transfer coefficient on the surface covered with 80 nm nanoparticles compared to the tube without a covering layer.

Considering only the results for DI-water on the tube as received from the manufacturer, it is noted in Figs. 3-(a), 3-(b) and 3-(c) that the heat transfer coefficient increases with increasing vapor quality. This behavior is typical of flow boiling heat transfer under predominance of convective effects. On other hand, Fig. 3-(d) shows a practically constant heat transfer coefficient with increasing vapor quality. Such a behavior is typical of flow boiling dominated by nucleate boiling effects.

For G=200 kg/m^{2}s and vapor quality higher than 0.06, the heat transfer coefficient differences between the tube as provided by the manufacturer and the tube with the surface coated with 80 nm nanoparticles are within the uncertainty range of the heat transfer coefficient measurements regardless of the volumetric concentration. On the other hand, for the surface covered with 15 nm nanoparticles and for both mass velocities (200 and 600 kg/m^{2}s), the heat transfer coefficient decreases with increasing nanoparticle volumetric concentration of the nanofluid used in the covering process. Under low vapor quality conditions, G=600 kg/m^{2}s and covered layer formed by 80 nm nanoparticles, the nanocoated surface provided higher heat transfer coefficients than the tube without covering. Moreover, under these conditions, the heat transfer coefficient seems to increase with increasing the nanoparticle volumetric concentration.

It can be figured out from the heat transfer coefficient behaviors displayed in Figs. 3-(b) and 3-(c) that the deposition of 80 nm nanoparticles on the surface provides an increment of the nucleate boiling effects under low vapor quality conditions. Moreover, as illustrated in Fig. 3-(c), for G=600 kg/m^{2}s, it seems that the deposition of nanoparticles on the surface improves nucleate boiling effects and is detrimental to convective effects due to changes on the surface micro-structure, improving the number of active nucleation sites compared to the original surface. From the results displayed in Fig. 3-(c), it can be concluded that nucleate boiling effects are enhanced by increasing the nanoparticle volumetric concentration of the solution employed to obtain the coating.

For the surface coated with 15 nm nanoparticles, it seems that the coating reduces the nucleate boiling effects. Such a statement is based on the heat transfer coefficient reduction with increasing the nanoparticle volumetric concentration of the solution used during the deposition process, as shown in Figs. 3-(a) and 3-(d).

Another aspect that should be highlighted and that corroborates the discussion presented in the last paragraph is the different deposition patterns according to the nanoparticles dimensions as shown in Fig. 2. According to this figure, the surface texture through the deposition of 80 nm nanoparticles seems almost similar to the commercial tube (without deposition). On the other hand, a non-uniform texture is observed for the surface with 15 nm nanoparticles.

Therefore, from the analysis of the heat transfer results displayed in Fig. 3, and the difference in the surface texture before and after nanoparticles deposition, as shown in Fig. 2, it can be concluded that the heat transfer coefficient does not varies significantly with 80 nm nanoparticle deposition, since the surface texture is kept almost the same and the thermal resistance generated by the nanoparticle deposition is almost negligible due to its reduced thickness. However, the deposition of 15 nm nanoparticles changes the surface texture, and consequently the number of nucleation sites. In fact, the present study agrees with the results of Wen et al. (2011) and Souza et al. (2014). According to these authors, the effect of the nanoparticle deposition on the heat transfer coefficient is affected by the relative size of the nanoparticles and surface cavities and the way that they interact in order to obtaining the final surface finishing.

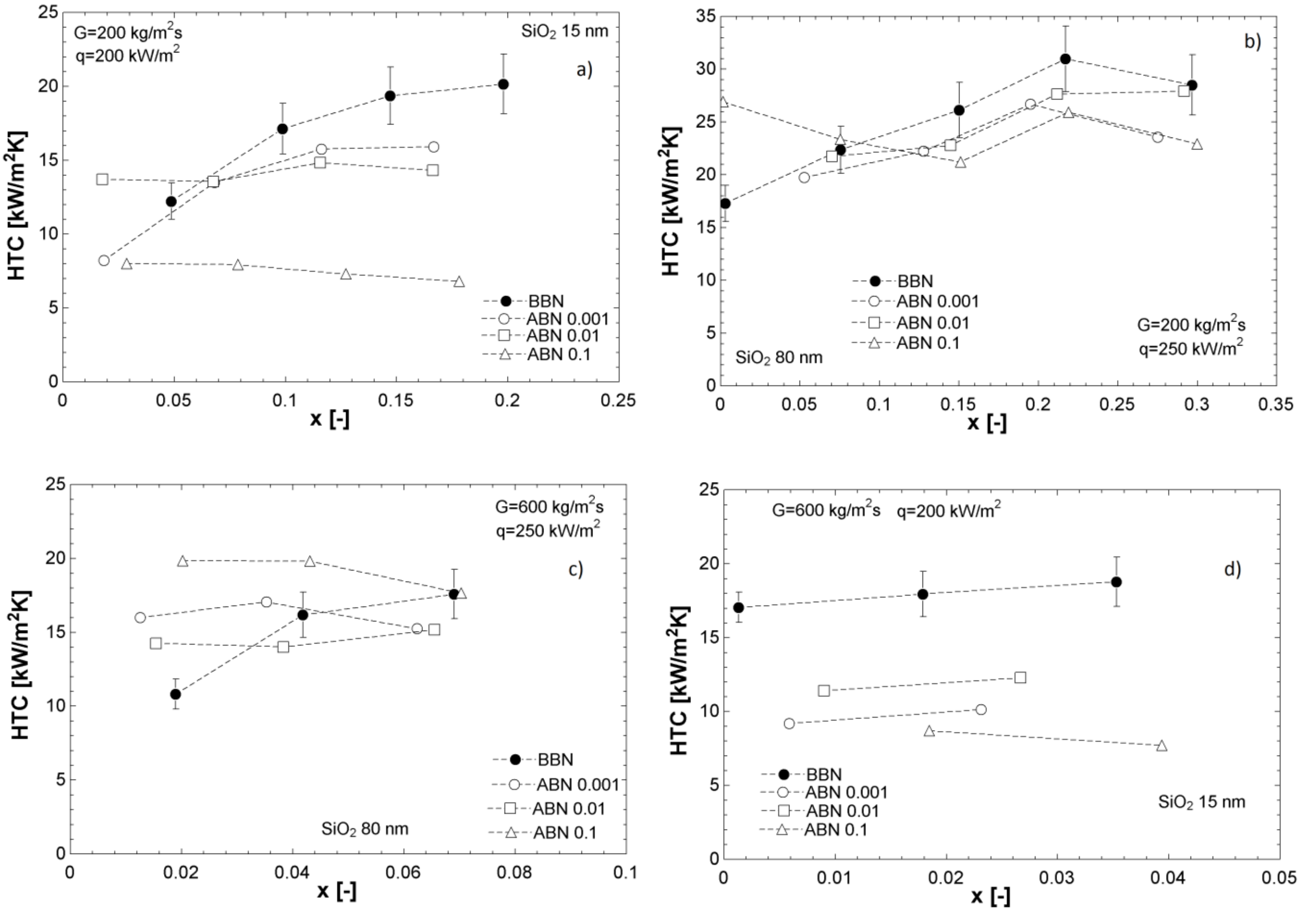


Figure 3. Heat transfer coefficient behavior with varying the vapor quality for a) SiO_2 15 nm nanoparticle coated surface, G=200 kg/m^{2}s; b) SiO_2 80 nm nanoparticle coated surface, G=200 kg/m^{2}s; c) SiO_2 80 nm nanoparticle coated surface, G=600 kg/m^{2}s and d) SiO_2 15 nm nanoparticle coated surface, G=600 kg/m^{2}s.

5. CONCLUSION

Based on the analyses of the experimental results obtained in the present study, the following conclusions are presented:

i. In general, the heat transfer coefficient increases with increasing vapor quality for flow boiling in the tube as commercially available. Such behavior is typical of flow boiling under performance of convective effects;

ii. For the surfaces covered with 15 nm nanoparticles, the heat transfer coefficient decreases with increasing the nanoparticles volumetric concentration of the solution used during the deposition process. For the surfaces covered with 80 nm nanoparticles and low vapor qualities, it seems that the heat transfer coefficient increases with increasing the nanoparticles volumetric concentration of the solution used during the deposition process. On the other hand, as the vapor quality increases, the effect of the nanoparticles volumetric concentration on the heat transfer coefficient seems to become negligible and the results are within the range of uncertainties of their measurements;

iii. Finally, it is important to highlight that the deposition of nanoparticles o the surface modifies its texture, and its heat transfer behavior. Moreover, the intensity of these effects on the heat transfer coefficient are related to the way that the nanoparticles fills the cavities on the surface and how it affects the number of nucleation sites and, consequently, the nucleate boiling behavior;

6. ACKNOWLEDGEMENTS

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8. RESPONSIBILITY NOTICE

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