FLOW BOILING PHENOMENOLOGICAL DIFFERENCES BETWEEN MICRO- AND MACRO-SCALE CHANNELS

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Abstract. *In this paper flow boiling phenomenological differences between micro and macro-scale channels are discussed. Analyses of heat transfer, pressure drop and flow pattern results are performed in order to identify the main differences between micro- and macro-scale phenomenas. Based on these analyses important flow pattern differences between micro and macro-scale behaviors were identified, and new transition criteria based on flow patterns are presented. These criteria are based on the existence of stratifed flow and the degree of uniformity of the liquid film along the tube perimenter during annular flow.*

Keywords*: microchannels, flow boiling, transition, flow pattern.*

1. INTRODUCTION

From an analyses of the literature referring to the term “micro-scale (or microchannel) flow boiling” through public search engines, it is noted that this term started becoming popular during the early 90s as observed in the works of Peng and Wang (1993) and Bowers and Mudawar (1994). In the following years microchannel flow boiling has became a preeminent research field, since small tube diameter are highly effective to dissipate high heat transfer rates as demonstrated by experimental results from different laboratories. As soon as comparisons against traditional macrochannel predictions methods started and some divergence appeared a discussion on what is micro- and macro-scale was posted. This discussion was important since even for single-phase flow, experimental results for small tube diameters were in disagreement with traditional single- phase flow theories developed based on conventional channels. It took almost one decade to confirm that these disagreements were most of them related to experimental errors. Factors as axial heat conduction within the tube wall, high heat losses and entrance effects (as mentioned by Celata et al., 2006) were not appropriately taken into account.

Criteria to distinguish the limits between macro and microchannels received a lot of attention in the last two decades, becoming a central point in works related to flow boiling in small diameter channels. Several criteria have been developed, from which the transitional diameter can be calculated. However, these methods show a large divergence when compared against each other, since each one uses a different criterion, neglecting in their conceptions effects related to the heat transfer coefficient, and critical heat flux. In the absence of a mechanistic threshold method that takes into account heat transfer and pressure drop aspects, for practical use, the term micro-scale flow boiling has been considered when the hydraulic diameter becomes smaller than 3mm.

In this manner, several research groups began to investigate flow boiling characteristics in channels with internal diameter within a range close to 2mm. Tibiriçá and Ribatski (2010) for 2.3mm channel, Tibiriçá-Ribatski-Thome (2012) and Saraceno et al. (2012) for 1.0mm channel, have demonstrated that Liu and Winterton (1991) correlation, developed for flow boiling heat transfer coefficient predictions in macro-scale channels worked as well as new correlations developed based on exclusively micro-scale flow boiling data. The same conclusions were achieved when comparing micro-scale critical heat flux and pressure drop data against macro-scale prediction methods as observed in Tibiriçá e Ribatski (2011) and Tibiriçá et al. (2012). Although some macro-scale prediction methods work relative well for micro-scale conditions some trends are not well predicted as the temperature effect on the heat transfer coefficient. For annular flow in small diameter tubes, it has been observed that the heat transfer coefficient increases with increasing the saturation temperature while for conventional tube diameters (larger than 3mm) the heat transfer coefficient decreases with increasing saturation temperature during annular flow.

Flow patterns for macro and micro-scale channels are quite different as previously showed by Arcanjo-Tibiriçá-Ribatski (2010) and Tibiriçá (2011). Firstly, stratified flows are not observed in small diameter tubes. Another important difference is that the liquid film thickness around the channel perimeter becomes uniform as the tube diameter decreases. Taking into account this context the present paper has the aim to present new transition criteria developed based on flow pattern differences between micro- and macro-scale two-phase flows.

2. NEW FLOW PATTERN BASED TRANSITION CRITERIA

Tibiriçá (2011) has proposed new criteria to identify differences between macro- and micro-scale flow boiling in horizontal tubes. Their criteria are based on characteristics which can affect parameters considered in heat exchangers design: heat transfer coefficient, critical heat flux and the pressure drop.

From experiments performed for tubes with internal diameter between 1.00 and 2.32mm and based on a broad literature review, Tibiriçá (2011) has identified the following characteristics which occur typically for two-phase flows in small tube diameters:

i. nonoccurrence of stratified flow;
ii. degree of uniformity of the liquid film along the tube perimeter during annular flows in horizontal channels.

The characteristic number (i) is an objective criterion that is analytically modeled in the present study. Stratified flow has direct implications in the performance of heat exchangers, since in this case the perimeter average heat transfer coefficient is composed by parcels involving dry and wet regions of the tube, and in case of the dry region the tube is in direct contact with vapor phase and a much lower local heat transfer coefficient is observed. So, this criterion to distinguish between macro- and micro-scale flow boiling includes an important characteristic to those developing heat transfer correlations to be used by heat exchanger designers.

The second characteristic proposed as criterion to segregated annular two-phase flow as macro- or micro-scale is the tendency of uniformity of the liquid film thickness along the tube internal perimeter with reducing the channel diameter. In case of annular flows, the local heat transfer coefficient is a direct function of the liquid film thickness. Uniform films are also observed during vertical two-phase flows. In case of horizontal tubes, the non-uniformity of the film is related to the influence of gravitational effects and in case of macro-scale channels an earlier dryout of the tube top wall is observed due to its effect. So, the degree of uniformity of the liquid film is also a suitable criterion to evaluate the transition between macro- to micro-scale based on heat transfer behaviors.

2.1 Transitional criterion based on the occurrence of stratified flows

Tibiriçá (2011) has proposed a model to predict stratified flow conditions. The model is based on a static plug of saturated liquid surrounded by vapor within a circular channel as illustrated in Fig. 1. The condition for the liquid plug be statically stable is the equality between the force due the hydraulic head pressure in the interface and the horizontal component of the surface tension force in the triple contact line, liquid-solid-vapor. Neglecting inertial and viscous effects, hypothesis adopted considering that stratified flows occurs at low mass velocities, the force due the hydraulic head pressure, F_p, and the force due the surface tension near the wall, F_{TS}, can be written as follows:

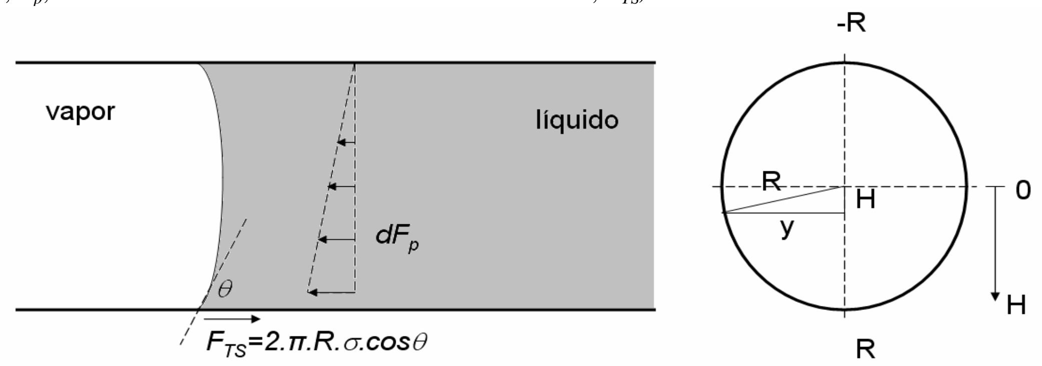

Figure 1. Pressure and surface tension used in the stratified condition model.

Force due the hydraulic head pressure in the interface:

$$F_p = \int_{-R}^{R} (\rho_l - \rho_v) \cdot g \cdot (H + R) \cdot 2 \cdot \sqrt{R^2 - H^2} \cdot dH$$

Force due the surface tension along the triple contact line:

$$F_{TS} = 2 \cdot \pi \cdot R \cdot \sigma \cdot \cos \theta$$

Equaling the forces:

$$F_{TS} = F_p$$

$$2 \cdot \pi \cdot R \cdot \sigma \cdot \cos \theta = \int_{-R}^{R} \left[(\rho_l - \rho_v) \cdot g \cdot (H + R) \cdot 2 \cdot \sqrt{R^2 - H^2} \right] \cdot dH \quad (1)$$

The solution of Eq. (1) gives the smaller tube radios, R, where the stratified flow still exists.

Table 1 shows the stratified diameters calculated by the Eq. (1) and the transition diameter obtained by the criteria of Triplet et al. (1999), D_{Lap}, Brauner and Moalem-Marom (1992), D_{Eo}, and Kew and Cornwell (1997), D_{Co} respectively. Experiments performed by Tibiriçá and Ribatski (2010) with a 2.1mm transparent tube showed no stratification at this diameter for R134a and R245fa at 31°C showing that Eq. (1) gives results close to experiments. An important factor is the inclusion of the contact angle in the transition, something not considered in other criteria.

To evaluate the criterion given by Eq. (1), experiments were conducted for quiescent air-water inside acrylic tubes. Figure 2 displays these results and the conditions for which an horizontal liquid-gas interface is present. According to this figure, the stratification occurs for tube diameters higher than 5.6mm. This value is quite close the transitional diameter of 5.5mm given by Eq. (1) based on a contact angle of 60°, measured in the present study for water droplets on an acrylic surface. Despite of the reasonable concordance between the values by Eq. (1) and the experimental results, it should be highlighted that the proposed model does not take in account inertial effects which seems to affect the transition between micro- and macro-scale based on the occurrence of stratified flow.

Table 1 - Transitional diameters according to literature criteria and the new criterion given by Eq. (1). (diameters in millimeters)

	D_{Lap}	D_{Eo}	D_{Co}	$D_{eq.(1)}$
R134a (31°C)	0,81	5,1	1,6	2,2 (θ_{cont}=7°)
R245fa (31°C)	1,01	6,4	2,0	2,9 (θ_{cont}=7°)
Water-air 25°C)	2,7	17,0	5,4	7,7 (θ_{cont}=7°) 5,5 (θ_{cont}=60°)

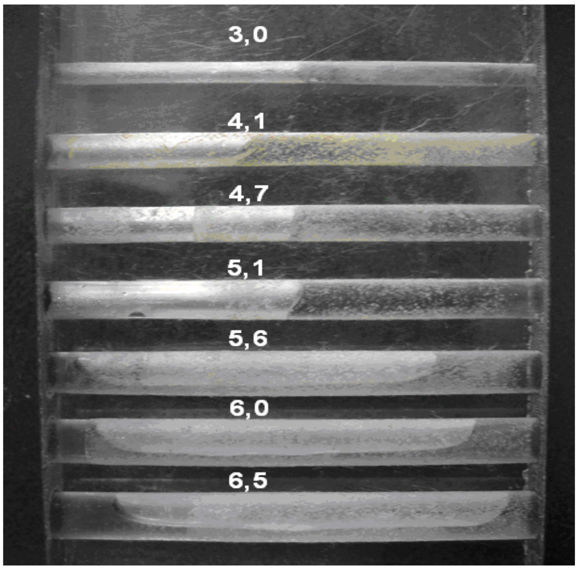

Figure 2. Air-water two-phase flow distribution inside horizontal round channels (diameter in millimeters)

2.2 Transitional criterion based on the liquid film uniformity

For annular horizontal flows, the degree of uniformity of the liquid film along the tube perimeter increases with decreasing the channel diameter and increasing the vapor velocity. According to Kandlikar (2010), surface tension forces overcome gravitational forces by reducing the diameter. Moreover, by increasing the vapor velocity, inertial forces overcome gravitational forces. So, assuming that the liquid film uniformity is intrinsically related to the flow boiling thermal-hydraulic performance, a criterion based on the liquid film characteristics and that takes into account heat transfer behaviors becomes logical.

Kandlikar (2010) has proposed five parameters to quantify the magnitude of the main forces acting during flow boiling inside channels. According to him the main forces are related to inertial, surface tension, shear stress, gravitational and evaporation effects. The degree of uniformity of the liquid film is related to the relative influence of gravitational, F_{grav}, and surface tension F_{σ}, forces. In the present study, based on Kandlikar (2010) parameters, the transition from macro- to micro-scale is attained when the gravitational force is about 5% of the surface tension force. So, the following transitional criterion is obtained:

$$\frac{F_{grav}}{F_{\sigma}} < 0,05 = \frac{1}{20} \rightarrow \frac{(\rho_l - \rho_v)\cdot g \cdot D^2}{\sigma} < \frac{1}{20} \rightarrow \qquad D < \sqrt{\frac{\sigma}{20\cdot(\rho_l - \rho_v)\cdot g}} \tag{2}$$

This criterion indicates the preponderance of surface tension forces over gravitational forces, and it can be used to identify the diameter where the flow liquid film thickness along the channel perimeter becomes almost uniform.

Table 2 presents transitional diameter values estimated according to Eq. (2), for R134a, R245fa and water. As indicated in this table the diameter provided by Eq. (2) is around 10 times smaller than the threshold diameter based on the criterion (i) given by Eq. (1).

Hulburt and Newell (2000) developed a predictive method to estimate the average film thickness, δ_m, and the film thickness in the bottom region of the channel, δ_0, during annular flow inside horizontal tubes. Then, they defined a uniformity parameter given by the ratio of δ_m/δ_0. This parameter is equal to the unity when the liquid film thickness is constant along to the tube perimeter. In the present study, a value of $\delta_m/\delta_0=0.95$ was adopted and the tube diameter was calculated according to the model of Hulburt and Newell (2000). For this estimative, a mass velocity of 50kg/m^{2}s was adopted in such a way that inertial effects are minimized. Table 2 shows also a comparison between the micro- to macro-scale transitional diameter estimated according to Eq. (2) and the tube diameter given according to Hulburt and Newell (2000) for $\delta_m/\delta_0=0.95$. It can be concluded from this table quite close results.

Table 2. Transition diameters for the liquid film symmetry criteria given by Eq. (2) compared with values given by the Hulburt and Newell (2000) model (diameters in millimeters).

	$D_{eq.(2)}$	$D_{\delta m/\delta 0=0,95}$ (G=50kg/m^{2}s) Hulburt and Newell (2000)
R134a (31°C)	0.18	0.20
R245fa (31°C)	0.23	0.16
Water (25°C)	0.61	0.75

Comparing results from Eq. (2), Table 2, and Eq. (1), Table 1, it can be observed that Eq. (2) gives values approximately 10 times lower than Eq. (1), indicating that tubes with diameter smaller than the criterion of Eq. (2) besides of the existence of a symmetric liquid film also do not develop the stratified flow.

3. CONCLUSIONS

In this paper flow boiling phenomenological differences between micro and macrochannels are discussed and two new transition criteria are presented. The conclusions are summarized as:

- Flow pattern analyses of macro- and micro-scale (also termed microchannel in the literature) flow boiling shows the absence of stratified flows in channels with reduced equivalent diameters. Based on this experimental evidence, a new criterion was developed in order to estimate the diameter when stratified flows become unfeasible. The results given by the proposed criterion agreed with the experimental data.
- Flow pattern analyses of macro- and micro-scale flow boiling shows that for small diameter tubes the liquid film thickness along the tube perimeter during annular horizontal flow tends to become uniform. Based on this experimental evidence, a criterion to estimate the macro- to micro-scale threshold diameter was proposed for annular flows based on the degree of film thickness uniformity. New experimental results are still necessary in order to confirm the validity of this method.

4. ACKNOWLEDGEMENTS

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