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OPTIMIZATION OF CRITICAL HEAT FLUX PREDICTION METHODS FOR MICRO-SCALE FLOW BOILING

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Abstract: *The objective in this research is an optimization of existing correlations for Critical Heat Flux (CHF) prediction during saturated 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 687 experimental points for the fluids R134a, R245fa, R113, R123, R1234ze, R236fa, water and helium, flowing in a single channel, for internal diameters up to 3.15 mm, rounded and rectangular cross sections, mass flux ranging between 10 and 6130 kg/m²s, test section length between 10 mm and 1200 mm and heat flux up to 19.2 MW/m². Katto and Ohno (1984), Zhang et al. (2006) and Wojtan et al. (2006) correlations were optimized using the present database. It was observed a decrease in Mean Absolute Error (MAE) for all correlations, and prediction of up 87% of database points with a MAE less than 30%. These new optimized correlations can be applied to predict the CHF during micro-scale flow boiling in a wide range of experimental conditions.*

Keywords: : *critical heat flux, micro-scale, flow boiling, heat transfer.*

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 require 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 these applications. Flow boiling heat transfer in microchannels are being intensively studied, since it has high cooling capacity and it allows the development of light and compact heat exchanger.

For high heat flux cooling applications using flow boiling in microchannels, the critical heat flux (CHF) in saturated flow boiling conditions is a very important operational limit. It indicates the maximum heat flux that can be dissipated at the particular operating conditions. Surpassing CHF means that the heated wall becomes completely and irrevocably dry, and is associated with a very rapid and sharp increase in the wall temperature as the flow passes into the mist flow (or post-dryout) heat transfer regime (Thome, J. R., 2004).

Thus, this work has the objective of optimizing existing correlations for prediction of critical heat flux 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 and different fluids can be found in this database in order to provide a great variety of experimental data.

Three correlations were modified in this work: Zhang et al. (2006), Katto and Ohno (1984) and Wojtan et al. (2006). The Zhang et al. (2006) and Katto and Ohno (1984) correlations showed the best performance in predicting the critical heat flux, according Tibiriçá et al. (2008). The Wojtan et al. (2006) correlation was implemented to compare the results of the other two correlations.

2. DATABASE

The original database for critical heat flux had 707 points, but the database passed through a filtering process where points that had inconsistent results in relation to the rest of the database were eliminated. This process eliminated few experimental points of fluids R134a and CO_2. At all, 20 points were removed from the database, and it became with 687 experimental points for flow in a single channel, with a total of 7 fluid, R134a, R113, water, R245fa, helium, R1234ze and R236fa, for a mass flux ranging between 10 and 6130 kg/m² s, test section lengths varying between 10 mm 1200 mm, hydraulic diameters between 0.2 mm and 3.15 mm and critical heat flux up to 19.2 MW/m².

The critical heat flux can occur in subcooled and in saturated conditions. The subcooled condition refers to the condition when the critical heat flux occurs with equilibrium thermodynamic vapor quality less than zero at the outlet of the test section. This scenario is noted for high mass fluxes and high level of subcooling at the entrance of the test section, and reduced length to diameter ratios. The critical heat flux in saturated conditions occurs when the vapor quality at outlet of the test section is higher than zero.

All data collected are for critical heat flux in saturated state, which makes the search for experimental points more difficult, since much of the studies in the area of critical heat flux are based on flows in subcooled condition. All points used in this study are for flow boiling a single channel. Table 1 shows details of the database.

Table 1. Critical heat flux database details

Author	Fluid	G (kg/m²s)	D (mm)	L (mm)	T_{sat} (ºC)	q_c (kW/m²)
Lowdermilk *et al.* (1958)	Water	27–3320	1.3;2.44	64–648	7–165	167–10850
Lazareck and Black (1982)	R113	235–498	3.1	126–250	55–97	93–336
Katto and Yokoya (1982)	Helium	10.5–70.8	1.0	25	-269	2.6
Sumith *et al.* (2003)	Water	23–150	1.45	100	100	145–723
Wojtan *et al.* (2006)	R134a	348–1540	0.5–0.8	20–70	30–35	116–599
Thompson and Macbeth (1964)	Water	48–6130	3.05–1.01	25–152	100–241	233–19261
Jensen and Roday (2009)	Water	315–1570	0.28–0.7	21–59	42–100	31–1249
Ong and Thome (2011)	R134a R245fa R236fa	96–1540	1.03;2.20; 3.04	180;396; 540	2–35	21–239
Jensen *et al.* (2011)	R134a	300–1500	0.5;0.96; 1.6	120;127; 128	15-45	15–283
Tibiriçá (2011)	R134a R1234ze R245fa	51–1500	1.0;2.2	152;180;361	23–42	24–299

3. CORRELATIONS

For the prediction of critical heat flux, were chosen two correlations that showed the best predictions, as shown by Tibiriçá et al. (2008), which are the correlation of Katto and Ohno (1984) and Zhang et al. (2006). The correlation of Wojtan (2006) was added to compare the results of the first two correlations due it simplicity of implementation.

3.1. 3.1 Katto and Ohno (1984) correlation

The correlation of Katto and Ohno (1984) is a correlation based on the conditions of entry of the test section. The authors divided their database in different experimental conditions, and for each condition there is a different correlation to predict the critical basic heat flux. The critical heat flux calculation is performed by the following equation:

$$q_c = q_{co}\left(1 + K\frac{\Delta h_i}{h_{lv}}\right) \tag{1}$$

where K is a parameter related to the sub cooling at the entrance of the test section and q_{co} is the critical basic heat flux, which can be calculated by the following equations:

$$q_{co} = G \cdot H_{fg} \cdot C\left(\frac{\sigma\rho_l}{G^2 L}\right)^{\beta_1} \cdot \left(\frac{L}{D}\right)^{-1} \tag{2}$$

$$q_{co} = G \cdot H_{fg} \cdot \beta_2\left(\frac{\rho_v}{\rho_l}\right)^{\beta_3} \cdot \left(\frac{\sigma\rho_l}{G^2 L}\right)^{\beta_4} \frac{1}{1 + 0.0031 \cdot (L/D)} \tag{3}$$

$$q_{co} = G \cdot H_{fg} \cdot 0{,}098 \cdot \left(\frac{\rho_v}{\rho_l}\right)^{0{,}133} \cdot \left(\frac{\sigma\rho_l}{G^2 L}\right)^{0{,}433} \cdot \frac{\left(\frac{L}{D}\right)^{0{,}27}}{1 + 0{,}0031\left(\frac{L}{D}\right)} \tag{4}$$

$$q_{co} = G \cdot H_{fg} \cdot 0{,}0384 \cdot \left(\frac{\rho_v}{\rho_l}\right)^{0{,}60} \cdot \left(\frac{\sigma\rho_l}{G^2 L}\right)^{0{,}173} \cdot \frac{1}{1 + 0{,}280\left(\frac{\sigma\rho_l}{G^2 L}\right)^{0{,}233}\left(\frac{L}{D}\right)} \tag{5}$$

$$q_{co} = G \cdot H_{fg} \cdot 0{,}234 \cdot \left(\frac{\rho_v}{\rho_l}\right)^{0{,}513} \cdot \left(\frac{\sigma\rho_l}{G^2 L}\right)^{0{,}433} \cdot \frac{\left(\frac{L}{D}\right)^{0{,}27}}{1 + 0{,}0031\left(\frac{L}{D}\right)} \tag{6}$$

where each equation performs the calculation of the critical heat flux for a certain condition. The *K* parameter values follow the same principle, and can be calculated in the following ways:

$$K = \frac{1{,}043}{4C\left(\frac{\sigma\rho_l}{G^2L}\right)^{0.043}} \tag{7}$$

$$K = \frac{5}{6}\cdot\frac{0{,}0124+\frac{D}{L}}{\left(\frac{\rho_v}{\rho_l}\right)^{0.133}\left(\frac{\sigma\rho_l}{G^2L}\right)^{\frac{1}{3}}} \tag{8}$$

$$K = 0{,}416\cdot\frac{\left(0{,}0221+\frac{D}{L}\right)\left(\frac{D}{L}\right)^{0.27}}{\left(\frac{\rho_v}{\rho_l}\right)^{0.133}\left(\frac{\sigma\rho_l}{G^2L}\right)^{0.433}} \tag{9}$$

$$K = 1{,}12\cdot\frac{1{,}52\left(\frac{\sigma\rho_l}{G^2L}\right)^{0.233}+\frac{D}{L}}{\left(\frac{\rho_v}{\rho_l}\right)^{0.60}\left(\frac{\sigma\rho_l}{G^2L}\right)^{0.173}} \tag{10}$$

The constant C that appears in equations for q_{co} and *K* is calculated as follows:

$$C = 0{,}25 \quad para \quad \frac{L}{D} < 50$$

$$C = 0{,}25 + 0{,}0009\left[\left(\frac{L}{D}\right) - 50\right] \quad para \quad 50 < \frac{L}{D} < 150$$

$$C = 0{,}34 \quad para \quad \frac{L}{D} > 150$$

To evaluate which coefficients would be modified in the correlation of Katto and Ohno (1984), a preliminary test with the database was carried out to assess which correlation is used to calculate critical basic heat flux at each point of the database. The result showed that only the equations (3) and (4) were used, and therefore only the coefficients of these two equations were adjusted in this work. The original coefficients are:

$$\beta_1 = 0.043 \qquad \beta_2 = 0.1 \qquad \beta_3 = 0.133 \qquad \beta_4 = 1/3$$

3.2. 3.2 Zhang et al. (2006) correlation

The correlation of Zhang et al. (2006) is also a correlation based on the conditions of entry of the test section, which according to the authors presents a greater efficiency in the calculation of the critical heat flux for critical flow conditions. The authors used artificial neural networks techniques to find which groups of dimensionless numbers had greater influence on the prediction of critical heat flux and then relate them in their correlation. The correlation of Zhang et al. (2006) is given by:

$$q_{CHF} = G(h_v - h_i)\beta_1\left(We_D + 0.0119\left(\frac{L}{D}\right)^{\beta_2}\left(\frac{\rho_v}{\rho_l}\right)^{\beta_3}\right)^{-0.295}\left(\frac{L}{D}\right)^{-0.311}\left(2.05\left(\frac{\rho_v}{\rho_l}\right)^{0.170} - x_{in}\right) \tag{11}$$

where, $We_D = \frac{G^2D}{\rho_l\sigma}$

The original coefficients are:

$$\beta_1 = 0.0352 \qquad \beta_2 = 2.31 \qquad \beta_3 = 0.361$$

3.3. Wojtan *et al.* (2006) correlation

To develop this correlation, the authors used their experimental database to evaluate the variables that had effects on the critical heat flux, as for example the mass flux, fluid properties and characteristics of the test section. The correlation is based on the correlation suggested by Katto and Ohno (1984), but does not consider sub cooling effects, since the authors did not find variations in critical heat flux when varied subcooling in test section. The correlation of Wojtan *et al.* (2006) is presented below, and their original coefficients are presented below:

$$q_{CHF} = \beta_1\left(\frac{\rho_v}{\rho_l}\right)^{\beta_2} We^{\beta_3}\left(\frac{L}{D}\right)^{\beta_4} G(h_v - h_l) \tag{12}$$

where: $We = \frac{G^2L}{\rho_l\sigma}$ $\qquad \beta_1 = 0.437 \qquad \beta_2 = 0.073 \qquad \beta_3 = -0.24 \qquad \beta_4 = -0.72$

4. MODIFICATIONS

A Matlab (Matlab, 2013) 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 originals correlations were also evaluated against the present database and were compared to the modified correlations results.

Graphics that illustrates the trends of the correlations are presented, in order evaluate if the correlation is respecting the experimentally observed trends

4.1. Katto and Ohno (1984) correlation results

The new coefficients obtained for the correlation of Katto and Ohno (1984) were:
$\beta_1 = 0.0623$ $\beta_2 = 0.0144$ $\beta_3 = 0.0391$ $\beta_4 = 0.2218$

Table 2 presents the statistical evaluation for this modification using filtered database. The results indicates a significant improvement compared to the modified correlation before filtering of database, and a slight improvement compared to the original correlation. The correlation of Katto and Ohno (1984) with their original coefficients was efficient in the calculation of the critical heat flux for the present database, and the modifications did not achieve a improvement in the statistical parameters evaluated, when compared before and after the database filtering. The authors believe that for the modified Katto and Ohno correlation a better segregation of the database is necessary for adjusting the q_{co1} and q_{co2} equations..

Table 2. Statistic evaluation for Katto and Ohno (1984) correlation

	Original correlation by Katto and Ohno (1984) (**before** database filtering)	Original correlation by Katto and Ohno (1984) (**after** database filtering)	Modified correlation by Katto and Ohno (1984) (**before** database filtering)	Modified correlation by Katto and Ohno (1984) (**after** database filtering)
Number of points evaluated	707	687	707	687
MAE (%)	26.24	20.64	29.12	24.00
$\lambda_{\pm 30\%}$ (%)	80.48	82.82	62.09	73.22

Figure 1 shows the relationship of the theoretical and experimental critical heat flux for the modified correlation with the filtered database, where a distribution of points around the line of symmetry (dotted line) indicates a better prediction.

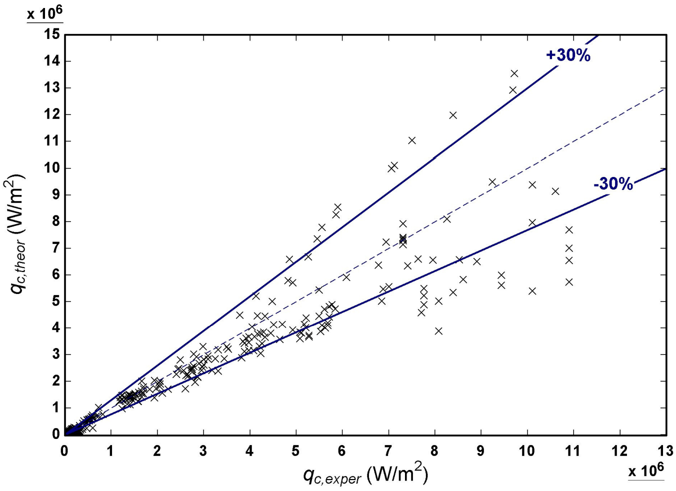

Figure 1. Modified correlation by Katto and Ohno (1984)

Figures 2 to 5 show trends for the correlation of Katto and Ohno (1984) with the new adjusted coefficients. This analysis is important in order to check whether the new coefficients are able to adequately predict the experimental trends observed in the laboratory. Figure 2 presents the trend of the modified Katto and Ohno (1984) correlation for a variation in the heated length of the channel. As well as observed experimentally, we can notice that for an increase in mass flux there is an increase in critical heat flux, being that this behavior is also observed for changes in other parameters, and a reduction in the length of the heated channel provides an increase in critical heat flux. This arises from the reduction of the heat transfer area, and to reach the same critical quality, a larger heat flux is necessary (Tibiriçá, 2011).

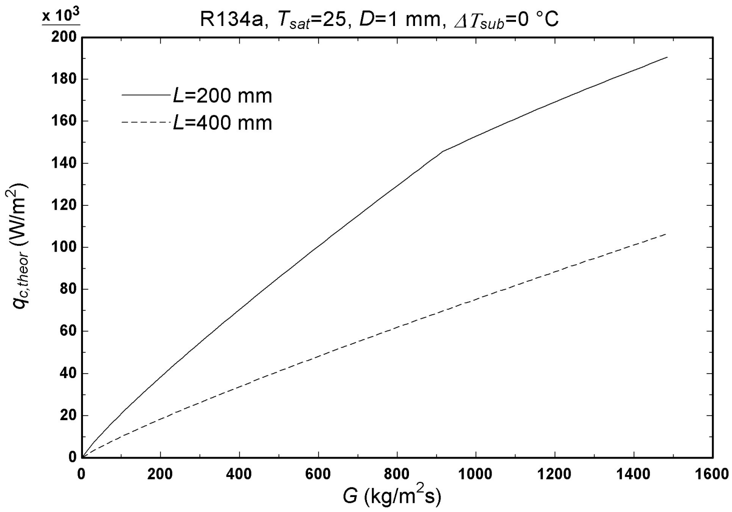

Figure 2. Effect of variation in the heated length for Katto and Ohno (1984) modified correlation

The trend of modified correlation of Katto and Ohno (1984) for a variation in the diameter is illustrated in Fig. 3. To properly evaluate the effect of the channel diameter on critical heat flux, the ratio between the heated length and the diameter (L/D) should be the same for all diameters measured in order to obtain similar outlet vapor qualities in the heated region. Therefore, we can see a small effect of variation of diameter in the critical heat flux, with the smaller diameter tube showing a critical heat flux slightly higher. The variation of critical flux obtained in this correlation is greater than the observed experimentally by Tibiriçá (2011), which occur for higher mass speeds. Noticeable differences between critical heat fluxes for the smaller and the larger diameter in the modified correlation of Katto and Ohno (1984) can already be noted with flow rates above 300 kg/m^{2}s. It is believed that this difference is by the change of equation to calculate the basic critical heat flux (q_{co}), due to the discontinuity point of the curve. For the original coefficients the same behavior is observed, but the difference between the smaller and higher diameter is noticeable for mass speed values higher than 800 kg/m^{2}s.

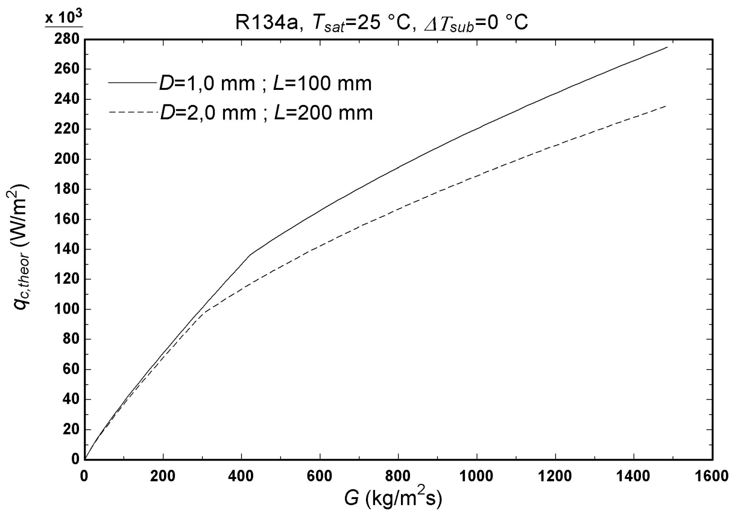

Figure 3. Effect of variation in the channel diameter for Katto and Ohno (1984) modified correlation

The trend of correlation due to the inlet subcooling is show in Fig. 4. Little noticeable differences are observed, with the curve for bigger subcooling giving slightly larger values than to the lower subcooling, when reaches higher flow rates. This can be explained as follows: for high subcooling the heating power needed to achieve a similar critical quality rises, resulting in a small increase in critical heat flux.

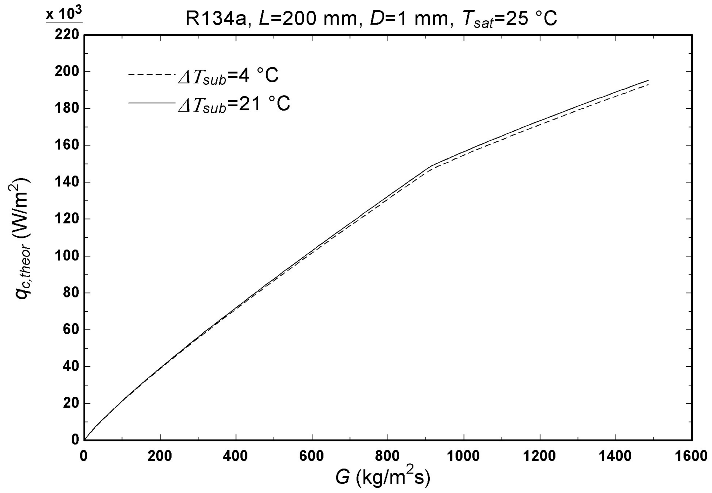

Figure 4. Effect of variation in the sub-cooling for Katto and Ohno (1984) modified correlation

The effect of saturation temperature variation can be seen in Fig. 5, where higher temperatures provide a decrease in critical heat flux, as well as noted experimentally in Tibiriçá (2011). This behavior is associated to the decrease of the latent heat of vaporization with a saturation temperature increment.

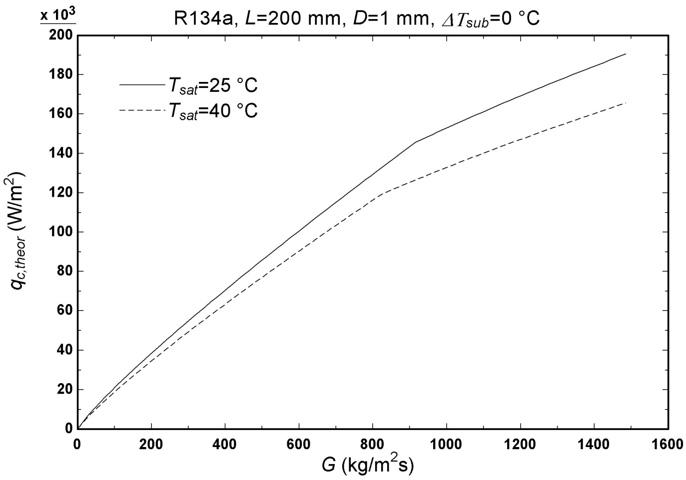

Figure 5. Effect of variation in the saturation temperature for Katto and Ohno (1984) modified correlation

4.2. Zhang *et al.* (2006) correlation results

The new coefficients obtained for the equation that performs the calculation of the critical heat flux are:

$\beta_1 = 0.0313$ $\beta_2 = 2.1262$ $\beta_3 = 0.386$

Table 3 shows the comparison between the original correlation, the correlation modified before the database filtering and correlation modified after filtering. Filtering enabled a significant improvement compared to the modified correlation to the unfiltered database, and an improvement in relation to the original correlation, which had already achieved a good performance for the database. Was possible a reduction of about 10% in the *MAE* and a small increase in the percentage of data with an error lower than 30%.

Table 3. Statistic evaluation for Zhang *et al.* (2006) correlation

	Original correlation by Zhang *et al.* (2006) (**before** database filtering)	Original correlation by Zhang *et al.* (2006) (**after** database filtering)	Modified correlation by Zhang *et al.* (2006) (**before** database filtering)	Modified correlation by Zhang *et al.* (2006) (**after** database filtering)
Number of points evaluated	707	687	707	687
MAE (%)	25.82	18.96	56.44	15.75
$\lambda_{\leq 30\%}$ (%)	86.28	88.79	21.08	87.92

Figure 6 shows the database distribution in a graph of the theoretical critical heat flux against the experimental critical heat flux.

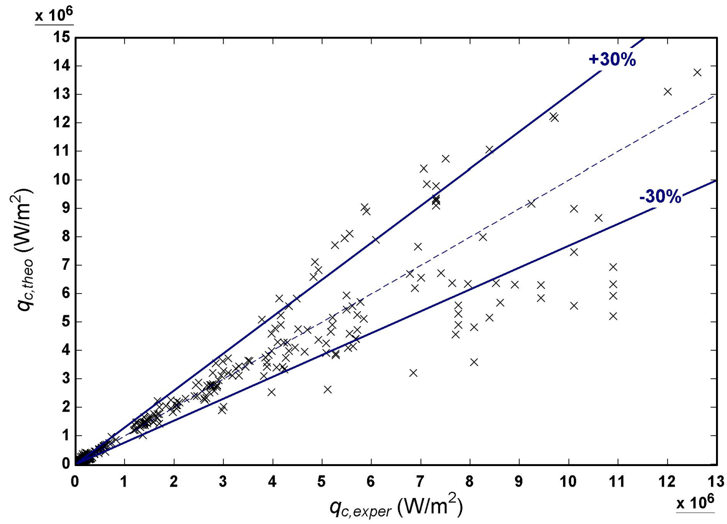

Figure 6. Modified correlation by Zhang *et al.* (2006)

Figure 7 presents the trend of the modified Zhang *et al.* (2006) correlation for a variation in the heated length of the channel. As observed experimentally, a reduction in the length of the heated channel provides an increase in critical heat flux, same trend observed for the correlation of Katto and Ohno (1984).

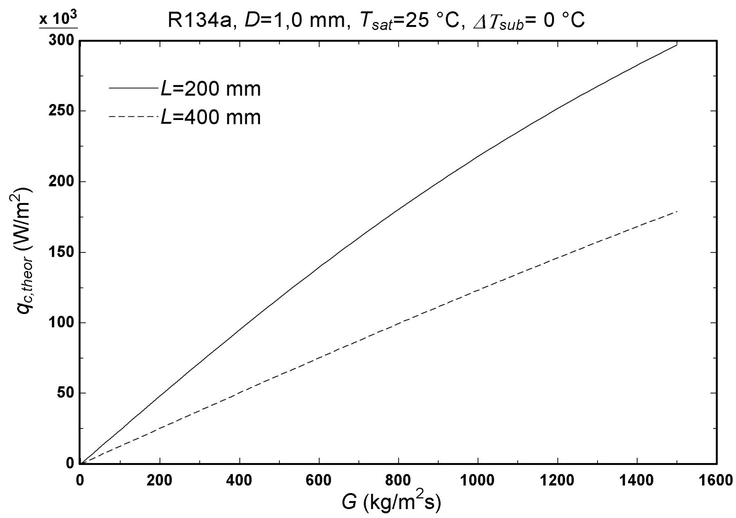

Figure 7. Effect of variation in the heated length for Zhang *et al.* (2006) modified correlation

The trend of correlation due to the inlet subcooling is show in Fig. 8. Little noticeable differences are observed, with the curve for bigger subcooling giving slightly larger values than to the lower subcooling, when reaches higher flow rates.

The Fig. 9 shows the behavior of the model with the new coefficients for a variation in the channel diameter. We can see a small effect of variation of diameter in the critical heat flux, with the smaller diameter tube showing a critical heat flux slightly higher. For this correlation, we can notice that the difference between the higher and the smaller diameter can be noted for mass fluxes higher than 700 kg/m^{2}s, which can be observed experimentally by Tibiriçá (2011). It is observed that for a higher mass flux, this difference tends to increase.

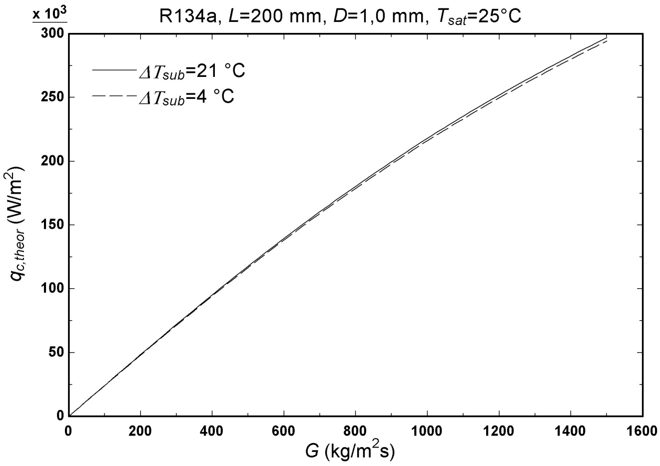

Figure 8. Effect of variation in the sub-cooling for Zhang *et al.* (2006) modified correlation

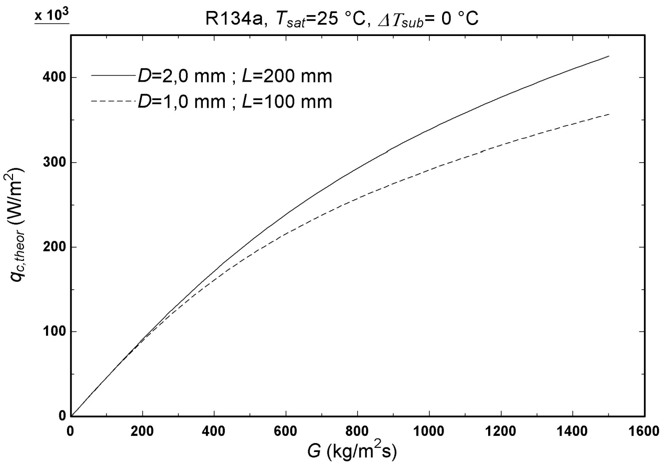

Figure 9. Effect of variation in the channel diameter for Zhang *et al.* (2006) modified correlation

Figure 10 illustrates the behavior of the model to a variation in saturation temperature. The increase in saturation temperature promotes a decrease in the critical heat flux, which is consistent with the experimental observations obtained by Tibiriçá (2011), and this difference increases as flow rate increases.

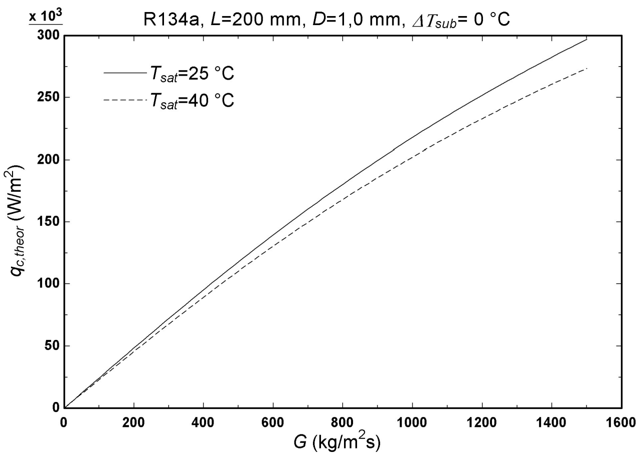

Figure 10. Effect of variation in the saturation temperature for Zhang *et al.* (2006) modified correlation

4.3. Wojtan *et al.* (2006) correlation results

The new adjusted coefficients for Wojtan *et al.* (2006) correlation with the filtered database are:

$\beta_1 = 0.0195$ $\beta_2 = 0.0306$ $\beta_3 = -0.2294$ $\beta_4 = -0.0710$

Table 4 presents the statistical parameters variation to the original correlation for the modified correlation of Wojtan *et al.* (2006). This correlation was not evaluated before the database filtering, because it was implemented after the filtering operation. These results shows a slight improvement of the prediction error of only 1%, but the amount of predicted data with an error lower than 30% increased more than 13%, which shows that there was a relative improvement in the performance of this correlation. However, this performance is still below the performance of the two correlations presented earlier, which is the same result obtained by Tibiriçá *et al.* (2008), where correlations with the best performance were the correlations of Katto and Ohno (2006) and Zhang *et al.* (1984).

Table 4. Statistic evaluation for Wojtan *et al.* (2006) correlation

	Original correlation by Wojtan *et al.* (2006)	Modified correlation by Wojtan *et al.* (2006)
Number of points evaluated	687	687
MAE (%)	34.12	33.15
$\lambda_{\pm 30\%}$ (%)	47.45	60.99

Figure 11 shows the database distribution in a graph of the theoretical critical heat flux against the experimental critical heat flux.

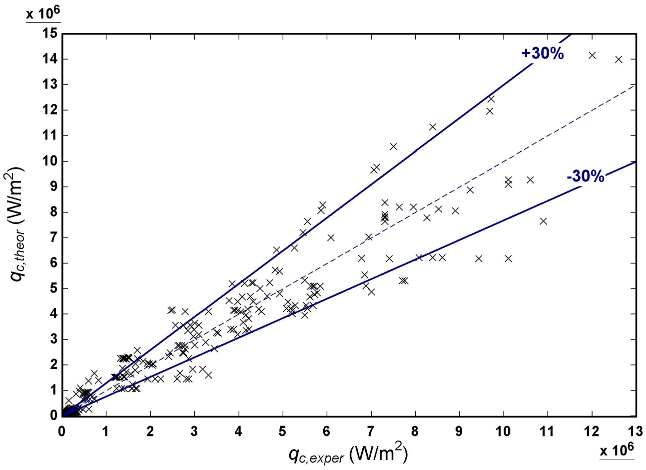

Figure 11. Modified correlation by Wojtan *et al.* (2006)

Figure 12 shows the behavior in relation to the diameter of the channel, where an increase in the diameter of the tube provides a decrease in critical heat flux. For this correlation, the variation has shown noticeable with low flow rates, which is different from the observed in Tibiriçá (2011), in which the difference in the value of critical heat flux between the smallest and largest diameters are only noticeable for higher flow rates. Finally, the effect of saturation temperature is shown in Fig. 12b. A decrease in saturation temperature causes an increase in critical heat flux, as observed experimentally.

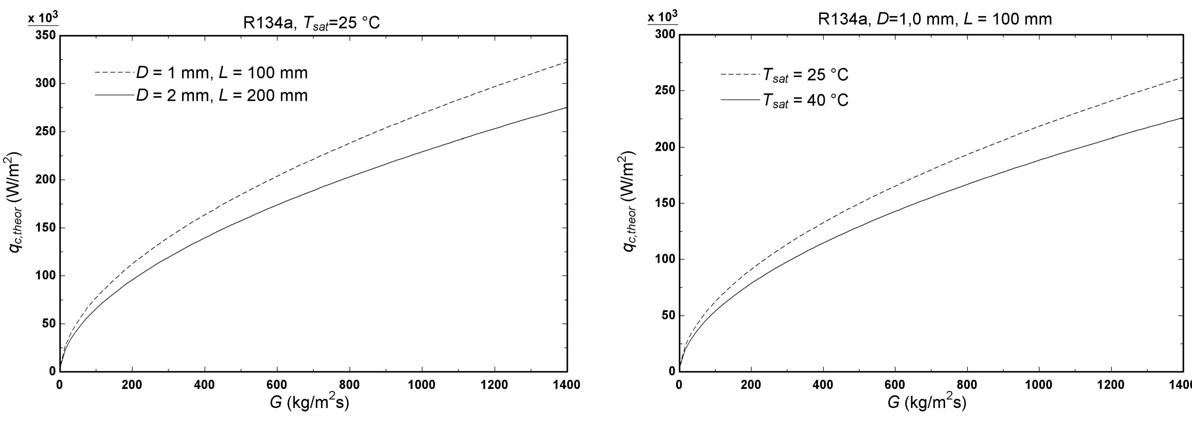

Figure 12. Wojtan *et al.* (2006) modified correlation (a) effect of variation in the channel diameter for (b) saturation temperature effect.

5. CONCLUSIONS

A database for prediction of critical heat flux was reunited and modifications were made in correlations available in the literature aiming to improve the performance of them. The conclusions are the follows:

- The modified correlation of Zhang *et al.* (2006) obtained the best result for prediction of critical heat flux, reaching a mean absolute error of 16% and predicting up to 87% of the database with an error lower than 30% and its recommend for application in saturated CHF predictions in micro-scale flow.
- The modified correlation of Katto and Ohno (1984) reached a mean absolute error of 24% and predicting up to 73% of the database with an error lower than 30%.
- The modified correlation of Wojtan *et al.* (2006) achieved a better performance compared to the original correlation, but its performance was below the other two evaluated correlations, confirming the results obtained in previous work (Tibiriçá *et al.* (2008)) which suggest that the correlations of Zhang *et al.* (2006) and Katto and Ohno (1984) present the best results for the critical heat flux prediction in saturated micro-scale flow.

6. ACKNOWLEDGEMENTS

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