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Prediction of Critical Heat Flux (CHF) for Vertical Round Tubes with Uniform Heat Flux in Medium Pressure Regime

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Abstract−The description of critical heat flux (CHF) phenomena under medium pressure (10 bar≤P≤70.81 bar) regime is complex due to the large specific volume of vapor and the effect of buoyancy that are inherent in the conditions. In this study, a total of 2,562 data points of CHF in uniformly heated round vertical tube for water were collected from 5 different published sources. The data consisted of the following parameter ranges: 93.7≤G (mass flux)≤18,580 kg/m^{2}s, 0.00114≤D (diameter)≤0.03747 m, 0.008≤L (length)≤5 m, 0.26≤q_c (CHF)≤9.72 MW/m^2, and −0.21≤L (exit qualities)≤1.09. A comparative analysis is made on available correlations, and a new correlation is presented. The new CHF correlation is comprised of local variables, namely, "true" mass quality, mass flux, tube diameter, and two parameters as a function of pressure only. This study reveals that by incorporating "true" mass quality in a modified local condition hypothesis, the prediction of CHF under these conditions can be obtained quite accurately, overcoming the difficulties of flow instability and buoyancy effects. The new correlation predicts the CHF data are significantly better than those currently available correlations, with average error 2.5% and rms error 11.5% by the heat balance method.

Key words: CHF (Critical Heat Flux), Dryout, Burnout, Heat Transfer Equipment

INTRODUCTION

Critical Heat Flux (CHF), which is also known as burnout, dryout, and boiling crisis, represents a heat transfer phenomenon in which there is a sudden decrease in the value of the heat transfer coefficient, or abrupt increase in the surface temperature. CHF occurs when the heat flux of a heating surface increases or flow condition changes such that the generated vapor completely or partially blankets the heating surface inhibiting good heat transfer. Thus, accurate prediction of critical heat flux (CHF) has been recognized to be particularly important in design and safe operation of heat exchanger equipment as well as in nuclear power plants.

A typical boiling demand curve of uniform heat flux in forced flow boiling water is shown in Fig. 1. The CHF is illustrated as the point "c," which is the maximum point of heat flux on the plot of the heat flux versus the surface temperature. The maximum value is independent of the material of the heating surface, but dependent on the curvature of the heating surface. The regime, "a-b," is the single phase subcooled forced convection regime, and "b-c" is the nucleate boiling regime. The transition regime, "c-d," is a normally unobservable regime, reached only by carefully controlling surface temperature. As the wall temperature is raised beyond the point "c," unstable films of vapor form on the wall as well as large unstable bubbles. In "d" to "e" the regime is known as film boiling regime in which the surface temperature increases rapidly, whereas the heat flux increases insignificantly. Therefore, a stable layer of vapor film is formed over the entire heating surface, preventing sufficient heat transfer, which, in some cases, can cause serious physical damage to the surface.

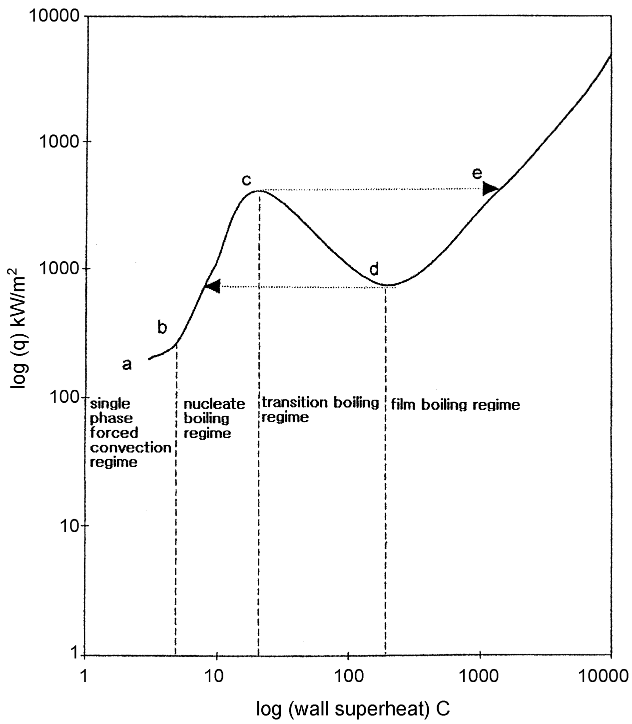

Fig. 1. Boiling curve of a heat flux controlled surface in forced flow boiling water.

Loss of coolant accidents (LOCA) of light water reactors, thermal safety performance analyses of power reactors or research reactors, and performance and safety evaluation of boilers are concerns of many researchers in recent years [Shim, 1997]. As Mishima and Nishihara [1987] pointed out, the prediction of CHF is complicated

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by the effect of buoyancy and flow instability. The flow becomes less stable due to the large specific volume of vapor at low pressure and the effect of buoyancy becomes significant at low flow conditions.

In the past, under various flow conditions, numerous studies on CHF for flow boiling of water in round tube have generated thousands of data, which lead to hundreds of empirical correlations with limited successes. These correlations used local condition hypothesis, non-local condition hypothesis, or mixed local and non-local hypothesis, and others divided the heat transfer regions into subcooled and quality boiling regions. Despite these numerous efforts on understanding the CHF mechanism, however, a complete understanding of the nature of the CHF phenomenon has not yet been reached.

EXPERIMENTAL CHF DATA

For this study, a total of 2,562 data points of CHF in uniformly heated round vertical tube for water were collected from 5 different published sources. Experimental data used here are those presented by Thompson and Macbeth [1964], Becker et al. [1971], Becker [1965], Casterline and Matzner [1964], and Griffel [1965]. The data used in the present analysis are pre-screen data via heat balance methods, within 5% error, and they are comprised of 1199 data from Thompson and Macbeth [1964], 272 data from Becker et al. [1971], 756 data from Becker [1964], 19 data from Casterline and Matzner [1964], and 316 data from Griffel [1965]. The ranges of the collected experimental data are $10 \le P$ (pressure)≤ 70.81 bar, $0.00114 \le D$ (diameter)≤ 0.03747 m, $0.008 \le L$ (length)≤ 5 m, $93.7 \le G$ (mass flux) $\le 18{,}580$ kg/m^{2}s, $0.26 \le q_c$ (CHF)≤ 9.72 MW/m^2 and $-0.21 \le X$ (exit quality)≤ 1.09, respectively. The ranges of operating conditions for the data are summarized in Table 1.

CHF CORRELATIONS

Among hundreds of correlations available, few representative correlations are chosen for the comparative analysis reported here. The correlations considered in the present analysis are Biasi et al. [1967], Katto and Ohno [1984], Shah [1987] and Jafri et al. [1995]. With exception of the Katto and Ohno model, these correlations are essentially mixed local and non-local condition correlations. The predictions by the correlations are mostly within the experimental data range used for this study. The purpose of this analysis is to check the validity of existing correlations.

Biasi et al. derived their correlation by using a local condition hypothesis. The model is essentially composed of two equations, one for the low quality and another for the high quality region. The data used for the correlation development cover the following ranges of parameters: $2.7 \le P \le 140$ bar, $100 \le G \le 6{,}000$ kg/m^{2}s, $0.2 \le L \le 6$ m, and $0.0003 \le D \le 0.0375$ m. Based on diameter size, the correlation can use one of two distinct values to include the diameter effect.

Katto and Ohno proposed a revised generalized correlation applicable for a range of fluids. The correlation is a non-local correlation that consists of 4 equations. The effect of inlet subcooling on the CHF is included in the correlation. The correlation requires an inlet subcooling enthalpy, a latent heat of vaporaization, and an inlet subcooling parameter. In the application of the correlation, CHF is divided into 2 regimes, which is determined by the values of vapor and liquid density ratios.

The Shah correlation consists of two correlations: one for the upstream condition correlation (UCC) and another for the local condition correlation (LCC). The 2,562 CHF data points used in this work can be predicted by the LCC. The data used includes the following: tube diameter range is from 0.315 to 37.5 mm; the tube length to diameter ratio range is from 1.3 to 940; mass velocity range is from 4 to 29,051 kg/m^{2}s; reduced pressure range is from 0.0014 to 0.96; inlet quality varies from –4 to 0.85; and critical quality range is from −2.6 to 1.

Jafri et al. suggested a new approach to correlate CHF with the 'true' mass vapor flux at CHF. They compiled and used approximately 10,000 CHF data points in developing the correlation. Their study resulted in the separation of CHF data into two regions, namely, a local region with high CHF regimes, and a non-local region with low CHF regimes. For pressure between 35 bar and 110 bar, CHF was determined by a local correlation, and for pressure less than 35 bar, a non-local correlation was proposed. Above 110 bar, the correlation is less satisfactory. The ranges of the data used to develop their correlation are: $2.0 \le P \le 196$ bar, $0.001 \le D \le 0.0375$ m, $0.15 \le L \le 5$ m, $250 \le G \le 7{,}500$ kg/m^{2}s, and $-0.80 \le X$ (exit quality)≤ 1.00, respectively.

Table 1. Ranges of experimental data used for present calculation

	Data points		P (bar)	D (m)	L (m)	G (kg/m^{2}s)	q_c (MW/m^2)	X_e
Thompson & Macbeth	1199	min	17.24	0.00114	0.08	93.72	0.90	−0.21
		max	70.81	0.03747	3.66	18,580.35	9.72	1.01
Becker et al.	272	min	30.00	0.01	2.00	180.00	0.26	0.00
		max	70.00	0.01	5.00	8,111.00	4.70	1.09
Becker	756	min	10.00	0.00607	0.60	118.30	0.74	0.29
		max	41.19	0.0201	3.75	2,075.40	3.88	0.91
Casterline & Matzner	19	min	68.95	0.01016	4.88	1,193.46	0.69	0.02
		max	68.95	0.01016	4.88	10,293.56	3.40	0.65
Griffel	316	min	68.97	0.03747	1.97	18,577.20	8.11	0.59
		max	68.97	0.03747	1.97	18,577.20	8.11	0.59
Total	2562	min	10.00	0.00114	0.08	93.72	0.26	−0.21
		max	70.81	0.03747	5.00	18,580.35	9.72	1.09

Table 2. Calculated error of correlation

	Data source	Data points	Correlation				
			Biasi	Katto	Shah	Jafri	New
Mean error (%)	Thompson & Macbeth	1199	−0.023	0.043	0.675	0.478	−0.033
	Becker et al.	272	−0.090	−0.109	−0.012	0.572	−0.050
	Becker	756	0.407	−0.617	−0.047	0.670	−0.029
	Casterine & Matzner	19	0.168	−0.287	−0.072	0.322	−0.104
	Griffel	316	−0.086	−0.104	0.071	0.339	0.042
	Total	2562	0.091	−0.188	0.133	0.515	−0.025
Rms error (%)	Thompson & Macbeth	1199	0.469	0.318	0.249	0.557	0.134
	Becker et al.	272	0.733	0.136	0.149	0.678	0.101
	Becker	756	0.619	0.626	0.121	0.744	0.091
	Casterine & Matzner	19	0.325	0.304	0.154	0.403	0.118
	Griffel	316	0.236	0.168	0.231	0.384	0.099
	Total	2562	0.530	0.411	0.206	0.600	0.115

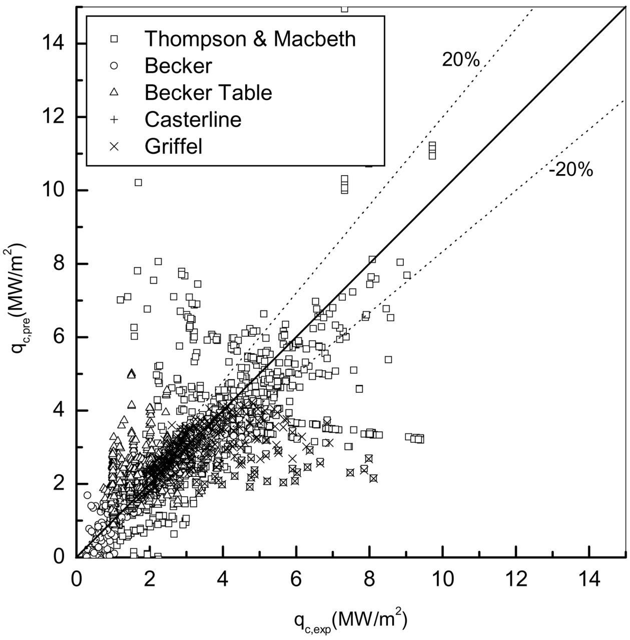

Fig. 2. Calculated vs. experimental CHF of Biasi correlation.

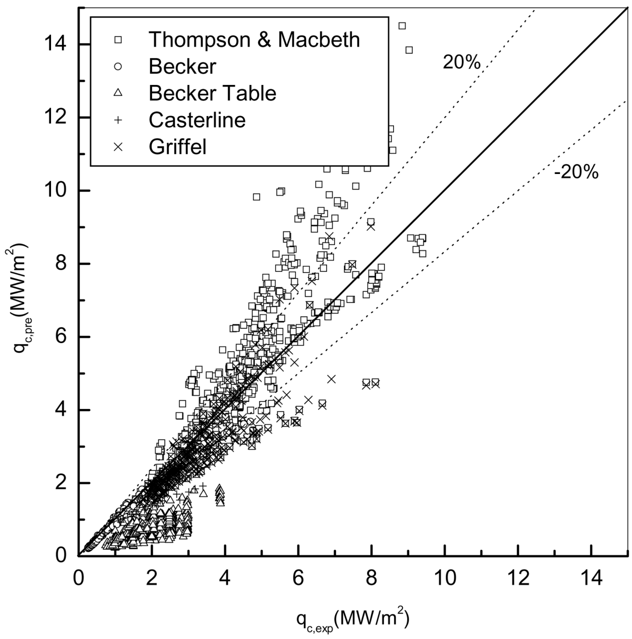

Fig. 3. Calculated vs. experimental CHF of Katto et al. correlation.

The results from a comparison of CHF predictions from the correlations mentioned are presented in Table 2 in terms of the calculated average and rms error based on the experimental data points used in this study. Table 2 shows that the accuracy of the representative correlations deteriorates significantly. A graphic representation of the results of the comparison is presented in Figs. 2-5.

A NEW LOCAL CORRELATION

It is revealed that the accuracy of the representative correlations deteriorates remarkably when predicted values of the correlations are compared to the medium pressure data. This result of deteriorating results is due to insufficient understanding of the effect of 'true' mass flux of vapor and pressure in relation to CHF.

It is assumed that the mass velocity is sufficiently high that the fluid inlet is thermally well equilibrated and effect of gravity is neglected, and the flow is assumed to be stable with no significant oscillations. The effect of the pressure variation along the tube is neglected, and the calculation is performed with the assumption that the pressure at each point equals the system pressure at the tube exit.

Under a given constant pressure and the quality at OSV (Onset of Significant Vaporization), CHF is a continuous function of local variables, namely, diameter (D), pressure (P), mass flux (G), and the true steam quality (X_t). For a vertical round tube, CHF is an exponentially decreasing function of true mass flux of vapor GX_t at the tube exit, which includes slip effect. The importance of these results is that CHF, in all flow patterns and boiling regime, is predicted sufficiently only by local condition at which CHF occurs.

For a given uniformly heated tube, using the mass and energy balance around the tube, a true steam quality (Xt) can be obtained in terms of the thermodynamic quality and the quality at OSV [Jafri,

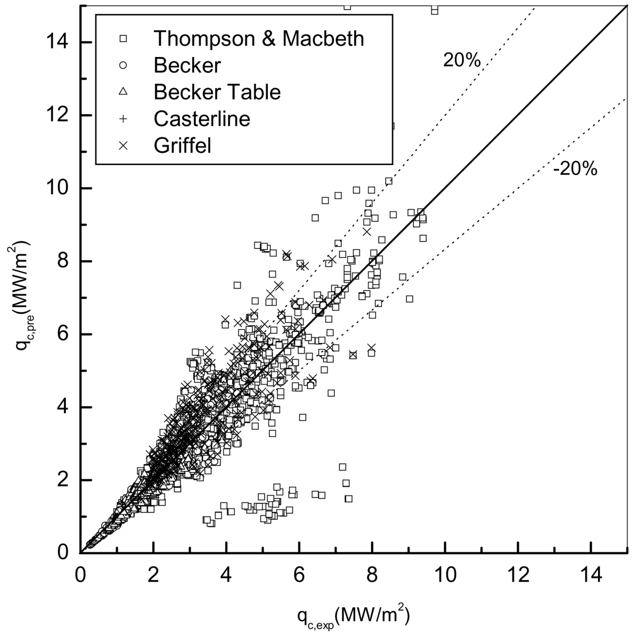

Fig. 4. Calculated vs. experimental CHF of Shah et al. correlation.

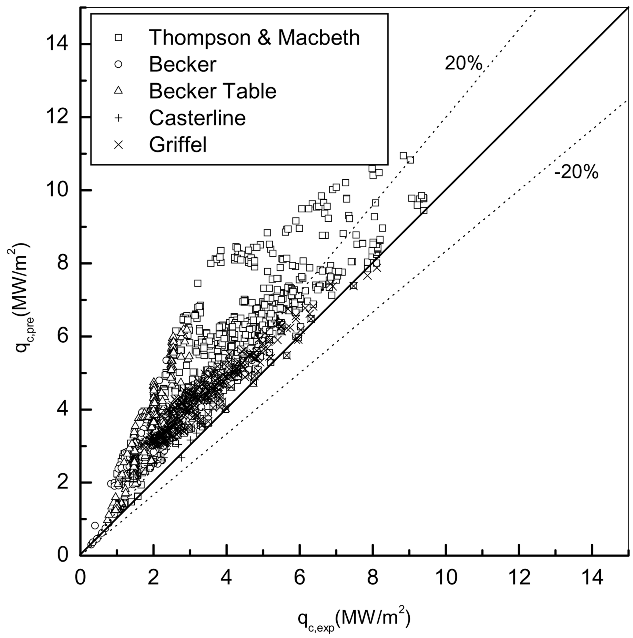

Fig. 5. Calculated vs. experimental CHF of Jafri correlation.

1993].

$$\frac{dX_t}{dX}=1+\frac{X_t-X}{X_{osv}(1-X_t)} \tag{1}$$

where,

$$X_t=\begin{cases}0 & \text{at } X=X_{osv} \quad \text{if } X_i<X_{osv}\\ 0 & \text{at } X=X_i \quad \text{if } X_{osv}<X_i<0\\ X & X_i>0\end{cases} \tag{2}$$

Integrating Eq. (1), it can be shown to be,

$$X_{osv}\ln\frac{X-X_i}{X_b}+\ln\frac{1-X+X_{osv}-X_{osv}X_t}{1-X_b+X_{osv}}=0 \tag{3}$$

where,

$$X_b=\max(X_{osv}, X_i) \tag{3a}$$

Thermodynamic quality (X) is obtained from the heat balance as,

$$X=X_i+\frac{4qL}{h_{fg}GD} \tag{4}$$

X_{osv} is obtained from the Saha-Zuber correlation [Saha and Zuber, 1974].

$$X_{osv}=-\frac{q}{SGh_{fg}} \tag{5}$$

where,

$$S=\begin{cases}0.0065 & \text{if } Pe\geq 70000\\ 455/(Pe) & \text{if } Pe<70000\end{cases} \tag{5a}$$

$$Pe=\frac{GDC_{pf}}{k_f} \tag{5b}$$

The data fall into two distinct regimes on St (Stanton number) vs. Pe (Peclet number) plot; vapor generation is either hydro-dynamically controlled (Pe≥70000) or thermally controlled (Pe<70000).

The prediction of CHF is carried out by HBM (Heat Balance condition Method). At each constant pressure, the prediction is made by initiating X_t with Eq. (2), calculating q_c from the correlation (6), then X_{osv} from Eq. (5), and X from heat balance by Eq. (4). Once X_{osv}, X are known, a new X_t can be calculated by Eq. (1) or (3). Then, by replacing the initial value of X_t with the updated X_t, the iteration continues until X_t value converges between iterations (% error< 10^{-5}). During the calculation, it is assumed that CHF always occurs at the tube exit and the calculation is performed with the assumption that the pressure at each point is equal to the exit pressure.

The results of systematic investigation on the effect of major variables on CHF showed that the 'true' mass flux of vapor at the tube exit (GX_t) is the most significant correlating parameter and the accuracy of prediction is improved by use of correction factors, α and γ as a function of pressure. The resulting expression of the new local correlation is

$$q_c=\frac{\alpha}{\sqrt{D}}\exp[-\gamma\sqrt{GX_t}(\cosh(X_t)^2)] \tag{6}$$

where,

$$\alpha=0.334+7.681\left(\frac{P}{P_c}\right)-12.42\left(\frac{P}{P_c}\right)^2 \tag{6a}$$

$$\gamma=0.06155-0.00664\left(\frac{P}{P_c}\right)+0.13512\left(\frac{P}{P_c}\right)^2 \tag{6b}$$

The parameters of α and γ are functions of reduced pressure.

The average and rms errors are given in Table 2 and a graphic representation is given in Fig. 6. Table 2 shows the possibility that CHF under the medium pressure and flow conditions can be predicted reasonably well if accurate local conditions and two parameters of function of pressure can be obtained.

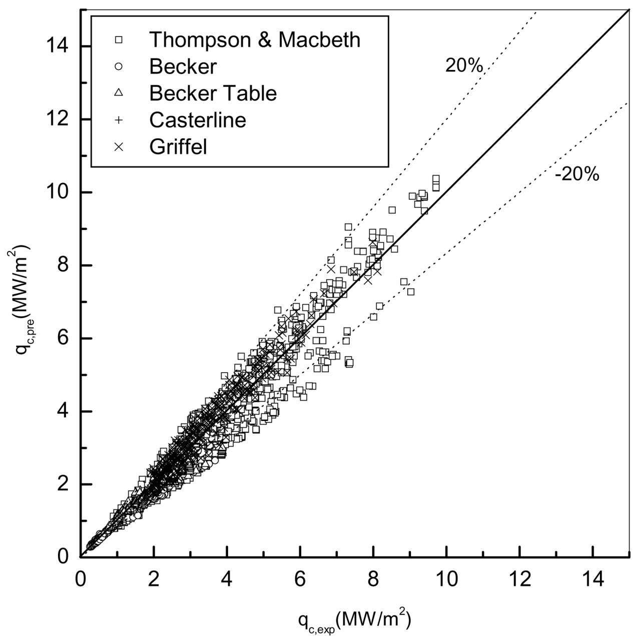

Fig. 6. Calculated vs. experimental CHF of a new local correlation.

RESULTS AND DISCUSSION

Most of the authors treated the experimental data as local or non-local, or both in the medium pressure and flow condition. A conclusion from this investigation has further confirmed that CHF depends only on local conditions. With the aim of establishing the validity of using the local condition hypothesis for the prediction of CHF at wide medium pressure and flow conditions, a total of 2,562 CHF data points were used in this analysis, from 5 different sources, of the ranges in 10≤P≤70.81 bar; 0.00114≤D≤0.03747 m; 0.008≤L ≤5 m; 93.7≤G≤18,580 kg/m^{2}s; 0≤ΔH_i≤653.6 kJ/kg; 0.26≤ q_c≤9.72 MW/m^2, and −0.21≤L (exit qualities)≤1.09.

Average and rms errors have been calculated for a new local correlation and 4 other correlations [Biasi et al., 1967; Katto and Ohno, 1984; Shah, 1987; Jafri et al., 1993]. A comparison of the predictions of each correlation with experimental data has been shown. Among the correlations, the Shah and the new local correlations show good agreement with experimental data. This study shows which CHF is accurately predicted by local correlation under medium pressure and flow conditions. Generally, it has been reported that the local condition hypothesis is not valid for short tubes such as L/D<80. This study, however, reiterates the earlier findings of Shim and Joo [2000] that it is possible to apply a local condition correlation to CHF conditions. In fact, accurate description of local conditions at the CHF seems to be very effective in simplifying the treatment of complexity of flow instabilities that is inherent in the medium and the low pressure conditions. From the result of this study, as shown in Fig. 6, we conclude that CHF decrease exponentially with “true mass flux” of vapor and CHF depends only on the local conditions, namely, P, G, D, and X_i.

The thermodynamic (equilibrium) quality, X, is generally inadequate to describe the actual physical condition at a given point in the tube if the fluid is at subcooled conditions. In this study, it is assumed that CHF is a function of the actual physical conditions existing at the point of CHF and the values of the local variables G, X_t, and P at the local point of CHF. As shown in Eq. (2), the value of X_t, however, depends on the inlet conditions when the inlet quality exceeds the OSV value. Thus, when X is used as a variable the correlation will show a dependence on L/D or, equivalently, the inlet quality X_i. This is a very important point because, in general, there is no obvious way to generalize a non-local correlation to other conditions, such as non-uniform power profiles. For the local correlation, however, there is no freedom of choice and the generalization to non-uniform profiles is immediate and unique.

In a uniform tube, CHF always occurs at the exit, but in calculating the value of X_t at the exit, it has been assumed that the pressure at any point from OSV to the exit is approximately equal to the exit pressure. In this way, flow and heat transfer has been simplified and effectively de-coupled. In most cases, the resulting error is small but it should be noted this may not be always true. Additional investigation is necessary to extend the current work to the high pressure conditions. We hope that our work can be used to develop a generalized CHF model in the near future.

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NOMENCLATURE

L : heated length [m]
D : tube diameter [m]
P : system pressure [bar]
G : mass velocity [kg/m^{2}s]
ΔH_i : inlet subcooling [kJ/kg]
ΔT_i : inlet subcooling [K]
q_c : critical heat flux [MW/m^2]
h_{fg} : latent heat of vaporization [kJ/kg]
X_i : inlet quality
X : thermodynamic quality
X_{osv} : thermodynamic quality at onset of significant vaporization (OSV)
X_t : true steam quality
S : Stanton number
Pe : Peclet number
P_c : critical pressure of water [221 bar]
α : parameter which depends on pressure [MW/m$^{1.5}$]
γ : parameter which depends on pressure [(kg/m^{2}s)$^{-1/2}$]

Subscripts

f : saturated liquid
g : saturated vapor

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