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Study of the critical heat flux condition with water and R-123 during flow boiling in microtubes. Part II – Comparison of data with correlations and establishment of a new subcooled CHF correlation

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ABSTRACT

This study's objective was to better understand the CHF condition in microchannels. The effect of different operating parameters – mass flux, inlet subcooling, exit quality, heated length and diameter – were assessed in detail in Part I of the study and compared to the behavior in conventional sized channels. Part II of the study compares the water and R-123 data with existing micro/macrochannel correlations. Existing correlations for predicting CHF in large-sized channels do not seem to be applicable to microchannels. This study has provided new subcooled CHF data for low mass fluxes and the earlier available subcooled boiling CHF correlation for microchannels (based on the data available for very high mass fluxes) is not suitable to predict such data. Based on the new subcooled CHF data, a correlation to predict CHF in low-flow subcooled boiling has been developed.

1. Introduction

Experiments to determine the CHF condition for flow of water in conventional sized vertical uniformly heated round tubes has been carried out for more than 50 years. A compilation of those data is provided by Thomson and Macbeth [1]. Macbeth's correlation is based on the "local conditions hypothesis," which suggests that the critical heat flux is solely a function of the exit (local) quality. Another popular correlation, built on the Macbeth correlation, was proposed by Bowring [2] for tube diameters in the range of 2–45 mm. A correlation scheme for low and high quality flows for 3–37.5 mm tube diameters involving in a vertical upflow boiling of water with uniform heating was suggested by Baisi et al. [3]. For a similar flow configuration, Levitan and Lantsman [4] recommended a correlation for DNB in an 8-mm-diameter tube. They also provided another correlation for critical quality for flow through an 8-mm diameter tube subjected to dryout conditions. An extensive tabulation of CHF data including the DNB as well as the dryout transitions was provided by the Heat and Mass Transfer Section of the Scientific Council, USSR Academy of Sciences [5] for flow of water through a vertical round tube with an inside diameter of 8 mm. A generalized correlation for CHF in vertical uniformly heated tubes was proposed by Katto and Ohno [6] and was found to agree reasonably well for tube diameters near 10 mm.

Attempts have been made to present the CHF data in tabular form. Doroshchuk and Lantsman [7] proposed the first CHF look-up table but did not cover all the ranges of interest. They suggested a diameter correction factor to extend the CHF table to values other than an 8-mm diameter. Their database was applicable for diameters ranging from 4 to 20 mm. Groneveld et al. [8] derived a look-up table based on the local conditions hypothesis, where the CHF is assumed to be a function of pressure, mass flux, quality, and diameter of the tube. Kirillov et al. [9] provided recommendations for determining heat-transfer burnout for 8-mm (reference) diameter tubes heated uniformly along their length. Hall and Mudawar [10] compiled and assessed the world CHF data for water flow in uniformly heated tubes. This database was a tool for the development of a subcooled CHF correlation [11] using the parametric trends observed in the data.

Some of the literature on CHF in microchannels compares the data with existing CHF correlations. Nariai et al. [12] reported CHF studies with water at ambient exit pressure in stainless steel tubes with inside diameters from 1 to 3 mm. For the 2- and 3-mm diameter tubes their data agreed well with the Katto [13] correlation in the saturated region; however, for the 1-mm diameter tube, they did not attempt to see if their data agreed with any existing CHF correlations. Bergles et al. [14] conducted studies for CHF with de-ionized water in a stainless steel 2.38-mm tube with $L/d = 15$, mass flux of 3000 kg/m^2 s, and an exit pressure of 207 kPa. The Zenkevich [15] correlation (for larger diameter tubes) grossly underpredicted the data. Roach et al. [16] studied the

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Nomenclature

Bo	boiling number
C_p	specific heat (J/kg K)
G	mass flux (kg/m^2 s)
H	heat transfer coefficient (W/m^2 K)
J	superficial velocity
L	length of the tube (mm)
P	pressure (kPa)
Pr	Prandlt number
Re	Reynolds number
T	temperature (°C)
V	voltage (V)
We	Weber number
d	diameter (mm)
h	specific enthalpy (J/kg)
k	thermal conductivity (W/m K)
q''	heat flux (W/m^2)
x	quality

Greeks

ΔT	temperature difference (°C)
Δh	specific enthalpy difference (J/kg)
μ	dynamic viscosity (N s/m^2)
ρ	density (kg/m^3)
σ	surface tension (N/m)

Subscripts

B	bubble
CHF	critical heat flux
c	critical
d	diameter
$exit$	at exit
$expt$	from experiment
f	liquid
fg	liquid–vapor
g	vapor
h	heated
i	inlet
i^*	pseudo-inlet
in	inside, tube
if	interfacial
o	outlet
$pred$	predicted
sat	saturation
sub	subcooling, inlet
$PNVG$	point of net vapor generation

CHF associated with flow boiling of subcooled water in circular tubes with diameters of 1.17 and 1.45 mm and mass velocities from 250 to 1000 kg/m^2 s. They concluded that the Bowring [2] correlation predicted the data reasonably well. However, the deviation for the smaller tube diameter was about 35% for most heat flux values. It should be noted that the Bowring correlation was obtained for data with inside diameters from 2 to 45 mm. Oh and Englert [17] conducted CHF experiments with sub-atmospheric water in a single rectangular aluminum channel of cross-section 1.98 mm × 50.8 mm heated on one side with electric strip heaters. CHF did not match well with the existing low flow-rate correlations, the closest being the match with the Lowdermilk correlation [18] which underpredicted the data by about 30%.

Lazarek and Black [19] studied CHF with R-113 in a stainless steel tube of inside diameter 3.15 mm ($L/d = 40$) in a vertical orientation with a heated length of 12.6 cm and a wall thickness of 0.40 mm. The data were compared with the Stevens and Kirby [20] empirical model which underpredicted the critical quality by about 35% in the worst case. This difference could be because the smallest test-section diameter Stevens and Kirby used was twice as large as that of Lazarek and Black. Qu and Mudawar [21] proposed a new CHF correlations based on CHF measurements in a water-cooled microchannel heat sink with 21 parallel 215 × 821 µm channels over a mass velocity range of 86–368 kg/m^2 s. Based on these data, they proposed a new correlation for CHF. Yu et al. [22] did CHF experiments with water in a stainless steel 2.98-mm inside diameter tubing ($L/d = 305$) and a pressure of about 200 kPa. The outside diameter of the test section was 4.76 mm. The data were compared with the correlation of Groneveld et al. [8] and, although it gave the right trend, the errors were quite large (about 35–40%). The relative size of the channel compared to the wall thickness suggests that conduction may have played a role in the CHF condition in these studies, but this effect was not analyzed. Lezzi et al. [23] reported experimental results on CHF in forced convection boiling of water in a horizontal tube of diameter 1 mm and $L/d = 250$, 500 and 1000. The tube wall thickness was 0.25 mm. The results were compared with the extrapolation of the Katto correlation [6] and were found to agree well. It was concluded that for low mass fluxes and tube diameters down to 1 mm, the effect of the diameter on CHF did not differ from the characteristics of the large diameter tubes. Wojtan et al. [24] investigated saturated critical heat flux in a single uniformly heated microchannel of 0.5 and 0.8 mm internal diameter using R-134a and R-245fa. They presented a new correlation to predict CHF in circular uniformly heated microchannel.

Thus, many researchers have attempted to predict their data with existing correlations, but with mixed results. Many different correlations have been developed, but they are mostly applicable to the limited data range over which the experiments were conducted. Most of the correlations predicting the critical heat flux condition are for flow boiling of water. The literature on CHF prediction methods for other fluids is much sparser.

Part II of this study assesses in detail the capability of using existing correlations for conventionally sized channels and available correlations for microchannels to predict the onset of the critical condition in microchannels and develop new correlations if needed.

2. Comparison of the subcooled water CHF data with existing correlations

The CHF data in the subcooled region were compared with the Hall and Mudawar correlation [11]. The form of this subcooled CHF correlation is given by

$$Bo = \frac{C_1 We_D^{C_2} (\rho_f/\rho_g)^{C_3} [1 - C_4 (\rho_f/\rho_g)^{C_5} x_{i^*}]}{1 + 4C_1 C_4 We_D^{C_2} \left(\frac{\rho_f}{\rho_g}\right)^{C_3+C_5} \left(\frac{L_h}{D}\right)}. \tag{1}$$

The comparison is shown for all the three diameters in Figs. 1–3. Following are observations and comments:

1. The Hall and Mudawar correlation grossly underpredicts the data (>50%) for the diameter of 0.286 mm (Fig. 1). Most of the underpredicted data are for the low mass flux value

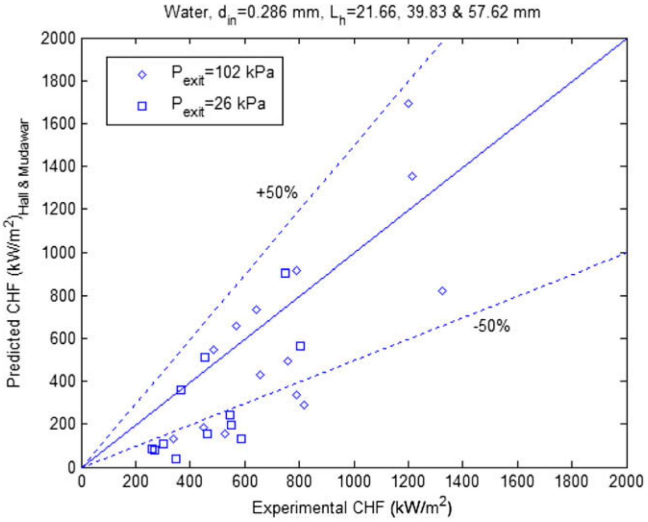

Fig. 1. Comparison of water subcooled CHF data with the Hall and Mudawar correlation for d_{in} = 0.286 mm.

(G = 320 kg/m^2 s). Flow instabilities can be higher at very low mass fluxes. It is likely that the data from which the correlation was developed were influenced by flow instabilities.

2. This correlation overpredicts the data at d_{in} = 0.427 mm by about 50% (Fig. 2). From the data (and not the plot), the difference increases as the mass flux increases. It underpredicts the data at qualities close to zero. The correlation overpredicts the data for d_{in} = 0.700 mm (Fig. 3) to a slightly lesser extent than for d_{in} = 0.427 mm.
3. The constants in the correlation have been developed using data at very high mass fluxes (5000–40,000 kg/m^2 s).
4. The correlation does not take into account the increase in CHF as qualities approach zero.

3. Comparison of the saturated water CHF data with existing correlations

For tube diameters of 0.427 and 0.700 mm, as previously seen, very few CHF data points could be obtained in the saturated region (for almost all of the data, $x_c < 0.2$), because the wall temperatures kept on linearly increasing with heat flux, and very high wall superheats were obtained even at significantly lower exit qualities. For most of the tests in the saturated region, the characteristic CHF was not observed and the experiment had to be terminated to save the test section. However, a few saturated CHF data points were obtained for d_{in} = 0.286 mm and much higher critical qualities were observed. These data were compared with the Qu and Mudawar correlation [21] which highly underpredicted the data. Comparisons with other correlations such as by Katto–Ohno [6], Wojtan et al. [24] and Zhang et al. [25] all overpredicted the data by more than 50%, and these are discussed in detail in Roday [26].

As seen previously in Part I of the paper [27], the CHF decreases with quality in the subcooled region, and then increases from the subcooled to the saturated region. At higher qualities, it still has either an increasing behavior or tends to become constant/slighty decrease depending on the operating conditions. It seems that there is a transition zone between the decreasing CHF with quality trend in subcooled region (DNB type of behavior) and the decreasing CHF with quality trend in the saturated region (dryout type of behavior). It is likely that this is due to the transition in flow patterns from the subcooled (slug type) to the saturated region (fully annular flow). Thus, most of the data obtained in the saturated region could be in the transition zone, and hence, it is difficult to predict these data with a correlation that predicts decreasing CHF with increasing quality; many of these comparisons are given in Roday [26].

4. Comparison of the R-123 CHF data with existing correlations

All the CHF data obtained for R-123 fell in the saturated region. For the three test sections, the ranges of critical qualities were: for d_{in} = 0.286 mm, x_c = 0.4–0.9; for d_{in} = 0.430 mm, x_c = 0.2–0.35; for d_{in} = 0.700 mm, x_c = 0.05–0.2.

The saturated CHF data were compared to predictions from the following correlations: Qu and Mudawar [21]; Wojtan et al. [24]; Katto–Ohno [6]. The Qu and Mudawar correlation and the Wojtan et al. correlation have a form similar to the Katto–Ohno correlation but do not take into account the inlet subcooling effect on the CHF condition. The form of the correlations for predicting saturated CHF condition is expressed as

$$Bo = C_1\left(\frac{\rho_g}{\rho_f}\right)^{C_2} We_L^{C_3}\left(\frac{L_h}{D}\right)^{C_4}. \tag{2}$$

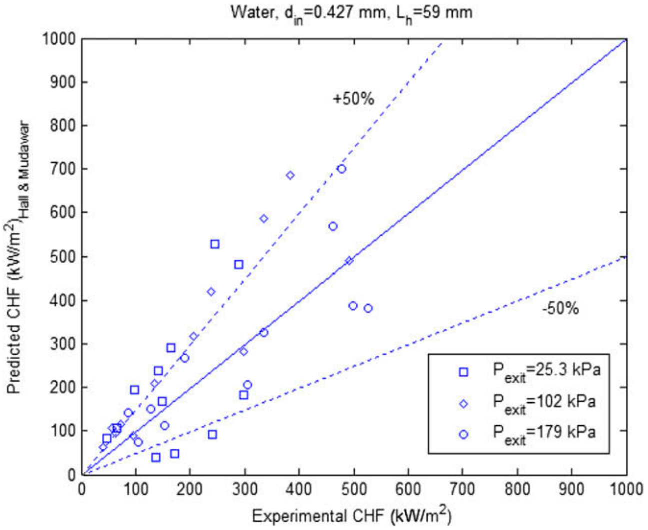

Fig. 2. Comparison of water subcooled CHF data with the Hall and Mudawar correlation for d_{in} = 0.427 mm.

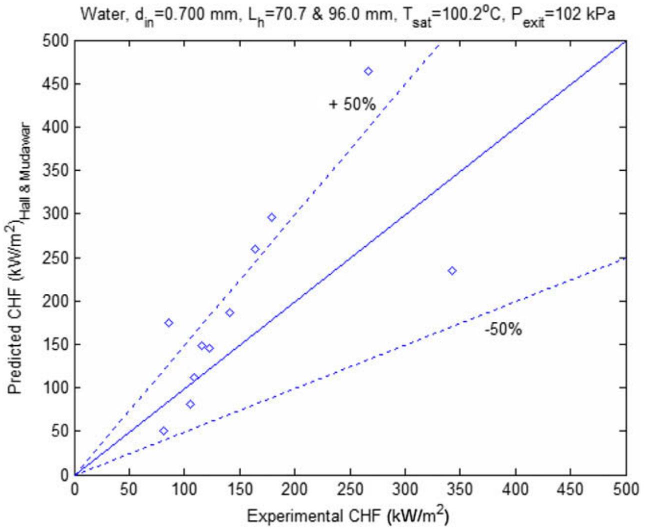

Fig. 3. Comparison of water subcooled CHF data with the Hall and Mudawar correlation for d_{in} = 0.700 mm.

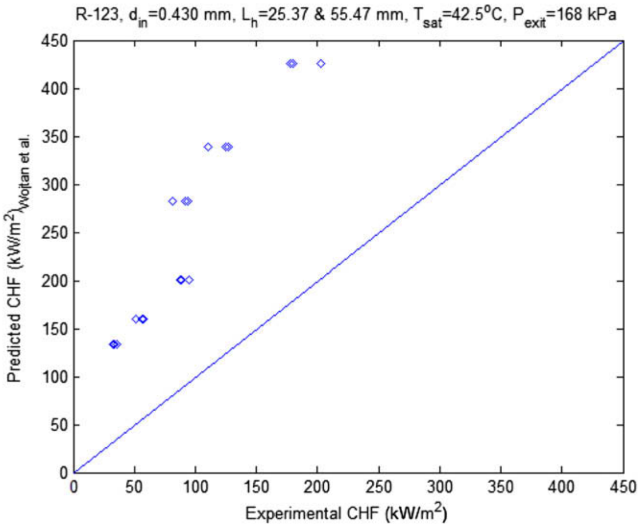

Fig. 4. Comparison of R-123 saturated CHF data with the Wojtan et al. correlation for d_{in} = 0.430 mm.

The Qu and Mudawar correlation highly overpredicts the data, and the deviation increases as the channel diameter increases. The Wojtan et al. and Katto–Ohno correlation also overpredicted the data for tube diameters of 0.430 and 0.700 mm; for d_{in} = 0.286 mm the extent to which the data are overpredicted is smaller. The deviations in the data from the Wojtan et al. correlation for d_{in} = 0.430 mm are depicted in Fig. 4. The results for the other tube diameters and comparisons with the remaining correlations can be found in Roday [26].

Thus, none of the correlations seem to predict the experimental data well. The Katto–Ohno correlation was developed for large tube diameters. The Qu and Mudawar correlation, as well as the Wojtan et al. correlation, are based on experiments conducted over limited ranges of conditions. Based on the discussion related to flow pattern, it seems that the experimental data of this study fall in the transition zone (where the CHF increases with quality) instead of the typical "dryout" region of annular flow of the saturated region. Therefore, it is reasonable to assume that none of these correlations should predict the data well.

5. Subcooled CHF correlation

As discussed in Part I [27] of this study, the trends of CHF with increase in exit quality are very complex. To summarize:

- The CHF was found to decrease with an increase in exit quality (decreased subcooling) in the subcooled region.
- As qualities approach zero, the behavior of CHF with quality has a reversal, with the CHF increasing with quality from the subcooled to the saturated region.
- With further increase in quality in the saturated region, the critical heat flux increases (transitional behavior from the subcooled CHF to dryout-type behaviors).
- Beyond a certain point, the CHF again has a decreasing trend of quality (dryout-type behavior).

All the subcooled data have been obtained for water. This data-set exhibits the decreasing trend of CHF with decreased subcooling until the point when the trend is reversed. All the CHF data points prior to the reversal point (which is determined in Section 5.1) have been considered for the subcooled CHF correlation.

5.1. Prediction of quality at the point of net vapor generation (PNVG)

As mentioned earlier, in the subcooled region, the CHF decreases with a decrease in exit quality until the exit qualities approach the saturated liquid point but still less than zero. In the subcooled region, near zero quality, the CHF starts to increase with further reduction in exit subcooling. Nariai et al. [12] and Bergles et al. [14] made similar observations during CHF studies with water. For such data which show a trend reversal, it is possible that the void fraction becomes appreciable which causes an increase in flow velocity and thereby increased the CHF as seen in the experimental data. To understand if this is a likely reason, it is necessary to find out if the data that show an increased trend of CHF lie beyond the point of net vapor generation (PNVG), where a significant void is present in the flow.

This section of the paper deals with predicting the quality at the point of net vapor generation (x_{PNVG}) for each CHF data point and comparing this quality with the observed critical quality (x_c). Most of the models available for the calculation of subcooled void fraction, such as those of Levy [28], Staub [29] and Saha and Zuber [30], are all suitable for high flow-rate boiling, whereas the experimental CHF data in this study are for fairly moderate mass fluxes. Recently, Sun et al. [31] developed a model for predicting PNVG in low-flow subcooled boiling. This model was established by satisfying the thermodynamic and hydrodynamic conditions at the PNVG, such that the amount of heat for vapor generation is equal to that for bubble condensation, and the forces acting on the bubbles that begin to detach from the wall at PNVG are balanced.

The equilibrium quality from the Sun et al. model is given by

$$x_{PNVG} = \frac{1 - \sqrt{1 + 1.6(\rho_f/\rho_g)(q''C_p/H'_{if}h_{fg})}}{2(\rho_f/\rho_g)}. \tag{3}$$

H'_{if} represents the interfacial heat transfer coefficient (=constant × H_{if}) and is calculated as

$$H'_{if} = \frac{k_f}{d'_B}(Re'_{fg})^{1/2}(Pr_f)^{-1.2}\left(\frac{\rho_g}{\rho_f}\right)^{0.41}, \tag{4}$$

where Re'_{fg} is defined as

$$Re'_{fg} = \frac{\rho_f J_g d'_B}{\mu_f}. \tag{5}$$

d'_B indicates the bubble diameter at PNVG (=constant × d_B) and J_g is the drift velocity of the bubbles. They are given by the following expressions:

$$d'_B = \left[\frac{\sigma}{(\rho_f - \rho_g)g + (3/4)(G^2/d_{in}\rho_f)}\right]^{1/2}, \tag{6}$$

$$J_g = 1.41\left[\frac{(\rho_f - \rho_g)g\sigma}{\rho_f^2}\right]^{1/4}. \tag{7}$$

Using Eq. (3), x_{PNVG} was calculated for each experimental CHF data point in the subcooled region for experiments with water and compared with x_c. This is shown in Fig. 5.

From Fig. 5, it is clear that for most of the data points where $x_c < x_{PNVG}$, a decreasing trend of CHF with increasing quality (or reduced subcooling) is seen. In such a region there is no appreciable increase of void fraction as the qualities are below that required to initiate net vapor generation. But for conditions where $x_c > x_{PNVG}$, most of the data shows an increasing trend of CHF with quality.

Thus, for critical qualities below the x_{PNVG}, one type of behavior (decreasing CHF with quality) is seen (Fig. 6, data points a1, b1, b2, c1 and d1) and for critical qualities higher than x_{PNVG} another type

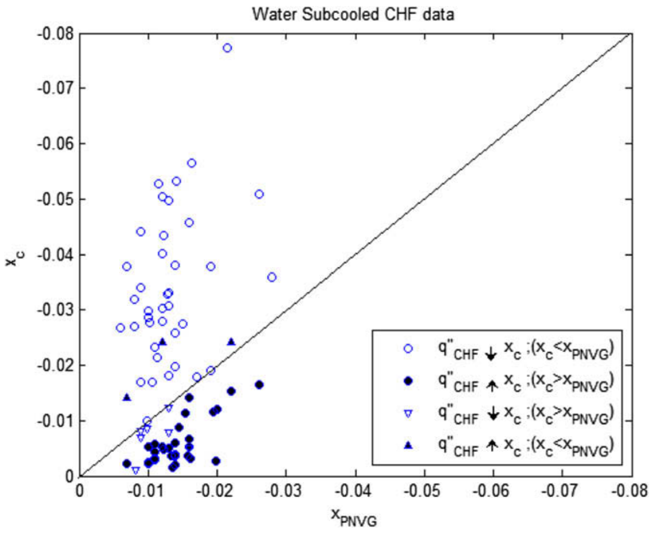

Fig. 5. x_c vs. x_{PNVG} (from Eq. (3)) for subcooled CHF water data.

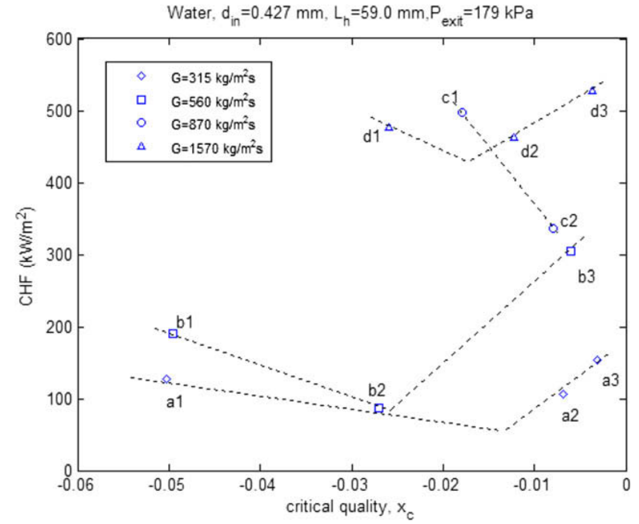

Fig. 6. CHF variation with quality for d_{in} = 0.427 mm in the subcooled region.

of behavior (increasing CHF with quality) is observed (Fig. 6, CHF points a2, a3, b3, d2 and d3). The CHF increases with quality due to an increase in velocity caused by increased void fractions beyond PNVG. Thus, it is likely that the net vapor generation point defines the transition in the subcooled region (from a decreasing trend of CHF with quality to an increasing trend) as discussed in Part I of the study.

The subcooled CHF data from the study by Nariai et al. [12] also showed an increasing trend of CHF as the qualities approached zero. However, the mass fluxes ranged from 7000 to 11,000 kg/m^2 s resulting in extremely high CHF values. Still, the x_{PNVG} corresponding to each CHF data point was calculated using Eq. (3) and since fluid temperatures were not known for any of the data points, an average value of temperature was assumed for property calculations. (Inlet water temperature was between 18 and 80 °C.) For all the CHF points, $x_c > x_{PNVG}$ even though some points showed a decreasing trend of CHF with quality. Thus, for higher mass fluxes, Eq. (3) seems to underpredict the quality at the PNVG. Similarly, for the data from Bergles et al. [14] for CHF in tube diameter of 2.38 mm at mass flux of about 3000 kg/m^2 s (CHF ranged from 9.4 to 14.5 MW/m^2) and exit pressure of 207 kPa, very low values of x_{PNVG} are predicted by Eq. (3). An average temperature of 70 °C (an estimated value considering ambient as 20 °C and T_{sat} = 121 °C) was used for the fluid property calculation as neither the inlet nor outlet fluid temperatures were known.

Thus, Eq. (3) is applicable to low mass fluxes, only as high as about 1500 kg/m^2 s. Below this mass flux, the quality at the PNVG seems to be predicted fairly well in the subcooled boiling regime as shown by Sun et al. [31] in their comparisons of the model with experimental boiling data (not CHF) at low mass fluxes for R-12 and water. The range of experimental data they took for comparison were: G (kg/m^2 s) = 150–1318, q'' (kW/m^2) = 132–1912 and P (MPa) = 0.117–13.8.

Nevertheless, a possible explanation for the trend reversal in CHF with quality observed in this experimental study is an increased void fraction of the flow.

5.2. Development of the correlation

The parametric effects on CHF condition have been previously discussed in details in Part I. A significant effect of the heated length to diameter ratio on CHF has been observed in the experimental studies. Hence, the CHF cannot be assumed as a local phenomenon (function of G, P and x_o or $\Delta T_{sub,o}$). Therefore, a correlation based on the inlet conditions has been developed. Here, four non-dimensional variables have been identified and are sufficient to predict the CHF condition. They are the Weber number (based on tube inside diameter, $We_d = G^2 d/\rho_f \sigma$), the density ratio ($\rho_f/\rho_g$), heated length-to-diameter ratio (L_h/d) and the enthalpy or inlet quality ($\Delta h_i/h_{fg} = (h_i - h_f)/h_{fg}$). The CHF is expressed as the Boiling number ($Bo = q''_{CHF}/Gh_{fg}$). Thus,

$$Bo = f\left(We_d, \frac{\rho_f}{\rho_g}, \frac{L_h}{d}, \frac{\Delta h_i}{h_{fg}}\right). \tag{8}$$

As discussed in the previous section, for most of the subcooled data, the CHF first decreases with increase in exit quality and beyond PNVG (qualities higher than that at PNVG for the given heat flux) the CHF has an increasing trend with quality. Those data points (41 in total) which show the decreasing trend for $x_c < x_{PNVG}$ have been used for developing the correlation (the points depicted by the first legend in Fig. 5).

The nature of the relationship of CHF with respect to each of the four variables specified in Eq. (8) was determined by varying one of the variables while keeping the others (approximately) constant and this process was repeated for all the four variables. This approach helped to determine a basic functional form for the relationship as described by Eq. (8). This functional form was then used in a non-linear regression program (DataFit [32] from Oakdale Engineering) to determine the final form of the correlation. Once the correlation was established, the behavior of predicted CHF with respect to these non-dimensional variables was analyzed and compared with the experimental data (described in the subsequent section).

The final form of the correlation after performing the non-linear regression is expressed as

$$Bo = \frac{C_1 \cdot We_d^{C_2} \cdot \left(\frac{\rho_f}{\rho_g}\right)^{C_3} \left(\frac{L_h}{d_{in}}\right)^{C_4} \left(\frac{\Delta h_i}{h_{fg}} + C_5\right)}{(We_d + C_6)\left(\frac{L_h}{d_{in}} + C_7\right)}. \tag{9}$$

The constants in the correlation are provided below in Table 1; Table 2 provides the non-dimensional parametric range used in establishing the correlation. The fluid properties are evaluated at the saturation temperature and exit pressure. The R^2 value from the regression analysis is 0.9311. The correlation was compared with all the subcooled CHF data from the present study. The mean error, mean absolute error and the root-mean square error are defined as

Table 1
Values of the constants in the proposed correlation (Eq. (9)).

C_1	44,587
C_2	1.136
C_3	−0.625
C_4	−1.680
C_5	−0.0157
C_6	−0.425
C_7	−279.8

Table 2
Non-dimensional parametric range for establishing the correlation.

Parameter	Range
Weber number, We_d	0.46–20.01
Density ratio, ρ_f/ρ_g	930–6022
Length-to-diameter ratio, L_h/d	75–200
Inlet subcooling/Enthalpy ratio, $\Delta h_i/h_{fg}$	−0.149 to −0.053

$$\text{mean error} = \frac{1}{\mathrm{N}} \sum \frac{Bo_{pred} - Bo_{expt}}{Bo_{expt}} \times 100\%, \tag{10}$$

$$\text{mean absolute error (MAE)} = \frac{1}{\mathrm{N}} \sum \frac{|Bo_{pred} - Bo_{expt}|}{Bo_{expt}} \times 100\% \tag{11}$$

and

$$\text{RMS error} = \sqrt{\frac{1}{\mathrm{N}} \sum \left(\frac{Bo_{pred} - Bo_{expt}}{Bo_{expt}}\right)^2} \times 100\%, \tag{12}$$

where N is the number of CHF data points.

The comparison of the predicted Boiling number (from the correlation in Eq. (9)) with the experimental boiling number for the subcooled CHF data is shown in Fig. 7. It can be seen that the correlation predicts the data reasonably well, with RMS error of 34.3%.

All the subcooled CHF data available in the literature are for very high mass fluxes and pressures such as [33–35] and, hence, cannot be compared with the new correlation. Bergles et al. [36] have CHF data at relatively lower mass fluxes of about 3000 kg/m^2 s, but the inlet conditions (temperature or enthalpy) are not provided and, hence, the data cannot be compared with the proposed correlation.

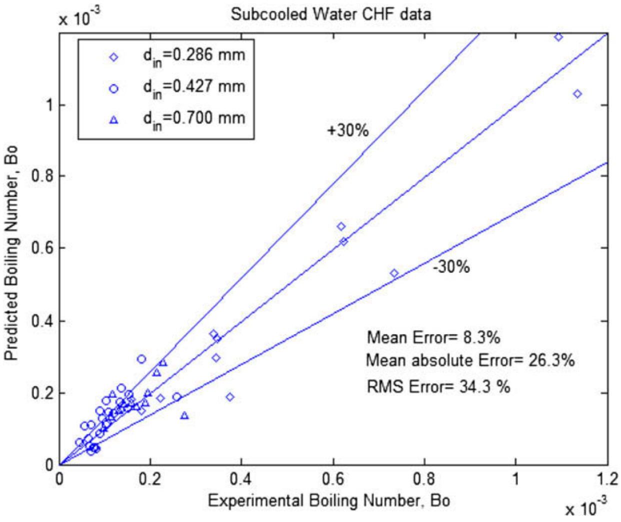

Fig. 7. Comparison of experimental data with the correlation from Eq. (9).

The behavior of CHF with each of the four parameters – We_d, ρ_f/ρ_g, L_h/d and $(\Delta h_i/h_{fg})$ – was analyzed (keeping other three parameters constant) using the proposed subcooled CHF correlation and compared with the trends obtained from the experimental data; details are given in Roday [26]. The proposed subcooled CHF correlation was able to predict the experimental data trends very well, and also depicted the same functional relationship of CHF with the four parameters as was observed from the experimental CHF data.

6. Conclusions and recommendations

In this study (Part I), new CHF data have been acquired in single microtubes and were analyzed for different parametric effects. Part II of this study compares the CHF data obtained with the existing correlations. It is seen from this study that:

- The saturated CHF for water data were not predicted well (either highly overpredicted or underpredicted) with existing microchannel correlations. Since most of the saturated CHF data in this study appear to be in the transition flow pattern zone as discussed in Part I of the paper (Section 4.3.2), it is not surprising that these data were not predicted well with the correlations.
- The subcooled CHF data for water were compared with the Hall and Mudawar correlation. This correlation underpredicted the data at low mass fluxes. Flow instabilities can be higher at low mass fluxes, and it is likely that the data from which the correlation was developed were influenced by flow instabilities. Also, the constants in the Hall and Mudawar correlation have been developed using data at very high mass fluxes and thus might not be suitable to predict CHF at low mass fluxes. Therefore, a new subcooled CHF correlation was developed to predict CHF values for qualities lower than that predicted at PNVG from the Sun et al. model. This correlation predicts the Boiling numbers of the present study with a RMS error of 34.3%.

Based on the understanding developed from the present studies (Part I and Part II), future work in this area should emphasize the following:

1. Experimental studies can be undertaken to obtain more data with different fluids and operating conditions to cover the entire range of qualities from the subcooled to the saturated region to get a clearer picture of CHF behavior with quality.
2. Such studies could aid in understanding the transition points of CHF with quality and attempts should be made to quantify them based on the operating conditions. One of the transition points in the data seems to be the PNVG but more studies should be done to confirm this hypothesis.
3. More CHF data in the subcooled region need to be obtained for fluids other than water and use them to validate the new correlation developed in this study.
4. The critical heat fluxes achieved in this experimental study are still less than the demands on heat fluxes to be removed from some of the current and future electronic devices. Research should be conducted with still smaller channel sizes and increased mass fluxes to meet the demands of the electronics industry.
5. In order to get a better understanding of flow patterns at the point of CHF, experiments could be performed in single micromachined channels using transparent cover which will aid in flow visualization and real-time flow images could be obtained. This will provide the information needed to further advance CHF research in microchannels.

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