한국해양공학회지 제22권 제1호, pp 13-21, 2008년 2월 (ISSN 1225-0767)

A Method for Critical Heat Flux Prediction in Vertical Round Tubes with Axially Non-uniform Heat Flux Profile

JAE-WOO SHIM
Department of Chemical Engineering, Dankook University, Yongin-si, Gyeonggi-do Korea

KEY WORDS: Critical heat flux, Burnout, Cosine heat flux, Non-uniform heat flux, Boiling crisis, Boiling heat transfer.

ABSTRACT: *In this study a method to predict CHF (Critical heat flux) in vertical round tubes with axially non-uniform cosine heat flux distribution for water was examined. For this purpose a local condition hypothesis based CHF prediction correlation for uniform heat flux in vertical round tubes for water was developed from 9,366 CHF data points. The local correlation consisted of 4 local condition variables: the system pressure (P), tube diameter (D), mass flux of water (G), and 'true mass quality' of vapor (X_t). The CHF data points used were collected from 13 different published sources having the following operation ranges: 1.01 $\leq$ P (pressure) $\leq$ 206.79 bar, 9.92 $\leq$ G (mass flux) $\leq$ 18,619.39 kg/m^{2}s, 0.00102 $\leq$ D (diameter) $\leq$ 0.04468 m, 0.0254 $\leq$ L (length) $\leq$ 4.966 m, 0.11 $\leq$ qc (CHF) $\leq$ 21.41 MW/m^2, and -0.87 $\leq$ X_c (exit qualities) $\leq$ 1.58. The result of this work showed that a uniform CHF correlation can be easily extended to predict CHF in axially non-uniform heat flux heater. In addition, the location of the CHF in axially non-uniform tube can also be determined. The local uniform correlation predicted CHF in tubes with axially cosine heat flux profile within the root mean square error of 12.42% and average error of 1.06% for 297 CHF data points collected from 5 different published sources.*

1. Introduction

The process of forced convective subcooled or saturated boiling is generally used to remove large amount of heat from the heated surface of heat transfer equipments, for example, a water-cooled nuclear reactor or a high load heat exchanger. The boiling heat transfer shows excellent heat removal efficiency compared to other methods. However, heat transfer limits exist in such a process, and they are called Critical heat flux (CHF), dryout, burnout or boiling crisis. At the point where CHF occurs, the boiling heat transfer coefficient between the heated surface and the fluid decreases drastically. Therefore, in the surface heat flux controlled system, CHF causes the temperature of the heated surface to increase substantially whereas in the surface temperature controlled system, CHF causes the heat flux to decrease significantly.

Understanding CHF phenomenon in uniformly heated vertical tubes is becoming more important as it can be used as a fundamental basis to predict CHF accurately in other complex situations that involves different fluids and geometries. CHF in tubes with axially non-uniform, commonly, cosine heat flux profile, can be found in many of the industrial heat transfer equipments. Thus accurate prediction of CHF is the utmost importance in optimal design and safe operation of highly efficient heat transfer facilities.

There are 3 representative methods to predict CHF in non-uniformly heated vertical tubes: 1) local condition hypothesis, 2) overall power hypothesis and 3) F-factor method.

Local condition hypothesis neglects the effects of the upstream condition, or the effect of length of heated tube and therefore, the correlation developed from the uniform CHF condition can be readily applied to the non-uniformly heated tubes if the heat flux profile can be formulated mathematically and incorporated into the prediction method. It is now well known fact that in the uniform heat flux CHF always occurs at the exit of tube. In non-uniform heat flux, unlike the uniform heat flux, CHF does not occur at the exit of tube; rather CHF occurs closer to the center of tube, away from the exit, depending on the degree of non-uniformity and heat flux distribution function of tube. Therefore, the local correlation method is particularly desired because it provides not only the prediction value of CHF but also with its location where CHF will occur.

In the overall power hypothesis, once the tube geometry and the inlet condition are set, total power that causes CHF condition is assumed to be constant independent of the heat flux profile. Thus the CHF prediction is based on non-local condition hypothesis. In this case a uniform CHF correlation can also be applied to non-uniform CHF, however, the position where CHF occurs cannot be predicted by this method, and furthermore,

교신저자 심재우: 경기도 용인시 수지구 죽전동 산44-1.
031-8005-3538 wjshim@dankook.ac.kr

there are questions to the accuracy of CHF prediction.

In F-factor method, heat flux distribution in the upstream is considered together with the local condition. This means that CHF can be influenced by not only local condition but also upstream heat flux distribution. Problem with this method is that it is purely empirical: it cannot predict the location of CHF occurrence, and there are difficulties of extending this method to more complex situations.

2. Experimental Data

For this study, a total of 9,366 data for water flow in uniformly heated vertical round tubes was collected from 13 published sources, namely, Thompson and Macbeth (1964), Becker et al. (1971), Lee and Obertelli (1963), Becker (1965), Kim et al. (2000), Mishima (1984), Lowdermilk et al. (1958), Casterline and Matzner (1964), Griffel (1965), Swenson et al. (1963), Cheh et al. (1992), Bertoletti et al. (1963) and Lee (1965). For the non-uniform data, a total of 305 CHF data for water in vertical round tubes with axially cosine heat flux profile was collected from 5 published sources: Lee (1965; 1966), Bertoletti et al. (1963), Casterline (1965), and Swenson et al. (1963).

The experimental range of uniform CHF data used for present analysis was as follows: 1.01 $\leq$ P (pressure) $\leq$ 206.79 bar, 0.00102 $\leq$ D (diameter) $\leq$ 0.04468 m, 0.025 $\leq$ L (length) $\leq$ 4.966 m, 9.92 $\leq$ G (mass flux) $\leq$ 18,619.39 kg/m^{2}s, -609.33 $\leq$ Inlet subcooling $\leq$ 1,655.34 kJ/kg, 0.11 $\leq$ q_c (CHF) $\leq$ 21.41 MW/m^2, and -0.87 $\leq$ X_c (exit quality) $\leq$ 1.58. For the non-uniform CHF data, the operational ranges were: 68.98 $\leq$ P (pressure) $\leq$ 137.9 bar, 0.0081 $\leq$ D (diameter) $\leq$ 0.0159 m, 0.64 $\leq$ L (length) $\leq$ 4.88 m, 542 $\leq$ G (mass flux) $\leq$ 9,710

Table 1 Ranges of uniformly heated vertical round tube CHF data used for present analysis

Data source	Data points		P (bar)	D (m)	L (m)	G (kg/m^{2}s)	Inlet subcooling (kJ/kg)	q_c (MW/m^2)	X_c
Thompson & Macbeth (1964)	3879	min	1.03	0.0010	0.03	9.92	0.00	0.11	-0.85
		max	206.79	0.0375	3.66	18,619.39	1,655.34	21.41	1.58
Becker et al. (1971)	1550	min	30.00	0.0100	1.00	156.00	26.80	0.14	-0.87
		max	200.00	0.0100	4.97	8,111.00	1,414.90	5.48	1.09
Lee & Obertelli (1963)	391	min	82.39	0.0141	0.64	332.28	60.46	0.87	-0.11
		max	125.83	0.0447	1.52	3,410.92	451.14	3.74	0.73
Becker (1965)	1974	min	2.16	0.0039	0.60	111.30	194.18	0.50	0.00
		max	99.04	0.0250	3.75	5,450.50	1,071.98	19.16	0.99
Kim et al. (2000)	511	min	1.04	0.0060	0.30	19.50	46.00	0.12	0.40
		max	9.51	0.0120	1.77	276.70	653.60	1.60	1.25
Mishima (1984)	53	min	1.01	0.0060	0.34	13.00	84.00	0.12	0.36
		max	1.01	0.0060	0.34	296.00	293.00	1.49	1.17
Lowdermilk et al. (1958)	95	min	1.01	0.0013	0.07	27.10	312.00	0.19	0.35
		max	1.01	0.0048	0.99	298.40	331.00	4.01	1.40
Casterline & Matzner (1964)	8	min	68.95	0.0102	4.88	2,644.63	48.41	1.15	0.23
		max	68.95	0.0102	4.88	9,290.13	338.14	2.50	0.34
Griffel (1965)	402	min	34.48	0.0062	0.61	637.32	51.46	1.40	-0.19
		max	103.45	0.0375	1.97	18,577.20	1,105.43	8.11	0.59
Swenson et al. (1963)	25	min	137.89	0.0104	1.75	678.11	40.93	0.59	0.19
		max	137.89	0.0105	1.80	1,763.09	566.08	1.06	0.53
Cheh et al. (1992)	21	min	3.59	0.0158	2.44	1,475.67	223.20	1.79	0.14
		max	10.53	0.0158	2.44	7,859.55	666.90	5.61	0.50
Bertoletti et al. (1963)	27	min	69.58	0.0081	0.65	1,496.60	-609.33	0.91	0.09
		max	70.14	0.0081	0.65	3,929.10	131.54	3.10	0.53
Lee (1965)	430	min	82.39	0.0141	0.64	332.28	60.46	0.87	-0.11
		max	125.83	0.0447	1.52	3,410.92	451.13	3.74	0.64
Total	9366	min	1.01	0.0010	0.03	9.92	-609.33	0.11	-0.87
		max	206.79	0.0447	4.97	18,619.39	1,655.34	21.41	1.58

kg/m^{2}s, -1,209.00 $\leq$ Inlet subcooling $\leq$ 612.53 kJ/kg, 0.14 $\leq$ q_c (CHF) $\leq$ 3.33 MW/m^2, and -0.03 $\leq$ X_c (exit quality) $\leq$ 0.83. These data are presented detail in Table 1 and 2, the uniform CHF data and the non-uniform CHF data, respectively. Table 2 shows the form factor and chop factor: they represent the ratio of maximum heat flux to average heat flux and heat flux distribution function of tube, respectively. The chopped cosine is used to simulate a reasonably symmetrical flux distribution with central peak. The test sections were made from thick walled tubes with the outside wall being machined into a cosine shape. The CHF data was collected by raising the power while holding inlet conditions constant.

All the data points were validated by heat balance method, within 5% errors; otherwise the data was discarded. The inconsistent data that are indicated in Thompson and Macbeth (1964) tables were excluded from the database, and after the validation, 3879 data points were used. There were reports of flow instability for some of tests of Bertoletti et al., in which 8 out of 48 data points were eliminated.

3. Modified OSV

Saha and Zuber (1974) calculated the equilibrium quality related to the heat flux at the onset of significant vaporization (OSV) using the concept of the point of net vapor generation, and they proposed an empirical correlation and simple criteria to determine the point for various fluids and channels. At low mass flow rates, the point of net vapor generation is determined by thermal conditions, whereas at high mass flow rates it is hydrodynamically controlled. Saha-Zuber's correlation is composed of two dimensionless numbers, Stanton number at OSV (S_{tOSV}) and Peclet number (P_e). The quality at OSV can be calculated as shown in Eq. (1).

$$X_{osv} = -\frac{q}{S_{tOSV} G \lambda} \tag{1}$$

where, q, S_{tOSV}, G , and λ, are heat flux (MW/m^2), Stanton number at OSV, mass flux of water (kg/m^{2}s), and heat of vaporization (kJ/kg), respectively.

At high mass flux regime, or more specifically at high Peclet number (P_e), many data indicated that CHF occurred prior to OSV, contradicting fundamental concept of convective boiling heat transfer. However when, S_{tOSV} in Eq. (1) was modified as shown in Eq. (2)~Eq. (4), only 4 data points were determined to be inapt for further analysis and they were discarded from the database.

$$S_{tOSV} = 455/Pe \quad \text{For } P_e \leq 70{,}000 \tag{2}$$

$$S_{tOSV} = 0.0065 \quad \text{For } 70{,}000 < P_e \leq 200{,}000 \tag{3}$$

and

Table 2 Experimental CHF data of axially non-uniform, cosine heat flux profile, vertical round tube from literature

Data source	Data		P (bar)	D (m)	L (m)	G (kg/m²s)	Inlet subcooling (kJ/kg)	q_c (MW/m²)	X_c	Form factor	Chop factor
Lee (1965)	40	min	65.90	0.0095	3.660	2,007	37.92	0.96	0.17	1.405	0.878
		max	70.67	0.0095	3.660	4,095	538.31	2.10	0.46		
Bertoletti et al. (1963)	40	min	70.09	0.0081	0.643	1,090	-1209.00	0.14	0.01	1.200	0.710
		max	70.09	0.0081	0.643	3,915	264.87	3.33	0.83		
Casterline (1965)	35	min	68.94	0.0102	4.877	1,396	56.92	0.77	0.10	1.571	1.000
		max	68.94	0.0102	4.877	9,710	612.53	2.76	0.62		
Swenson et al. (1963)	7	min	137.90	0.0106	1.829	678	40.49	0.58	0.19	1.230	0.819
		max	137.90	0.0106	1.829	1,763	176.96	1.05	0.50		
Lee (1966)	122	min	86.18	0.0159	1.000	542	88.39	1.31	-0.03	1.270	0.744
		max	125.13	0.0159	1.000	3,398	468.28	2.91	0.39		
Lee (1966)	53	min	86.18	0.0158	1.000	1,624	92.12	1.57	-0.02	1.170	0.608
		max	124.10	0.0158	1.000	2,735	399.19	2.99	0.16		
Total	297	min	68.98	0.0081	0.643	542	-1209.00	0.14	-0.03	1.170	0.608
		max	137.90	0.0159	4.877	9,710	612.53	3.33	0.83	1.571	1.000

$$S_{tOSV}= 0.08923\exp\left[-\frac{\frac{P_e\cdot(k^{0.45})}{D^{0.53}\cdot G^{0.37}}}{25313.63287}\right] + 0.00659\exp\left[-\frac{\frac{P_e\cdot(k^{0.45})}{D^{0.53}\cdot G^{0.37}}}{211422.70151}\right]+0.00146 \quad (4)$$

For $P_e > 200{,}000$

Peclet number is defined in Eq. (5), and C_{pf} and K_f represent specific heat (kJ/kg · K) and thermal conductivity (W/m · K) of fluid, respectively.

$$P_e = \frac{G\,D\,C_{pf}}{k_f} \quad (5)$$

4.Local Condition Hypothesis

Unlike non-local condition hypothesis, a correlation based on local condition hypothesis is determined only by the local variables at the local location of CHF: the system pressure (P), tube diameter (D), mass flux of water (G), and 'true mass quality' of steam (X_t). It should noted here, that instead of the usual thermodynamic equilibrium quality, X_t used here is defined as the ratio of the 'true' mass flow rate of steam to the total mass flow rate of the steam-water mixture. Because the 'true mass quality' of steam can describe the true behavior of steam generated in the heated tube, this is much more meaningful than the thermodynamic equilibrium quality that can result in a negative number which has no physical significance. For a given pressure, subcooled boiling of water in vertical round uniformly heated tubes, Jafri et al. (1996), Deng et al. (1997) and Deng (1998) have that the estimate of 'true mass quality', X_t, can be obtained from the thermodynamic equilibrium quality (X) and the quality at OSV from the following rate equation:

$$\frac{dX_t}{dX} = 1+\frac{X_t - X}{X_{OSV}(1-X_t)} \quad (6)$$

where,

$$X_t = \begin{Bmatrix} 0 \ at\, X = X_{OSV} & \text{if } X_i < X_{OSV} \\ 0 \ at\, X = X_i & \text{if } X_{OSV} < X_i < 0 \\ X_i \ at\, X = X_i & \text{if } X_i > 0 \end{Bmatrix} \quad (7)$$

Here X_i represents the inlet equilibrium quality of water. Integrating Eq. (6) by using Eq. (7) as the boundary conditions, it can be shown to be,

$$X_{OSV}\ln\frac{X - X_t}{X_b} + \ln\frac{1 - X + X_{OSV} - X_{OSV}X_t}{1 - X_b + X_{OSV}} = 0 \quad (8)$$

where,

$$X_b = \max(X_{osv}, X_i) \quad (9)$$

The equilibrium quality is obtained from the energy balance as,

$$X = X_i + \frac{4q_cL}{\lambda GD} \quad (10)$$

where q_c represents CHF value. The results of a systematic investigation of CHF by Deng (1997) and Shim and Joo (2002) showed that true mass flux of vapor at the tube exit (GX_t) and the diameter of the tube (D) are the most significant parameters. There was a general trend in exponential decline of $q_c\sqrt{D}$ with increasing $\sqrt{GX_t}F(X_t)$, and this general form was the basis for data analysis in developing the correlation. With optimized values of correlation factors, α and γ, which are a function of reduced pressure (P/P_c), and exponent parameters k_1 and k_2, a local correlation for uniform heat flux was developed as follows:

$$q_c = \frac{\alpha}{D^{k1}}exp\left[-\gamma\left(G^{0.55}\sqrt{X_t(1+X_t^2)^3}\right)^{k2}\right] \quad (11)$$

$$\alpha = 0.7 + 4.6\left(\frac{P}{P_c}\right) - 5.32\left(\frac{P}{P_c}\right)^2 \quad (11a)$$

$$\gamma = 0.1 - 0.587\left(\frac{P}{P_c}\right) + 1.9825\left(\frac{P}{P_c}\right)^2 - 1.54275\left(\frac{P}{P_c}\right)^3 \quad (11b)$$

$$k_1 = -0.37295 + 0.22626(\ln G) - 0.01409(\ln G)^2 \quad (11c)$$

$$k_2 = 1.00027 - 0.16213(X_t) + 0.21796(X_t)^2 \quad (11d)$$

The local uniform correlation resulted in an average error of -1.03% and root mean square error of 11.91% for all the uniform heat flux CHF data used, and this correlation is an improved correlation over an earlier one by Shim and Lee (2006). The uniform data used in developing the correlation is presented in Table 1. Calculated vs. experimental uniform CHF of the new correlation is presented in Fig. 1.

Table 3 Calculated average error (%) of correlation prediction of CHF

Data source	Katto		Shah		Kim		Present Work	
	Data Used	Error (%)	Data Used	Error (%)	Data Used	Error (%)	Data Used	Error (%)
Lee (1965)	40	1.36	40	14.17	40	6.26	40	4.67
Bertoletti et al. (1963)	40	22.13	40	9.99	9	19.5	40	4.99
Casterline (1965)	35	0.86	33	12.44	35	0.82	35	2.92
Swenson et al. (1963)	7	8.27	6	30.94	7	2.93	7	1.78
Lee (1966)	122	4.23	117	20.86	122	11.72	122	2.21
Lee (1966)	53	2.91	53	22.01	53	15.77	53	7.19
Total	297	4.96	289	17.67	266	8.05	297	1.06

Table 4 Calculated root mean square error (%) of correlation prediction of CHF

Data source	Katto		Shah		Kim		Present Work	
	Data Used	Error (%)	Data Used	Error (%)	Data Used	Error (%)	Data Used	Error (%)
Lee (1965)	40	5.29	40	16.31	40	8.37	40	7.14
Bertoletti et al. (1963)	40	50.47	40	19.66	9	33.73	40	21.73
Casterline (1965)	35	10.37	33	22.70	35	20.29	35	9.21
Swenson et al. (1963)	7	8.96	6	31.56	7	6.27	7	2.55
Lee (1966)	122	8.23	117	24.55	122	17.97	122	11.59
Lee (1966)	53	6.55	53	24.42	53	19.68	53	10.17
Total	297	19.92	289	22.79	266	18.15	297	12.42

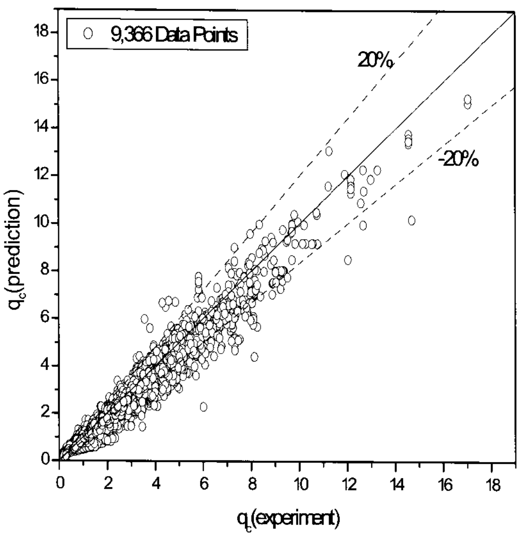

Fig. 1 Calculated vs. experimental CHF of new correlation in uniformly heated vertical tube

5.Non-Uniform Heat Flux Profile

The non-uniform CHF data used for the present study had axial cosine heat flux profile, and the profile is presented in the following form:

$$q(z) = q_{\max}\cos\left[\pi\theta\left(\frac{z}{L}-\frac{1}{2}\right)\right] \tag{12}$$

$$X(z) = X_i + \frac{4}{DG\lambda}\int_0^z q(z)dz \tag{13}$$

$$= X_i + \frac{4Lq_{\max}}{\pi\theta DG\lambda}\left[\sin\left\{\frac{\pi\theta}{L}\left(z-\frac{L}{2}\right)\right\}+\sin\left(\frac{\pi\theta}{2}\right)\right] \tag{14}$$

where $q_{\max}$ represent the maximum heat flux value. X_{OSV} along the tube length, z, is found by the following equation,

$$X_{OSV}(z) = -\frac{q_{\max}}{S_{tOSV}G\lambda}\left[\cos\left\{\frac{\pi\theta}{L}\left(z-\frac{L}{2}\right)\right\}\right] \quad (15)$$

Given a constant operation condition of *G*, *P* and *D*, at a low power, the non-uniform heat flux profile will have the same profile but a low heat flux magnitude such that it will be below and not in contact with the local correlation. When the power is increased to the critical level, the magnitude of non-uniform heat flux distribution will be sufficiently large such that it will just intersect the local uniform correlation as shown in Figure 2. Local CHF value and the location of CHF occurrence in the non-uniform heat flux profile of the tube can now be determined by locating the tangent point where the non-uniform heat flux profile of the tube and the uniform CHF correlation curve meet on a heat flux versus axial location plot. It should be noted here that without any added complexity, the uniform correlation can be applied directly to accurately predict CHF in axially non-uniform cosine heat flux tube and its location. An illustration of the method is shown in Fig. 2 for a Casterline's data.

The local uniform correlation applied to axially non-uniform cosine heat flux tubes is shown in Fig. 3. The local uniform correlation predicted CHF in tubes with axial cosine heat flux profile within the root mean square error of 12.42% and average error of 1.06% for 297 CHF data points. Tables 3 and 4 show the average error and root mean square error by each data source, respectively.

6.Overall Power Hypothesis

In overall power hypothesis, it can is assumed that the total power that can be fed to an axial non-uniform heat flux profile tube is the same for the uniform heat flux tube as long as the diameter, the length of tube and inlet condition are the same (Collier and Thome (1994)). In the following 3 representative generalized correlations for uniform heat flux were applied to the axially non-uniform CHF data for comparison.

Kim and Lee (1997) found an inlet condition correlation through the ACE (Alternating conditional expectation) algorithm. This generalized correlation covers a broad range of flow parameters in uniformly heated vertical round tubes. The correlation showed an average error of 8.05% and root mean square error of 18.15% for the 266 data points that were within their applicable range. Calculated vs. experimental CHF of this correlation is presented in Fig. 4.

Shah (1987) developed a generalized correlation that is divided into two correlations, one for the upstream condition correlation (UCC) and another for the local condition correlation (LCC). This correlation can also be applied to various fluids such as ammonia, benzene, potassium, helium,

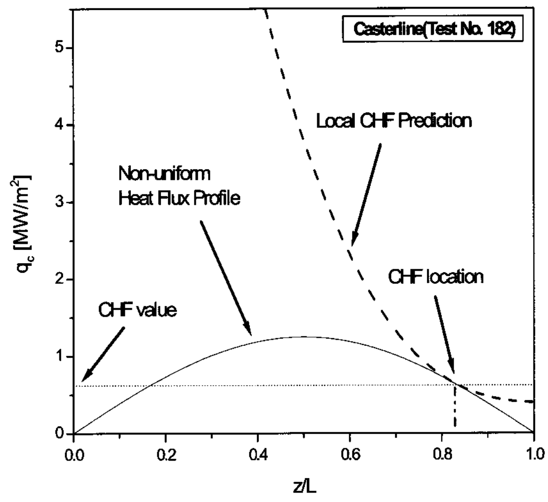

Fig. 2 A schema of prediction of CHF in non-uniformly heated vertical tubes

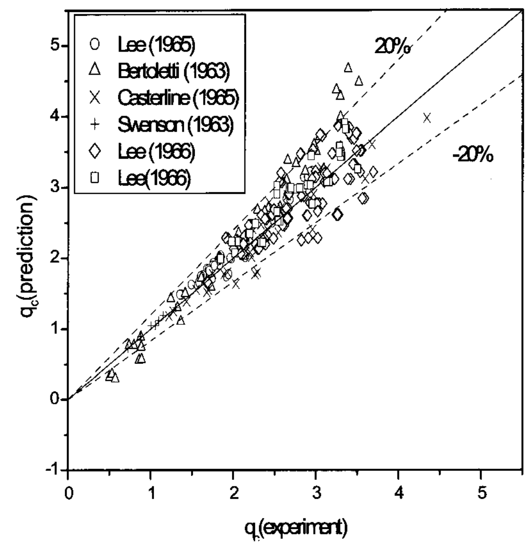

Fig. 3 Calculated vs. experimental CHF for local correlation applied to non-uniformly heated vertical tubes

nitrogen, etc. The applicable ranges of parameters are: $0.00032 \le D \le 0.0378$ m, $0.0014 \le P/P_c \le 0.962$, $4 \le G \le 29{,}051$ kg/m^{2}s, $0.00011 \le q_c \le 45$ MW/m^2, $1.3 \le L/D \le 940$, and 4

$\le X_i \le 0.81$. The correlation showed an average error of 17.67% and root mean square error of 22.79% for the 297 data points applicable for this method. Calculated vs. experimental CHF of this correlation is presented in Fig. 5.

Katto and Ohno (1984) 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

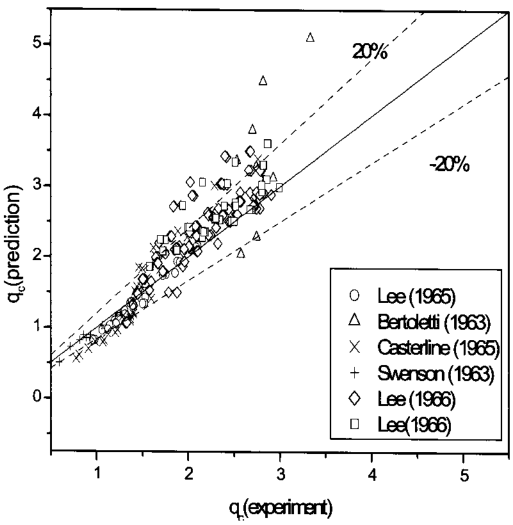

Fig. 4 Calculated vs. experimental CHF of Kim and Lee correlation in non-uniformly heated vertical tubes

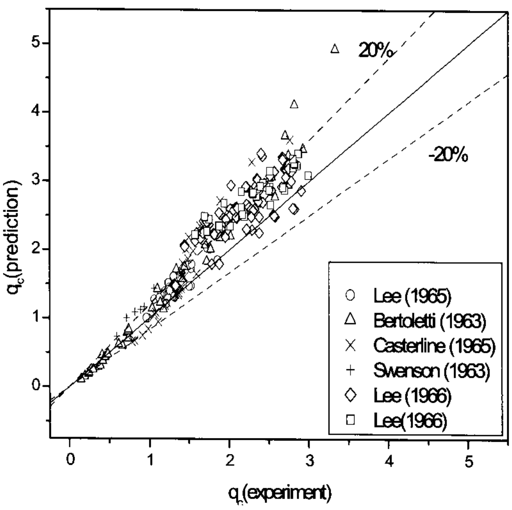

Fig. 5 Calculated vs. experimental CHF of Shah correlation in non-uniformly heated vertical tubes

correlation. The correlation requires an inlet subcooling enthalpy, a latent heat of vaporization, 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 applicable ranges of parameters are: $0.001 \leq D \leq 0.08$ m, $0.01 \leq L \leq 8.8$ m, $5 \leq L/D \leq 880$, $0.5 \leq P \leq 203$ bar, and $0.0003 \leq$ (vapor density) / (liquid density) ≤ 0.41. The correlation showed an average error of 4.96% and root mean square error of 19.92% for the 297 applicable data points. Calculated vs. experimental CHF of this correlation is shown in Fig. 6. The calculated average and root mean square errors of these correlations were presented detail in Tables 3 and 4.

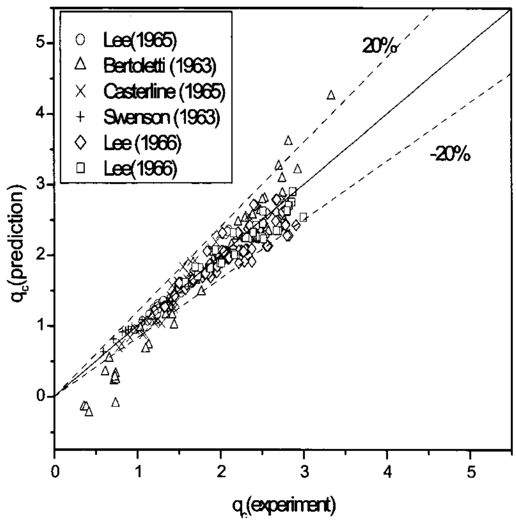

Fig. 6 Calculated vs. experimental CHF of Katto and Ohno orrelation in non-uniformly heated vertical tubes

7. Results and Discussion

The non-uniform data discussed are restricted to axially symmetrical cosine profile, produced by Lee (1965; 1966), Casterline and Matzner (1964), Bertoletti et al. (1963) and Swenson et al. (1963).

Casterline and Matzner concluded that non-uniform CHF conditions could not be predicted by a correlation based on experimental results obtained with uniform tubes. However, the present results show that a local uniform correlation can be applied directly to predict CHF in non-uniform heat flux without any added complexity.

Bertoletti et al. published data on CHF with non-uniform heat flux distribution in round vertical tubes with steam-water mixtures at inlet. The non-uniform profiles was approximately a chopped cosine. They found that the critical power was independent of power distribution and CHF or burnout always happened at the exit. Flow instability was reported in these tests, and there appear some error on their data. The local correlation predicts CHF location between 1/2 and 3/4 of the tube length from inlet. Furthermore, the results indicate that unless the tube was of uniform heat flux profile, CHF or burnout are not likely to occur at the exit of tube.

Lee (1965; 1966) reported the location of CHF for some of his data. He noticed that the zone in which CHF was detected moved further upstream with increasing mass flux. The predicted locations of CHF are mainly around 1/4 of length upstream of the tube exit, and move upstream with increasing inlet quality. Deng (1997) and Shim and Joo (2002) showed that there is a general trend in exponential decline of $q_c\sqrt{D}$ with increasing $\sqrt{GX_t}\,F(X_t)$. $q_c\sqrt{D}$ was proportional to $\sqrt{GX_t}$ times some function in terms of X_t. Data analysis using this general form has resulted in equation 11. When mass flux increases, $\sqrt{GX_t}$ terms gets even smaller and corresponding CHF increases. This is in agreement with Lee's observation. The present results show no burnout is predicted at the exit. This finding can be verified from Fig. 2. The intersection of a local uniform correlation and a non-uniform heat flux profile can not meet at the exit unless the heat flux profile is uniform. If heat flux profile is uniform, the burnout will always occur at the exit of tube.

The results of this study predicted by the local correlation agrees well with the experimental data as shown in Tables 3 and 4, and Fig. 3. The difference between data and prediction is, for a wide range of CHF values, quite small. This result shows that the local correlation can be applied to conditions with negative and positive qualities, including inlet steam-water mixtures. The new local uniform correlation predicts 297 axially non-uniform cosine heat flux CHF data points accurately within root mean square error and average error of 12.4% and 1.06%, respectively.

8. Conclusions

In this study, a local condition hypothesis based CHF correlation in uniformly heated vertical round tubes for water was developed. This correlation was then applied directly to predict CHF in non-uniform heat flux. Without any added complexity, the local correlation accurately predicted and located CHF of water in the vertical tubes with axially non-uniform heat flux distribution. The results showed that a local uniform correlation can be used to predict CHF in both uniform and axially non-uniform heat flux profiles. In fact it suggests CHF is fundamentally based on local condition hypothesis.

Determination of the location of burnout can be difficult since conditions close to burnout can exist over a fairly broad range of locations. In the present analysis, the verification of predicted CHF location was incomplete because majority of the original data did not include the CHF locations; however, in theory, it can be determined exactly because the location of CHF to be determined is the point of intersection of a local uniform correlation and a heat flux profile. This result can be extended to explain why the location of the CHF or burnout in uniform heat flux profile always occurs at the exit of tube.

Although the uniform CHF database of 9,366 data points is perhaps not sufficient to develop a generalized correlation that covers all the operating and flow conditions, this work shows a possibility that non-uniform heat flux CHF and its location can be predicted well by a uniform correlation based on local condition hypothesis.

Acknowledgements

The present research was conducted by the research fund of Dankook University in 2005.

References

Becker, K.M. (1965). Burnout Data for Flow of Boiling Water in Vertical Round Ducts, Annuli, and Rod Clusters, Aktiebolaget Atomenergie Report AE-177, Sweden.

Becker, K.M., Strand, G. and Osterdahl, C. (1971). Round Tube Burnout Data for Flow Boiling of Water at Pressures between 30 and 200 bar, Royal Institute of Technology, Laboratory of Nuclear Engineering, KTH-NEL-14, Sweden.

Bertoletti, S., Gaspari, G.P., Lombardi, C. and Zavattarelli, R. (1963). Critical Heat Flux Data for Fully Developed Flow of Steam Water Mixtures in Round Vertical Tubes with Non Uniform Axial Power Distribution, CISE Report R-74.

Casterline, J.E. (1965). Second Experimental Study of Dryout in a Long Vertical Tube with a Cosine Heat Flux, Topical Report No. 5, TASK-XVI, Columbia University.

Casterline, J.E., and Matzner, B. (1964). Burnout in Vertical Long Tubes with Uniform and Cosine Heater Using Water at 1000 psia, Topical Report No. I, TASK-XVI, Columbia University, New York.

Cheh, H.Y., Fighetti, C.F., and McAssey, E.V. (1992). Single Tube Tests (for) Critical Heat Flux Test Program, Report No. CU-HTRF-T8.

Collier J.G. and Thome J.R. (1994). Convective Boiling and Condensation, 3rd ed. Oxford University Press, New York.

Deng, Z., Dougherty, T. J. and Yang, B.W. (1997). "A New Correlation for Flow Boiling of Water in Subcooled and Quality Region", Proc. 8th Int. Topl. Mtg. Nuclear Reactor Thermal-Hydraulics, Kyoto, Japan, Vol 2, pp 981.

Deng, Z. (1998). Prediction of Critical Heat Flux for Flow Boiling in Subcooled and Saturated Regions, Ph.D. Thesis, Columbia University.

Griffel, J. (1965). Forced Convection Boiling Burnout for Water in Uniformly Heated Tubular Test Sections, NYO-187-7, Columbia University, New York.

Jafri, T., Dougherty, T.J. and Yang, B.W. (1996). "Local and non-local correlations for Critical Heat Flux at Low and Medium Pressures", Proceedings of the ASME Heat Transfer Division, Vol 3, ASME HTD-Vol 334, pp 229-238.

Katto, Y. and Ohno, H. (1984). "An Improved Version of the Generalized Correlation of Critical Heat Flux for Forced Convection Boiling in Uniformly Heated Vertical Tubes", Int. J. Heat Mass Transfer, Vol 27, No 9, pp 1641-1648.

Kim, H.C., Baek, W.P. and Chang, S.H. (2000). "Critical Heat Flux of Water in Vertical Round Tubes at Low Pressure and Low Flow Conditions", Nuclear Engineering and Design, Vol 199, pp 49-73.

Kim, H.G. and Lee, J.C. (1997). "Development of a Generalized Critical Heat Flux Correlation through the Alternating Conditional Expectation Algorithm", Nuclear Engineering and Design, Vol 127, pp 300-316.

Lee, D.H. (1965). An Experimental Investigation of Forced Convection Burnout in High Pressure Water, Part III. Long Tubes with Uniform and Non uniform Axial Heating, AEEW-R355.

Lee, D.H. (1966). An Experimental Investigation of Forced Convection Burnout in High Pressure Water, Part IV. Large Diameter Tubes at about 1600 PSI, AEEW-R479.

Lee, D.H. and Obertelli, J.D. (1963). An Experimental Investigation of Convection Burnout in High Pressure Water. Part I, Round Tubes with Uniform Heat Flux Distribution, AEEW-R213.

Lowdermilk, W.H., Lanzo, C.D. and Siegel, B.L. (1958). Investigation of Boiling Burnout and Flow Stability for Water Flowing in Tubes, NACA-TN-4382.

Mishima, K. (1984). Boiling Burnout at Low Flow Rate and Low Pressure Conditions, Ph. D. Thesis, Kyoto University, Japan.

Shah, M.M. (1987). "Improved General Correlation for Critical Heat Flux during Upflow in Uniformly Heated Vertical Tubes", Heat and Fluid Flow, Vol 8, No 4, pp 326-335.

Saha, P. and Zuber, N. (1974). Point of Net Vapor Generation and Vapor Void Fraction in Subcooled Boiling, Proc. of the 5th International Heat Transfer Conference, Tokyo, Paper B4.7, pp 175-179.

Shim, W.J. and Joo, S.K., (2002). "Development and Analysis of a Uniform CHF Database", JIEC, 8, No 3, pp 268-275.

Shim, W.J. and Lee, J.S. (2006). "Prediction of CHF in Vertical Round Tubes with Uniform Heat Flux for Water", JIEC, 12, No 1, pp 127-133.

Swenson, H.S., Carver, J.R. and Kakarala, C.R. (1963). The Influence of Axial Heat Flux Distribution on the Departure from Nucleate Boiling in a Water Cooled Tube, ASME,-62-WA-297.

Thompson, B. and Macbeth, R.V. (1964). Boiling Water Heat Transfer Burnout in Uniformly Heated Round Tubes: A Compilation of World Data with Accurate Correlations, AEEW-R-356, United Kingdom Atomic Energy Authority.

Tong, L.S. (1965). Boiling Heat Transfer and Two Phase Flow, John Wiley & Sons, New York.

2008년 1월 30일 원고 접수
2008년 2월 19일 최종 수정본 채택