EXPERIMENTAL PRESSURE DROP AND FLOW PATTERN RESULTS DURING FLOW BOILING OF R134A INSIDE HORIZONTAL TUBE

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Abstract. *In the present paper, new frictional pressure drop results of R134a inside a 5/8" (15.785mm) ID horizontal smooth tube are presented. Accurate experiments were performed covering mass velocities between 75 and 250 kg/m²s, saturation temperatures of 5 and 15 °C and vapor qualities up to 0.95. It was found that the pressure drop increases with increasing mass velocity and decreasing saturation temperature. Additionally, the pressure drop gradient presents a maximum at a vapor quality close to the dryout. The experimental data were compared against the leading pressure drop and flow pattern predictive methods available in the literature. Grönnerud (1979) provided the best predictions of the pressure drop results predicting 88% of the present database within an error band of ±30%.The flow pattern method of Wojtan et al. (2005) predicted correctly only half of the flow pattern visualizations performed in the present study.*

Keywords*: Pressure drop, Flow pattern, Two-phase flow, Flow boiling, R134a.*

1. INTRODUCTION

In the refrigeration and air-conditioning industries, the pressure drop optimization is an important aspect when designing evaporators, since, for the same cooling capacity, the vapor compressing power increases with increasing the evaporator pressure drop. Usually, in case of in-tube evaporation, the heat exchanger designers work in their projects with pressure differences lower than 1.4°C given in terms of the respective saturation temperature differences between the evaporator inlet and outlet. So, accurate pressure drop correlations and models that can be used as designing tools are necessary to estimate accurately the pressure drop within this narrow range.

Studies on pressure drop and flow patterns during flow boiling inside tubes have attracted the attention of researcher from academy and industry for several decades. Most of these studies have focused on obtaining comprehensive databases and developing accurate predictive methods. Experimental results have revealed that the frictional pressure drop increases with increasing mass velocity and decreasing saturation temperature. Moreover, the heat flux has a negligible effect on the frictional pressure drop and by increasing vapor quality from saturated liquid, firstly the pressure drop increases and then passes through a peak for a vapor quality close to 0.9. After the maximum the pressure drop decreases abruptly tending to the vapor single-phase pressure drop for a vapor quality of 1. It is highlighted the fact that although authors have found similar pressure drop trends, data from different laboratories can present differences higher than 50%. This scenario partially explains why most of the frictional predictive methods fail when applied to independent databases. In order of building reliable pressure drop models, the knowledge of the two-phase flow topology is a key aspect, since the energy dissipation during the flow depends of how the phases interact between them.

The flow pattern also affects the heat transfer coefficient and void fraction which are also important aspects to the heat exchanger design. The most quoted two-phase frictional pressure drop predictive methods in the flow boiling field are segregated as follows: (i) *purely empirical*, this group comprises empirical correlations that consist basically on fitting an equation to a broad database. In this group, the correlation of Müller-Steinhagen and Heck (1986) have been indicated as the most accurate one; (ii) *two-phase multiplayer based*, these are also empirical methods and consist to adjust an equation for the two-phase multiplier given as the ratio between the two-phase pressure drop and the single-phase pressure drop. The accuracy of these methods is a function of the comprehensiveness of its database. The most used correlations within this group are the Friedel (1979), and Grönnerud (1979) methods. (iii) *flow pattern based*, recently Moreno-Quibén and Thome (2007) have proposed a new pressure-drop prediction method by modeling the pressure-drop mechanisms according to the different flow patterns. Their method is based on Wojtan et. al (2005) flow pattern predictive method. It is important to mention that generally the methods classified as groups i and ii are based on data for annular flow and so they give better predictions under this flow condition.

Based on the abovementioned, the present paper presents new accurate pressure drop data. Results of flow pattern visualizations based on high speed filming (2000 frames/s) are also presented. The pressure drop data are compared against the leading pressure drop predictive methods. The capability of Wojtan et al. (2005) to predict flow patterns of R134a in a horizontal 5/8" ID tube is also evaluated.

2. EXPERIMENTAL APPARATUS

The experimental campaign was performed in an apparatus built by the Heat Transfer and Microfluidics Research Group of the Escola de Engenharia de São Carlos of University of São Paulo. It is comprised of refrigerant (test circuit) and water/glycol circuits. The water–glycol circuit is intended to condense and subcool the fluid in the test circuit. The refrigerant circuit is a closed-loop where a gear pump (self lubricating without oil) drives the working fluid through the circuit and its flow rate is measured by a Coriolis mass flow meter. Figure 1 presents experimental apparatus main loop.

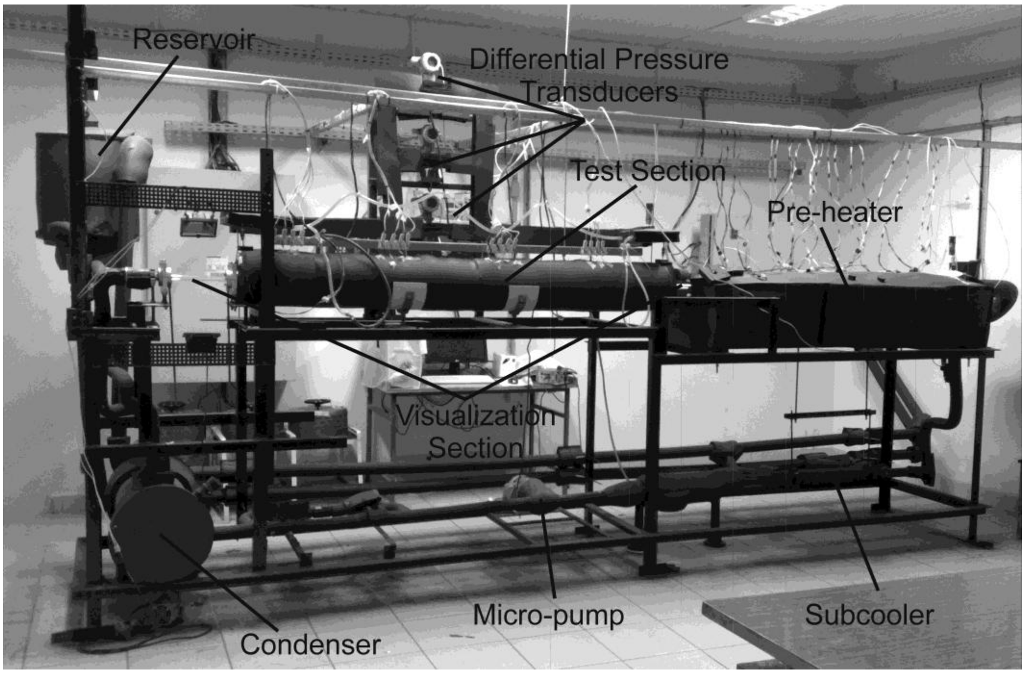


Figure 1. Experimental apparatus.

The test section consists of a horizontal copper tube with internal diameter of 15.875 mm (5/8 inch), wall thickness of 3.175 mm (1/8 inch) and 2.0 m length. The pre-heater and the test section are heated by tape resistors uniformly wrapped on the tube external surface. Both are thermally insulated. The power is supplied to the tape resistors by voltage converters manually operated. The working fluid is condensed and subcooled in a shell-and-tube type heat exchanger by exchanging heat with the anti-freezing ethylene glycol aqueous solution.

The temperature and the pressure at the pre-heater inlet are measured by a thermocouple within the fluid and an absolute pressure transducer (0 to 1100 ± 1.4 kPa), respectively. The pressure at the test section inlet is also measured by an absolute pressure transducer (0 to 1100 ± 1.5 kPa). Fluid temperature at the test section outlet just downstream the visualization section is given by a thermocouple within the tube. A piezoresistive differential pressure transducer was used to measure the pressure drop over the test section length with measuring range of 3.0 kPa with accuracy up to 0.075% of the set span. The test facility posses two visualization sections, one upstream and other downstream the test section, both made of borosilicate. So, the flow patterns at both sections can be compared and a unique flow pattern along the test section can be assured. The refrigerant circuit posses also a non-heated section for the flow development with length of approximately 90 times its internal diameter (15.875mm). This section is located just upstream the first visualization section.

The refrigerant vapor quality at the test section inlet was settled by adjusting the electrical power supplied to the pre-heater and its value was estimated from an energy balance over this component, and after achievement of steady state condition, measured data were recorded during at least 1 minute. The heat losses to the ambient from the pre-heater were preliminary estimated from single-phase flow experiments and their average value was about 6 % of the total power input. The saturation temperature was estimated as the average temperature given by two thermocouples within the fluid. The frictional pressure drop gradient results are given by the ratio between the measured pressure drop and the test section length since the measurements were performed for a horizontal tube and under adiabatic conditions.

Images from a high-speed video-camera (2000 frames/s with a resolution of 1280 x 256) obtained through the second visualization section were used to identify the flow patterns. Temperature measurements were calibrated and the higher uncertainty was evaluated equal to ±0.13 °C according to the procedure suggested by Abernethy and Thompson (1973). The uncertainties of the calculated parameters were estimated using the method of sequential perturbation according to Moffat (1988).

Electrical signals from the transducers were received, processed and stored by a National Instruments data acquisition system with Labview (version 7.01) software on a Personal Computer.

The experiments were performed for the following conditions: mass velocity, G, between 75 and 250 kg/m²s, inlet vapor qualities, x, from 0.05 to 0.95 and saturation temperature, T_{Sat}, of 5 and 15 °C.

Initially, single-phase pressure drop experiments were performed in order to validate the experimental test facility and its instrumentation. These results are displayed in Fig. 1 that compares single-phase friction factors calculated by predictive methods from literature, $f_{Predicted}$, and their correspondent values estimated from the pressure drop measurements, $f_{Experimental}$. It can be noticed in Fig. 1 that the experimental and predicted results agree reasonable well. This result proves that the present experimental facility is capable of performing accurate two-phase pressure drop measurements.

3. DATA REDUCTION

The total pressure drop, Δp_T, is given by the sum of parcels corresponding to gravitational, Δp_g , momentum, Δp_m, and frictional pressure drops Δp_f, , as follows:

$$\Delta p_T = \Delta p_g + \Delta p_m + \Delta p_f \quad (1)$$

Based on the fact that the test section is horizontal, the parcel corresponding to the gravitational pressure drop is null. Moreover, the parcel corresponding to the momentum variation is negligible due to the fact that the measurements were performed under adiabatic conditions, which corresponds to 0.3% of the total pressure drop. Based on this, the frictional pressure drop is given directly by the measured pressure drop as follows:

$$\Delta p_f = \Delta p_T \quad (2)$$

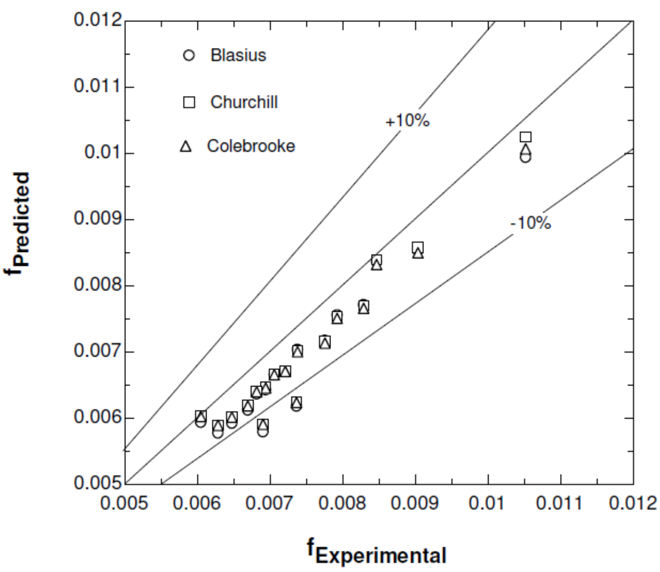


Figure 2. Comparison of predicted friction factors and their corresponding values estimated from the single-phase pressure drop experiments.

The experimental pressure drop gradients obtained in the present study, $\Delta p/L$, are displayed in Figures 2 to 4, as a function of the average vapor quality over the test section. According to these figures and as expected, the pressure drop increases with increasing mass velocity, and decreasing saturation temperature. A pressure drop peak is displayed at vapor qualities close to 0.9. It is noted in Fig. 3 a much higher pressure drop increment with decreasing saturation temperature than the relative pressure drop variation displayed in Figures 2 and 4. Such a behavior is related to a flow pattern transition from stratified to annular with increasing the vapor specific volume by decreasing the saturation temperature.

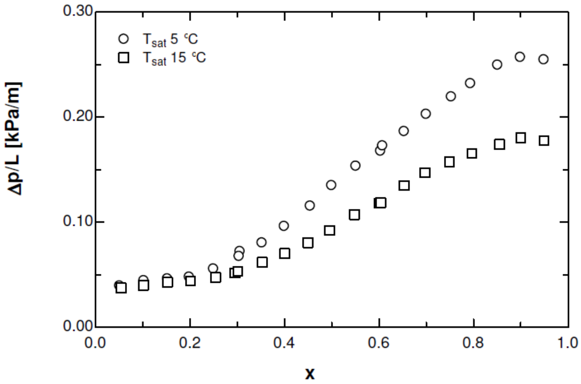


Figure 3. Pressure drop variation with vapor quality for mass velocity of 75 kg/m²-s.

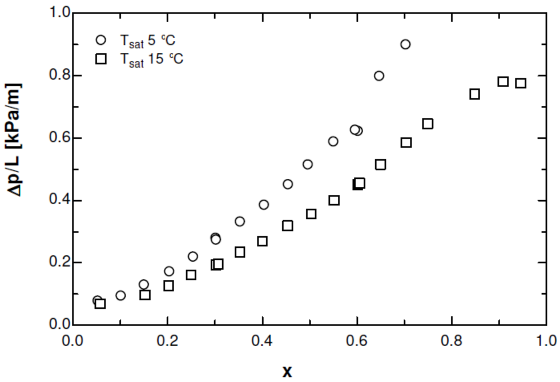


Figure 4. Pressure drop variation with vapor quality for mass velocity of 150 kg/m²-s.

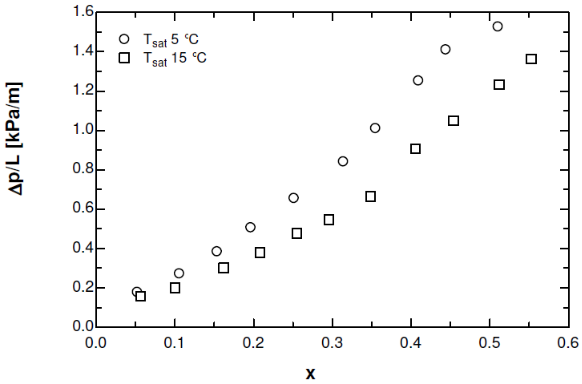


Figure 5. Pressure drop variation with vapor quality for mass velocity of 250 kg/m²-s.

Experiments at higher mass velocities and high vapor qualities were not performed due to the pumping power limitations of our experimental facility and the fact that are out of interest of industry for this range of tube diameters.

Based on visual observations of images captured by a high speed camera, the following flow patterns were observed:

- Stratified flow: characterized by liquid and vapor phases separated by a non perturbed interface with liquid at bottom of cross sectional area and vapor at top;
- Stratified-wavy (SW): separated phases with liquid at cross section bottom and vapor at cross section top, with a perturbed interface between them;
- Slug: a class of intermittent flow, characterized by liquid plugs separated by elongated gas bubbles;
- Stratified wavy + Slugs (Slug+SW): intermittent slugs, with stratified wavy flow in periods between them;
- Annular: continuous liquid film along tube perimeter, with vapor in the core, usually thicker at bottom;

Dryout and mist flows were not observed, since experiments under these conditions were avoided in order to not damage the test section.

Figure 6 presents the observed patterns in a flow pattern map. The specific vapor volume and, consequently, the vapor velocity decreases with increasing saturation temperature. Such a behavior moves the transition between intermittent and annular flows to higher vapor qualities as illustrated in Figure 5.

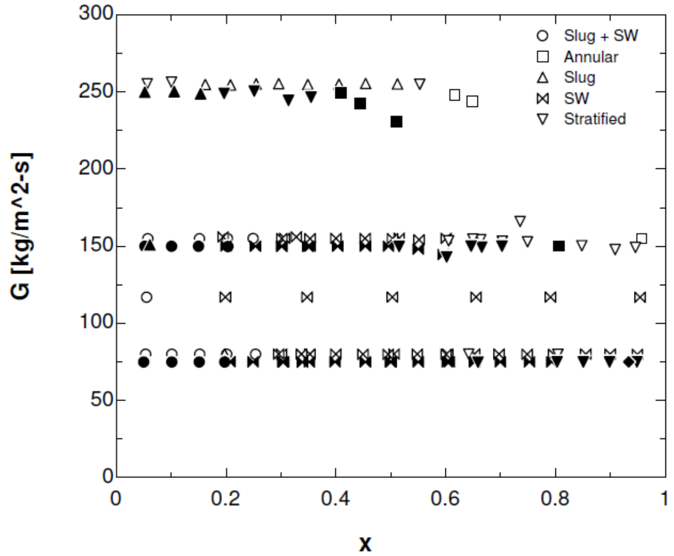
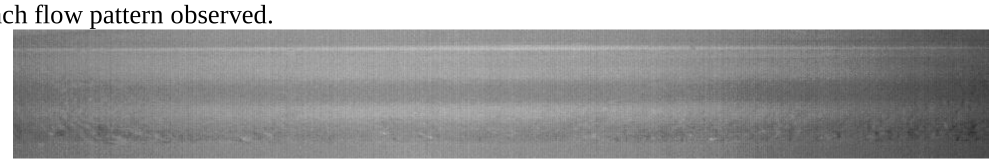
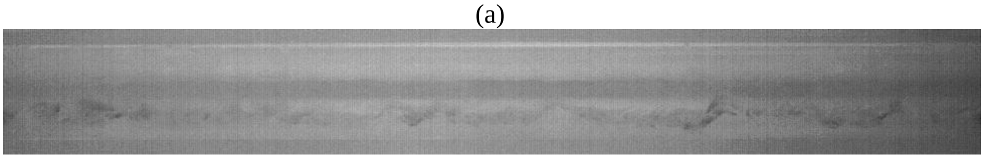


Figure 6. Experimental flow patterns. Filled symbols for T_{sat} of 5°C, and empty symbols for T_{sat} of 15°C.

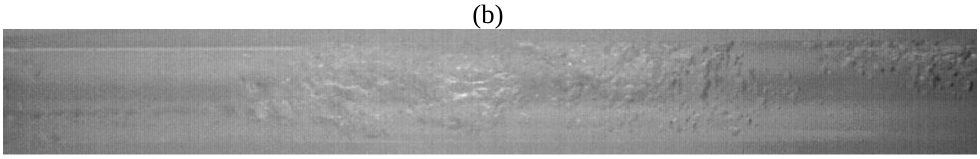
Figure 7 presents images obtained with high speed camera (2000 frames/second and resolution of 1280 x 256), illustrating each flow pattern observed.



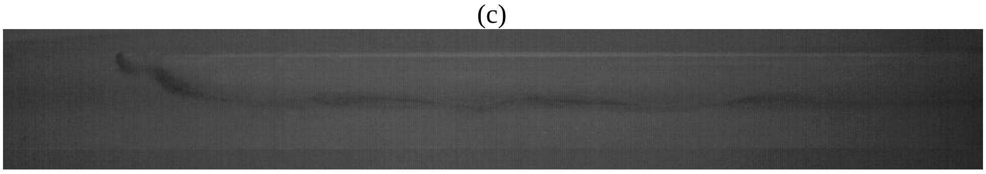
(a)



(b)



(c)



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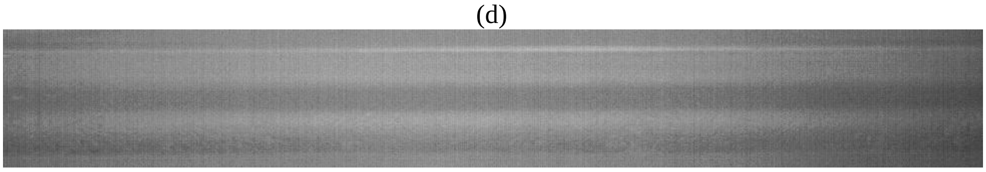

(e)

Figure 7 – Images of flow patterns. (a) Stratified corresponding to G of 150kg/m²-s, T_{Sat} of 5°C and x of 0.65. (b) Stratified Wavy corresponding to G of 75kg/m²-s, T_{Sat} of 5°C and x of 0.35. (c) Slug corresponding to G of 150kg/m²-s, T_{Sat} of 5°C and x of 0.05. (d) Stratified-wavy + slugs corresponding to G of 75kg/m²-s, T_{Sat} of 5°C and x of 0.05. (e) Annular corresponding to G of 150kg/m²-s, T_{Sat} of 15°C and x of 0.95.

4. PRESSURE DROP AND FLOW PATTERN RESULTS COMPARISON

The experimental pressure drop data obtained in the present study were compared against the following leading frictional pressure drop predictive methods available in literature: Friedel (1979), Müller-Steinhagen and Heck (1986), Grönnerud (1979) and Moreno-Quibén and Thome (2007). The results of these comparisons are displayed in Figs. 8 to 11. Table 1 presents the statics of these comparisons in terms of the parcel of the data predicted within an error band of ± 30%.

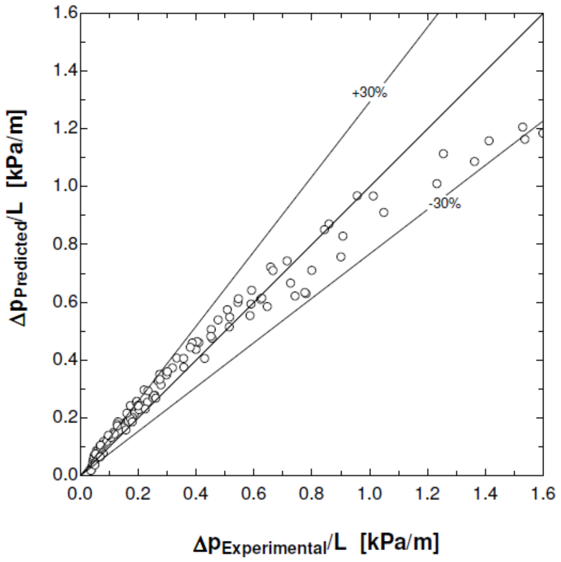

Figure 8. Comparison of Müller-Steinhagen and Heck (1986) predictions and the experimental results.

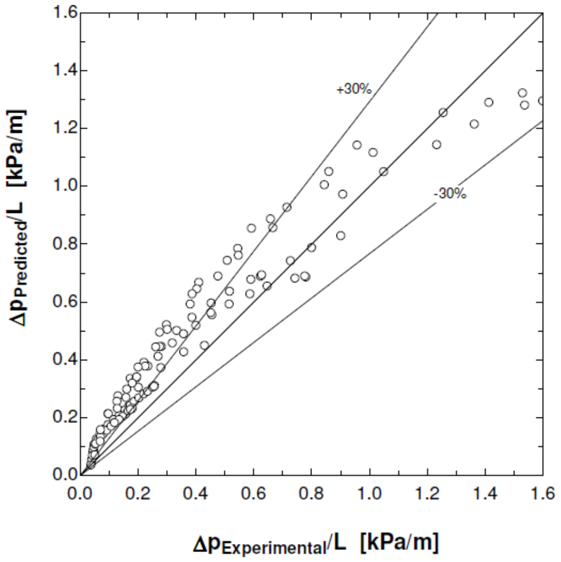

Figure 9. Comparison of Friedel (1979) predictions and the experimental results.

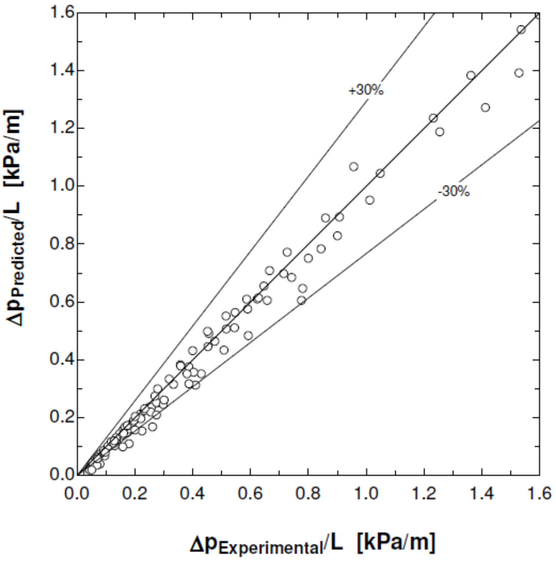

Figure 10. Comparison of Grönnerud (1979) predictions and the experimental results.

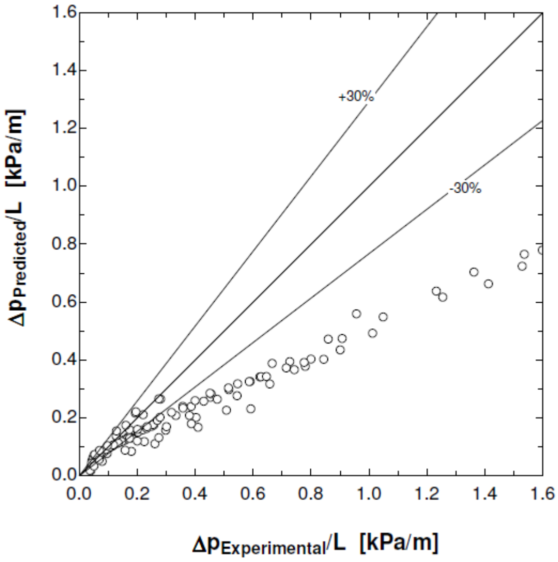

Figure 11. Comparison of Moreno-Quibén and Thome (2007) predictions and the experimental results.

Table 1 presents comparison between predicted and experimental pressure drop results. Comparing prediction methods to the overall database, the best prediction was obtained by the method proposed by Grönnerud (1979) according to this table. Müller-Steinhagen and Heck (1986) is ranked as the second best predictive methods. Friedel (1979) predicts reasonable well the high pressure drop data while fails in predicting low pressure drops. Most of high pressure drop data obtained for high mass velocities and vapor qualities were segregated as annular flows. So, such a result is related probably to the fact that the proposed by Friedel (1979) was developed based mainly on annular flow results. It should be highlighted that annular flows is the prevailing flow pattern in fin coil heat exchangers. Moreno-Quibén and Thome (2007) predictive method agrees reasonably well with low pressure drop data and fails to predict high pressure drop data. As abovementioned, the pressure drop method of Moreno-Quibén and Thome (2007) was developed based on Wojtan et al. (2005) flow pattern predictive method and the development of both methods considers experimental results only for tube diameters from 8 to 13mm. So, it can be speculated that this pressure drop method is not adequate for tube diameters higher than 13mm.

Figures 12 and 13 compares the predictions by Wojtan et al. (2005) method and the flow pattern visualizations performed in the present study. Wojtan et al. (2005) predicted correctly only 52% of the present flow pattern database. The fact that their method failed to predict the present database can be also explained by their database that does not include tube diameter larger than 13mm. However, it should be also highlighted that the method used for definition of experimental flow patterns is subjective, so different observers can define judge the flow topology as different flow patterns.

Table 1. Results of the comparisons between predictive methods and the experimental data,

Method	% of data points in ±30%
Friedel (1979)	35.6
Müller-Steinhagen e Heck (1986)	80.0
Grönnerud (1979)	88.1
Moreno-Quiben e Thome (2007)	44.1

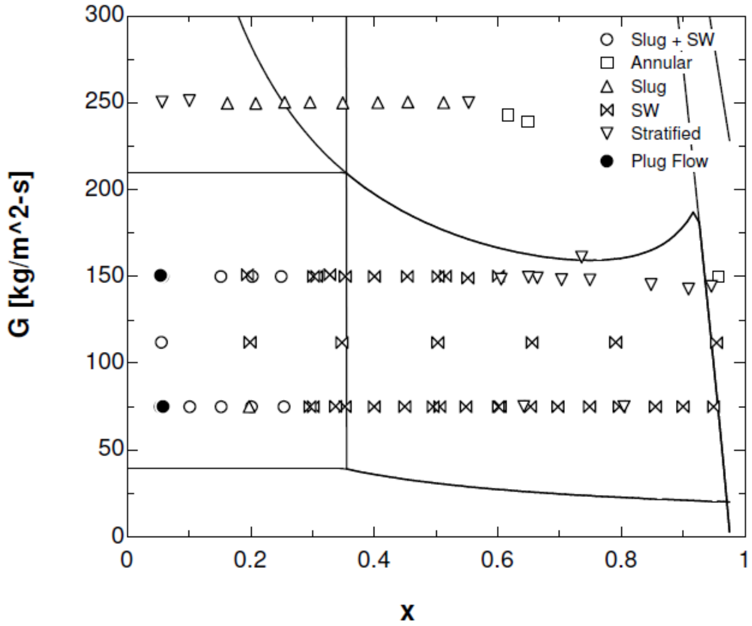

Figure 12. Flow pattern map and experimental data,G=150kg/m²-s, Tsat=15°C and ϕ=10kW/m².

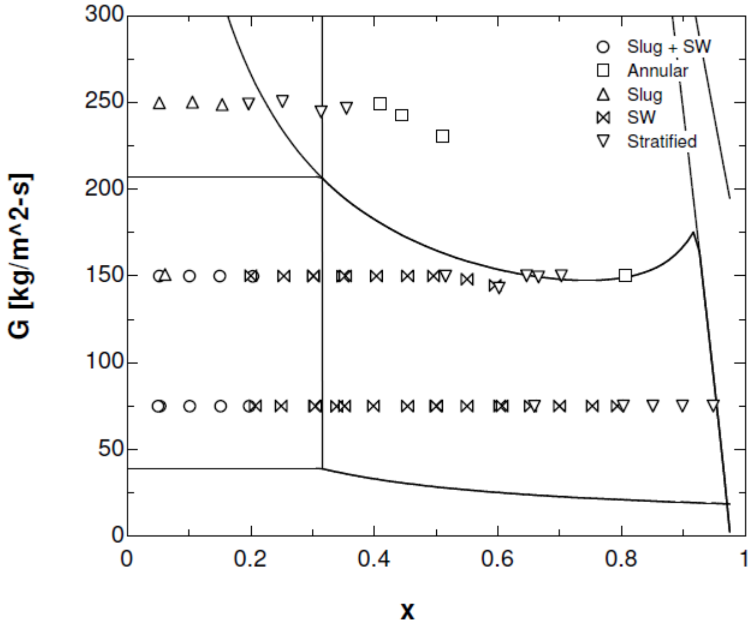

Figure 13. Flow pattern map and experimental data. Flow pattern built for G=150kg/m²-s, Tsat=5°C and ϕ=10kW/m².

5. CONCLUSIONS

The following conclusions can be drawn from the present study:

- Experimental pressure drop and flow pattern results during two-phase flow of R134a in a 15.9 mm ID tube are presented;
- As expected, the pressure drop gradient increases with increasing vapor quality until to a vapor quality value close to 0.9, after that, the pressure drop gradient decreases sharply;
- Pressure drop increases with decreasing the saturation temperature from 15 to 5 °C;
- By comparing the present database against pressure drop predictive methods, Grönnerud (1979) and Müller-Steinhagen and Heck (1986) were ranked as the best methods predicting 88 and 80% of data points, respectively, within an error band of ±30%.
- Friedel (1979) over predicts , while Moreno-Quibén and Thome (2007) under predicts most of experimental data.
- Wojtan et al. (2005) failed to predict the present two-phase flow pattern visualizations.

6. ACKNOWLEDGEMENTS

The authors gratefully acknowledge the scholarships under contract numbers 2006/52089-1 and 2008/55003-6 given by FAPESP (The State of São Paulo Research Foundation, Brazil). The research grant given by CNPq (The National Council for Scientific and Technological Development, Brazil) under contract number 474403/2008-4 is also acknowledge. The technical support given to this investigation by Mr. José Roberto Bogni is appreciated and deeply recognized.

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