AN EXPERIMENTAL ANALYSIS OF R245fa TWO PHASE FLOW PATTERNS IN A 2.3 mm. I.D. TUBE

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Abstract. *In the present paper new experimentals results concerning R245fa two-phase flow patterns in a 2.3 mm I.D. tube are presented. Experiments were performed for mass velocities from 100 to 600 kg/m²s and saturation temperatures of 22°C, 31°C and 41°C. On contrary to air-water experiments in which the flow pattern establishment can be affected by the two-fluid mixer, in the present study the two-phase flow structure is a result of the evaporation process itself. In the experiments, a stainless tube was heated by applying direct DC current to its surface. Images from high speed filming (8000 frames/s) were obtained through a transparent tube just downstream of the heated section. Through a careful visual analysis of these images, the following flow patterns were identified: bubbly, elongated bubbly, churn and annular. The experimental results were compared against three different micro-scale flow pattern prediction methods from the literature. From this comparison, it was found that the method proposed by Felcar et al. (2007) worked the best and the method proposed by Ong and Thome (2009) also predicted relatively well the present database.*

Keywords: *flow patterns, micro-scale, flow boiling, two-phase flow*

1. INTRODUCTION

In-tube macro-scale two-phase flow pattern transitions and flow characteristics such as superficial void fraction, liquid film thickness, interfacial waviness, and vapor piston velocity have been targeted by innumerous researchers since the early 40s. These studies were motivated by the fact that heat transfer, pressure drop and the presence of flow instabilities are intrinsically related to the flow configuration and, consequently, the establishment of a good knowledge of the flow characteristics is crucial in order to built reliable heat transfer and pressure drop prediction methods and heat exchanger design tools.

In the late 90s, by the drastic increase in the number of transistors in a microprocessor and its inherent need of dissipating larger amounts of energy, a massive number of papers on single-phase and flow boiling in micro-scale channels have started to come up focusing on the development of heat spreaders capable of dissipating heat fluxes up to 3MW/m^2 (see Ribatski *et al*. (2007)) For the same reasons that for macro-scale channel, since the late 90s until now, a significant parcel of studies concerning flow boiling and two-phase flow in micro-scale channels have been performed to characterize flow pattern transitions and two-phase flow characteristics.

Most of studies focusing on flow pattern transitions in micro-scale channels were performed for air-water flows. Moreover, mixer devices were applied to promote the two-phase mixture. Such a scenario is quite different than what occurs in an evaporator, where the two-phase configuration is a result of the evaporating process itself. Moreover, halocarbon refrigerants, fluids under consideration to be used in heat spreaders, presents surface tension of almost one order of magnitude lower than that of air-water. Significant differences in the liquid viscosity are also observed. These physical properties may affect considerably the flow pattern as pointed out by Yang and Shieh (2001) when performing flow pattern visualizations with R134a and air-water.

To the best of the authors' knowledge, there is no general model for flow pattern transition in micro-scale channels. Generally, only curve fitting of dimensionless numbers based on restricted databases have been found as, for example, the one by Revellin and Thome (2007) or Ong and Thome (2009), for halocarbon refrigerants, Vaillancourt *et al.* (2004), and Akbar *et al.* (2003), for air/water, besides flow pattern maps developed for specific experimental conditions. Thus, they cannot be considered generalized methods.

Barnea *et al.* (1983) were the first to implement a flow pattern prediction method to be used for small channels. They considered as reference the theoretical analysis of two-phase flow transitions by Taitel and Dukler (1976) for macro-scale channels. Instead of Kelvin-Helmhotz instability, assumed by Taitel and Dukler (1976), Barnea *et al.* (1983) proposed surface tension effects as the leading transition mechanism from stratified to intermittent flows in micro-scale channels. They modeled this transition by comparing gravity and surface tension forces. Based on a previous study (Barnea *et al.*, 1982), they also proposed a new threshold value of 0.35 for the ratio between the liquid level and the tube diameter in the transition between intermittent and annular flows.

According to Ullman and Brauner (2006), the transition to annular flow in micro-scale channels is a result from wetting and inertial effects and not from a combination of Kelvin-Helmhotz instability and the liquid level as assumed by Taitel and Dukler (1976), for macro-scale channels, and Barnea *et al.* (1983), for small tube diameters. This assumption is reasonable since, for smaller channels, the meniscus radius of the wall-liquid interface may have the same order of magnitude of the tube diameter.

Felcar *et al.* (2007) in order to predict flow patterns in micro-scale channels introduced new modifications in the transitions from stratified and intermittent to annular flow in the method proposed by Taitel and Dukler (1976) and later modified by Barnea *et al.* (1983). They altered the transition from stratified to annular flow by adding a new parameter in the criterion proposed by Taitel and Dukler which is a function of a modified Eötvos number, relating capillary and gravitational effects, and the Weber number, relating inertial and surface tension effects. The transition from intermittent to annular flow is determined according to a superficial void fraction threshold given as a function of the Weber and Eötvos numbers, the latter being defined in terms only of the surface tension instead of the capillarity effects. A new definition of the Eötvos number neglecting wetability effects is reasonable since under intermittent and annular flow patterns the internal surface of the tube is wet with no meniscus being present. The Felcar *et al.* (2007) method was adjusted based on data from the literature and worked reasonably well in predicting its own database.

In this study, based on an analysis of high-speed videos, two-phase flows were characterized according to the following flow patterns: elongated bubbles, churn and annular. The tests were run for R245fa evaporating in a stainless steel tube with diameter of 2.32 mm, mass velocities from 100 to 600 kg/m²s and saturation temperatures of 22°C, 31°C and 41°C. The flow images were obtained with a high-speed video-camera (8000 frames/s) from a transparent tube just downstream of the heated section. The visualized flow patterns were compared against the predictions provided by Barnea *et al.* (1983), Felcar *et al.* (2007) and Ong and Thome (2009). The method proposed by Felcar *et al.* and the one proposed by Ong and Thome predicted relatively well the present database.

2. EXPERIMENTS

2.1. Test apparatus and experimental procedure

The experimental setup is comprised of refrigerant and ethylene-glycol circuits. The refrigerant circuit is shown schematically in Fig. 1. It globally comprises a micropump, to drive the working fluid through the circuit, a pre-heater, to establish the experimental conditions at the inlet of the test section, a test section, a visualization section, a condenser to condense the vapor created in the heated sections, and a reservoir. The water-glycol circuit (not shown) is intended to condense and subcool the fluid in the refrigerant circuit. The cooling effect is obtained by a 60% solution of ethylene glycol/water that operates as intermediate fluid in a system that comprises electrical heaters actuated by PID controllers, 3 water/glycol tanks, heat exchangers and a refrigeration circuit.

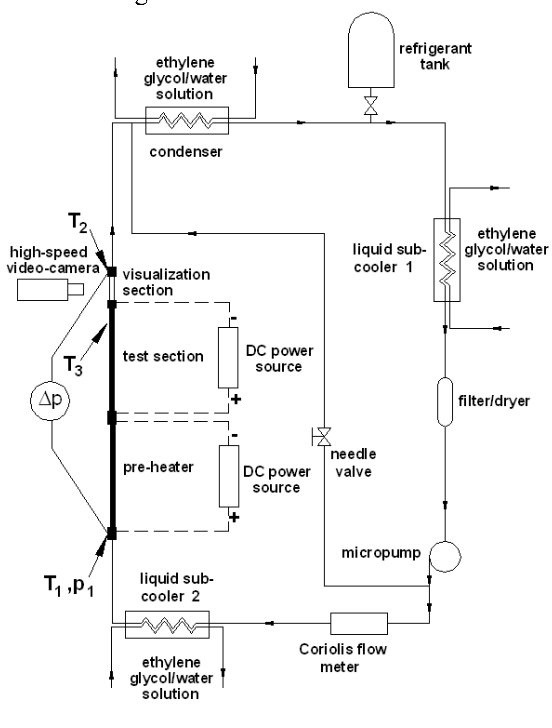

Figure 1. Schematic diagram of the refrigerant circuit.

In the refrigerant circuit, starting from the subcooler 1, the test fluid flows through the filter to the micropump (self-lubricating without oil). Downstream the micropump, a bypass piping line containing a needle-valve is installed so that together with a frequency controller on the micropump the desired liquid flow rate can be set. There is then a Coriolis mass flow meter and the subcooler 2 to assure that the fluid entering the pre-heater is subcooled. Just upstream the pre-heater inlet, the enthalpy of the liquid is estimated from its temperature T_1 by a 0.25mm thermocouple within the pipe and its pressure p_1 by an absolute pressure transducer. At the pre-heater, the fluid is heated up to the desired condition at the test section inlet. The pre-heater and the test section are horizontal stainless steel tubes 464mm long and 2.32mm ID. Both are heated by applying direct DC current to their surface and are thermally insulated. The power is supplied to them by two independent DC power sources controlled from the data acquisition system. The visualization section is a horizontal fused silica tube with an inner diameter of 2.1mm, a length of 85mm, and is located just downstream to the test section. The pre-heater, and the test and visualization sections are connected through junctions made of electrical insulation material and specially designed and machined in such way to match up their ends and keep a smooth and continuous internal surface. Once the liquid leaves the visualization section its temperature T_2 is determined from a 0.25mm thermocouple within the pipe. The corresponding absolute pressure is estimated from a differential pressure transducer that gives the total pressure drop between the pre-heater inlet and the visualization section outlet, Δp. Then, the working fluid is directed to the tube-in-tube type heat exchanger where it is condensed and subcooled by exchanging heat with the anti freezing ethylene glycol aqueous solution. The refrigerant tank operates as a reservoir of the working fluid and is used to control the saturation pressure in the test section in such way that refrigerant is transferred from the refrigerant circuit to the tank when aiming to reduce the operating pressure, and refrigerant is transferred in the opposite way to increase the operating pressure.

2.2. Data reduction

Vapor quality at the inlet of the visualization section. The vapor quality was determined by an energy balance over the pre-heater and the test section according to the following equation:

$$x = \frac{1}{h_{LG,out}}\left[\frac{4(P_1 + P_2)}{G\pi D^2} + \left(h_{L,in} - h_{L,out}\right)\right]$$

(4)

The enthalpy of the liquid at the inlet of the pre-heater, $h_{L,in}$ was estimated based on the measured temperature T_1 and pressure p_1. The liquid enthalpy and the latent heat of vaporization at the visualization section ($h_{L,out}$ and $h_{LG,out}$, respectively) were estimated based on the fluid temperature measured just downstream the visualization section, T_2, and assuming saturated state. In Eq. 4, P_1 and P_2 are the electrical power supplied by the DC power sources to the heated sections.

Flow patterns. The flow patterns were characterized based on analyses of flow images just at the beginning of the visualization section by high-speed filming. In order to use a common flow pattern terminology and based on Barnea *et al.* (1983) and Felcar *et al.* (2007), the following flow pattern characterization is applied in the present study:

- Dispersed flow that includes such configurations as bubbly and mist flows, with the gas bubbles in the liquid having smaller diameter than the tube, and gas dispersed in a continuous liquid phase and all the liquid detached from the wall and flowing as small droplets within the gas core;
- Annular flow is characterized by a gas core surrounded by a liquid film on the tube wall;
- Intermittent flow occurs when the flow geometry has a periodic or time varying character;
- Stratified flow (smooth + wavy) is observed when the two phases flow separately with the liquid in the lower region of the tube due to gravitational effects;

So, usual flow pattern denominations found in the literature are included in the four flow patterns abovementioned. Churn, slug, elongated bubbles, plug and pseudo-slug flows are characterized as intermittent flows. Annular and slug-annular are considered as annular flows. Flow pattern images segregated according to the present criteria are illustrated in Fig. 2. Usual and more constricted denominations commonly found in the literature are also indicated in Fig. 2 between parenthesis and next to the most general nomenclature adopted by the predictive methods (Felcar *et al.* (2007) and Barnea *et al.* (1983)).

Dryout conditions are characterized by heating stepwise the test section until the occurrence of a drastic wall temperature increase. In the present study, such conditions were characterized by a thermocouple installed near the end of the test section (T_3 according to Fig. 1). To avoid the damage of the test section, the power supply was cut when this thermocouple indicates a wall superheating higher than 65ºC.

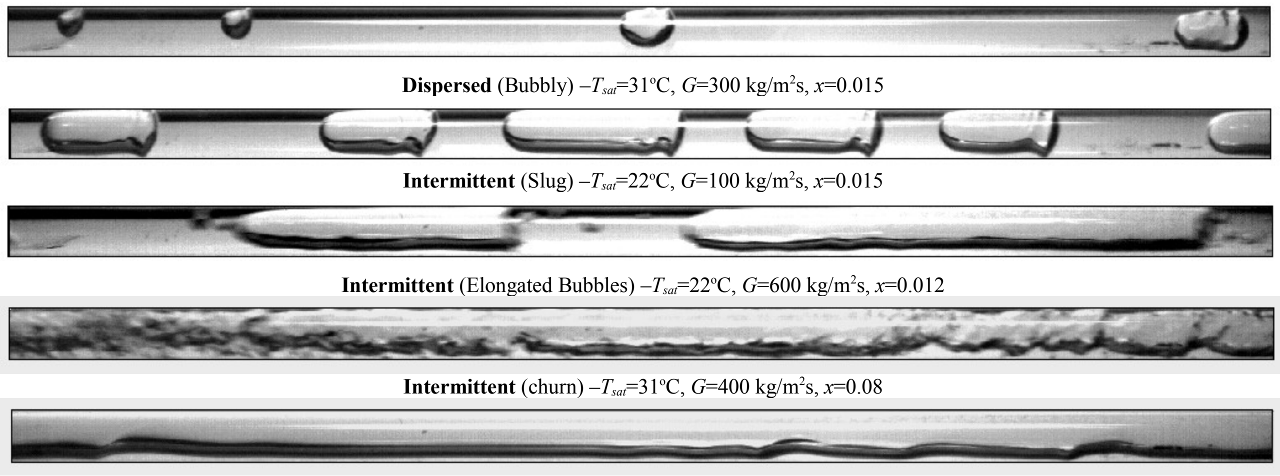

Figure 2. Flow patterns visualizations and their nomenclature, D = 2.32 mm, R245fa

2.3. Experimental validation and uncertainties

Compressible volume instabilities also termed in the literature by "explosive boiling" (see Hetsroni *et al.* (2005) for further details) are a common phenomenon in micro-scale flow boiling. These instabilities can promote severe pressure and temperature oscillations in the flow and seem related to some of discrepancies observed when comparing experimental results from different authors (see Consolini *et al*. (2007)). During the present experimental campaign, such instabilities were not observed and the fluctuations of the fluid temperature and pressure were kept within the uncertainty range of their measurements by acting on a needle valve located upstream the pre-heater.

Single-phase flow experiments were performed in order to assure the accuracy of the estimated vapor quality and evaluate the effective rate of heat transferred to the single phase refrigerant, *(ΔE/E)*, defined as follow:

$$\left(\Delta E \big/ E\right) = \frac{\left(\left[\pi D^2/4\right]\ G\left(h_{out} - h_{in}\right)\right)}{P_1 + P_2} - 1$$
(5)

where h_{in} and h_{out} are the refrigerant enthalpies estimated at the pre-heater inlet and just downstream the visualization section, respectively.

As one can see in Fig. 3, the percentage of error of the effective rate of heat transferred to the refrigerant decreases with increasing the mass velocity, according to this figure the absolute error is lower than 12% for $G \geq 100$kg/m²s and than 6% for $G \geq 400$kg/m²s.

Temperature measurements were calibrated and the temperature uncertainty 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 Moffat (1988). The experimental uncertainties associated with the sensors and calculated parameters are listed in Table 1.

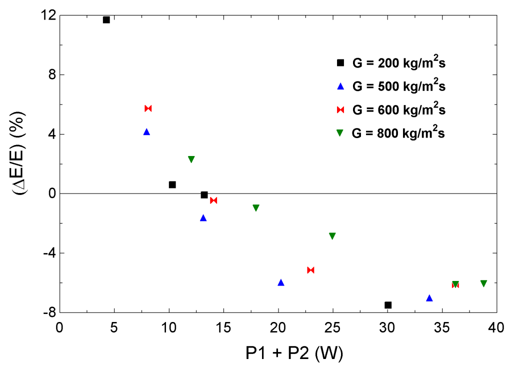

Figure 3. Evaluation of the effective rate of heat transferred to the single phase flow refrigerant, R245fa

Table 1. Uncertainty of measured and calculated parameters.

Parameter	Uncertainty	Parameter	Uncertainty
D	± 20µm	Δp	± 0.15 kPa
f_b	2 bubbles	P_1,P_2	± 0.8%
G	± 0.88%	T	± 0.15 ºC
L	± 1mm	U_G	2%
L_b	0.2mm	x	<5%
p	± 4.5kPa		

3. EXPERIMENTAL RESULTS AND DISCUSSIONS

3.1 Experimental Results

Figures 4 to 6 displays comparisons of micro-scale flow pattern predictive methods and the flow pattern results obtained in the present study. Bubbly flows are not displayed in these figures since they were observed only for calculated thermodynamic equilibrium vapor quality just above zero and, under this condition, saturated flow boiling conditions, the focus of this study, are not assured due to the uncertainties in the vapor quality estimation. Bubbly flows are also expected at mass velocities higher than 700kg/m^{2}s, however such high flow rates are not achievable by the current experimental setup.

According to Fig. 4, Barnea *et al.* (1983) method captured adequately the non-occurrence of stratified flows. Though not show, this is also observed for 31ºC and 41ºC. Moreover, Fig. 4 shows that according to the present experimental results, the predictive method by Barnea *et al.* is unable to satisfactorily represent the transition from intermittent (elongated bubbles plus churn) to annular flows. The method does not capture the decrease of the transitional vapor quality with increasing the mass velocity; instead the method proposes a constant transitional vapor quality. Such a result is related to the assumptions of a linear relationship between vapor and liquid superficial velocities and a fix superficial void fraction at the transition. These both hypotheses together yield a constant transitional vapor quality. Increasing the saturation temperature from 22ºC to 31ºC and then to 41ºC make this method work worst due to the fact that the variation of the transitional vapor quality with mass velocity becomes steeper with increasing saturation temperature.

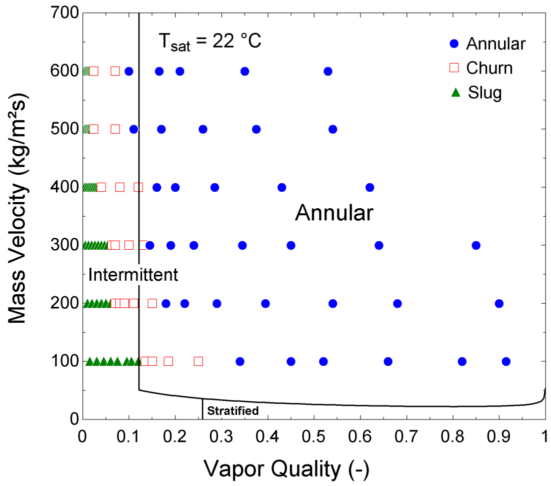

Figure 4. Comparison of the predictive method (lines) by Barnea *et al.* (1983) and the experimental data (symbols), R245fa, D=2.32mm and T_{sat}=22ºC

Figure 5 compares the flow pattern visualization results against the transitions lines given by Ong and Thome (2009) for temperature saturations of 22°C, 31°C and 41°C. In this figure, IB and CB refer to isolated and coalescing bubble regimes respectively, as proposed in reference (Ong and Thome (2009)). This figure shows that the method proposed by Ong and Thome predicts relatively well the present database; moreover the method captures appropriately the decrease of the intermittent-annular vapor quality threshold with increasing mass velocity. However, the method proposed by Ong and Thome based on experimental results in a 1.030 mm circular channel fails to predict previous results obtained by Revellin and Thome (2007) in a 0.5 mm circular channel. Here, it is important to highlight that both studies were performed in the same test facility. Based on this, it can be speculated that despite of the fact that Ong and Thome method worked well for the present database, their method can not be considered as general since failed capturing the tube diameter effect for smaller channels. According to Fig. 5, the predictions improve as the saturation temperature increases. A transition to stratified flows is not provided by Ong and Thome (2009) method since its proposition is based only on data for tube diameters smaller than 1mm, a condition for which stratified flows are not feasible. Dryout conditions were not achieved in the current experiments due to the limitations of the experimental apparatus, but based on previous results for R134a by Arcanjo *et al.* (2009), it is speculated that the method by Ong and Thome also fails into predict dryout conditions, since they seems to occur at much higher vapor qualities than those indicated by their method.

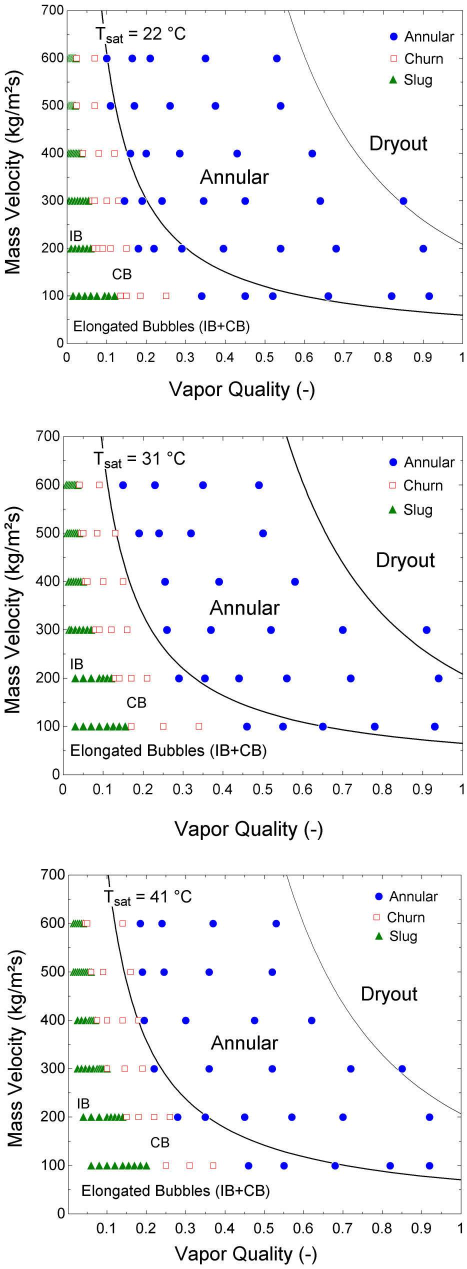

Figure 5. Comparison of the predictive method (lines) by Ong and Thome (2009) and the experimental data (symbols), R245fa, *D*=2.32mm

Figure 6 shows a comparison of the present database against the flow pattern transitions provided by the method of Felcar *et al.* (2007) for saturation temperatures of 22°C, 31°C and 41°C. In general Felcar *et al.* (2007) method predicts relatively well the independent data obtained in the present study. The transition from intermittent to annular is predicted relatively well, capturing the fact that the transitional-annular-intermittent vapor quality decreases with increasing mass velocity. As indicated by the experimental results, Felcar *et al.* (2007) method also suggests the absence of stratified flows for flow boiling of R245fa in a tube of 2.32mm ID. For high vapor qualities and mass velocities lower than 100kg/m^{2}s, according to Fig. 6, Felcar *et al.* (2007) method fails into predict annular flows and, so, this method is not suitable to predict flow pattern transitions under these conditions.

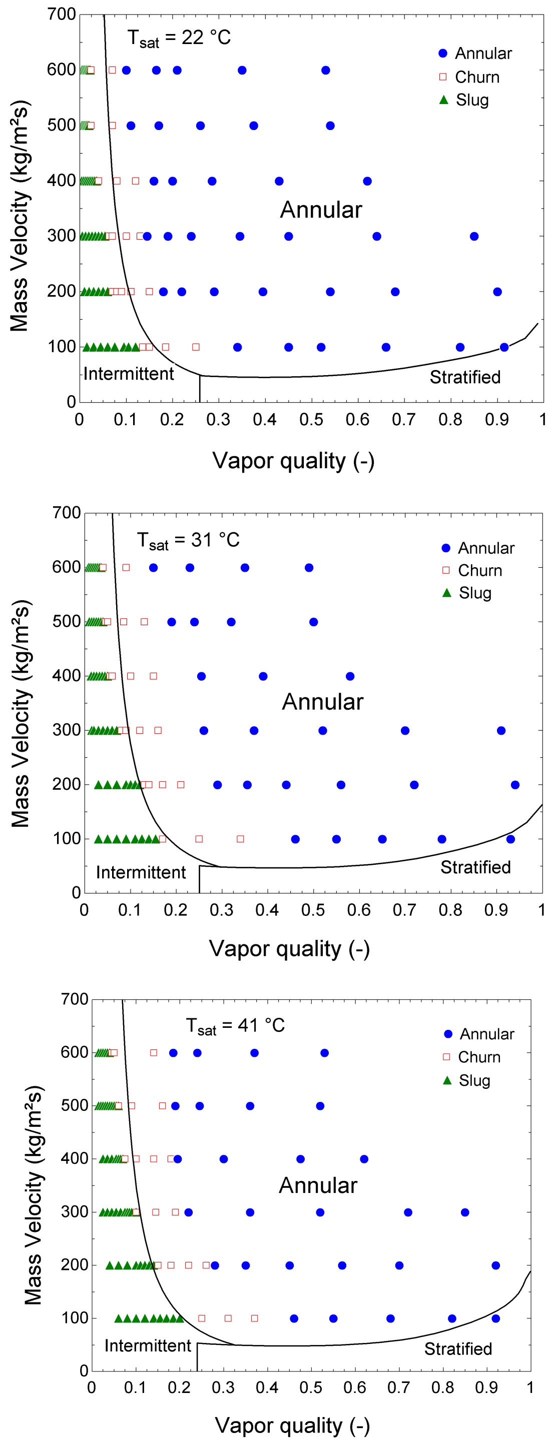

Figure 6. Comparison of the predictive method (lines) by Felcar *et al*. (2007) and the experimental data (symbols), R245fa, *D*=2.32mm.

3.2 Conclusions

A summary of the conclusions drawn from the results of the present experimental investigation on flow pattern and elongated bubble characteristic during flow boiling of R134a in a micro-scale channel is as follows:

a) In general, the flow pattern predictive method proposed by Felcar *et al.* (2007) predicts relatively well the independent data obtained in the present study; however, this method should be further improved in order to more accurately predict the flow pattern transitions at low mass velocities and high vapor qualities.
b) Despite of the fact that method proposed by Ong and Thome (2007) predicts relatively well the independent data obtained in the present study, this method should be improved in order to more accurately predict the flow pattern transitions at high mass velocities and low vapor qualities.
c) It should be also mentioned that stratified flows seem improbable for flow boiling of R245fa in a 2.32mm diameter tube.
d) The method of Barnea *et al.* (1983) gets the worse predictions of the three methods due to the fact that its transition for intermittent to annular flow is based on a constant transitional vapor quality.

4. ACKNOWLEDGEMENTS

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