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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

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

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