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AN ANALYSIS OF CORRELATIONS FOR HIGH LEVELS OF CRITICAL HEAT FLUX FOR CONVECTIVE BOILING

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Abstract. Critical heat flux (CHF) is the maximum amount of heat flux that can be allowed in phase change thermal systems before causing irreversible damage to them. Due to the complexity of modelling the CHF in convective boiling, the methods for its prediction are usually based on empirical correlations based on dimensionless groups. In this work we analyse CHF literature correlations for high levels of CHF. This study is aiming at evaluation the existing CHF correlations for flow boiling with available databases. The reference dataset is composed of 315 and 460 data points for saturated and subcooled conditions respectively, covering wide ranges of operating conditions of outlet pressure from 0.13 to 17.24 MPa; internal diameter from 0.33 to 2.67 mm; heated length from 2.67 to 100 mm; outlet temperature from 33 to 187.5 °C and critical heat flux from 0.167 to 276 MW/m². Among the predictive tools available in literature eight correlations for saturated and three for subcooled coditions were selected. The Tibiriçá (2011) correlation seem to be the most reliable predictive tool for saturated conditions at high levels of CHF while the Hall and Mudawar (1999) correlation seem to be the most reliable for calculation of the CHF in subcooled flow boiling.

Keywords: Critical heat flux, correlations, burnout

1. INTRODUCTION

Critical heat flux (CHF) is the maximum amount of heat flux that can be allowed in thermal systems before causing irreversible damage to them. Several factors influence the value of the CHF, as the channel shape, fluid properties, heated tube length / diameter ratio, input quality, velocity, among others. Beside, distinct mechanisms of CHF occurrence are observed under sub-cooled and saturated conditions. On the CHF occurs a sudden decrease in the heat transfer coefficient and possible catastrophic failure of a device in which evaporation or boiling is occurring. Surpassing the CHF can prompt an unexpected enormous increment in the wall temperature, which can lead to a catastrophic system failure. The capacity to predict the CHF is in this manner of fundamental significance to the security in a high flux system.

Critical heat flux can be classified as either saturated or subcooled. Saturated CHF occurs when the exit vapor quality is above zero, and subcooled when the vapor quality is bellow zero. A different set of correlations is proposed depending of the CHF type. Zhang *et al.* (2006) concluded that correlation from Mudawar and Bowers (1999) and the one from Shah (1987) seem to be the most reliable tools for CHF prediction in the subcooled and saturated flow boiling regions, respectively.

Just a couple of studies have been published about high levels of CHF. These investigations have demonstrated that the higher levels of CHF can be accomplished with subcooled type of CHF, using water as working fluid with high mass velocities on small diameters tubes. Mudawar and Bowers (1999) made a review of prior CHF work and found inconsistencies between the findings because of prior inability to isolate the effects of the key parameter, on their work they concluded that CHF increases with increasing mass velocity, increasing subcooling, decreasing tube diameter and decreasing heated length-to-diameter ratio.

Due to the complexity of modelling the CHF in convective boiling, the methods for its prediction are usually based on empirical correlations based on dimensionless groups. The goal of this work is to make a literature correlations review and to evaluate them in high levels of CHF conditions with available experimental databases.

2. REVIEW OF LITERATURE CORRELATIONS

In this section seven correlations of the literature for the critical heat flux will be presented. For each of them,

the parameters, validation conditions and uncertainties are presented, according to the experiments performed by their respective authors. Correlations with a single equation are written below for reference.

2.1 Katto and Ohno (1984)

Katto and Ohno (1984) developed a generalised correlation to solve problems presented for certain configurations when using the correlation previously proposed by Katto (1978). They proposed a set of four correlations separated according to CHF regimes, which depending on the vapor-to-liquid density ratio. The adjustment of the correlation coefficients where based on an existing database and the fluids used were water, R12, R22 and helium. The channel hydraulic diameter is in the range of 1 to 13 mm and the heated length is 1.00 m. The pressure varies from 1.96 to 3.44 MPa, the mass velocity from 120 to 2100 kg/m^{2}s and the inlet subcooling enthalpy from 0.4 to 39.9 kJ/kg.

2.2 Shah (1987)

The correlation conceived by Shah (1987) is composed of several subcorrelations selected according to specific criteria. He proposes the CHF prediction for vertical flows in evenly heated pipes and his work covers saturated and sub-cooled conditions. The correlation was based on data from 62 independent sources and it included 23 fluids, among which are water, R11, R114, ammonia, helium and hydrogen. The tube diameters varied from 0.32 to 37.8 mm and the lengths from 1.3 to 940 times the diameter. The reduced pressures were in the range 0.0014 to 0.96 MPa and the mass velocity varied from 4 to 29051 kg/m^{2}s. These ranges for the parameters can be use for the analysis of all stable fluids. However, for helium, a specific set of parameter must be adopted. Shah (1987) obtained the absolute mean errors of 16 % when comparing its correlation to the totality of its experimental data.

2.3 Mudawar and Bowers (1999)

There are three dimensionless CHF correlations by Mudawar and Bowers (1999) for subcooled CHF, based on inlet or outlet conditions. They consisted of a single equation having only five adjustable constants, it was developed to examine the parametric trends exhibited by a small fraction of the database but had a root-mean-square error of 17.2 %, 19.1 % and 15.1 % for the entire database. It was validated with data covering a broad range of pressures from atmospheric to near the critical point and mass velocities (1500-134000) kg/m^{2}s. Mudawar and Bowers (1999) recommend the inlet conditions correlation for the prediction of subcooled CHF with water.

Outlet

$$Bo = 0.0332 We_D^{-0.235} \left(\frac{\rho_f}{\rho_g}\right)^{-0.681} \left[1 - \frac{0.0227}{0.0332}\left(\frac{\rho_f}{\rho_g}\right)^{-0.7037} x_o\right] \tag{1}$$

Inlet

$$Bo = \frac{0.0332 We_D^{-0.235} \left(\frac{\rho_f}{\rho_g}\right)^{-0.681} \left[1 - \frac{0.0227}{0.0332}\left(\frac{\rho_f}{\rho_g}\right)^{-0.7037} x_o\right]}{1 + 0.0908 We_D^{-0.235} \left(\frac{\rho_f}{\rho_g}\right)^{0.151} \left(\frac{L}{D}\right)} \tag{2}$$

Correlation parameters are defined by Bo as the Boiling number, D the inside diameter of tube, L the heated length, ρ_f the liquid density, ρ_g the vapor density, Wed_D the Weber number and x_o the thermodynamic equilibrium quality at the outlet.

2.4 Zhang et al. (2006)

The correlation of Zhang *et al.* (2006) was developed for minichannels conditions. The authors used artificial neural networks to determine the predominant dimensionless parameters in saturated CHF. A database with more than 2000 experimental points for water with tube diameters varying between 0.33 to 6.22 mm was used. The correlation is composed of only one equation, but this equation is not easily linearized and it has a total mean deviation of 16.8 %. The inverse function – a transformation that is important in some situations – of some parameters of their correlation can not be analytically found.

$$Bo = 0,0352 \left[We_D + 0,0119\left(\frac{L}{D}\right)^{2,31} (\rho_g/\rho_f)^{0,361}\right]^{-0,295} \cdot (L/D)^{-0,331} \left[2.05\,(\rho_g/\rho_f)^{0.170} - x\right] \tag{3}$$

2.5 Wojtan et al. (2006)

Wojtan *et al.* (2006) correlation for saturated CHF in microchannels is based in a functional form of Katto and Ohno (1984) correlation. It was used a database with fluids R134a and R245fa and diameters of 0.5 mm and 0.8 mm for the

experiment. The test section had a 80 mm long stainless steel tube as preheater, a heated length from 20 to 70 mm and mass velocity from 400 to 1600 kg/m^{2}s. Wojtan *et al.* (2006) improved Katto and Ohno (1984) correlation and predicted the experimental data with the mean absolute error of 7.6 % with the 82.4 % of the data falling within a 15 % error band. The correlation is recommended only for annular flow.

$$q = 0,437 \left(\frac{\rho_g}{\rho_v}\right)^{0,073} We^{-0,24} \left(\frac{L}{D}\right)^{0,72} G \cdot h_{lg} \tag{4}$$

with h_{lg} defined as the latent heat of vaporization and G as the mass velocity.

2.6 Ong and Thome (2011)

Ong and Thome (2011) improved the Wojtan *et al.* (2006) correlation. They created a correlation for saturated CHF data of single channels using the fluids R134a, R236fa and R245fa with diameter ranging from 0.35 to 3.04 mm. They obtained a new simple correlation for CHF that is valid for mass velocity of 84 to 3736 kg/m^{2}s, circular channels with 0.51 and 0.79 mm of internal diameters and heated diameters of 0.35 and 0.88 mm.

$$\frac{q}{Gh_{lg}} = 0,12 \left(\mu_f/\mu_g\right)^{0,183} \left(\frac{\rho_g}{\rho_f}\right)^{0,062} We^{-0,141} \left(\frac{L}{D}\right)^{0,7} \left(\frac{D}{D_{th}}\right) \tag{5}$$

with D_{th} defined as:

$$D_{th} = \frac{1}{0.5} \cdot \sqrt{\frac{\sigma}{g\left(\rho_f - \rho_g\right)}} \tag{6}$$

and the parameters μ_f and μ_g defined as liquid and vapor viscosity respectively.

2.7 Wu et al. (2011)

Wu *et al.* (2011) used water and non water fluids (R134a, R245fa, R236fa, R123, nitrogen) with tube diameters ranging from 0.286 to 2.98 mm to develop a simple correlation based on the boiling number, length-to-diameter ratio, and exit quality. All the properties must be taken at the outlet of the channel. Heated length and equivalents heated lengths were adopted in the length-to-diameter ratio, considering the current heat transfer conditions. According to the authors, the new correlation can predict the overall microchannel database accurately on the whole. The new method predicts almost 97.0 % of the non-aqueous data (except R12 data points located in the macro-scale region) and 94.0 % of the water data within the ±30 % error band.

$$\frac{q}{Gh_{fg}} = 0.60 \left(L/D\right)^{-1.19} x^{0.817} \tag{7}$$

2.8 Tibiriçá (2011)

Tibiriçá (2011) adjusted new coefficients with its own experimental CHF database by modifying the correlation of Zhang et al, Katto and Ohno and Ong and Thome. He used R134a, R245fa and R1234ze (E) and tube diameters of 1.1 and 2.2 mm. The results obtained fall into only two regimes, both related to wall-drying conditions: reduced flow rates and high flow rates. Thus, the correlations were optimized for these two regimes. For other regimes, the author suggest the use of the original method of Katto and Ohno.

The correlations can be applied with low error to non-circular tubes by the use of the equivalent diameter and equivalent length of non-circular tubes in the original correlations for circular tubes. Also, it can be used for three different refrigerant fluids, while the original by Zhang et al. was valid only for water. In general, the modified correlations of Katto and Ohno (1984) and Zhang *et al.* (2006) presented excellent agreement with an absolute mean error of 3 % and approximately 80 % of data with error less than 5 %.

$$\frac{q}{Gh_{lg}} = 0.02843 \left(\frac{G^2 D}{\sigma \rho_l} + 0.0119 \left(\frac{L}{D}\right)^{2.138} \left(\frac{\rho_g}{\rho_f}\right)^{0.529}\right)^{-0.295} \cdot \left(\frac{L}{D}\right)^{-0.311} \left(2.05 \left(\frac{\rho_g}{\rho_f}\right)^{0.17} - x_i\right) \tag{8}$$

with the parameter σ defineda as surface tension and x_i as the inlet thermodynamic equilibrium quality.

2.9 Tibiriçá et al.(2017)

Tibiriçá *et al.* (2017) developed a simple and optimized correlation for flow boiling and two-phase conditions in microchannel using a database with 1110 data points, for saturated CHF, covering a wide range of parameters, such as

mass fluxes from 23.6 to 8800 kg/m^{2}s, critical heat fluxes from 0.051 to 19.26 MW/m^{2}s, diameters of channel from 0.24 to 6.92 mm, and inlet vapor qualities from 57.9 to 14 %. The correlation has a operational range which varies according to the dimensionless numbers of heated tube length/diameter ratio of 20 to 500, liquid /vapor density ratio of 6.5 to 129,000 and inlet vapor quality from -0.6 to 0.15. In addition, the database covers the fluids water, R12, R123, R134a, R236fa, R245fa, R1234ze(E) and nitrogen.

In general way, the new correlation predicts well all individual databases but for very low mass velocities G <150 kg/m^{2}s, for synthetic refrigerants, it had slight tendency of overpredicting the experimental results.

$$Bo = 0.242 \cdot We^{-0.1635} \left(\frac{L}{D}\right)^{-0.6834} \left(\frac{\rho_g}{\rho_f}\right)^{0.0598} \cdot (1 - x_i)^{0.881} La_l^{-0.0714} \tag{9}$$

The laplace number is defined as:

$$La_l = \frac{\sigma \rho_l D}{\mu_f^2} \tag{10}$$

2.10 Shibahara et al.(2017)

Shibahara *et al.* (2017) obtained a simple correlation for high CHF on small tube based on experimental data obtained by the author with flow velocities ranging from 4.3 to 30.6 m/s. The correlation can predict CHF for subcooled boiling of water with 30 % of accuracy and the thermal properties of saturated water are determined from the outlet pressure.

$$Bo = 0.149 \left(\frac{\rho_f}{\rho_g}\right)^{0.47} D^{*-0.1} We^{-0.3} \left(\frac{L}{D}\right)^{-0.1} Sp^{0.14} \tag{11}$$

with the paramenter Sp defined as:

$$Sp = \frac{\rho_f c_{pf} \triangle T_{sub,o}}{\rho_g h_{fg}} \tag{12}$$

and the parameters c_{pf} and $\triangle T_{sub,o}$ defined as specific heat at constant pressure and outlet liquid subcooling respectively.

3. DATABASE

There are two databases used in this work, the first is showed in Tab. 1. The data were obtained from Tibiriçá *et al.* (2017) in which the highest CHF values are tested. The collected database is made for saturated CHF, covering the fluids water and R123 for mass fluxes from 23.6 to 8800 kg/m^{2}s^{-1}. The diameters of channel varies from 0.24 to 6.92 mm and the inlet vapor qualities from 57.9 to 14 %. The critical heat fluxes obtained were from 0.051 to 19.26 MW/m^{2}s.

The second database is showed in Tab. 2. The data were obtained from three sources. Celata *et al.* (1993) conducted CHF experiments of critical heat flux (CHF) in subcooled flow boiling in short tubes. The experimental work was carried out with water at pressures ranging from 0.1 to 2.5 MPa and water velocities from 10 to 40 ms^{-1}. employing stainless steel 2.5 mm i.d. tubes. The heated length was 0.1 m and the wall thickness was 0.25 mm. Achieving high values of CHF ranging from 12.1 to 60.6 MWm^{-2}.

Mudawar and Bowers (1999) obtained CHF data using high mass velocity subcooled water flow through short, small diameter tubes. The data include the ranges of tube diameter from 0.406 to 2.54 mm, heated length-to-diameter ratio of 2.4 to 34.1, mass velocity ranging from 5000 to 134000 kg/m^{2}s^{-1}, inlet temperature from 18 to 70°C and outlet pressure from 2.5 to 172.4 bars. The tests produced CHF data ranging from 9.4 to 276 MW/m^2.

Vandervort *et al.* (1994) performed experiments with metallic tubes having inside diameters ranging from 0.3 to 2.7 mm. Mass fluxes ranged from 5000 to 40 000 kg/m^{2}s^{-1}, and exit subcoolings from 40 to 135°C. Exit pressures ranged from 0.2 to 2.2 MPa, and length-to-diameter ratios ranged from 2.0 to 50.0. Over 200 CHF stable data points for water were obtained ranging from 4.6 to 130.4 MW/m^2.

Table 1. Critical heat flux levels for saturated experimental database.

Authors	Fluid	CHF[MW/m^2]
Lowdermilk *et al.* (1958)	Water	$0.167 - 10.85$
Thompson and Macbeth (1964)	Water	$0.2333 - 19.26$
Koşar and Peles (2007)	R123	$0.279 - 1.06$

Table 2. Critical heat flux levels for subcooled water experimental database.

Authors	CHF[MW/m^2]
Celata *et al.* (1993)	$12.1 - 60.6$
Mudawar and Bowers (1999)	$9.4 - 276$
Vandervort *et al.* (1994)	$4.6 - 130.4$

4. CORRELATIONS ANALYSIS

The correlations were evaluated using the MAE (mean absolute error). Table 3 shows the comparison for the database of Tab. 1. Considering the entire database, the correlation from Tibiriçá (2011) obtained the lower weighted media error (16.1 %) followed by Zhang *et al.* (2006), with 16.3 %. These correlations are believed to have performed better due to the database that has similar characteristics to the database used in their creations.

Table 3. Evaluation of mean absolute error (MAE %) for high levels of CHF in literature correlations for saturated experimental database.

Database	Katto and Ohno (1984)	Shah (1987)	Zhang *et al.* (2006)	Woj- tan *et al.* (2006)	Ong and Thome (2011)	Wu *et al.* (2011)	Tibir- içá (2011)	Tibir- içá *et al.* (2017)
Lowdermilk *et al.* (1958)	24.4	28.9	12.8	30.3	18.3	16.9	14.7	14.3
Thompson and Macbeth (1964)	40.7	54.8	19.5	49.7	45.0	21.6	16.7	30.7
Koşar and Peles (2007)	21.8	18.1	25.4	13.9	22.8	44.0	22.4	16.8
- Mean -	29.7	36.7	16.3	35.4	27.9	21.1	16.1	20.2

Table 4 shows the comparison for the database of Tab. 2. Considering the entire database, the correlation from Hall and Mudawar (1999) obtained the lower average error (21.6 %) followed by Zhang *et al.* (2006), with 32.8 %. The correlation from Mudawar had a good performance due to the extensive database used in its creation. Even though the correlations from Tibiriçá (2011) and Zhang *et al.* (2006) are not recommended for subcooling conditions they were tested to check how they would perform on the subcooled database.

Table 4. Evaluation of mean absolute error (MAE %) for high levels of CHF in literature correlations for subcooled experimental database.

Database	Num- ber of data points	Hall and Mu- dawar (1999)In- let	Hall and Mu- dawar (1999)Out- let	Zhang *et al.* (2006)	Tibir- içá (2011)	Shiba- hara *et al.* (2017)
Celata *et al.* (1993)	78	20.0	64.1	12.6	17.1	17.9
Vandervort *et al.* (1994)	210	33.7	43.5	34.1	40.6	49.1
Mudawar and Bowers (1999)	173	7.7	43.9	40.4	50.2	84.1
- Mean -		21.6	47.1	32.8	40.2	56.9

5. CONCLUSIONS

The results showed that the correlations are able to predict the values in the database for high levels of saturated CHF with an average error that varies from 16.1 to 36.7 %. The correlation from Tibiriçá (2011) performed best considering the database with an average error of 16.1 %. For subcooled conditions, the correlations predicts the experimental values with an error that varies from 21.6 to 56.9 % the correlation from Hall and Mudawar (1999) performed the best with an average error of 21.6 %. Although the correlations from Tibiriçá (2011) and Zhang *et al.* (2006) were recommended to predict CHF of saturated flow boiling, they performed better than some developed specifically for subcooled conditions.

6. ACKNOWLEDGEMENTS

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8. RESPONSIBILITY NOTICE