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OPTIMIZATION OF FLOW PATTERN PREDICTION METHODS FOR MICRO-SCALE FLOW BOILING

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Abstract. *The main objective in this article is an optimization of existing correlations for flow pattern prediction during micro-scale flow boiling. A database containing data from several laboratories was obtained, including the Heat and Mass Transfer Group of EESC-USP laboratory. The database has 419 experimental flow pattern transition points for air-water, R134a, R245fa, R236fa, R1234ze and nitrogen flowing in a single channel, for a maximum diameter of 6 mm, rounded, triangular and rectangular cross sections, mass flux ranging between 5 and 8000 kg/m²s and temperature between -192 °C (for nitrogen) and 35 °C. The optimization of Ong and Thome (2011) correlation increased 21% number of points with mean absolute error less than 30% (λ), while the optimization of Felcar et al. (2007) increased λ in until 23%. Reductions in the mean avarege error exceeding 50% were achieved for all flow patterns prediction. The optimized correlations obtained a better prediction of the flow patterns than the original correlations and can be applied in a wider range of experimental conditions.*

Keywords: *two-phase flow patterns, annular flow, slug flow, bubble flow*

1. INTRODUCTION

A large number of applications involving the removal of high heat transfer rates in micro-scale emerged in the last decade. New generation processors requires high capacity of heat dissipation. Automotive air conditioning systems have sought material reduction in their manufacturing and reduction of the refrigerant inventory necessary for its operation. Compact heat exchangers are being used for cooling fuel cells and satellites electronic components due low mass requirements in this applications. Flow boiling heat transfer in microchannels are being intensively studied, since it has high cooling capacity and allows the development of light and compact heat exchanger.

For two-phase flows, the respective distribution of the liquid and gas phases in the flow channel is an important aspect of their description. Their respective distribution can be grouped in some commonly observed flow structures, which are defined as two-phase flow patterns. Heat transfer coefficients and pressure drops are closely related to the local two-phase flow structure of the fluid, and thus two-phase flow pattern prediction is an important aspect for the design of heat exchangers. In fact, recent heat transfer models for prediction flow boiling and condensation are based on the local flow pattern, which requires reliable flow pattern prediction (Thome, J. R., 2004). Two-phase flow pattern maps can be thought as an equivalent of Reynolds number for prediction of laminar to turbulent flow transition in single-phase flows.

Several classifications and terminologies have been applied in order to classify the liquid/gas two-phase flow patterns (Felcar *et al.*, 2007). For reduced liquid superficial velocities at macro-scale flows, it is observed that the stratified flow pattern appears at horizontal flow. As the liquid and gas phase velocity increases, the flow pattern can changes to bubble, slug, churn or annular flow pattern (Tibiriçá, 2011). Additional increments in the gas phase velocity causes an increase of entrainment until the totally of liquid phase becomes dispersed at the gas phase. Several factors can influence the establishment of a flow pattern, such as the flow orientation (vertical/horizontal), channel cross section geometry and tube diameter.

Thus, this work has the objective of optimizing existing correlations for prediction of two-phase flow patterns transition in a wide range of experimental conditions for micro-scale flows. A database containing experimental data from several laboratories was obtained, including the Heat and Mass Transfer Group of EESC-USP laboratory. Different experimental conditions can be found in this database in order to provide a great variety of experimental data.

Two correlations were modified in this work: Felcar *et al.* (2007) and Ong and Thome (2011). These correlations showed the best performance in predicting flow pattern transitions, according Arcanjo *et al.* (2010).

2. DATABASE

The obtained database has experimental points not only for adiabatic, but to diabatic flows, since experimental evidences indicates that there is not substantial differences between both situations (Arcanjo *et al.,* 2010). In diabatic flows occurs the increase of the gas portion in the mixture as the fluid evaporates along the length of the test section,

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whereas in the adiabatic flows the ratio between the gas phase and the total mass is approximately constant along the flow (Tibiriçá, 2011).

The present database has 419 experimental points for air-water, R134a, R245fa, R236fa, R1234ze and nitrogen flowing in a single channel. The channel cross section geometries that can be found in this database are circular, rectangular and triangular. The test section orientation are both vertical and horizontal, and the entire database has tube with hydraulic diameter smaller than 3 mm and may be considered as micro channel. Only one database for water has diameter of 5.5 mm, since accordint to Tibiriçá (2011) water has macro-microscale transiton around 5.5 mm The experimental conditions have the mass flux ranging between 5 and 8000 kg/m^{2}s, temperature between -192 ºC (for nitrogen) and 35 ºC and gas mass fractions up to 0.96. The flow patterns that can be found in the present database are: bubble-intermittent, intermittent-annular, bubble-slug, slug-churn and churn-annular.

Different methods can be used to identify the flow pattern in a two-phase flow. For the investigated database most of the used methods were based on photographs or video images taken from a transparent tube section. Dynamic pressure measurements and signal analyses from lasers lights crossing the transparent section of the tube also can be used to determinate the flow pattern in the flow, which avoids subjective interpretations of the flow pattern. Table 1 shows the experimental database arranged by the authors.

Table 1. Flow Pattern experimental database details

Author	**Fluid**	**Orientation**	**Geometry**	***D_h* (mm)**	**Identification Method**
Damianides and Westwater, 1998	Air-water	Horizontal	Circular	1.0;2.0;3.0	Photographs and pressure traces
Fukano *et al.,*1993	Air-water	Horizontal Vertical	Circular	1.0;2.4	Photographs and differential pressure traces
Barajas and Panton, 1993	Air-water	Horizontal	Circular	1.6	Photographs
Wilmarth and Ishii, 1994	Air-water	Horizontal Vertical	Rectangular	1.0;2.0	Video camera
Mishima and Hibiki, 1996	Air-water	Vertical	Circular	1.0;2.0;3.0	High speed video camera
Coleman and Garimella, 1999	Air-water	Horizontal	Circular Rectangular	1.3-5.5	Video camera
Triplett *et al.,* 1999	Air-water	Horizontal	Circular Triangular	1.10;1.45 1.09;1.49	Photographs
Yang and Shieh, 2001	Air-water	Horizontal	Circular	1.0;2.0;3.0	Photographs
Zhao and Bi, 2001	Air-water	Vertical	Triangular	0.87;1.44;2.87	High speed video camera and transient pressure drop traces
Chen *et al.,* 2002	Air-water	Horizontal Vertical	Circular	1.0;1.5	High speed video camera
Kawahara *et al.,* 2002	Air-water	Horizontal	Circular	0.1	Video camera
Serizawa *et al.,* 2002	Air-water	Horizontal	Circular	0.02;0.025;0.1	High speed video camera
Chung and Kawagi, 2004	Air-water	Horizontal	Circular	0.05;0.1;0.25;0.53	Video camera
Vaillancourt *et al.,* 2004	Air-water	Horizontal	Circular	0.8;1.0;3.0	Photographs
Zobeiri, 2006	Air-water	Horizontal	Circular	1.0;3.0	High speed video camera and the variation in the intensity of a micro-laser beam through the two-phase flow within the glass tube

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Ide *et al.,* 2007	Air-water	Horizontal Vertical	Circular Rectangular	1.0;2.4 1.0;1.33;1.67;1.81	Photographs
Tibiriçá, 2011	R1234ze R1234a R245fa	Horizontal	Circular	1.0; 1.1; 2.2; 2.32	High speed video camera
Revellin e Thome, 2007	R134a	Horizontal	Circular	0.509; 0.709	Two laser beams captured by photodiodes
Ong e Thome, 2010	R134a R236fa	Horizontal	Circular	1.03; 2.20; 3.04	Laser beam captured by photodiodes
Zhang *et al.,* 2008	Nitrogen	Vertical	Circular	1.931	High speed video camera

3. CORRELATIONS

Recently, Arcanjo *et al.* (2010) rated several flow pattern prevision methods using a database for micro scale and concluded that the correlations by Felcar, Ribatski and Jabardo (2007) and Ong and Thome (2011) were those that best predicted the transitions. For this reason, these correlations were chosen to be optimized in this work.

3.1 Ong and Thome (2011) Correlation

The Ong and Thome (2011) original's correlation is based on experiments performed for channels with diameter ranging between 0.5 and 3.04 mm, and includes dimensionless numbers that take into account gravity, inertia and surface tension effects. Inserting the confinement number (*Co*) takes into account the bubble confinement effects as a function of the surface tension while the Froude number (*Fr*) relates the inertia and the gravity effects (Ong and Thome, 2011). The Ong and Thome (2011) correlation and their symbols are presented below.

Co: confinement number (dimensionless);
Re_V, Re_L: gas and liquid phase Reynolds number (dimensionless);
Bo: bond number (dimensionless);
We_L: liquid phase Weber number (dimensionless);
Fr_L: liquid phase Froude number (dimensionless);
μ_V, μ_L: gas and liquid phase viscosity, respectively (Pa-s);
ρ_V, ρ_L: gas and liquid phase density, respectively (kg/m^3);
g: gravity acceleration (m/s^2)

- Transition between isolated bubbles and coalescing bubbles (IB/CB):

$$X_{IB/CB}=0{,}36\cdot\left(Co^{0{,}20}\right)\cdot\left(\frac{\mu_V}{\mu_L}\right)^{0{,}65}\cdot\left(\frac{\rho_V}{\rho_L}\right)^{0{,}9}\cdot Re_V^{0{,}75}\cdot Bo^{0{,}25}\cdot We_L^{-0{,}91} \tag{1}$$

- Transition between coalescing bubbles and annular (CB/A):

$$X_{CB/A}=0{,}047\cdot\left(Co^{0{,}05}\right)\cdot\left(\frac{\mu_V}{\mu_L}\right)^{0{,}7}\cdot\left(\frac{\rho_V}{\rho_L}\right)^{0{,}6}\cdot Re_V^{0{,}8}\cdot We_L^{-0{,}91} \tag{2}$$

- Transition between plug-slug and coalescing bubble (S-P/CB):

$$X_{S\text{-}P/CB}=9\cdot\left(Co^{0{,}20}\right)\cdot\left(\frac{\rho_V}{\rho_L}\right)^{0{,}9}\cdot Fr_L^{-1.2}\cdot Re_L^{0{,}1} \tag{3}$$

- Transition between plug-slug and anular (S-P/A):

$$X_{S\text{-}P/A}=X_{CB/A} \tag{4}$$

where:

$$Re_V=\frac{GD}{\mu_V},\quad Re_L=\frac{GD}{\mu_L},\quad Bo=\frac{q}{GH_{LV}},\quad We_L=\frac{G^2D}{\sigma\rho_L},\quad Fr_L=\frac{G^2}{\rho_L^2gD}$$

3.2 Felcar *et al.* (2007) Correlation

The authors originally developed a procedure to estimate the transitions in the flow pattern based on the model proposed by Taitel and Dukler (1976) for horizontal flows. They introduced modifications in the transitions stratified/annular and intermittent/annular in order to incorporate the surface tension, contact angle and secondary flows. They added a new parameter that is function of the modified Eötvos parameter (*Eo*), that relates gravity and capillarity

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effects, and the Weber number (We), which relates surface tension and inertial effects. Experimental results for air-water flow were used to adjust the empirical coefficients. The original correlation is shown below:

Z: transitional parameter (dimensionless)
Eo: Eötvos number (dimensionless)
We: Weber number (dimensionless)
α: superficial void fraction (dimensionless)

- Annular to stratified transition

$$Z=-56Eo^{-0,6}(1-e^{-0,02Eo^{-0,5}We}) \quad (5)$$

- Intermittent to annular transition

$$\alpha=1,2Eo^{-0,088}We^{-0,16} \quad (6)$$

In this work, a modification of this correlation was implemented for the purpose of improving the transitions prediction. The modification was made in the calculation of the void fraction (α), where the Woldesemayat (2007) correlation was used instead of Tatiel and Dukler method. Better results were obtained with this modification, and they will be presented in this paper.

Only the equation for intermittent to annular transition was used to adjust the parameters, since the stratified flow pattern is not observed at microchannels, and the same equation format was used to calculate the transition of bubble/slug, slug/churn, churn/annular, bubble/intermittent and intermittent annular, which can be found in this present database.

4. MODIFICATIONS

A Matlab routine was utilized to perform the modifications. The function uses a non-linear regression by the Newton-Gauss method, estimating the coefficients by the Root Mean Square method.

In order to evaluate and compare the results given by the modified correlations, two statistics parameters were used: the Mean Absolute Error (*MAE*) and the percentage of points that have *MAE* less than 30%, represented by $\lambda_{\pm 30\%}$, the parameters that are usually used in the literature. The original correlations were also evaluated against the present database and were compared to the modified correlations results.

Figures that illustrate the trends of the correlations are presented and compared to the database, in order to make possible an observation of the transition lines against the flow pattern points.

4.1 Ong and Thome (2011) correlation results

Table 2 shows the statistic parameters from analyses against the complete database containing all fluids. The database was also divided in fluids groups, to quote refrigerants, air-water and nitrogen. Different coefficients were obtained when these different databases were evaluated, and the results of these evaluations will be shown next.

Table 2. Complete database statistic evaluation for Ong and Thome (2011) correlation

Coefficients	Bubble-Intermittent = [0.0038 0.7204 0.5604 0.6527 0.7516 -0.6992]; Slug-Churn = [0.3275 0.8543 0.7591 -1.0634 0.1646]; Intermittent-Annular = [0.0208 0.3754 0.7024 0.5957 0.8021 -0.7154];			
Database	Transition		Original	Modified
Complete Database	Bubble-Intermittent	Nº of Points in the evaluation	108	108
		MAE (%)	>20000	1003.00
		$\lambda_{\pm 30\%}$ (%)	0.00	21.29
	Slug-Churn	Nº of Points in the evaluation	76	76
		MAE (%)	345.24	85.08
		$\lambda_{\pm 30\%}$ (%)	10.52	5.26
	Intermittent-Annular	Nº of Points in the evaluation	235	235
		MAE (%)	97.55	57.02
		$\lambda_{\pm 30\%}$ (%)	37.87	46.38

The complete database results shows that the *MAE* decreased for all the transitions with the modified correlation, but it is still high. It can be explained by the database diversity, once it has points for Air-Water, Refrigerants and Nitrogen. Much better results were obtained when databases were adjusted by group of fluids, which shows that fluid properties has a crucial point in these results. Tables 3, 4 and 5 shows the statistic evaluations for each database group.

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Table 3. Air-Water statistic evaluation for Ong and Thome (2011) correlation

Coefficients	Bubble-Intermittent = [0.0001 0.4076 0.6500 0.6521 0.8194 -0.5152]; Intermittent-Annular = [0.0435 0.3147 0.6999 0.6001 0.7803 -0.6805];			
Database	Transition		Original	Modified
Air-Water	Bubble-Intermittent	Nº of Points in the evaluation	48	48
		MAE (%)	53.93	39.43
		$\lambda_{\pm 30\%}$ (%)	22.91	54.16
	Intermittent-Annular	Nº of Points in the evaluation	127	127
		MAE (%)	93.83	82.60
		$\lambda_{\pm 30\%}$ (%)	26.77	40.16

Table 4. Refrigerants statistic evaluation for Ong and Thome (2011) correlation

Coefficients	Bubble-Intermittent = [0.0038 0.8381 0.5426 0.6493 0.7496 -0.7027]; Slug-Churn = [44.3845 0.4086 0.9766 -0.1740 -0.2621]; Intermittent-Annular = [3.8618 -0.3198 -7.9155 5.0153 -0.7389 0.1607];			
Database	Transition		Original	Modified
Refrigerants	Bubble-Slug	Nº of Points in the evaluation	60	60
		MAE (%)	>5000	43.07
		$\lambda_{\pm 30\%}$ (%)	0.00	38.33
	Slug-Churn	Nº of Points in the evaluation	69	69
		MAE (%)	368.67	44.42
		$\lambda_{\pm 30\%}$ (%)	10.14	49.27
	Churn-Annular	Nº of Points in the evaluation	93	93
		MAE (%)	59.05	45.81
		$\lambda_{\pm 30\%}$ (%)	11.83	54.84

Table 5. Nitrogen statistic evaluation for Ong and Thome (2011) correlation

Coefficients	Bubble-Intermittent = [0.1815 0.2324 0.8136 0.8939 0.5219 -0.3563]; Slug-Churn = [8.9930 0.2400 1.2013 -0.2188 0.1287]; Intermittent-Annular = [0.6321 0.0807 0.8549 0.8310 0.5668 -0.4202];			
Database	Transition		Original	Modified
Nitrogen	Bubble-Slug	Nº of Points in the evaluation	6	6
		MAE (%)	>3000	6.75
		$\lambda_{\pm 30\%}$ (%)	0.00	100.00
	Slug-Churn	Nº of Points in the evaluation	7	7
		MAE (%)	114.24	7.69
		$\lambda_{\pm 30\%}$ (%)	14.18	100.00
	Churn-Annular	Nº of Points in the evaluation	5	5
		MAE (%)	111.98	4.45
		$\lambda_{\pm 30\%}$ (%)	20.00	100.00

With fluid separated by groups , the *MAE* of the modified correlation was less than 50% for almost all transitions, except for the intermittent-annular transition for air-water database, which the error was 82.6%, showing that the function can not fit the database very well for that transition. For the nitrogen database, the *MAE* achieved a small value, and the parameter λ achieved 100% because the reduced number of points in this database.

Figure 1 presents the ratio between the evaluated and the experimental transition quality for the complete database. A distribution around the symmetry line indicates a better prevision. The ±30% *MAE* lines also are shown in the graphic.

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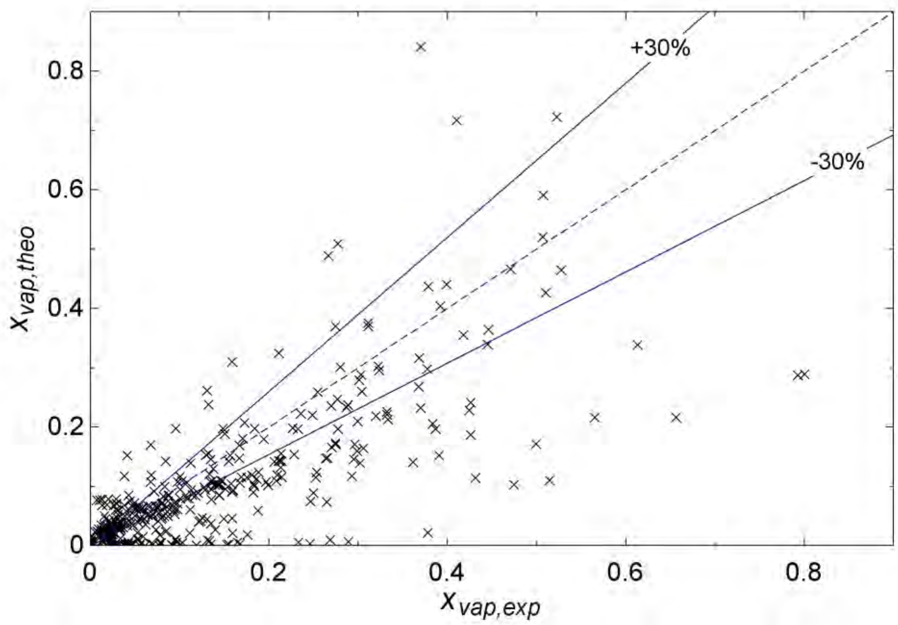

Figure 1. Ong and Thome (2011) optimization

Figure 2 shows the refrigerant's database transition lines against the database for R134a. It can observed that the transition lines for the modified coefficients fit the transitions between the flow patterns better than the original coefficients, showing that the modification took effect. The IB-CB curve is totally moved from its original position because the calculation of this transition takes into account the boiling number (*BO*), which was not used in this modification because the database contains also adiabatic data.

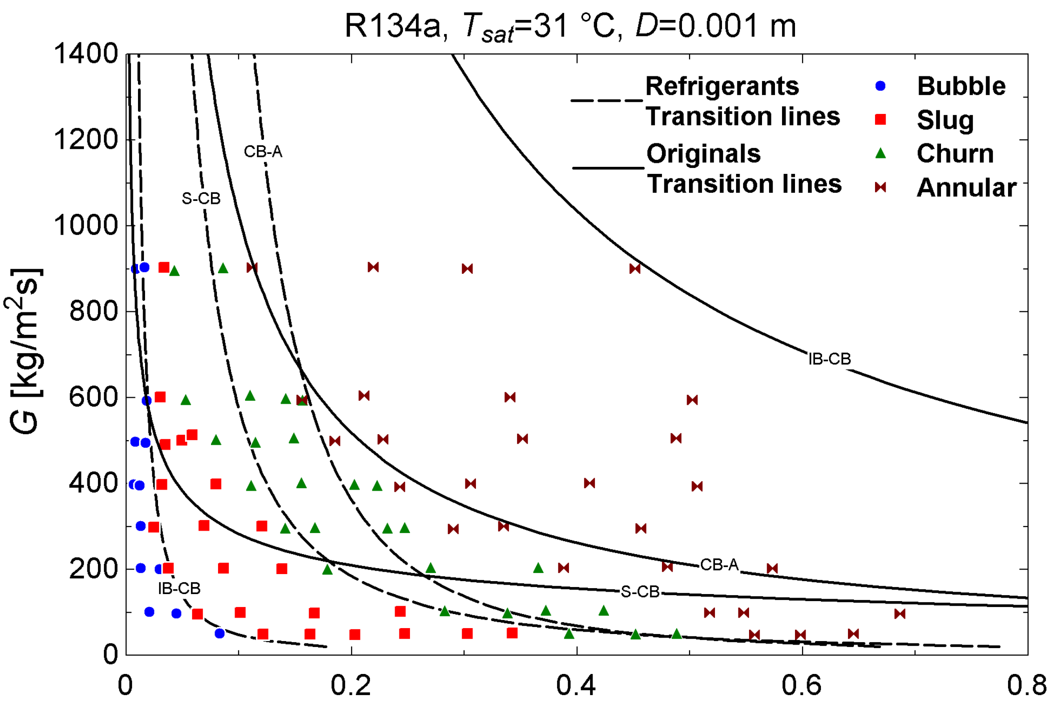

Figure 2. R134a database analysis for Ong and Thome (2011) correlation

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4.2 Felcar *et al.* (2007) correlation results

Table 6 shows the statistics parameters for the complete database coefficients with Felcar *et al.* (2007) correlation and the modified. The obtained results are similar to the results for the Ong and Thome (2011) correlation, and similar considerations can be made: the high error can be explained by the database diversity. The "$\alpha=0.5$" column refers to a new evaluation, which considers that the bubble-intermittent occurs for a void fraction (α) equals to 0.5. This consideration is based on the bubble-slug transition definition, which says that the transition occurs when the bubble diameter is close to the tube diameter, and it occurs near to this void fraction value.

Table 6. Complete database statistic evaluation for Felcar *et al.* (2007) correlation

Coefficients	Bubble-Intermittent = [0.1884 -0.0151 -0.0831]; Slug-Churn = [0.6938 -0.0283 -0.0162]; Intermittent-Annular = [0.8461 -0.0203 -0.0058];				
Database	Transition		Original	Modified	α=0.5
Complete Database	Bubble-Intermittent	Nº of Points in the evaluation	108	108	108
		MAE (%)	>7000	213.57	328.79
		$\lambda_{\pm 30\%}$ (%)	0.00	22.81	12.28
	Slug-Churn	Nº of Points in the evaluation	76	76	
		MAE (%)	118.45	88.88	
		$\lambda_{\pm 30\%}$ (%)	36.32	29.78	
	Intermittent-Annular	Nº of Points in the evaluation	235	235	
		MAE (%)	133.63	61.24	
		$\lambda_{\pm 30\%}$ (%)	14.47	26.32	

Tables 7, 8 and 9 shows the statistic evaluations for the database divisions.

Table 7. Air-water statistic evaluation for Felcar *et al.* (2007) correlation

Coefficients	Bubble-Intermittent = [0.2261 -0.0568 -0.0006]; Intermittent-Annular = [0.8822 -0.0149 -0.0046];			
Database	Transition		Original	Modified
Air-Water	Bubble-Intermittent	Nº of Points in the evaluation	48	48
		MAE (%)	>5000	39.45
		$\lambda_{\pm 30\%}$ (%)	0.00	56.25
	Intermittent-Annular	Nº of Points in the evaluation	127	127
		MAE (%)	76.33	88.15
		$\lambda_{\pm 30\%}$ (%)	27.55	29.13

Table 8. Air-water statistic evaluation for Felcar *et al.* (2007) correlation

Coefficients	Bubble-Intermittent = [0.3775 -0.1477 -0.0169]; Slug-Churn = [0.6894 -0.0356 -0.0102]; Intermittent-Annular = [0.8373 -0.0379 -0.0033];			
Database	Transition		Original	Modified
Refrigerants	Bubble-Slug	Nº of Points in the evaluation	60	60
		MAE (%)	791.89	37.48
		$\lambda_{\pm 30\%}$ (%)	0.00	46.66
	Slug-Churn	Nº of Points in the evaluation	69	69
		MAE (%)	142.79	65.07
		$\lambda_{\pm 30\%}$ (%)	10.14	23.19
	Churn-Annular	Nº of Points in the evaluation	93	93
		MAE (%)	40.91	42.41
		$\lambda_{\pm 30\%}$ (%)	51.61	50.53

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Table 9. Air-water statistic evaluation for Felcar *et al.* (2007) correlation

Coefficients	Bubble-Intermittent = [0.8554 -0.3250 -0.0214]; Slug-Churn = [0.9900 -0.2278 -0.0156]; Intermittent-Annular = [1.1274 -0.1354 -0.0364];			
Database	Transition		Original	Modified
Nitrogen	Bubble-Slug	Nº of Points in the evaluation	6	6
		MAE (%)	253.27	12.44
		$\lambda_{\pm 30\%}$ (%)	0.00	100.00
	Slug-Churn	Nº of Points in the evaluation	7	7
		MAE (%)	43.29	6.03
		$\lambda_{\pm 30\%}$ (%)	57.14	100.00
	Churn-Annular	Nº of Points in the evaluation	5	5
		MAE (%)	38.24	15.31
		$\lambda_{\pm 30\%}$ (%)	50.00	83.33

Figure 3 presents the ratio between the evaluated and the experimental transition quality for the complete database. A distribution around the symmetry line indicates a better prevision.

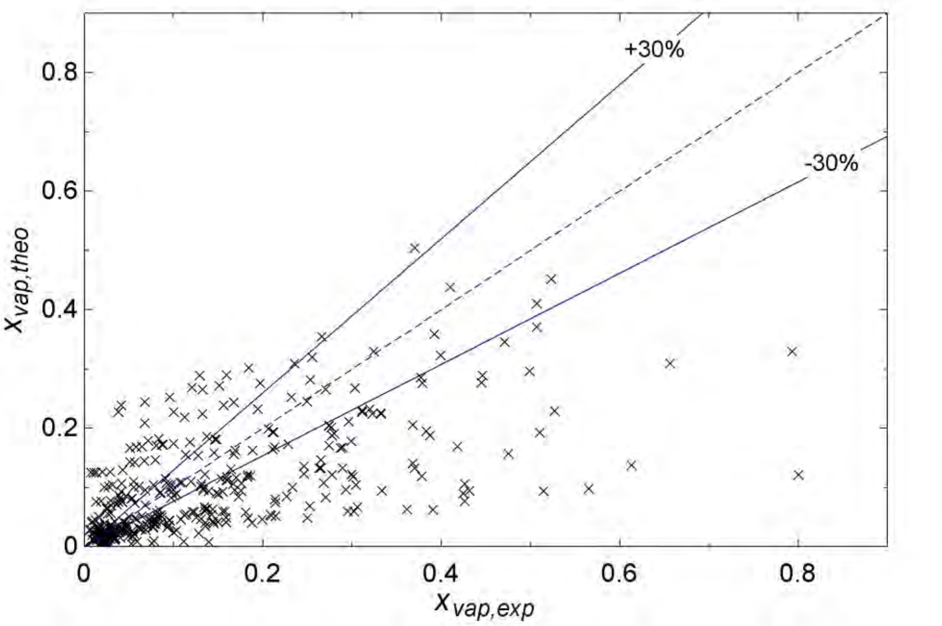

Figure 3. Felcar *et al.* (2007) optimization

Figure 4 shows the refrigerant's database transition lines, and the transition line associated with the $\alpha = 0.5$ consideration against the database for R134a. The original transition was not showed in this graph because only the Eq. (6) was used to predict the transitions, and the original coefficients for the correlation are the same for all transitions. The continuous line refers to the *α=0.5* evaluation, and we can observe that this line is slightly shifted to the right, indicating that the modified correlation achieved better results. Another observation is that the Ong and Thome (2011) lines fit better this database.

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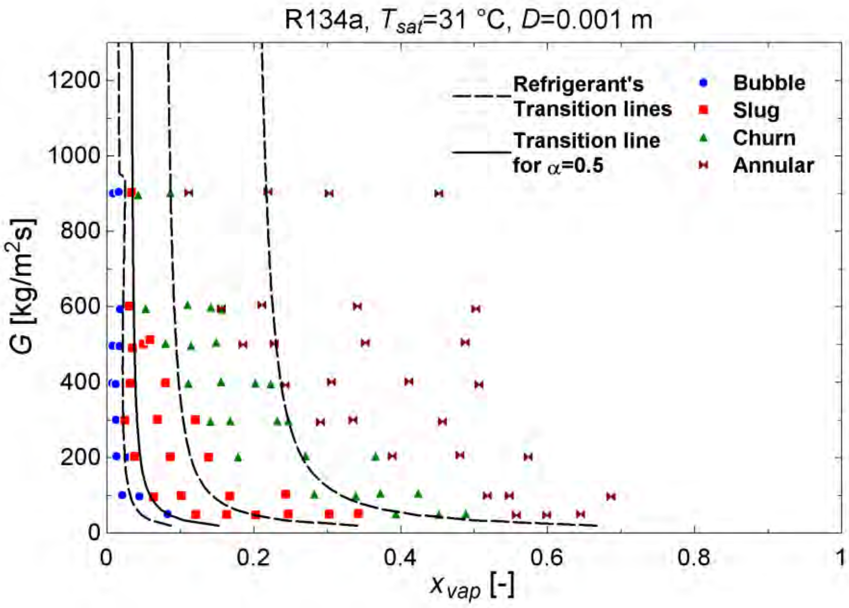

Figure 4. R134a database analysis for Felcar *et al.* (2007) correlation

5. CONCLUSIONS

A database containing 419 experimental points for flow pattern transitions in micro-scale flow from several laboratories was obtained, and this database was utilized to modify two existing correlations for flow pattern transition prediction during micro-scale flow boiling. The main conclusion are:

- Mean absolute error reductions exceeding 50% were achieved for all flow patterns with the modified correlations.
- The modified Ong and Thome (2011) correlation was able to predict up to 46% of the experimental data with a *MAE* less than 30% for the intermittent-annular transition for the complete database.
- The modified Felcar *et al.* (2007) correlation was able to predict up to 30% with a *MAE* less than 30% for the slug-churn transition for the complete database.
- The two correlations analyzed had similar performance for each database analyzed, generated from the division of the entire database;

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7. RESPONSIBILITY NOTICE

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