THEORETICAL MODELING OF HEAT TRANSFER FLOW BOILING OF NANOFLUIDS INSIDE HORIZONTAL MICRO-SCALE CHANNELS

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Abstract: *The present study presents a new theoretical model to predict heat transfer coefficient of nanofluids under flow boiling conditions inside horizontal micro-scale channels. The proposed model has its predictions compared against experimental data available in the literature. The model was developed based on Liu and Winterton (1991) flow boiling predictive method with the nucleate boiling parcel given by Stephan and Abdelsalam (1978) and the convective parcel modeled as conduction and evaporation through a liquid film during annular flow. In the new method, transport properties of nanofluids were evaluated according to predictive methods from literature. The constant and exponents of the Stephan and Abdelsalam (1978) correlation were modified in order to fit nanofluid pool boiling data from the literature. The nucleate boiling suppression factor and the forced convective heat transfer enhancement factor were also modified. According to the proposed model, the heat transfer coefficient increases with increasing nanoparticle concentration and vapor quality. The model seems to predict accurately well independent pure water flow boiling data by Cioncolini et al. (2007) and nanofluid data by Peng et al. (2009).*

Keywords*: Heat transfer coefficient, nanofluids, flow boiling, microchannel.*

1. INTRODUCTION

With the rapid advance of technologies in areas such as nuclear and data processing, the improvement of the efficiency of heat exchangers has became obligatory, since some of these technologies generate extremely high heat fluxes that must be taken out. Refrigeration systems based on vapor-compression cycles include at least one evaporator which can be made according to different designs, depending on its application. For some applications the heat transfer capacity of the actual heat exchangers (evaporators) available in the market is not enough in terms of the following constrains: maximum heat flux and temperature difference, and available space to allocate the device. Such refrigeration incapability many times can make a project technically or economically unviable. To meet such demands in an environment characterized by quick changes, it is essential to keep working on new alternatives to dissipate higher heat fluxes under confined conditions. One of these technologies that has been intensively studied last decade is the use of nanoparticles suspended in a base fluid, denominated by Choi et al. (1995) as nanofluid. Nanofluids were first investigated by Choi et al. (1995). These authors observed that particles with mean dimension smaller than 100nm were able to compose a stable suspension and promote dramatic heat transfer augmentation under forced convection conditions. According to Lee and Choi (1999) nanofluids constitute a very interesting alternative for advanced thermal applications, in particular, for micro and nano scale heat transfer processes, which requires high heat fluxes removal.

Initial studies have indicated the thermal conductivity enhancement by adding fractions of nanoparticles to a base fluid. In case of convective heat transfer by adding nanoparticles, authors have pointed heat transfer increment rates higher than those expected only by the thermal conductivity augmentation (Hwang et al. (2009)). Based on theses aspects, researchers carried out experimental and theoretical investigations on the nanofluids transport properties, its behavior during heat transfer convective processes and methods to obtain nanoparticles and stable nanofluids.

Nanofluid characterization is a fundamental step since that just with well-kwon solutions the reliability of experimental results is assured. Therefore, nanofluid properties have been widely investigated, specially the transport ones, such as thermal conductivity (Vajjha and Das, 2009), viscosity (Murshed et al., 2008) and specific heat (Bergman, 2009). The available studies show that the thermal conductivity of a base fluid is enhanced by adding nanoparticles (Xuan and Li (1999), Eastman et al. (2001), Wen and Ding (2004) and Das et al. (2003)). McKrell et al. (2010) investigated the nanofluids thermal conductivity through the results obtained by 32 organizations worldwide participating of International Nanofluid Property Benchmark Exercise (INPBE). They analyzed four sets of test nanofluids through the same nanofluid preparation and handling methodology. The results showed that the thermal conductivity is enhanced with the nanoparticles addition and that these enhancements are increased with increasing the volume fraction, particle aspect ratio and also that the thermal conductivity of nanofluids increases with basefluid thermal conductivity decreasing. The nanofluid viscosity also increases with increasing the nanoparticle concentration (Nguyen et al. (2008) Pak and Cho (1998), Wen and Dingy(2004), Das et al. (2003)).

Although researches on nanofluids heat transfer have been intensively carried out in the last decade, the available studies on this field are greatly focused on single-phase flows. Wen and Ding (2004) have investigated the entry region for laminar flows and various concentrations of Al_2O_3 nanoparticles in water. They have observed local heat transfer coefficient enhancements up to 41% comparing to pure water. They also observed that the degree of enhancement increases with augmenting the Reynolds number. Kim et al. (2009) investigated the effect of nanofluids on laminar and turbulent single-phase convective heat transfer for a circular tube and conditions of constant heat fluxes. They evaluated alumina/water and amorphous carbonic nanoparticles/water and verified for a 3 vol% concentration solution increments in the heat transfer coefficient of 20 % and 8%, respectively. Convective heat transfer at the entrance region was also observed. According to Jung et al. (2009), the convective heat transfer coefficient of water solution containing Al_2O_3 with 170 nm in particle size under laminar flow regime in a rectangular microchannel was increased up to 32% at a volume fraction of 1.8% comparing to the base fluid. Ho et al. (2010) performed a study on convective heat transfer of Al_2O_3/water nanofluid in rectangular microchannels. They found heat transfer coefficient enhancements up to 75% compared to pure water.

Studies on two-phase flow of nanofluids are also found in the literature and most of them concern pool boiling. This heat transfer mechanism provides high heat dissipation rates and is frequently used in industrial processes. As described by Hsu and Graham (1962), pool boiling is compound of two sub-processes which consists in the (I) bubble formation, comprising its waiting and growing time, and (ii) bubble departure from the surface and the replacement of its volume by cold fluid from the liquid bulk. The bubble formation is influenced by liquid-surface properties such as surface wettability and its roughness. In order to investigate such aspects in case of nanofluids, Suriyawong and Wongwises (2010) have performed experiments for pool boiling of TiO_2/water nanofluid under atmospheric pressures on circular plates of copper and aluminum with roughness of 0.2 and 4.0 μm varying the volume concentration of nanoparticles from 0.00005% to 0.01% . The authors verified that for concentrations of 0.0001% both surfaces independent of their roughness presented an enhancement in the heat transfer coefficient compared to pool boiling of pure water. They also observed that as higher the nanoparticle concentration, lower the heat transfer coefficient enhancement. The aluminum surface with a surface roughness of 0.2 μm has presented a higher heat transfer coefficient than the copper surface with a surface roughness of 0.4 μm. Wen and Ding (2005) evaluated the heat transfer coefficient of 10- 50 nm γ-alumina nanoparticles suspended in water under nucleate pool boiling conditions. They found that the heat transfer coefficient increases with increasing particle concentration and its increment can reaches values up to 40% for 1.25% weight concentration.

Some studies concerning pool boiling of nanofluids have found that the heat transfer coefficient decreases with increasing the nanoparticle volume fraction, such as Das et al. (2003). These authors analyzed nucleate pool boiling heat transfer of alumina/water nanofluids. They suggested that the modifications on the heated surface caused by nanoparticles deposition are responsible for the decrease of the heat transfer coefficient by adding nanoparticles.. Recently, Kathiravan et al. (2010) studied the effect of 10 nm copper nanoparticles suspended in water on the pool boiling heat transfer varying the weight concentrations of 0.25%, 0.5% and 1.0%. According to their results, the heat transfer coefficient decreases with increasing nanoparticle concentration while the critical heat flux increases by 25%, 40% and 48% with increasing nanoparticle concentration to 0.25%, 0.5% and 1.0%, respectively.

Distinct heat transfer behaviors with increasing nanoparticle concentration were observed by a single author according to the nanoparticle characteristics. Soltani et al. (2009) investigated Al_2O_3 (20 – 30 nm) and SnO (55 nm) water-based nanofluids. The alumina nanofluid was evaluated for nanoparticles weight concentration from 0.3% to 2.0% and the SnO nanofluid for concentrations between 0.5% and 3.0%. For alumina nanofluids, it was found that the heat transfer coefficient increases with increasing nanoparticle concentration. For the SnO_2 nanofluid, the heat transfer coefficient for a concentration of 0.5 wt% was lower than for pure water and for concentrations different than 0.5 wt% the heat transfer coefficient increased with increasing nanoparticle concentration.

Just recently, studies on nanofluid flow boiling started to come up, but their number are still reduced. Flow boiling is a heat transfer mechanism involving pool boiling and convective heat transfer and evaporation. So, all the aspects abovementioned influencing pool boiling are also present during flow boiling. Kim et al. (2010) analyzed the critical heat flux of alumina/water nanofluid under subcooled flow boiling conditions and verified CHF enhancements up to 70%. Kim et al. (2009) studied the CHF during flow boiling in a rectangular channel for alumina nanoparticles at 0.01% volume fraction in water. The test surface was characterized and the results suggested that the enhancement of CHF is related to the deposition of nanoparticles on the boiling surface. Henderson et al. (2010) carried out flow boiling experiments with SiO_2 and CuO nanoparticle suspended in R-134a. They evaluated also the effect of a surfactant on nanofluids thermal behavior. The dispersion of SiO_2 nanoparticles in R-134a causes a decrease of about 55% on the heat transfer coefficient compared to the performance of pure base R-134a.The head transfer coefficient degradation was credited to the difficulties in obtaining a stable dispersion. For the experiments with CuO/R-134a nanofluid, polyolester oil was added to the suspension and the experiments were performed for nanoparticle volume concentrations of 0.02%, 0.04% and 0.08%. The heat transfer coefficient for the lower concentration did not present any significant variation, while for concentrations of 0.04% and 0.08% heat transfer coefficient increments of 52% and 76%, respectively, were found compared to the baseline R-134a/polyolester results. The authors attributed such behavior to a uniform dispersion of the nanoparticles in the base liquid. Peng et al. (2009) by varying the nanoparticles concentrations of 0.1%, 0.2% and 0.5 wt% investigated the influence CuO nanoparticles on the flow boiling heat transfer characteristics of R113 refrigerant-based nanofluid inside a horizontal smooth tube,. Their results presented a maximum heat transfer coefficient enhancement of 29.7%. Peng et al. (2009) based on their experimental results proposed a flow boiling heat transfer correlation for nanofluids. By comparing this correlation against their own experimental results and data from literature, they verified 93% of the experimental data with a deviation of less than 20%. Their model consists on a multiplier based on nanofluid properties applied to a pure-fluid based flow boiling heat transfer correlation. Kim et al., (2009) investigated the flow boiling heat transfer coefficient of 0.1% alumina/water nanofluid and found no significant effect of nanofluid on the coefficient. Throughout microscopic examination of the test section they observed nanoparticle deposition on the surface. According to them, such deposition tends to increase the surface roughness increasing the nucleation sites density. On the other hand, the nanoparticle deposition causes also an increase of the surface wettability decreasing the nucleation site density. The combination of both effect have resulted an insignificant effect of the nanoparticles on the heat transfer coefficient.

Based on the present study of the literature, it is concluded that the status quo of the studies on pool and flow boiling of nanofluids is characterized by several experimental databases presenting controversial heat transfer behaviors. Until now, heat transfer models trying to explain some of the effects of nanoparticles on flow boiling heat transfer behaviors are still unavailable. So, in the present study, a new theoretical model is proposed to predict heat transfer coefficient of nanofluids under conditions of flow boiling inside horizontal smooth channels. The model is based on experimental data from literature for pool boiling and convective boiling which presents reasonable and coincident behaviors. In order to evaluate the model predictions, independent experimental results from the literature are compared against the data predicted according to the model.

2. PROPOSAL OF A NEW MODEL

In the present work, a flow boiling heat transfer model for nanofluids based on Liu and Winterton (1991) predictive method is proposed. According to these authors, the flow boiling heat transfer coefficient is composed by a pool boiling and a convective parcels given by Cooper (1984) and Dittus-Boelter (1930) correlations, respectively. The Liu and Winterton (1991) model, Eq. (1), was chosen based on its simplicity and the broad database considered by the authors during its development. Despite the fact that the original model was proposed based on conventional fluids, in the present study, the model was implemented for nanofluids with the transport properties evaluated according to predictive methods from the literature. The thermal conductivity was evaluated according to Maxwell correlation (1876), the viscosity was calculated from Einstein model (1954) and the specific heat estimated as proposed by Pak and Cho (1998).

$$h_{tp}{}^2 = (S * h_{pool} * e_s)^2 + (F * h_L * e_f)^2 \tag{1}$$

Since reduced properties of nanofluids are unknown, in order to estimate the nucleate boiling parcel in the Liu and Winterton (1991) method, Cooper correlation was replaced in the new proposed model by Stephan and Abdelsalam (1980) pool boiling correlation. In this correlation, the modified Nusselt number ($Nu=h*d_b/k_l$) based on the bubble detachment diameter is given as product of dimensionless numbers and by data regression analyzes an empirical constant and exponents were adjusted based on a broad database from the literature. The bubble departure diameter is calculated as follow, where β is the contact angle of the fluid and b is the Laplace constant:

$$b = \sqrt{\frac{2*\sigma}{g*(\rho_l-\rho_v)}} \tag{2}$$

$$d_b=0.146*\beta*b \tag{3}$$

Thirteen different dimensionless numbers were combined according to four fluid groups (water, hydrocarbons, cryogenic fluids and refrigerants). In the present study, all the dimensionless number proposed by Stephan and Abdelsam were evaluated. In their method, the dimensionless X_1 is a type of pool boiling vapor velocity Number that was included in the present method in order to capture convective effects related to the intense liquid movement close to the wall due to the bubble growing, detachment and collapsing processes. These effects become stronger as the heat flux and bubble diameter increases. The Prandtl number is given by X_6 and in case of pool boiling represents the effects not only of the ratio between momentum and thermal diffusivity but also of the bubble detachment frequency through the effect of thermal conductivity on the bubble waiting and growing times. Additionally, thermal conductivity and viscosity of nanofluids are greatly affected by the nanoparticle concentration, so it seems logical including them explicitly in the new method in order to capture nanoparticle effects. In these dimensionless, k_l is the liquid thermal conductivity, d_b is the departure break-off diameter or bubble departure diameter, T_{sat} is the saturation temperature, $\dot{q}$ is the heat flux density, ν' is the kinematic viscosity of saturated liquid, a' is the thermal diffusivity of saturated liquid.

$$X_1 = \frac{\dot{q}*d_b}{k_l*T_{sat,l}} \tag{4}$$

$$X_6 = \frac{\nu'}{a'} \quad (5)$$

So, based on these dimensionless numbers and experimental data for Al_2O_3 from Wen and Ding (2004), a pool boiling correlation was adjusted through linear regression analyzes. First, for each nanoparticle concentration a different equation given by $Nu = C'_1 \cdot X_1^{a'_1}$ was adjusted. Then, a unique exponent a_1 given as the arithmetic mean of the a'_1 exponents was calculated. Based on the a_1 value, new constants C'_1 given by the ratio between the Nusselt number and $X_1^{a_1}$ were calculated for each nanoparticle concentration. Then, C'_1 was correlated as a 1st order polynomial of X_2 Fig. 1 displays a plot of C'_1 vs. X_2 plus its curve fit. According to this figure a 1st order polynomial fits quite well the C´1 values calculated from the experimental results.

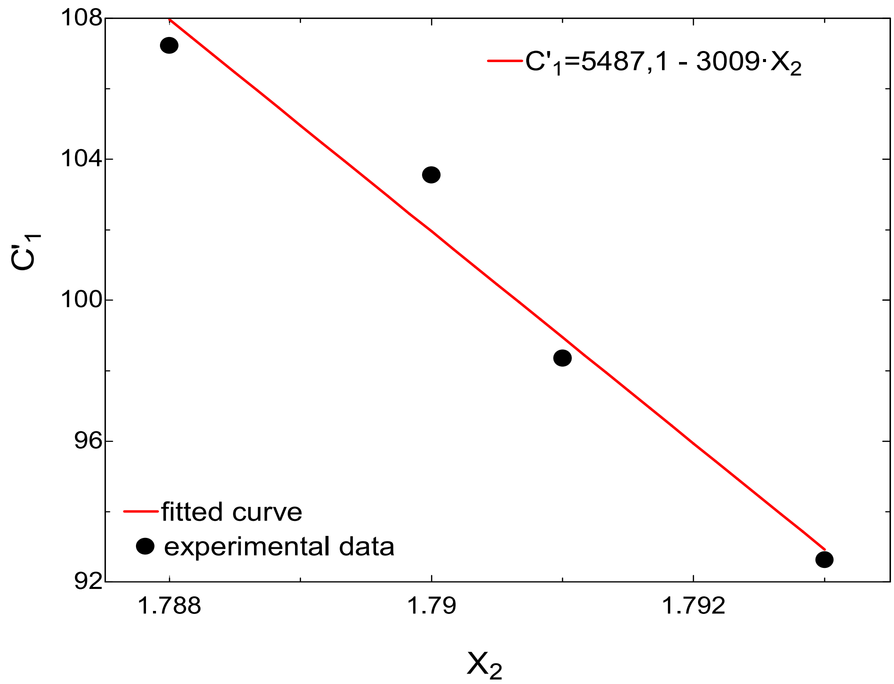

Figure 1- Experimental C'_1 vs. X_2 and its curve fit.

From this analysis, the following correlation for nucleate boiling of nanofluids was obtained:

$$Nu = (5487.1 - 3009 * X_6\ ) * {X_1}^{0.72} \quad (6)$$

Based on the lack of experimental data relating surface characteristics to pool boiling heat transfer, such effects were neglected. Also, due to the absence of a quantitative study of the nanoparticles effects on the contact angle, when calculating the bubble departure diameter, a contact angle of 45º was adopted. However, it should be highlighted that the present authors agree that these aspects are crucial to predict accurately the pool heat transfer coefficient of nanofluids. Contact angle and surface characterization during pool boiling of nanofluids are currently under investigation at the Escola de Engenharia de São Carlos of University of São Paulo. Such results will be incorporated in a new version of the present method. Figure 2 displays a reasonable agreement between the experimental results of Wen and Ding (2004) and the predictions given by Eq. (6). This agreement is verified in Fig.2, where the heat transfer coefficient of experimental data and the data predicted by the proposed model are presented.

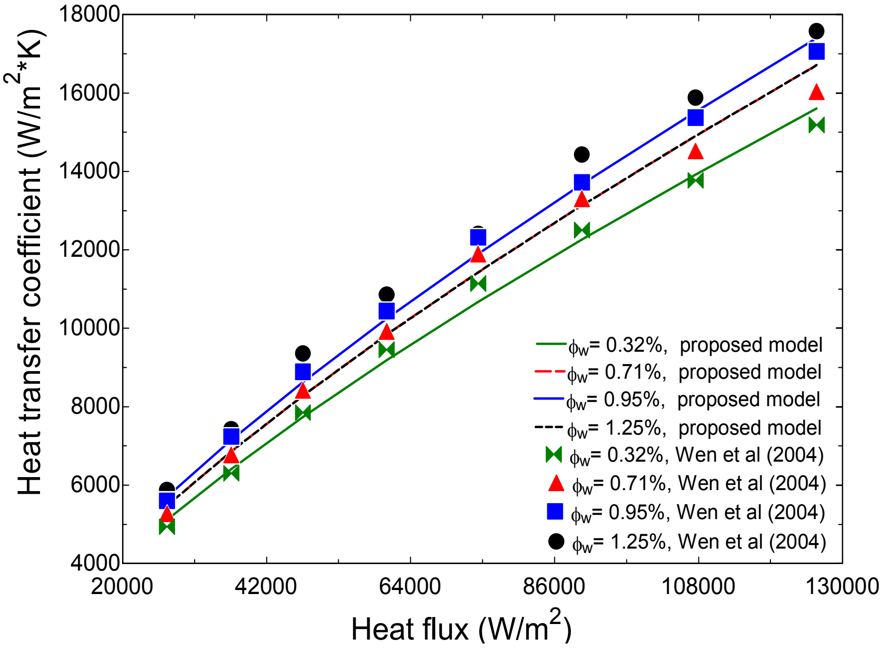

Figure 2- Comparison of the proposed nanofluid nucleate boiling correlation and experimental data from Wen and Ding (2004)

In case of flow boiling of nanofluids, it is important to highlight that the nanoparticle concentration in the liquid phase increases along the evaporator with increasing vapor quality. So, it is fundamental to evaluate the nanofluid concentration along the evaporator to estimate properly its properties. Figure 3 presents a plot showing the nanoparticle volume fractions in the liquid against the vapor quality for each weight fraction of interest in the present study. It is observed that with the augmentation of nanoparticles weight fraction the relative influence of vapor quality on the volume fraction enhances causing a pronounced enhancement of its value. According to Fig. 3, a nanoparticle weight concentration of 5% corresponds a volume concentration of 0.015 and 0.025 at vapor quality of 0.1 and 0.45, respectively. This volume fraction enhancement causes a similar effect on the properties of the nanofluid contained in the liquid phase as shown in Fig. 4 for the thermal conductivity. The heat transfer coefficient is directly affected by thermal conductivity liquid film. So, if the increase of the vapor quality enhances the volume fraction of the liquid film consequently the heat transfer coefficient it will be also enhanced.

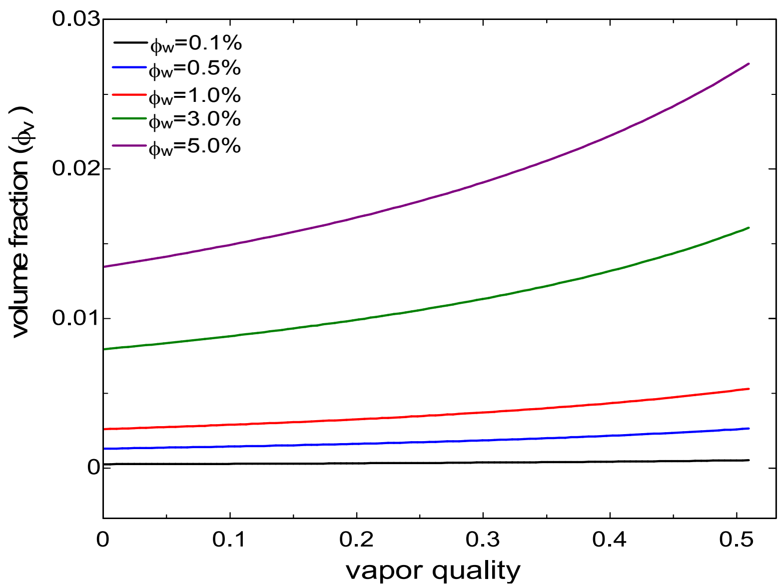

Figure 3- Evaluation of vapor quality effects on the volume fraction of a water/ alumina nanofluid for different mass concentrations at a mass velocity of 600 $kg/m^2.s$ and a constant heat flux of 30 kW/m^2.

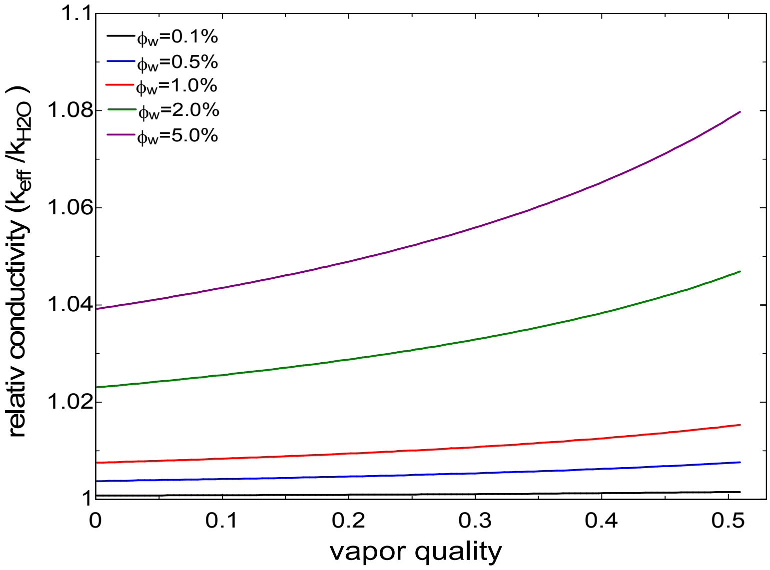

Figure 4- Evaluation of vapor quality effects on the thermal conductivity of a water/ alumina nanofluid for different mass concentrations at a mass velocity of 600 *kg/m²*.*s* and a constant heat flux of 30 *kW/m²*.

The convective effects were evaluated assuming annular flow since according to the literature this flow pattern is observed at vapor qualities higher than 0.04. It was also assumed laminar hydrodynamic and thermally developed flow, so the heat transfer coefficient was evaluated by combining the Fourier and the Newton's Cooling Law for the liquid film as follow:

$$h_l = \frac{k_l}{\delta} \tag{7}$$

The void fraction was calculated as Rouhani-Axelsson (1970) model, ε is the void fraction as follow:

$$\varepsilon = \frac{x}{\rho_v * \left[\left(\left(1+0{,}12*(1-x)\right)*\left\{\left(\frac{x}{\rho_v}\right)+\left(\frac{1-x}{\rho_l}\right)\right\}\right)+\frac{1.18*(1-x)*(g*\sigma*(\rho\_l-\rho\_v\,)^{0.25}}{G*\left(\rho_l^{0.5}\right)}\right]} \tag{8}$$

And the film thickness as follow:

$$\delta = \frac{\pi*d*(1-\varepsilon)}{2*((2*\pi)} \tag{9}$$

The nucleate boiling suppression factor (*S*) and the forced convective heat transfer enhancement factor (*F*) proposed initially by Kutateladze (1961) and considered by Liu and Winterton (1991) in their correlation were also modified to predict the effect of nanoparticles on the flow boiling heat transfer coefficient. The present study is focused on flow boiling through a micro-scale channel. Gravitational effects are negligible for two-phase flow in microchannels and surface tension effects are the dominant forces, for instance stratified flow does not occur in micro-scale channels. So, the vapor/liquid density ratio present on the forced convective heat transfer enhancement factor was eliminated from the correlation. Physics properties that affect the hydrodynamic and heat transfer processes and consequently the relevance of convective effects given by *F* during annular flow as the surface tension, the inertial and viscous forces were not accounted in the correlation. For this purpose the Weber (*We*) number replaced the Prandtl number in *F* correlation and instead of vapor quality, the dynamic viscosity was used as the Weber number multiplier as follow:

$$We = \frac{\mathrm{G_V^2*(d-\delta)}}{\mathrm{\sigma*\rho_{nf}}} \tag{10}$$

$$F = 1 + \mu_{nf} * \sqrt{We} \tag{11}$$

As the forced convective effects increases the nucleate boiling effects decreases so the nucleate boiling suppression factor was also modified to predict the nanoparticles influence as well as to fit the flow boiling experimental results from the literature. Peng et al. (2009) investigated saturated flow boiling of copper nanoparticles suspended in R113 in different mass concentrations of nanoparticles up to 0.5%, under low mass velocities, varying the heat flux from 3.08 to 6.16 *kW/m²*. They found that the heat transfer coefficient increases with increasing vapor quality. This observation can be possibly explained by the convective effects that occur under conditions of vapor qualities above 20%, which reduce the thermal layer thickness consequently increasing the necessary superheating to nucleate vapor bubbles. So, the convective effects become the mean mechanism to the heat transfer since the bubble nucleation is suppressed. The proposal suppression factor was formulated as follow:

$$S = \frac{1}{(1+0.1*F^{0.25})} \tag{12}$$

Figure 5 displays results simulated according to the proposed model for a nanofluid composed by water and γ-alumina with a density of 3700 *kg/m².s*that corresponds to a characteristic dimension of 15 nm. The figure displays data for vapor qualities lower than 0.5, since it is expected that at higher vapor qualities other mechanism as intermittent surface dryout and its rewetting my play an important role on the heat transfer process. The data in Fig. 5 were calculated for the nanofluid flowing inside a tube of 1.1 mm internal diameter, mass velocity of 600 *kg/m²s* and a constant heat flux of 30.0 *kW/m²*. According to this figure, the heat transfer coefficient increases with increasing vapor quality and nanoparticle volume concentration. Unfortunately, studies focusing on flow boiling of nanofluids are still in their infancy stage, so, are rarely found in the literature and most of them concerns halocarbon refrigerants. Only one experimental work concerning flow boiling of water based nanofluids was found for comparison porpoises. Kim et al. (2010) evaluated the zinc oxide, diamonds and alumina nanoparticle effects on the heat transfer coefficient of a subcooled flow boiling process under atmospheric pressure. Their experiments were performed at mass velocities varying from 1500 to 2500 *kg/m².s* so much higher than the value considered in the present study. They observed almost similar heat transfer coefficients for pure water and nanofluids. This behavior does not agree with the predictions by the proposed model, since according to them the heat transfer coefficient increases up to 14.1% compared to pure water with the convective parcel being responsible for 8.0% of this enhancement due to the increment of the thermal conductivity. The behaviors provided by the present model agree qualitatively with the experimental data by Peng et al. (2009) that experimentally investigated flow boiling of Copper oxide nanoparticles in R113 and observed that the heat transfer coefficient enhances with the increase of nanoparticle concentration as well as with the increase of vapor quality. Cioncolini et al. (2007) obtained experimental results for flow boiling heat transfer coefficient (*h*) of pure water inside a small diameter tube (4.3 mm) which values similar to those given by the present model.

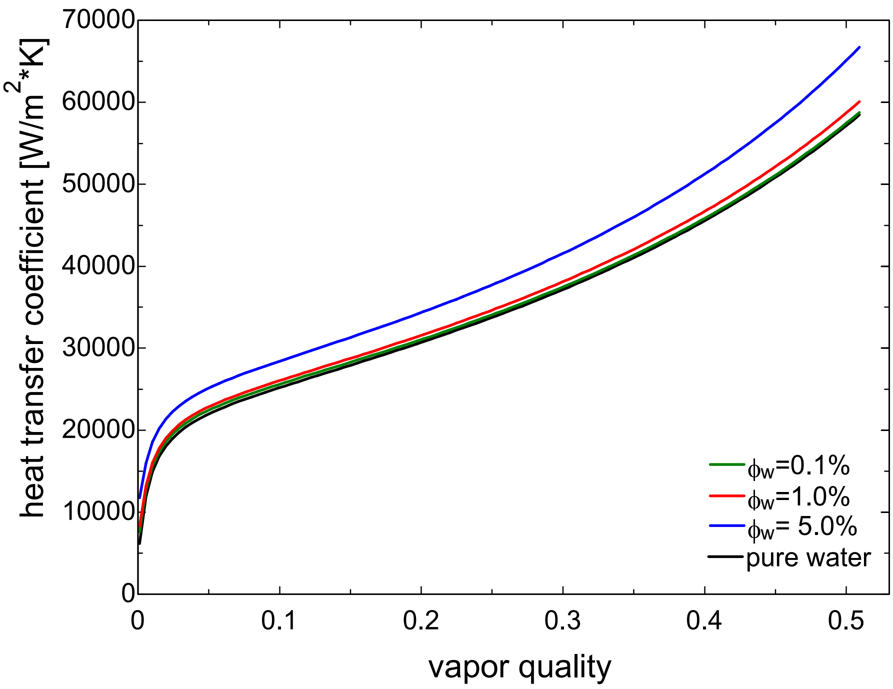

Figure 5- Evaluation of heat transfer coefficient with the vapor quality under flow boiling conditions for a mass velocity of 600 *kg/m².s* and a constant heat flux of 30*kW/m²*.

The proposed model predicts that the heat transfer coefficient increases with increasing nanoparticle concentration and vapor quality. Under low vapor qualities the heat transfer is mainly dominated by nucleate boiling effects and according to part of the literature the nanofluid pool boiling heat transfer coefficient increases with increasing nanoparticle concentration as observed by Wen and Ding (2004). This fact can explain the enhancement of heat transfer coefficient under low vapor quality conditions. For a similar vapor quality, the increment of the heat transfer coefficient for nanofluids compared to the pure water at higher vapor quality is given mainly by the increase of the thermal conductivity since the liquid film thickness seems to increase with nanoparticle concentration due to the increase of nanofluid viscosity by adding nanoparticles to the base fluid.

3. CONCLUSIONS

The following conclusions can be pointed out from the present study:

- A literature review concerning pool boiling and flow boiling of nanofluid was presented. From these analyses, it was found for pool boiling several contradicting behaviors among authors. In case of flow boiling, only few studies were found.
- A heat transfer model for flow boiling of nanofluids in small diameter tubes was developed and its behavior was compared against experimental results from the literature.
- New experimental studies concerning the heat transfer of alumina/ water nanofluid under flow boiling conditions are under development by our research group and they will be used to validate the present model.

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6. RESPONSIBILITY NOTICE