PERGAMON

International Journal of Heat and Mass Transfer 43 (2000) 2605–2640

International Journal of
HEAT and MASS TRANSFER

www.elsevier.com/locate/ijhmt

Critical heat flux (CHF) for water flow in tubes—II. Subcooled CHF correlations

David D. Hall, Issam Mudawar*

Boiling and Two-Phase Flow Laboratory, School of Mechanical Engineering, Purdue University, West Lafayette, IN 47907, USA

Received 29 September 1998; received in revised form 24 May 1999

Abstract

The proliferation of critical heat flux (CHF) prediction methods typifies the lack of understanding of the CHF phenomenon and makes it difficult to choose a suitable correlation, look-up table, or model. In fact, an exhaustive literature search by the authors of this study identified over 100 CHF correlations applicable to subcooled water flow in a uniformly heated round tube. The accuracy of the latest versions of these correlations was ascertained using the PU-BTPFL CHF database from Part I of the present study. This database contains the largest volume of subcooled CHF data (5544 data points) of any database available in the literature. In response to the many inaccurate and inordinately complex correlations, two nondimensional, subcooled CHF correlations were formulated, containing only five adjustable constants and whose unique functional forms were determined without using a statistical analysis but rather using the parametric trends observed in less than 10% of the subcooled CHF data. The correlation based on inlet conditions (diameter, heated length, mass velocity, pressure, inlet quality) was by far the most accurate correlation, having mean absolute and root-mean-square errors of 10.3% and 14.3%, respectively, and is recommended for water flow in a tube having a uniform axial heat flux. The outlet (local) conditions correlation was the most accurate correlation based on local CHF conditions (diameter, mass velocity, pressure, outlet quality) and may be applied to water flow in a tube having a nonuniform axial heat flux. Both correlations proved more accurate than a recent CHF look-up table commonly employed in nuclear reactor thermal hydraulic computer codes. The parametric range for the inlet conditions correlation ($0.25\times10^{-3}\leq D\leq 15\times10^{-3}$ m, $2\leq L/D\leq 200$, $300\leq G\leq 30{,}000$ kg m^{-2} s^{-1}, $1\times10^{5}\leq P\leq 200\times10^{5}$ N m^{-2}, $-2.0\leq x_{\mathrm{i}}\leq 0.0$, $-1.0\leq x_{\mathrm{o}}\leq 0.0$) was chosen so as to include those regions where data were most abundant, containing approximately 85% of the subcooled CHF database. Superiority of the correlations was attributed to the systematic development of the functional forms of the correlations from the CHF parametric effects; thus, re-optimization of the constants, when additional subcooled CHF data become available, is not expected to produce an appreciable increase in accuracy. © 2000 Elsevier Science Ltd. All rights reserved.

---

1. Introduction

Critical heat flux (CHF) refers to the heat transfer limit causing a sudden rise in surface temperature and possible catastrophic failure (burnout) of a device in which evaporation or boiling is occurring. CHF in flow boiling is an important limit to the design and safe-operation of nuclear reactors and other devices in which it is important to extract the maximum amount of heat without risk of physical burnout. A large volume of experimental and theoretical studies on the CHF phenomenon have been carried out by many researchers, resulting in numer-

---

* Corresponding author. Tel.: +1-765-494-5705; fax: +1-765-494-0539.

E-mail address: mudawar@ecn.purdue.edu (I. Mudawar).

0017-9310/00/$ - see front matter © 2000 Elsevier Science Ltd. All rights reserved.
PII: S0017-9310(99)00192-1

Nomenclature

Bo	boiling number, q_m/Gh_{fg}
c	constant defined in Eq. (4)
C_j	constant defined in Eq. (7), $j = 1, 2, 3, 4$, or 5
D	inside diameter of tube
f_j	function of density ratio defined in Eqs. (5) and (6), $j = 1$ or 2
fn( )	function of ( )
G	mass velocity
h	enthalpy of fluid
h_{f}	enthalpy of saturated liquid
h_{fg}	latent heat of vaporization
K_j	coefficients in dimensional CHF correlation, $j = 1, 2$, or 3 (see Fig. 6)
L	heated length of tube
N	number of CHF data points
P	pressure
q_m	critical heat flux (CHF) defined using tube inside area
$q_{m,*}$	CHF from look-up table
T	temperature
T_{i}	bulk liquid temperature at inlet
T_{o}	bulk liquid temperature at outlet (defined only if $x_{\mathrm{o}} < 0$)
ΔT_{sub}	liquid subcooling, $T_{\mathrm{sat}} - T$, with saturation temperature evaluated at pressure associated with the CHF data point (usually outlet pressure)
We_D	Weber number, $G^2D/\rho_{\mathrm{f}}\sigma$
x	thermodynamic equilibrium quality, $(h - h_{\mathrm{f}})/h_{\mathrm{fg}}$, with saturated thermophysical properties evaluated at pressure associated with the CHF data point (usually outlet pressure)
$x_{\mathrm{i},*}$	pseudo-inlet quality, $(h_{\mathrm{i}} - h_{\mathrm{f,o}})/h_{\mathrm{fg,o}}$, with saturated thermophysical properties evaluated at outlet pressure

Greek symbols

ρ	density
σ	surface tension

Subscripts

f	liquid
g	vapor
i	inlet of heated length
meas	measured
o	outlet of heated length
pred	predicted
sat	saturated conditions
sub	subcooled conditions

ous empirical correlations and mechanistic models. Design engineers typically utilize CHF correlations to insure that the extreme operating conditions for an application maintain heat fluxes safely below CHF. Unfortunately, most existing CHF correlations have been developed using a small number of data points covering a limited range of flow conditions and, consequently, the correlations can not be extended to other flow conditions without uncertainty.

Part I [1] complements the present study with the compilation and assessment of the Purdue University Boiling and Two-Phase Flow Laboratory (PU-BTPFL) CHF database for water flow in a uniformly heated tube. Only 4885 vertical upflow (out of 31,661) and 659 horizontal flow (out of 883) CHF data points were obtained with subcooled conditions at the end of the heated length; 83% of the CHF data were acquired with saturated conditions. Part I also describes the identification of unacceptable data mainly on the basis that data were unreliable according to the original authors, unknowingly duplicated, or in violation of an energy balance. The parameter ranges of the 4860 acceptable, subcooled CHF data points are given in Table 1. The upper and lower number in each table cell represents the smallest and largest value, respectively, of that parameter for the acceptable, subcooled CHF data with the indicated flow orientation. The PU-BTPFL CHF database contains the largest volume of subcooled CHF data of any database available in the literature and will be quite effective in the assessment of subcooled CHF correlations and the identification of a superior correlation.

The present study was motivated by the lack of a simple, accurate, subcooled CHF correlation for water flow in a uniformly heated tube. The objectives of the present study are the following: (1) identify all known subcooled CHF correlations for water flow in a uniformly heated tube, (2) develop a superior design correlation for accurate prediction of subcooled CHF, and (3) evaluate these correlations using the subcooled CHF data in the PU-BTPFL CHF database (hereafter, referred to as the subcooled CHF database) from Part I [1] of the present study.

2. Compilation of subcooled CHF correlations

During the past 50 years, 100s of CHF correlations

Table 1
Parameter ranges of the acceptable subcooled CHF data in the PU-BTPFL CHF database[a]

	Acceptable subcooled CHF data[b]	Tube dimensions				Inlet condition		Outlet condition		CHF
		$D \times 10^3$ (m)	L/D	$G \times 10^{-3}$ (kg m^{-2} s^{-1})	$P \times 10^{-5}$ (N m^{-2})	$\Delta T_{sub,i}$ (°C)	x_i	$\Delta T_{sub,o}$ (°C)	x_o	$q_m \times 10^{-6}$ (W m^{-2})
Vertical upflow	4227	0.25	2	0.3	1	12	−3.00	0	−2.25	0.5
		44.7	684	134.0	218	347	−0.04	305	0.00	276.0
Horizontal flow	633	0.6	3	0.9	0.7	28	−0.72	1	−0.42	1.2
		15.0	327	52.8	104	215	−0.06	168	0.00	54.4

[a] The upper and lower number in each cell of a parameter column represents the smallest and largest value, respectively, of that parameter for the acceptable subcooled CHF data with the indicated flow orientation. Outlet conditions were calculated using the inlet temperature from the database and an energy balance. Saturated thermophysical properties were evaluated at the pressure associated with the CHF data point (usually outlet pressure).

[b] Acceptable subcooled CHF data indicate the total number of CHF data points minus the number of saturated CHF data and the number of invalid subcooled CHF data identified in Part I [1] of the present study.

have been formulated for a multitude of fluids and flow configurations. The authors of the present study have conducted an exhaustive literature search in order to identify all correlations applicable to subcooled water flow (i.e., negative outlet quality) in a uniformly heated tube [2–78]. A detailed description of each correlation is provided in Refs. [79,80]. Table 2 lists the earliest and most archival publication of these correlations. Multiple rows were utilized where a publication recommended more than one correlation. The related publications listed in Table 2 include those containing an earlier version of the correlation, a refined or extended parametric range for the correlation, or an assessment of the correlation using a larger database. The following types of correlations were not considered in the present study:

1. correlations not applicable to internal axial flow of water in a uniformly heated round tube,
2. correlations applicable only to saturated conditions at the outlet (correlation parametric range for the outlet quality has a lower limit above zero),
3. earlier versions of a correlation later revised or proven unreliable by the author of the correlation or co-workers at those authors' institution (parametric range of the revised correlation must be the same as or larger than that of the earlier correlation for the earlier correlation to be discarded), and
4. correlations developed from a CHF look-up table (the most recent CHF look-up table is evaluated separately in the present study).

Correlations were not rejected based on a small parametric range or a minimum number of data sources or data points utilized to develop the correlation.

CHF correlations generally assume one of the following forms: dimensional correlation based purely on a statistical analysis of the data, nondimensional correlation based on dimensionless groups applicable to flow boiling, or a correlation based on superposition of a pool boiling CHF model or correlation and a single-phase forced convection correlation. The latter correlation may seem attractive at first; however, it speculates that the physical mechanism which initiates CHF in pool boiling is hydrodynamically identical to that in flow boiling, which has not been confirmed experimentally.

CHF correlations are classified as either an inlet (upstream) conditions correlation based on independent variables such as inlet enthalpy (or inlet subcooling or quality) and heated length,

$$q_m = \mathrm{fn}(D, L, G, P, h_i), \tag{1}$$

or an outlet (local) conditions correlation based on a dependent variable such as outlet enthalpy (or outlet subcooling or quality),

$$q_m = \mathrm{fn}(D, G, P, h_o). \tag{2}$$

Table 2 identifies each correlation as an inlet and/or outlet conditions correlation. If a correlation is indicated as both an inlet and outlet conditions correlation, then either the correlation requires both an inlet and outlet condition in the same equation, thus producing a correlation which is inconsistent with an energy balance and unusable [28,37,40], or the correlation has a conditional statement for choosing between equations or sets of equations, one based on inlet conditions and the other on outlet conditions [58,73]. Two correlations were independent of both inlet and outlet conditions [41,60].

Table 2 also lists the number of adjustable constants within each correlation and indicates whether or not the correlation requires iteration, both of which give an indication of the complexity of a correlation. An

Table 2
Subcooled CHF correlations

Subcooled CHF correlation	Inlet conditions	Outlet conditions	Adjustable constants[a]	Iteration required	Saturated CHF[b]	Multi-fluid[b]	Multi-geometry[b]	Related publications
Buchberg et al. [2]		●	3					Tramontini et al. [81]
Gunther [3]		●	2				●	
Jens and Lottes [4]		●	11					
McGill and Sibbitt [5]		●	3					
Epstein et al. [6]		●	13					
Hoe and Senghaus [7]		●	3		● 2		●	Hoe and Helve [82]
Griffith [8]		●	5[c]		●	●	●	
Longo [9]		●	6					
Gambill and Greene [10]		●	4				●	Gunther [3], Gambill and Greene [83]
Green et al. [11]		●	5		●		● 4	Hunt et al. [84], Jacket et al. [85,86], Cunningham and Zerbe [87], DeBortoli et al. [88]
Menegus [12]		●	24				●	
Sonnemann [13]	●		7	●	●		●	Sonnemann [89]
Bernath [14]		●	11			●	●	Bernath [90]
Ivashkevich [15]		●	6		● 1	●	●	Ivashkevich [91]
Jacobs and Merrill [16]	●		24		●			
Povarnin and Semenov [17]		●	22				●	Povarnin and Semenov [92]
Labuntsov [18]		●	8				●	
Miropol'skii and Shitsman [19]		●	6		● 3		● 3	
Torikai et al. [20]		●	3					
Levedahl [21]		●	3		● 1			Levedahl [93]
Levy [22]		●	0	●	● 1		● 1	
Michiyoshi and Matsumoto [23]	●		2	●	● 2		●	
Ornatskii and Kichigin [24]		●	4					Ornatskii and Kichigin [94], Ornatskii [95]
Chang [25]		●	5		●	● 4	● 4	
Gambill [26]		●	2			●	●	
Shitsman [27]		●	3		● 5		●	
Tong et al. [28]	●	●	12		● 9		●	Tong et al. [96,97]
Weatherhead [29]		●	14		●		●	Weatherhead [98]
Ryabov and Berzina [30]		●	5					
Shtokolov [31]		●	2			●		
Wilson and Ferrell [32]	●		8		●		● 6	Wilson and Ferrell [99]
Zenkevich [33]		●	9				●	Zenkevich and Subbotin [100], Subbotin et al. [101], Zenkevich [102,103], Alekseev et al. [104]
Griffel and Bonilla [34]		●	4		● 4			Griffel [105]
Ornatskii and Vinyarskii [35]		●	4					
Skinner and Loosmore [36]		●	5					
Tong [37]	●	●	17		●		●	Tong et al. [28], Tong [106,107]
Tong [38]		●	4		●			Tong et al. [108]
Glushchenko [39]		●	4				●	

Table 2 (*continued*)

Subcooled CHF correlation	Inlet conditions	Outlet conditions	Adjustable constants^{a}	Iteration required	Saturated CHF^{b}	Multi-fluid^{b}	Multi-geometry^{b}	Related publications
Ornatskii et al. [40]	●	●	5		●			Glushchenko and Maevskii [109]
Vasil'yev and Kirillov [41]	–	–	4					
Becker et al. [42]	●		6		●			
Bowring [43]	●		25		●			Macbeth [110–114], Thompson and Macbeth [115] Lee [116]
Purcupile and Gouse [44]		●	7	●				Purcupile et al. [117]
Ahmad [45]	●		3		●	●	● 6	
Hancox and Nicoll [46]		●	8		●			
Thorgerson et al. [47]		●	0	●			● 2	Thorgerson [118]
Levitan and Lantsman [48]		●	8		●			Doroshchuk et al. [119,120]
Tong [49]		●	7	●	● 1		●	
Chernobai [50]		●	4	●	●			
Koba et al. [51]	●		3					
Bergel'son et al. [52]		●	8					Bergel'son [121]
Hebel et al. [53]	●		6		●		● 2	Hebel and Detavernier [122]
Ivashkevich [54]		●	3					
Smogalev [55]		●	2				●	
Sapankevich [56]		●	0		●		●	
Inasaka and Nariai [57]		●	9					Nariai et al. [123], Inasaka and Nariai [124–128], Nariai and Inasaka [129,130], Inasaka [131]
Shah [58]	●	●	35		●	●		Shah [132]
Avksentyuk [59]		●	1	●		●		Avksentyuk and Ovchinnikov [133]
Boyd [60]		●	2					
Boyd [60]	–	–	2					
Gambill and Mochizuki [61]		●	0	●			●	Thorgerson et al. [47]
Gromova et al. [62]		●	16		● 13		●	Smolin et al. [134]
Siman-Tov et al. [63]		●	0	●			●	Gambill [26], Thorgerson et al. [47], Gambill and Mochizuki [61]
Vasil'yev [64]		●	8		● 6			
Caira et al. [65]	●		11					Caira et al. [135]
Celata et al. [66]		●	6		● 2			Celata et al. [136–138], Celata [139], Cumo [140]
Vandervort et al. [67]		●	16					
Caira et al. [68], Caruso [69]	●		138					Caira et al. [65,135]
Hechanova et al. [70]		●	8					
Lombardi [71]	●		4					
Pernica and Cizek [72]	●		25	●	●		● 7	
Jafri et al. [73]	●	●	16	●	●			Jafri [141], Jafri et al. [142]

(continued on next page)

Table 2 (*continued*)

Subcooled CHF correlation	Inlet conditions	Outlet conditions	Adjustable constants[a]	Iteration required	Saturated CHF[b]	Multi-fluid[b]	Multi-geometry[b]	Related publications
Kabata et al. [74]		●	3					
Yagov et al. [75]		●	16				●	Yagov and Puzin [143], Yagov et al. [144], Yagov [145]
Zeigarnik et al. [76]		●	[c]					Zeigarnik et al. [146,147], Zeigarnik [148]
Boscary et al. [77]		●	6					
Hall and Mudawar [78]		●	5					Bowers [149], Mudawar and Bowers [150]
Hall and Mudawar [78]	●		5					Bowers [149], Mudawar and Bowers [150]
Present study (see Table 4)		●	5					Bowers [149], Mudawar and Bowers [150], Hall and Mudawar [78]
Present study (see Table 4)	●		5					Bowers [149], Mudawar and Bowers [150], Hall and Mudawar [78]

[a] Adjustable constants refer to those constants which the authors of a correlation manipulated in order to increase the accuracy of their correlation.

[b] This column identifies those correlations which are valid for a test condition other than water flow in a uniformly heated round tube with a subcooled outlet. A number in one of the columns indicates the number of adjustable constants (in addition to those required for the prediction of subcooled CHF for water flow in a uniformly heated tube) required to predict CHF under the test condition listed.

[c] A term within the correlation was only presented graphically as a function of an independent parameter (diameter or pressure).

iterative solution procedure was required when a correlation could not be explicitly solved for CHF. Adjustable constants are those which the authors manipulated in order to increase the accuracy of their correlation. Adjustable constants include those appearing in conditional statements which specify the appropriate equation from a set of equations. The condition that a parameter such as outlet quality be either less than or greater than zero is not considered adjustable. The exponent of a parameter in a polynomial function is also not considered adjustable. Correlations which are the superposition of a pool boiling CHF correlation and a single-phase forced convection heat transfer correlation often have few, if any, adjustable constants [22,26,59,63]. Also, correlations which are the product of a two-phase heat transfer coefficient (determined from friction factor and Nusselt number correlations) and the sum of wall superheat (determined from a previously published correlation) and outlet subcooling had zero adjustable constants [47,61].

While all of the correlations considered in the present study are applicable to subcooled CHF for water flow in a uniformly heated tube, some may also be applicable to saturated CHF (i.e., positive outlet quality), fluids other than water, or flow geometries other than a round tube. These correlations are indicated as such in Table 2. Also shown is the number of adjustable constants (in addition to those required for the prediction of subcooled CHF for water flow in a uniformly heated tube) required to predict CHF under these other conditions.

The parametric range of each correlation was obtained from the main or related publications listed in Table 2. If the entire parametric range for a correlation was not explicitly stated by the authors of the correlation, then the parametric range was determined by inspecting the data (if discussed or cited in their publication) utilized to develop the correlation. If the correlation was based on inlet conditions, then an attempt was made to ascertain the parametric ranges of D, L or L/D, G, P, and either $\Delta T_{\mathrm{sub,i}}$ or x_{i} (see Eq. (1)). If the correlation was based on outlet conditions, then an attempt was made to ascertain the parametric ranges of D, G, P, and either $\Delta T_{\mathrm{sub,o}}$ or x_{o} (see Eq. (2)). If an outlet conditions correlation contained an L/D term and a parametric range for L/D was explicitly stated, then it was included in the present study. In no case was a parametric range utilized for CHF since it was the dependent parameter. The outlet quality (or subcooling) calculated from the measured CHF and not predicted CHF was always utilized to determine if a data point was within the parametric range of a correlation. If the authors of the correlation presented different parametric ranges for both a saturated and a subcooled CHF correlation, then only the parametric range pertaining to the subcooled CHF correlation was utilized in the present study. The parametric range of each correlation as determined by the authors of the present study is provided in Refs. [79,80].

Many of the subcooled CHF correlations considered in the present study are quite complex having either many constants, many equations, terms presented graphically as a function of an independent parameter, or conditional statements for choosing an equation or set of equations. Furthermore, correlations having conditional statements allow severe discontinuities in the predicted CHF as a parameter is varied across a boundary described by one of these statements. Also, many of the correlations are dimensional and require specific units for the parameters. Furthermore, the functional forms of the correlations were not based on observed trends in the CHF data, but rather the equation form was often guessed and a statistical analysis performed to obtain values for the adjustable constants. The present study aims to develop a nondimensional correlation containing as few constants as possible and whose functional form is determined without using a statistical analysis but rather using the parametric trends observed in the subcooled CHF database.

3. Development of CHF correlation

The functional form of a subcooled CHF correlation based on outlet conditions was ascertained from a parametric study performed by the authors in a previous study [78,151]. Initially, the constants appearing in the correlation were methodically determined from a small subset of the subcooled CHF database by examining the effects of mass velocity, outlet quality, and pressure on CHF. This outlet conditions correlation was transformed into an inlet conditions correlation using an energy balance which accounted for the difference in pressure between the inlet and outlet of the heated length. Finally, the constants were optimized to yield a minimum root mean square (RMS) error for the inlet conditions correlation when evaluated with the entire subcooled CHF database.

3.1. Determination of functional form

A parametric study on CHF for subcooled water flow in small diameter tubes revealed key relationships between the variables in an outlet conditions correlation and CHF [78,151]:

1. CHF is proportional to D to a negative power.
2. CHF is proportional to G to a positive power.
3. CHF decreases linearly with increasing x_{o}.
4. Effect of pressure on CHF was not determined since data were not available with inlet (or outlet) quality held constant while pressure was varied.

The functional dependence of an outlet conditions correlation (Eq. (2)) can be written in nondimensional form as

$$Bo = \mathrm{fn}\left(We_D, \frac{\rho_{\mathrm{f}}}{\rho_{\mathrm{g}}}, x_{\mathrm{o}} \right), \tag{3}$$

where the ratio of saturated liquid density to saturated vapor density was chosen as the dimensionless group to represent mostly the effect of pressure. The trends listed above immediately lead one to conclude that a possible nondimensional, outlet conditions correlation is

$$Bo = We_D^c (f_1 - f_2 x_{\mathrm{o}}), \tag{4}$$

where the constant c is negative and the functions f_1 and f_2 may be positive constants or functions of density ratio. The process by which these unknown constants and functions are determined is described in detail in Ref. [78] and is only briefly described below.

3.2. Determination of constants

The constant and functions in Eq. (4) were determined using several sets of CHF data in which all but one of the dimensionless terms appearing on the right-hand side of Eq. (3) were held constant. The data from Mudawar and Bowers [151], Ornatskii and Kichigin [24,94], and Ornatskii [95] were the only data available in the literature which were systematically obtained over a broad range of pressure. While the data from Mudawar and Bowers were obtained over a broad range of mass velocity for a given pressure and inlet and outlet quality, the data from Ornatskii and Kichigin [24,94] and Ornatskii [95] were obtained over a broad range of inlet and outlet quality for a given pressure and mass velocity. Thus, the combination of these data proved very effective in the systematic development of a new, superior CHF correlation based solely on observed parametric trends.

The constant c in Eq. (4) was determined using 48 CHF data points from Mudawar and Bowers [151] obtained with a diameter of 0.902 mm, inlet temperature of 25°C, pressures from 3.4 to 172 bar, and mass velocities from 5000 to 40,000 kg m^{-2} s^{-1}. The constant c was found to be independent of pressure and equal to -0.235, indicating that CHF is approximately proportional to the square root of mass velocity at all pressures [78]. For a given set of data taken at the same pressure, inlet quality was constant and outlet quality varied by less than 10% (essentially, only mass velocity and CHF changed).

Mudawar and Bowers [151] had limited control over inlet temperature, preventing the acquisition of sufficient data at different pressures with a broad range of inlet qualities. Thus, the dependence of CHF on outlet quality was investigated using 399 data points from Ornatskii and Kichigin [24,94] and Ornatskii [95]. These data were obtained with $D = 2 \times 10^{-3}$ m, $L/D = 20$, $5000 \leq G \leq 30{,}000$ kg m^{-2} s^{-1}, and $9.8 \times 10^5 \leq P \leq 196 \times 10^5$ N m^{-2}. Data from two different institutions were also required since Ornatskii and Kichigin [24,94] and Ornatskii [95] did not obtain a set of data with a constant inlet temperature, thus prohibiting the application of the procedure for determining c from their data. At each of nine different pressures, the data were curve-fit using Eq. (4) with the exponent of the Weber number already determined as discussed in the preceding paragraph. The values of f_1 and f_2 varied with density ratio (pressure) and were accurately represented by

$$f_1 = 0.0332\left(\frac{\rho_\mathrm{f}}{\rho_\mathrm{g}}\right)^{-0.681} \tag{5}$$

and

$$f_2 = 0.0227\left(\frac{\rho_\mathrm{f}}{\rho_\mathrm{g}}\right)^{0.151}. \tag{6}$$

Substitution of Eqs. (5) and (6) into Eq. (4) and rearranging yields

$$Bo = C_1 We_D^{C_2}\left(\frac{\rho_\mathrm{f}}{\rho_\mathrm{g}}\right)^{C_3}\left[1 - C_4\left(\frac{\rho_\mathrm{f}}{\rho_\mathrm{g}}\right)^{C_5} x_\mathrm{o}\right], \tag{7}$$

where $C_1 = 0.0332$, $C_2 = -0.235$, $C_3 = -0.681$, $C_4 = 0.684$, and $C_5 = 0.832$ [78].

3.3. Transformation of outlet conditions correlation

The outlet conditions correlation (Eq. (7)) which is based on a dependent variable (x_o), can be transformed into an inlet conditions correlation based on independent variables (L/D, x_i) by using an energy balance between the inlet and outlet of the heated length,

$$h_\mathrm{o} = h_\mathrm{i} + 4\frac{L}{D}\frac{q_m}{G}. \tag{8}$$

In nondimensional form, the energy balance equation becomes

$$x_\mathrm{o} = x_\mathrm{i}\left(\frac{h_{\mathrm{fg,i}}}{h_{\mathrm{fg,o}}}\right) + \frac{h_{\mathrm{f,i}} - h_{\mathrm{f,o}}}{h_{\mathrm{fg,o}}} + 4\frac{L}{D}\frac{q_m}{G\,h_{\mathrm{fg,o}}}, \tag{9}$$

where x_i and x_o are the thermodynamic equilibrium qualities with saturated thermophysical properties evaluated at the inlet and outlet pressures, respectively. The subscripts i and o in Eq. (9) indicate the pressure at which to evaluate the enthalpy of saturated liquid and the latent heat of vaporization. Eq. (9) can also be written as

$$x_\mathrm{o} = x_{\mathrm{i},*} + 4Bo\frac{L}{D}, \tag{10}$$

where all saturated thermophysical properties are evaluated at the outlet pressure, including those appearing in the pseudo-inlet quality, $x_{\mathrm{i},*}$. If the pressure drop across the heated length is relatively small, then the inlet and outlet pressures are approximately equal as are the pseudo- and true-inlet qualities. Substitution of Eq. (10) into the outlet conditions correlation (Eq. (7)) yields an inlet conditions correlation,

$$Bo = \frac{C_1 We_D^{C_2}\left(\rho_\mathrm{f}/\rho_\mathrm{g}\right)^{C_3}\left[1 - C_4\left(\rho_\mathrm{f}/\rho_\mathrm{g}\right)^{C_5} x_{\mathrm{i},*}\right]}{1 + 4C_1C_4 We_D^{C_2}\left(\rho_\mathrm{f}/\rho_\mathrm{g}\right)^{C_3+C_5}(L/D)}, \tag{11}$$

where all saturated thermophysical properties are evaluated at the outlet pressure. Note that this correlation does not require knowledge of the inlet pressure. While the inlet conditions correlation exhibits the effect of L/D on CHF, the outlet conditions correlation does not show the effect of L/D since this correlation hypothesizes that CHF is only a function of local conditions at CHF and unaffected by heated length.

3.4. Optimization of correlation

In sharp contrast to other correlations, these new, dimensionless CHF correlations each consist of a single equation having only five adjustable constants. As shown in a preceding section and Ref. [78], the constants appearing in Eqs. (7) and (11) were systematically determined from parametric trends observed in less than 10% of the subcooled CHF data and not nonlinear regression with the entire database. This subset contained only data obtained at high mass velocities ($G \geq 5000$ kg m^{-2} s^{-1}) in small diameter tubes ($D \leq 2 \times 10^{-3}$ m), often resulting in high-CHF values above 25 MW m^{-2}, and was not representative of the entire subcooled CHF database. Consequently, an analysis of these correlations with the entire subcooled CHF database should yield optimal values of the constants which are slightly different than the original values even though the functional forms of the correlations remain unchanged. The subcooled CHF database contains data having a much larger range of diameters and mass velocities than the small subset of data utilized in the development of the high-CHF correlations. In the present study, nonlinear regression was utilized with both the inlet and outlet conditions correlations to determine a new set of constants which minimized their RMS error.

Table 3 shows the mean error, mean absolute error, and RMS error for both the inlet and outlet conditions correlations using (a) the entire subcooled CHF database (4860 data points) and (b) a large subset of the subcooled CHF database having an outlet quality less than −0.05 (3202 data points or two-thirds of the database). The second case was utilized since the outlet conditions correlation with the original constants yielded much higher errors for near-saturated conditions, indicating a possible transition in the CHF trigger mechanism [78]. Four sets of constants were utilized in each case: (1) original constants [78], (2) constants obtained by optimizing the outlet conditions correlation (Eq. (7)) with the entire database, (3) constants obtained by optimizing the outlet conditions correlation (Eq. (7)) with data having an outlet quality less than −0.05, and (4) constants obtained by optimizing the inlet conditions correlation (Eq. (11)) with the entire database. The four sets of constants were employed with both the inlet and outlet conditions correlations.

Table 3(a) reveals that the constants, obtained by optimizing the inlet conditions correlation with the entire database, also yield nearly the lowest mean absolute error for the outlet conditions correlation. These constants produce the mean error closest to zero for both correlations, indicating that the correlations are only slightly more likely to underpredict CHF than they are to overpredict CHF. In each instance, the optimized constants yield correlations more accurate than those obtained with the original constants. Table 3(b) indicates that the constants, obtained by optimizing the inlet conditions correlation with the entire database, yield the lowest mean absolute error and RMS error for the inlet conditions correlation and data having an outlet quality less than −0.05. These constants also produce a mean absolute error and RMS error for the outlet conditions correlation that are similar to those obtained with constants optimized specifically for the outlet conditions correlation and outlet quality less than −0.05; the mean error actually exhibits a substantial improvement. Thus, the constants, obtained by optimizing the inlet conditions correlation with the entire database, are recommended for use with both the inlet and outlet conditions correlations. This eliminates the complications arising from the use of a different set of constants for each type of correlation.

The exponent of the Weber number, C_2, governs the effect of mass velocity on CHF, one of the more important factors affecting CHF, the other being the quality. Notice that the value of this constant changes slightly between the different cases. The other constants change somewhat more, partially in response to the change in C_2. Fig. 1 shows the effect of the Weber number exponent on RMS error for the inlet conditions correlation when the exponent is fixed prior to optimization of the remaining constants. The optimal value of C_2 yields an RMS error of 14.3% while non-optimal values within 20% of the optimal value still yield an RMS error below 15%. Thus, slight changes in the value of C_2 will not significantly alter the accuracy of the correlation. Furthermore, re-optimization of the constants when additional subcooled CHF data become available is not warranted since an improvement in the accuracy of the correlation is unlikely. Of course, the correlation should be tested with these new data so that the parametric range of the correlation can be expanded.

The inlet conditions correlation is recommended for predicting subcooled CHF for flow in a uniformly heated tube since it yields the lowest error values for any set of constants when compared with the outlet conditions correlation. CHF occurs at the outlet of a uniformly heated tube, but it often occurs upstream of the outlet when the axial heat flux profile is nonuniform as is often the case with nuclear reactor fuel elements. Thus, only the outlet (local) conditions correlation, which depends solely upon the flow conditions at the location of burnout, is well suited for predicting CHF in a tube having a nonuniform axial heat flux profile (see Ref. [78]). The mean absolute error and RMS error for the outlet conditions correlation are reduced by 17% and 12%, respectively, when the near-saturated data having an outlet quality greater than −0.05 (approximately one-third of the subcooled CHF database) are excluded; thus, the outlet conditions correlation is recommended for use only outside of this near-saturated region. The final correlations are summarized in Table 4 along with the recommended parametric range for each correlation. The parametric ranges differ only in the range of outlet quality and in the specification of a range for the heated length-to-diameter ratio and inlet quality only for the inlet conditions correlation. The range of each

Table 3

Assessment of inlet and outlet conditions, subcooled CHF correlations developed by the authors of the present study using (a) entire subcooled CHF database (4860 data points) and (b) subset of subcooled CHF database having an outlet quality less than −0.05 (3202 data points)

Source of constants	C_1	C_2	C_3	C_4	C_5	Outlet conditions, subcooled CHF correlation, Eq. (7)			Inlet conditions, subcooled CHF correlation, Eq. (11)[a]		
						Mean error (%)	Mean absolute error (%)	RMS error (%)	Mean error (%)	Mean absolute error (%)	RMS error (%)
(a) Entire subcooled CHF database (4860 data points)											
Hall and Mudawar [78]	0.0332	−0.235	−0.681	0.684	0.832	−10.9	24.2	31.6	−5.5	12.1	16.1
Optimized outlet conditions correlation	0.0322	−0.252	−0.542	0.941	0.631	−8.6	22.1	29.7	−5.3	11.5	15.4
Optimized outlet conditions correlation ($x_o < -0.05$)	0.0260	−0.256	−0.432	1.369	0.482	−5.9	22.8	30.8	−4.1	11.8	15.9
Optimized inlet conditions correlation[b]	0.0722	−0.312	−0.644	0.900	0.724	−2.1	22.3	31.6	−2.0	10.3	14.3
(b) Subset of subcooled CHF database having an outlet quality less than −0.05 (3202 data points)											
Hall and Mudawar [78]	0.0332	−0.235	−0.681	0.684	0.832	−4.7	20.5	27.2	−2.7	11.4	15.2
Optimized outlet conditions correlation	0.0322	−0.252	−0.542	0.941	0.631	−6.3	18.6	25.2	−4.3	10.6	14.0
Optimized outlet conditions correlation ($x_o < -0.05$)	0.0260	−0.256	−0.432	1.369	0.482	−5.9	18.3	25.0	−4.0	10.5	14.1
Optimized inlet conditions correlation[b]	0.0722	−0.312	−0.644	0.900	0.724	1.7	18.5	27.7	−0.2	9.6	13.5

[a] Subcooled CHF correlation recommended by the authors of the present study for use with water flow in a uniformly heated tube.

[b] Constants recommended by the authors of the present study for use in both the inlet and outlet conditions, subcooled CHF correlations.

parameter for the inlet conditions correlation was chosen so as to include those regions where data were most abundant, containing approximately 85% of the subcooled CHF database. This restriction does not mean that the correlation is inaccurate outside of the parameter range, only that sufficient data were unavailable for validating the correlation.

4. Statistical assessment of CHF correlations

In this section, a detailed methodology for evaluation of the subcooled CHF correlations is outlined. The results obtained from a statistical analysis of all correlations identify the optimized, inlet conditions correlation from the present study (see Table 4) as the most accurate subcooled CHF correlation for water flow in a uniformly heated tube.

4.1. Methodology

The present study utilized the following methodology in assessing the predictive capabilities of the subcooled CHF correlations:

1. Thermophysical properties of water were evaluated at the temperature specified by the correlation using published equations or equations developed by the authors of the present study from published data (see Ref. [152] for details). These equations accurately predict the given property from the triple point to near the critical point of water.
2. If a function appearing in a correlation was presented only in graphical form [8,17,76], then the authors of the present study developed curve-fits for these functions so that the evaluation of the correlation could be automated (see Refs. [79,80] for details).
3. The inlet parameter (e.g., inlet quality or subcooling) required by an inlet conditions correlation was determined from the inlet temperature associated with the CHF data point. Definitions for quality and subcooling are given in the Nomenclature.
4. The outlet parameter (e.g., outlet quality or subcooling) required by an outlet conditions correlation was determined by first calculating the outlet enthalpy associated with the CHF data point using an energy balance (Eq. (8)) and then employing the appropriate definition given in the Nomenclature. An outlet parameter calculated in this manner corresponds to the actual experimental condition associated with the CHF data point. CHF was predicted with an outlet conditions correlation by simply substituting the value of the parameter directly into the correlation. The debate over using this direct substitution method rather than an energy (heat) balance method has been discussed by the present authors in a prior publication [153] as well as by many others [126,128,154–159] and will not be repeated here. The energy balance method utilizes numerical iteration to adjust the value of the outlet parameter so that both the predicted CHF and predicted outlet parameter (not equal to that associated with the CHF data point) simultaneously satisfy an energy balance and the correlation. Siman-Tov [160] provided an especially noteworthy discussion on this issue which is in complete agreement with the opinions of the present authors.
5. An underpredicted CHF does not violate any conditions, but, occasionally, an outlet conditions correlation may overpredict CHF and yield an inlet temperature below the triple-point temperature (0.01°C for water) when the inlet temperature is calculated using the predicted CHF, experimental outlet quality, and an energy balance. If the absolute error was rather large, this signifies that the exper-

C_1	C_2	C_3	C_4	C_5	RMS Error
0.301	-0.440	-0.771	0.986	0.802	16.6
0.242	-0.420	-0.750	0.970	0.789	16.0
0.193	-0.400	-0.729	0.955	0.776	15.5
0.155	-0.380	-0.708	0.941	0.764	15.0
0.124	-0.360	-0.689	0.928	0.752	14.7
0.0990	-0.340	-0.670	0.916	0.740	14.4
0.0791	-0.320	-0.651	0.906	0.728	14.3
0.0631	-0.300	-0.633	0.898	0.717	14.3
0.0502	-0.280	-0.615	0.891	0.706	14.5
0.0400	-0.260	-0.597	0.887	0.695	14.8
0.0318	-0.240	-0.579	0.884	0.683	15.3
0.0252	-0.220	-0.562	0.884	0.672	15.9
0.0199	-0.200	-0.545	0.887	0.660	16.6

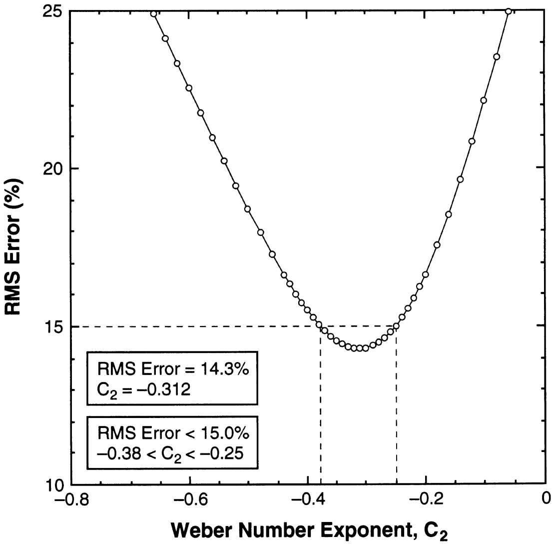


Fig. 1. Effect of Weber number exponent (fixed before optimization of remaining constants) on RMS error for the inlet conditions, subcooled CHF correlation.

imental inlet temperature was well below the triple-point and the correlation did a poor job of predicting CHF. If the error was small, then the experimental inlet temperature was only slightly higher than the triple-point and the correlation performed quite well. The present authors decided that the extra effort to account for this anomaly was not warranted since the poor performance of a correlation experiencing a multitude of these violations would be illustrated by its higher error.

6. Occasionally, an inlet conditions correlation may overpredict CHF and yield a positive outlet quality, indicating saturated fluid at the outlet, when the outlet quality is calculated using the predicted CHF, experimental inlet temperature, and an energy balance. This would seem inappropriate since the correlation is applicable only to CHF with subcooled flow at the outlet. However, the CHF trends exhibited in low-quality CHF are probably quite similar to the trends observed in subcooled CHF near saturation. Thus, a correlation based on observed parametric trends such as that developed in the present study may be able to accurately predict positive low-quality CHF as well as subcooled CHF. This apparent violation was also not recorded for reasons similar to those discussed in the preceding paragraph.
7. Correlations were identified as unusable for the following reasons (see Refs. [79,80] for details): (a) The correlation specified a different set of constants for different, discrete values of a parameter (instead of a continuous function of that parameter) and, thus, could not predict CHF for values of the parameter without known constants [4,6,27]. (b) The correlation consistently predicted CHF values several orders of magnitude below or above the corresponding experimental CHF values [8,50] or predicted CHF values inconsistent with those of the authors of the correlation [60]. (c) The correlation required both an inlet and outlet condition in the same equation and, thus, was inconsistent with an energy balance [28,37,40]. (d) The correlation did not exhibit the effect of either inlet or outlet quality (or subcooling) on CHF [41,60]. (e) The authors of the correlation provided insufficient or inaccurate information for evaluating a quantity required by the correlation [46,56,64,73]. (f) The correlation predicted negative CHF values for a majority of the data that were outside of the parametric range specified by the correlation [55,67].
8. Correlations were identified as partially unusable if the correlation could not predict CHF for a minority of the data that were outside of the parametric range specified by the correlation (see Refs. [79,80] for details). Error values pertain only to those CHF data for which the correlation predicts a positive CHF [16] and for which the parameters calculated by the correlation (such as wall superheat [14,26], heat flux at onset of nucleate boiling [23], and void fraction [44,49]) have realistic values.
9. Mean error, mean absolute error, and RMS error of

Table 4
Optimized subcooled CHF correlations developed in the present study[a,b]

Correlation	Equation	Constants
Outlet[a]	$Bo = C_1 We_D^{C_2}\left(\dfrac{\rho_f}{\rho_g}\right)^{C_3}\left[1 - C_4\left(\dfrac{\rho_f}{\rho_g}\right)^{C_5} x_o\right]$	$C_1 = 0.0722$ $C_2 = -0.312$ $C_3 = -0.644$
Inlet (recommended)[a,b]	$Bo = \dfrac{C_1 We_D^{C_2}(\rho_f/\rho_g)^{C_3}\left[1 - C_4(\rho_f/\rho_g)^{C_5} x_{i,*}\right]}{1 + 4C_1C_4 We_D^{C_2}\left(\dfrac{\rho_f}{\rho_g}\right)^{C_3+C_5}\left(\dfrac{L}{D}\right)}$	$C_4 = 0.900$ $C_5 = 0.724$

Parametric range

Correlation	$D \times 10^3$ (m)	L/D	$G \times 10^{-3}$ (kg m^{-2} s^{-1})	$P \times 10^{-5}$ (N m^{-2})	x_i	x_o
Outlet	0.25		0.3	1		−1.00
	15.0		30.0	200		−0.05
Inlet	0.25	2	0.3	1	−2.00	−1.00
	15.0	200	30.0	200	0.00	0.00

[a] Saturated thermophysical properties are evaluated at the pressure corresponding to the CHF location (i.e., end of the heated length for a uniformly heated tube).

the correlations were defined as

$$\text{mean error} = \frac{1}{N}\sum \frac{q_{m,\text{pred}} - q_{m,\text{meas}}}{q_{m,\text{meas}}} \times 100\%, \quad (12)$$

mean absolute error

$$= \frac{1}{N}\sum \frac{|q_{m,\text{pred}} - q_{m,\text{meas}}|}{q_{m,\text{meas}}} \times 100\%, \quad (13)$$

and

$$\text{RMS error} = \sqrt{\frac{1}{N}\sum\left(\frac{q_{m,\text{pred}} - q_{m,\text{meas}}}{q_{m,\text{meas}}}\right)^2} \times 100\%, \quad (14)$$

where N is the number of CHF data points. The mean error provides an indication as to whether a correlation is more likely to underpredict or overpredict CHF. The mean absolute error treats the absolute error from each data point equally. On the other hand, RMS error assigns greater weight to those predictions exhibiting larger deviations from the experimental value.

4.2. Results

Table 5 lists the mean error, mean absolute error, and RMS error for each correlation when evaluated with the subcooled CHF database and the subcooled CHF data within the parametric range specified by the correlation. A dash indicates that a correlation was unusable for one of the reasons listed in the preceding section. As expected, most correlations had lower mean absolute and RMS errors when evaluated with subcooled CHF data only within their parametric range. This emphasizes the principle of not extrapolating a correlation beyond its specified parametric range. Correlations having small parametric ranges often had mean absolute and RMS errors lower than those having larger parametric ranges since the small parametric range often only contained the data that were used to develop the correlation. The optimized, inlet conditions correlation developed in the present study (see Table 4) had the lowest mean absolute and RMS errors of all subcooled CHF correlations. Remarkably, the inlet conditions correlation previously developed by the present authors for high-CHF conditions [78], whose constants were systematically determined from parametric trends observed in less than 10% of the subcooled CHF database and not nonlinear regression with the entire database, had the next lowest error values.

Fig. 2 shows the mean error and standard deviation from the mean error for the 25 most accurate correlations in order of increasing mean absolute error. By definition, CHF predictions for 68% of the data will have errors which lie within a standard deviation from the mean error. Error values for the inlet and outlet conditions correlations with original (nonoptimized) constants [78] are listed in Table 5, but not included in Fig. 2 since the correlations with optimized constants (see Table 4) supersede these earlier correlations. Surprisingly, the first subcooled CHF correlation ever developed for water flow in a uniformly heated tube [2], which consisted of only one equation and three adjustable constants, was ranked 21st out of the 77 correlations. The inlet conditions correlation developed in the present study (see Table 4), whose constants were optimized using nonlinear regression with the entire subcooled CHF database, had a mean error near zero and the smallest standard deviation among all correlations. The mean absolute error (10.3%) and RMS error (14.3%) for this inlet conditions correlation were both 41% lower than those of the next most accurate correlation [65], not including those previously developed by the present authors. The optimized, outlet conditions correlation developed in the present study (see Table 4) also had a mean error near zero and the smallest standard deviation among all correlations based on outlet conditions. The mean absolute error and RMS error for this outlet conditions correlation were 20% and 15%, respectively, lower than those of the next most accurate correlation based on outlet conditions [75], not including those previously developed by the present authors.

5. Supplemental discussion

5.1. Analysis of inlet conditions correlation

The inlet conditions correlation developed in the present study (see Table 4), whose constants were optimized using nonlinear regression with the entire subcooled CHF database, was shown in the previous section to be the most accurate of all subcooled CHF correlations. However, before the final optimization of the constants in the inlet conditions correlation, the inlet conditions correlation with the original constants (based on high-CHF data) was utilized to identify questionable data sets. The mean absolute error for this correlation was calculated for each data source containing subcooled CHF data. The 110 data points from Mayinger et al. [161] had, by far, the worst mean error (−41.4%) and largest mean absolute error (41.4%) of any of the data sources. A comparison of these data with similar data from other sources

Table 5
Assessment of the subcooled CHF correlations

Subcooled CHF correlation	Subcooled CHF data within parametric range of correlation[a]				Subcooled CHF database (4860 acceptable data points)		
	No. of data points	Mean error (%)	Mean absolute error (%)	RMS error (%)	Mean error (%)	Mean absolute error (%)	RMS error (%)
Buchberg et al. [2]	37	1.1	6.0	8.4	−8.9	37.6	47.4
Gunther [3]	771	−35.5	39.0	45.4	−35.1	49.3	58.2
Jens and Lottes [4][b]	79	−5.1	9.4	12.6	–	–	–
McGill and Sibbitt [5]	27	0.4	17.7	25.6	22.5	45.9	63.5
Epstein et al. [6][b]	53	−1.9	6.7	8.1	–	–	–
Hoe and Senghaus [7]	98	−0.3	10.0	13.0	−11.5	42.3	52.8
Griffith [8][b]	–	–	–	–	–	–	–
Longo [9]	20	3.5	12.1	16.0	−15.9	51.4	67.9
Gambill and Greene [10]	218	−43.4	46.5	53.3	−64.8	67.8	72.2
Green et al. [11]	681	−4.1	13.8	17.5	1138.2	1146.0	6884.3
Menegus [12]	1213	9.4	27.2	36.1	53.1	73.7	196.7
Sonnemann [13]	202	−7.7	10.1	12.5	−6.9	24.2	30.6
Bernath [14][c]	3931	3.5	31.1	43.3	16.7	40.4	59.5
Ivashkevich [15]	3629	1.3	31.6	39.3	−3.5	34.8	42.8
Jacobs and Merrill [16][c]	667	9.5	18.5	26.3	666.2	674.6	4107.9
Povarnin and Semenov [17]	2954	9.3	23.7	31.5	7.1	30.4	42.6
Labuntsov [18]	4677	21.1	40.9	56.9	19.0	41.0	56.6
Miropol'skii and Shitsman [19]	1198	4.9	17.9	28.3	138.4	149.3	288.7
Torikai et al. [20]	2660	2.1	31.3	41.8	−10.7	37.4	47.8
Levedahl [21]	4625	13.2	42.9	81.0	12.1	42.4	79.4
Levy [22]	3062	2.1	24.3	32.7	−1.1	28.0	37.6
Michiyoshi and Matsumoto [23][c]	1442	24.0	40.5	61.5	25.1	41.7	60.3
Ornatskii and Kichigin [24]	226	0.3	11.3	14.1	−9.7	37.2	46.3
Chang [25]	10	12.7	12.7	15.0	−40.6	43.8	49.7
Gambill [26][c]	4759	6.3	39.7	49.3	5.7	39.7	49.3
Shitsman [27][b]	366	3.5	24.8	38.2	–	–	–
Tong et al. [28][b]	–	–	–	–	–	–	–
Weatherhead [29]	3802	34.2	49.9	79.3	70.1	83.2	129.1
Ryabov and Berzina [30]	960	8.8	17.0	25.2	3.2	30.2	43.8
Shtokolov [31]	958	14.3	32.8	41.1	19.7	46.1	58.6
Wilson and Ferrell [32]	585	2.1	13.0	16.1	28.6	39.3	59.1
Zenkevich [33]	3208	17.5	32.7	44.2	6.2	33.6	43.8
Griffel and Bonilla [34]	1407	−16.7	25.7	30.9	−11.5	41.4	55.4
Ornatskii and Vinyarskii [35]	102	−4.2	5.8	8.6	131.9	156.9	242.5
Skinner and Loosmore [36]	380	60.9	67.7	110.0	28.2	47.2	71.5
Tong [37][b]	–	–	–	–	–	–	–
Tong [38]	180	−5.8	16.3	18.5	108.4	117.8	189.8
Glushchenko [39]	1451	−0.3	22.2	30.2	−15.2	35.0	43.9
Ornatskii et al. [40][b]	–	–	–	–	–	–	–
Vasil'yev and Kirillov [41][b]	–	–	–	–	–	–	–
Becker et al. [42]	155	−4.8	5.7	6.4	−39.7	40.1	46.9
Bowring [43]	2805	11.4	21.0	33.8	−2.5	30.9	43.3
Purcupile and Gouse [44][c]	911	−2.5	13.4	16.7	120.3	132.7	255.9
Ahmad [45]	2510	505.0	505.0	662.0	456.1	456.2	639.2
Hancox and Nicoll [46][b]	–	–	–	–	–	–	–
Thorgerson et al. [47]	259	62.8	67.3	99.5	12.4	78.5	107.2
Levitan and Lantsman [48]	1613	−3.4	13.8	18.6	927.7	951.0	31070.5
Tong [49][c]	651	−28.3	28.5	31.7	17.4	62.0	97.3
Chernobai [50][b]	–	–	–	–	–	–	–

Table 5 (*continued*)

Subcooled CHF correlation	Subcooled CHF data within parametric range of correlation[a]				Subcooled CHF database (4860 acceptable data points)		
	No. of data points	Mean error (%)	Mean absolute error (%)	RMS error (%)	Mean error (%)	Mean absolute error (%)	RMS error (%)
Koba et al. [51]	589	91.8	91.8	104.7	175.1	175.1	305.2
Bergel'son et al. [52]	229	69.9	72.0	86.0	149.5	152.1	182.1
Hebel et al. [53]	1025	−5.6	11.8	15.5	−2.3	29.0	45.9
Ivashkevich [54]	146	10.2	11.5	14.5	132.2	136.7	245.8
Smogalev [55][b]	1	19.4	19.4	19.4	–	–	–
Sapankevich [56][b]	–	–	–	–	–	–	–
Inasaka and Nariai [57]	2573	6.5	34.4	46.1	30.5	52.7	94.8
Shah [58]	4106	32.5	38.6	83.1	27.2	36.2	77.5
Avksentyuk [59]	2970	32.8	40.1	68.1	29.3	37.2	60.9
Boyd [60][b]	–	–	–	–	–	–	–
Boyd [60][b]	–	–	–	–	–	–	–
Gambill and Mochizuki [61]	1871	7.4	33.8	42.8	−25.8	50.6	58.9
Gromova et al. [62]	1857	6.6	13.9	18.8	61.0	66.9	138.6
Siman-Tov et al. [63]	1778	8.1	32.4	45.6	12.1	37.4	50.7
Vasil'yev [64][b]	–	–	–	–	–	–	–
Caira et al. [65]	1480	−7.6	16.6	20.5	−0.7	17.5	24.4
Celata et al. [66]	1480	−41.9	44.3	47.8	−7.7	38.9	49.9
Vandervort et al. [67][b]	889	−18.9	40.1	49.1	–	–	–
Caira et al. [68], Caruso [69]	1480	4.2	15.3	24.3	62.4	71.0	125.1
Hechanova et al. [70]	551	−28.8	29.4	32.5	50.8	87.6	162.3
Lombardi [71]	4792	5.6	17.4	28.6	5.3	17.6	29.1
Pernica and Cizek [72]	2590	43.6	47.9	91.3	40.1	48.5	82.5
Jafri et al. [73][b]	–	–	–	–	–	–	–
Kabata et al. [74]	20	14.2	15.1	18.6	−29.9	39.4	47.2
Yagov et al. [75]	564	11.3	20.3	27.0	3.4	27.7	37.0
Zeigarnik et al. [76]	656	6.2	20.5	31.2	58.5	68.3	111.2
Boscary et al. [77]	2570	6.8	32.9	48.9	15.0	34.7	78.3
Hall and Mudawar [78]	2710	−2.3	19.8	26.7	−11.0	24.2	31.6
Hall and Mudawar [78]	3282	−5.0	13.5	17.5	−5.5	12.1	16.1
Present study (see Table 4)	2809	2.6	18.7	28.6	−2.1	22.3	31.6
Present study (see Table 4)	4147	−2.0	10.3	14.4	−2.0	10.3	14.3

[a] See Refs. [79,80] for parametric range of each correlation.

[b] See Refs. [79,80] for justification of an unusable subcooled CHF correlation.

[c] See Refs. [79,80] for justification of a partially unusable subcooled CHF correlation. Error values pertain only to those CHF data for which the correlation predicts a positive CHF and for which the parameters calculated by the correlation (such as heat flux at onset of nucleate boiling, wall superheat, and void fraction) have realistic values.

revealed that the Mayinger et al. data were, indeed, questionable. The mean absolute error of 108 data points from Mayinger et al. having diameters between 6 and 7 mm was 41.8% compared with 112 other data points having an error of 8.1%. Furthermore, the mean absolute error of 102 data points from Mayinger et al. having $L/D \leq 10$ was 43.2% compared with 143 other data points having an error of 19.9%. Also, of the 1064 CHF data points tabulated in Mayinger et al., over half were identified by Mayinger et al. as premature CHF. Thus, the test section fabrication procedure or the experimental apparatus or methods employed by Mayinger et al. may have led to inaccurate CHF measurements and even the data labeled as non-premature CHF may be questionable. Consequently, the optimization of the constants in the inlet conditions correlation as well as all statistical analyses presented in this study were conducted without the subcooled CHF data from Mayinger et al.

Fig. 3(a–i) show the distribution of data within the subcooled CHF database and the mean error and standard deviation from the mean error for the optimized, inlet conditions correlation (see Table 4). The bar charts in Fig. 3(a–i) show the distribution of data within the subcooled CHF database based on diameter, heated length-to-diameter ratio, mass velocity, pressure, inlet subcooling, inlet quality, outlet subcooling, outlet quality, and critical heat flux, respectively. Two bar charts are shown for each parameter except inlet subcooling. The main bar chart shows the distribution of data over the entire range of that parameter. The secondary bar chart shows the distribution of data using a smaller bin width and over a much smaller range corresponding to the longest bars from the main chart. Data points obtained with a value of a parameter corresponding to the upper boundary of a bin are always included within that bin. In some cases, the number of data points within a bin is so small that a bar is not visible. In other cases, the number of data points within a bin exceeds the maximum value of the ordinate and must be noted next to the bar. The mean error and standard deviation from the mean error is shown above the bar charts for each bin in which CHF data exist. The mean error deviates farthest from zero and the standard deviation is largest for those bins in which few data exist. The mean error plus or minus the standard deviation rarely exceeded ±20% in the main chart unless less than 20 data points (0.4% of the subcooled CHF database) existed within a bin. These bins were always close to the upper or lower limit for a parameter. Fig. 3(a–i) also aided in the selection of a parametric range (shown in Table 4) for

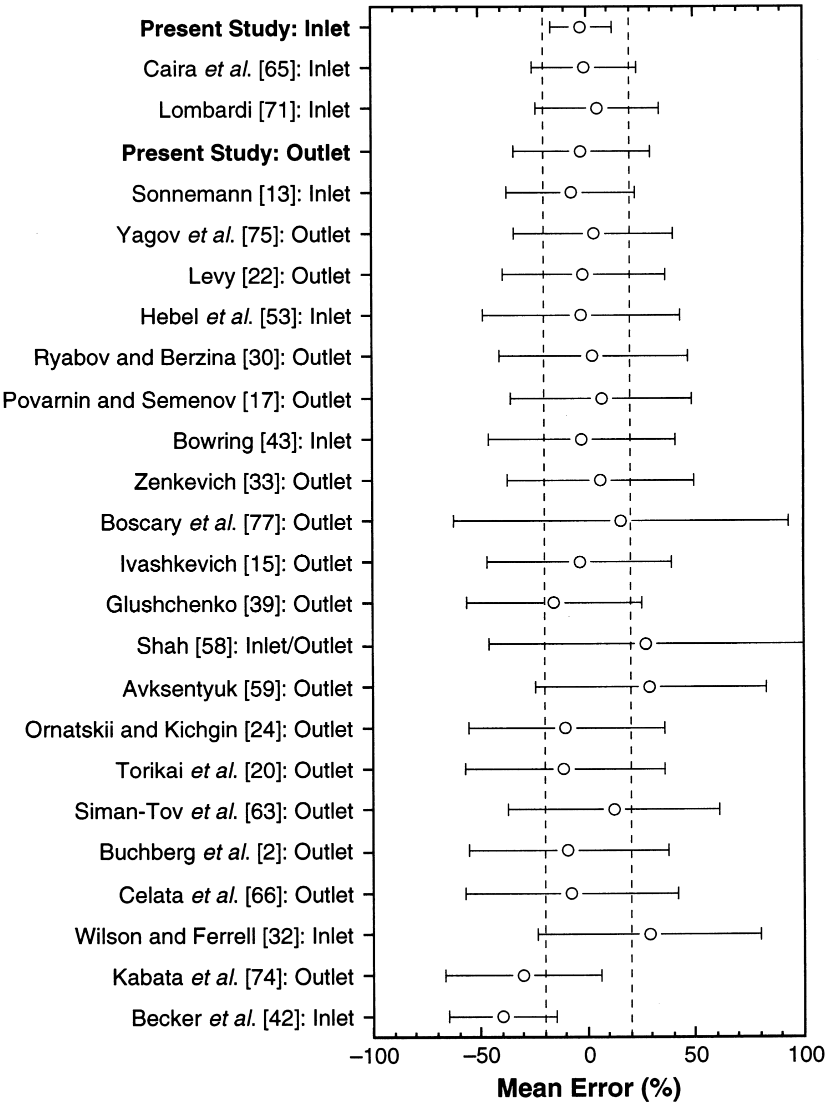


Fig. 2. Mean error and standard deviation for the 25 most accurate subcooled CHF correlations in order of increasing mean absolute error.

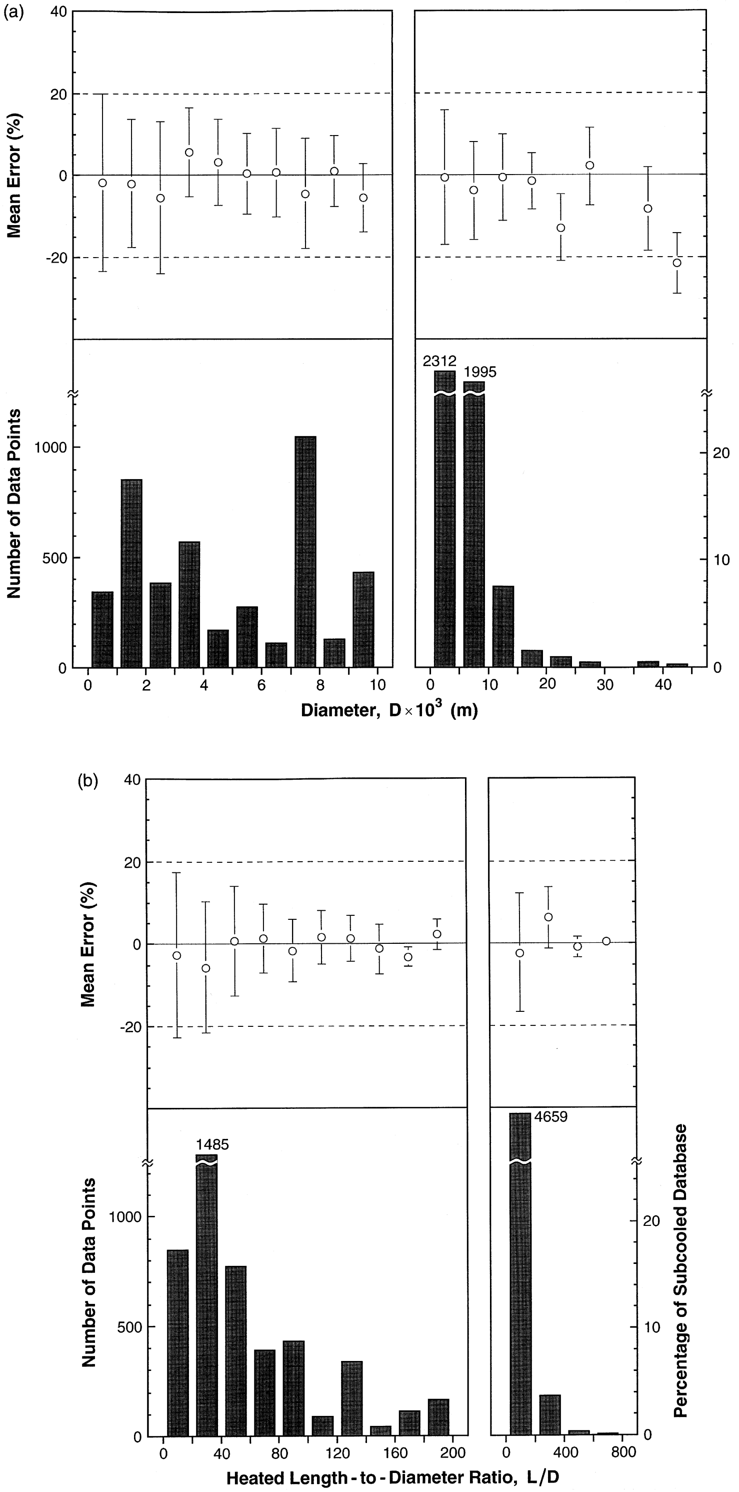


Fig. 3. Distribution of subcooled data in the PU-BTPFL CHF database and mean error and standard deviation for the optimized, inlet conditions, subcooled CHF correlation: (a) diameter, (b) heated length-to-diameter ratio, (c) mass velocity, (d) pressure, (e) inlet subcooling, (f) inlet quality, (g) outlet subcooling, (h) outlet quality, and (i) critical heat flux.

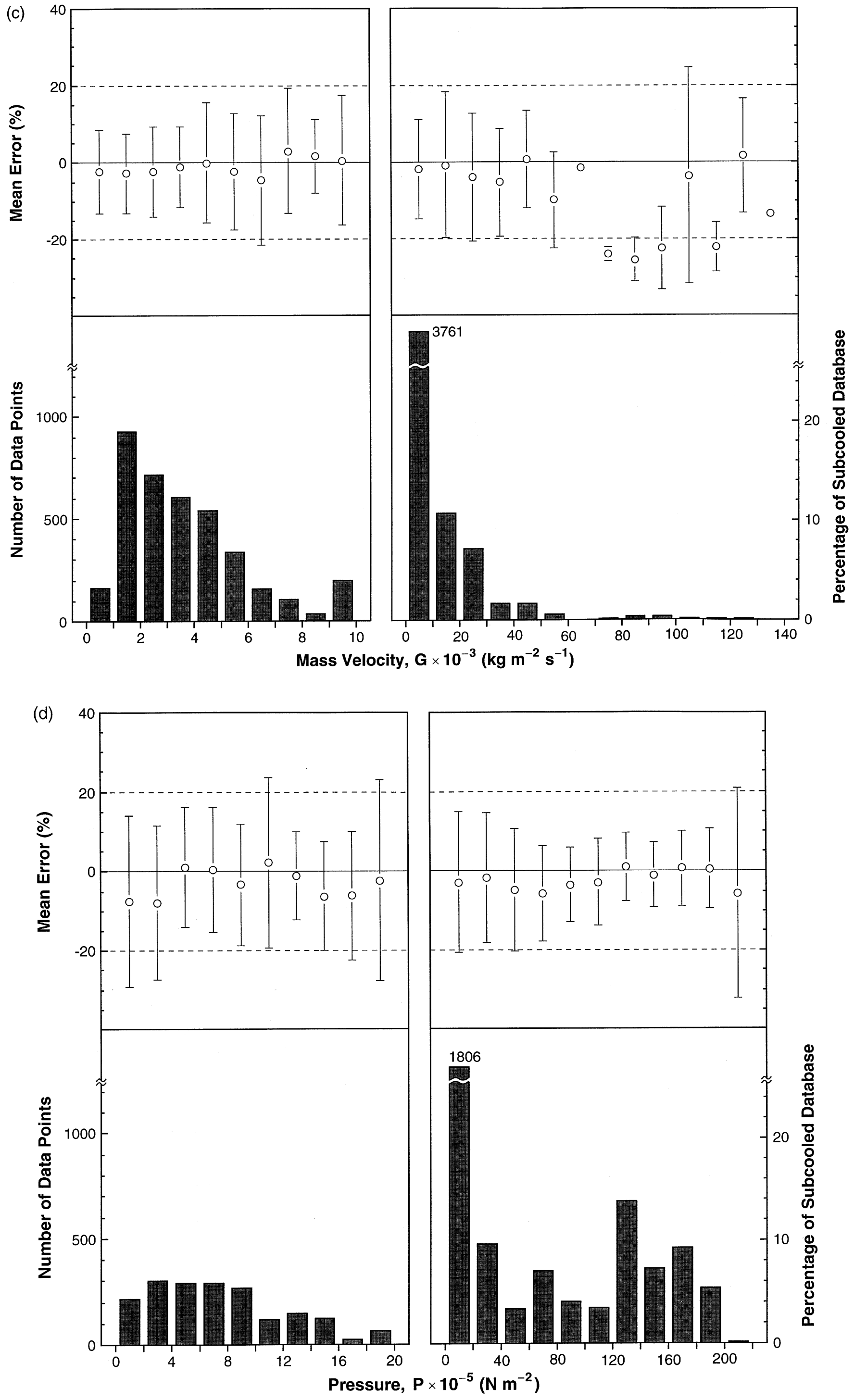


Fig. 3 (*continued*)

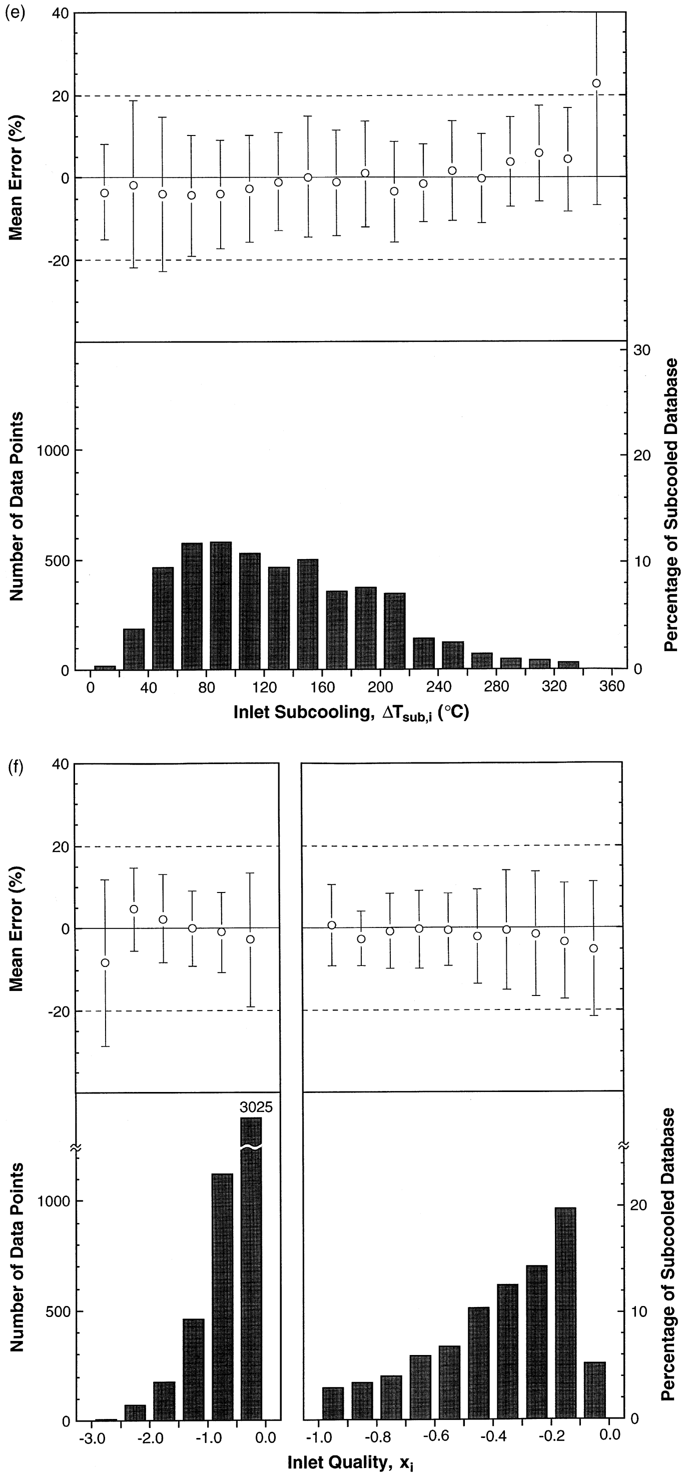


Fig. 3 (*continued*)

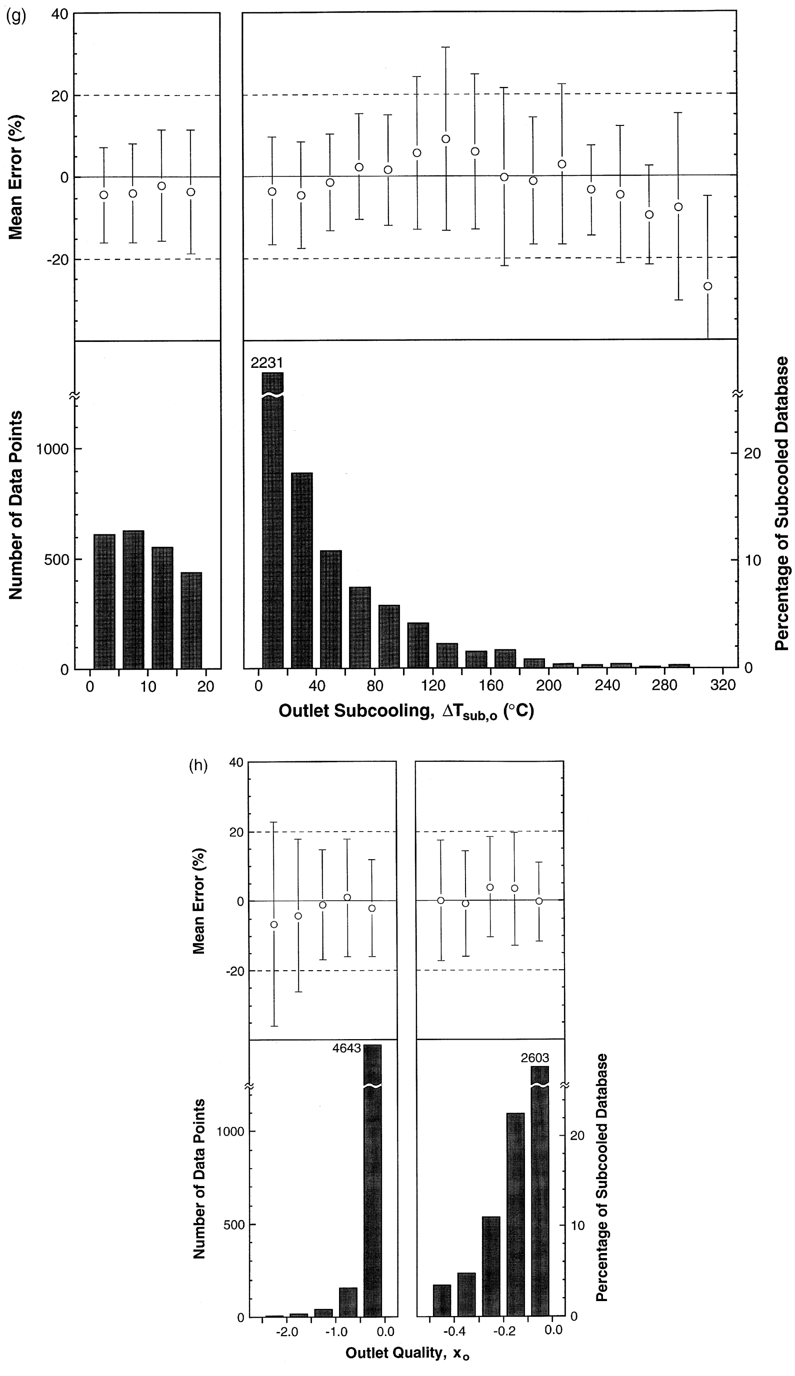


Fig. 3 (*continued*)

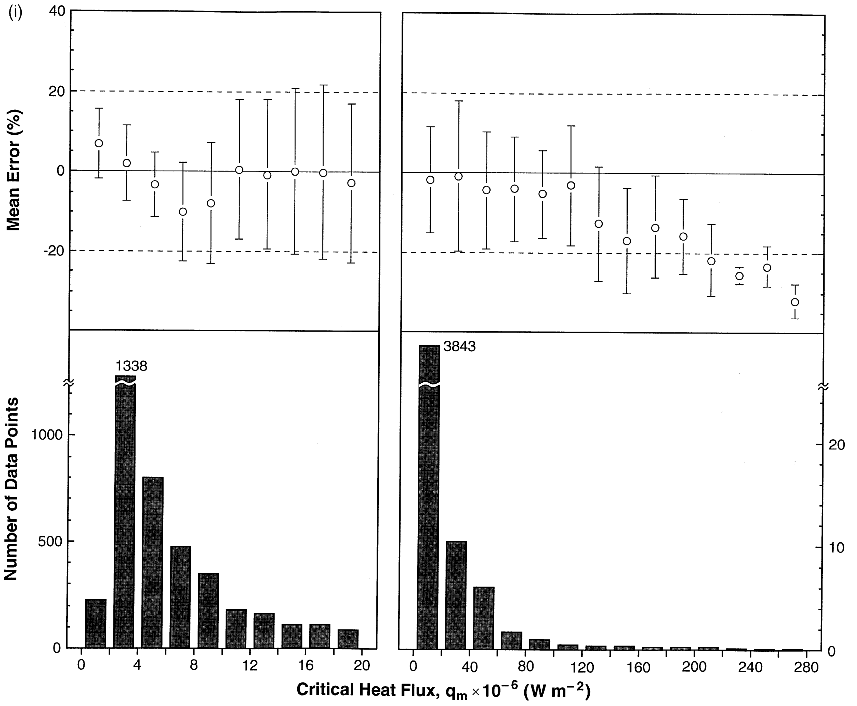


Fig. 3 (*continued*)

the correlations by identifying those regions where data are most abundant and the standard deviation is relatively small. Overall, the inlet conditions correlation performed quite well within most bins, indicating that the accuracy does not vary significant within the parametric range of the correlation.

Fig. 4(a–i) show the ratio of predicted CHF to measured CHF versus diameter, heated length-to-diameter ratio, mass velocity, pressure, inlet subcooling, inlet quality, outlet subcooling, outlet quality, and measured critical heat flux, respectively. The plots are somewhat deceiving, since a substantial amount of data often exists in the dense regions. In fact, less than 5% of the subcooled CHF database had an error outside of ±30%. The correlation underpredicted CHF for large diameters, high mass velocities, and high measured critical heat fluxes, indicating a sizable negative mean error in these regions which happen to contain few data; this was also observed in Fig. 3(a, c, i). Note that these regions are not within the parametric range specified for these correlations (see Table 4). In other regions, especially those containing many data, the correlation did not have a tendency to either substantially overpredict or underpredict CHF.

Fig. 5(a) shows CHF predicted with the optimized, inlet conditions correlation (see Table 4) versus measured CHF. Recall that this inlet conditions correlation had the lowest mean absolute error (10.3%) and RMS error (14.3%) of all correlations and also had a near zero mean error (−2.0%). The data outside of the ±30% deviation lines do not share any common characteristics (experimental conditions or data source) and their larger deviations seem random. Fig. 5(b) shows that a histogram of the prediction errors is similar to a normal (Gaussian) distribution. The skewness and kurtosis of the error distribution were 0.367 and 2.94, respectively, indicating that the distribution is only slightly shifted and that a larger portion of error values are near the mean error than for a normal distribution. Both Fig. 5(a–b) indicate an absence of systematic measurement errors in the subcooled CHF database and an absence of a fundamental defect in the correlation. In fact, the mean absolute and RMS errors of the inlet conditions correlation are actually less than the uncertainty in a CHF measurement. Tong [107] estimated the total uncertainty as ±18% with ±3% due to the statistical nature of flow turbulences and surface roughness, ±5% due to fabrication tolerances of test sections, and ±10% due to random errors in CHF detection instrumentation and flow loop characteristics. The latter contribution would be a systematic error for a given data source, but a random error for the database since the number of data sources is large. Thus, the acquisition of additional data and re-

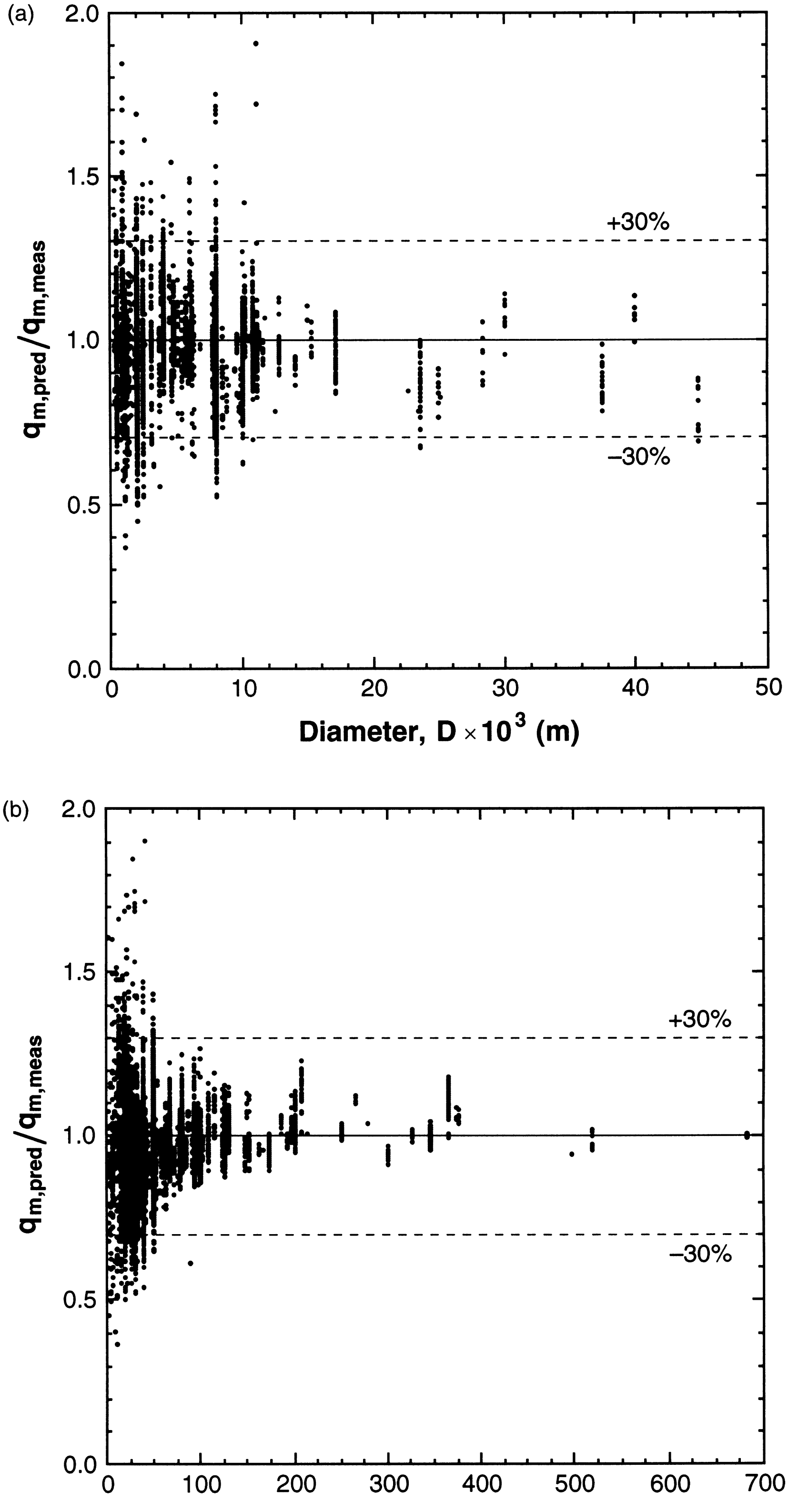


Fig. 4. Ratio of predicted CHF (optimized, inlet conditions, subcooled CHF correlation) to measured CHF vs. (a) diameter, (b) heated length-to-diameter ratio, (c) mass velocity, (d) pressure, (e) inlet subcooling, (f) inlet quality, (g) outlet subcooling, (h) outlet quality, and (i) measured critical heat flux.

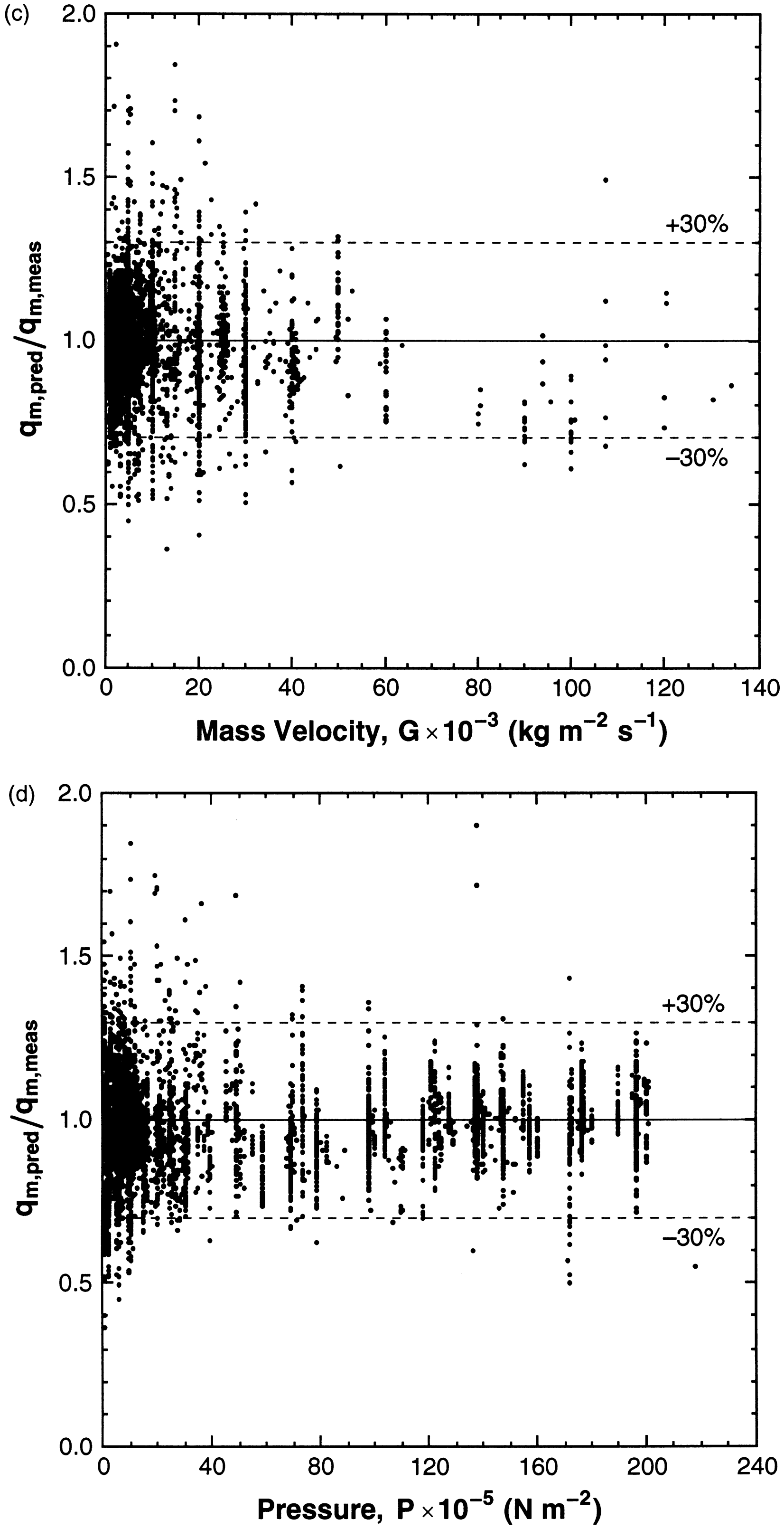
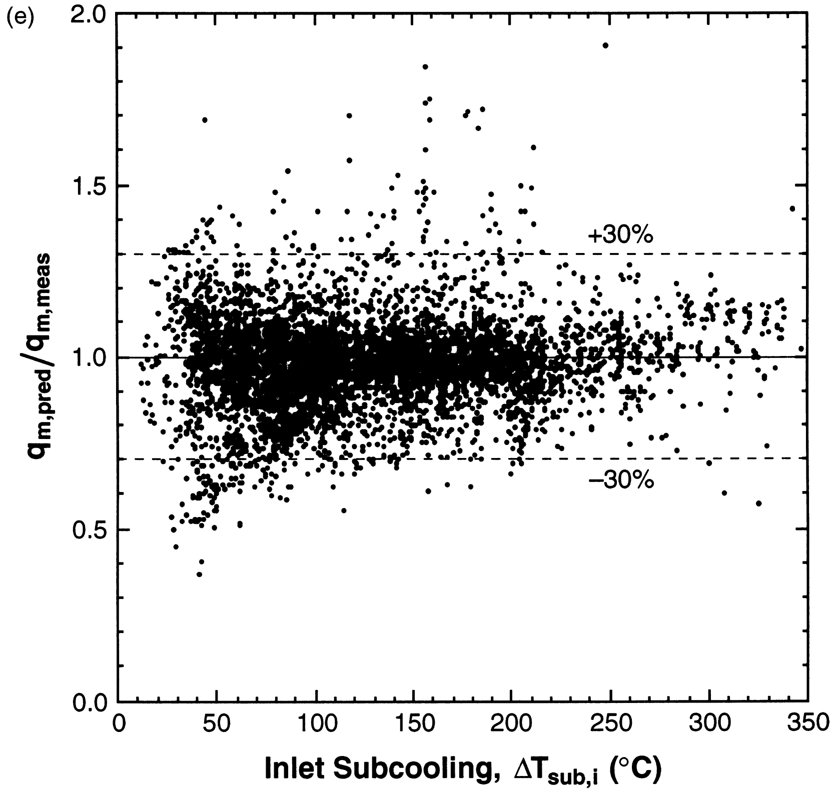


Fig. 4 (*continued*)



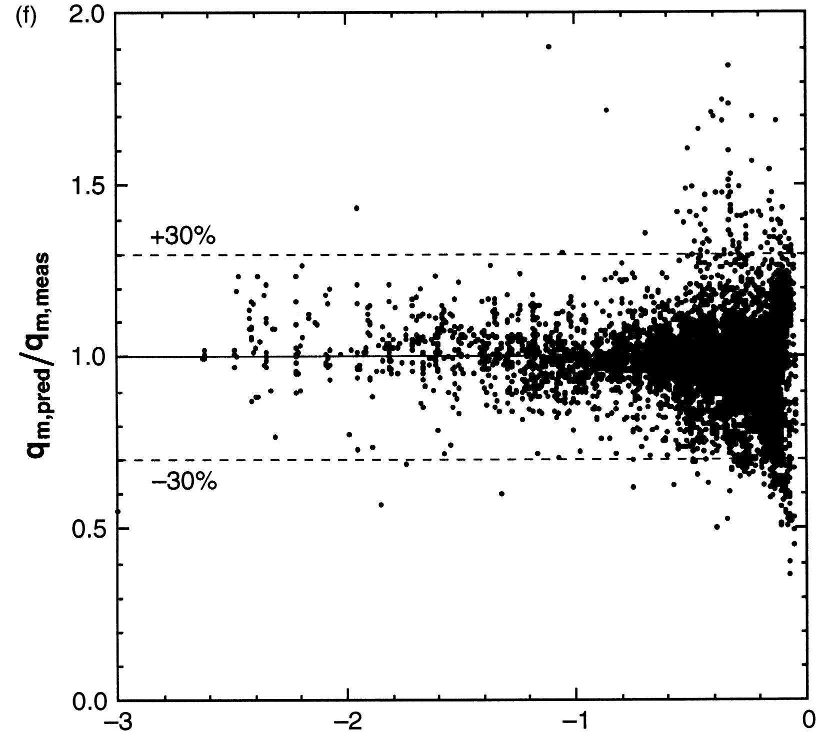


Fig. 4 (*continued*)

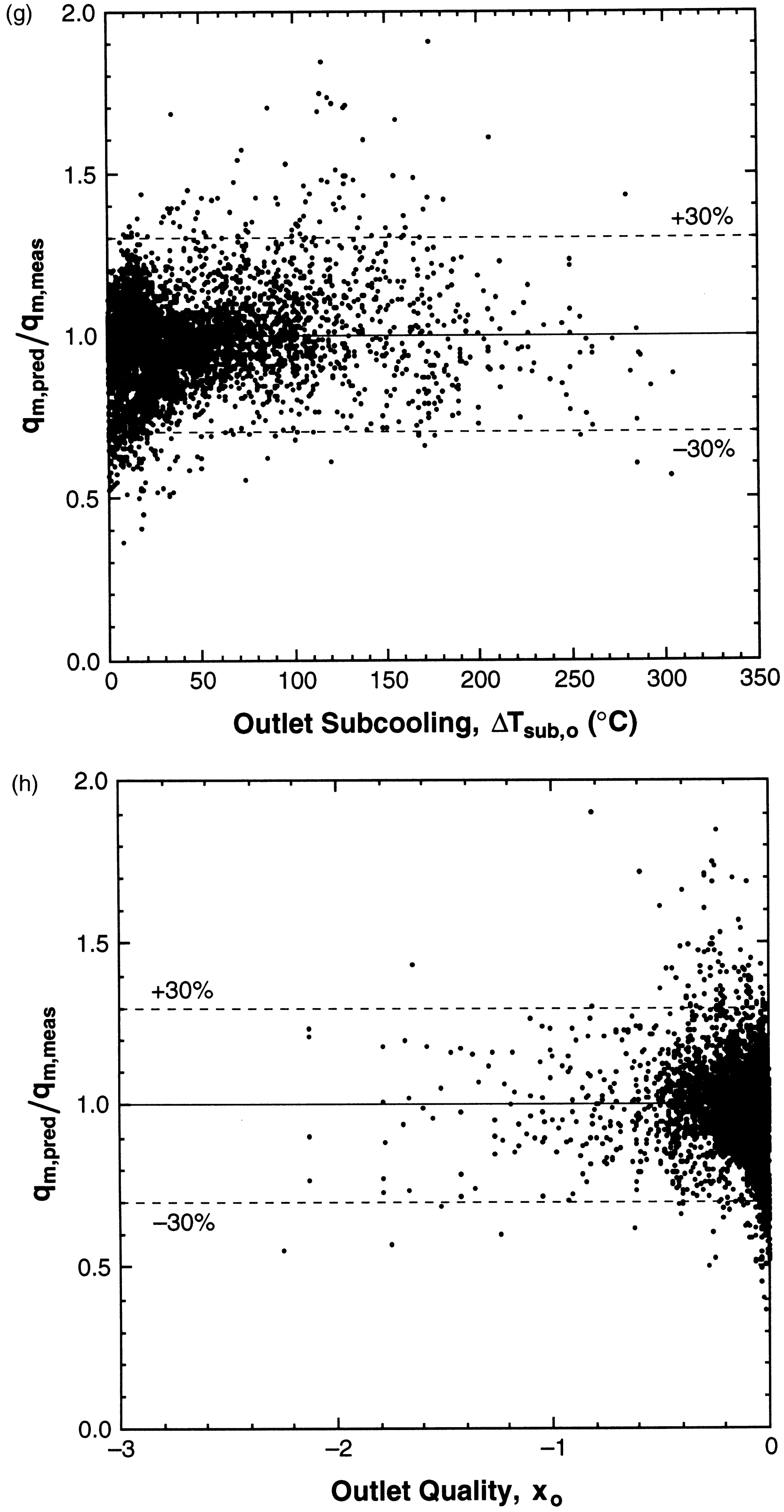


Fig. 4 (*continued*)

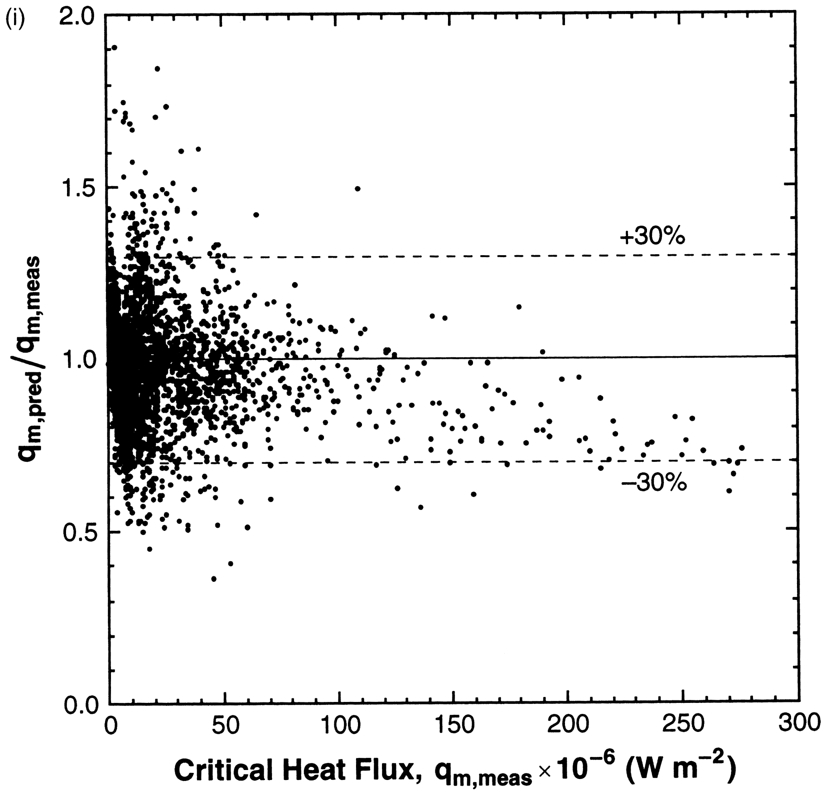


Fig. 4 (*continued*)

optimization of the constants in the inlet conditions correlation is unlikely to produce an appreciable increase in accuracy.

5.2. Statistical assessment of CHF look-up table

Doroshchuk and Lantsman [162] published the first CHF look-up table from which a design engineer could locate standard CHF values as a function of local conditions (i.e., outlet of a uniformly heated tube),

$$q_{m,*} = \mathrm{fn}\big(G, P, \text{and } \Delta T_{\text{sub,o}} \text{ or } x_{\text{o}}\big). \tag{15}$$

CHF was assumed to be a local phenomenon and, thus, independent of heated length and steam content at the inlet. CHF values were provided at discrete values of the dependent variables (given in Eq. (15)) for vertical upflow in a tube having a diameter of 8 mm. This reference value was chosen since most of the available data were for an 8 mm diameter tube. A supplemental equation was provided for converting the value in the look-up table to one applicable to a different diameter tube. Determining CHF at a non-tabulated condition required linear interpolation.

Groeneveld et al. [163] and Kirillov [164] listed several advantages of this tabular prediction method over mechanistic models and empirical correlations: higher accuracy, wider application range, correct parametric and asymptotic trends, ease of use (thermophysical properties not required), and ease of updating. In the opinion of the present authors, an empirical correlation, which has been thoroughly tested with a large error-free CHF database, nullifies all of these so-called advantages except for the evaluation of thermophysical properties, which is quite inconsequential considering the widespread use of computers. Disadvantages of the look-up table method, which were not mentioned, include: only applicable to a single fluid unless supplemental scaling equations are utilized, extrapolation beyond parametric range (i.e., high mass velocity or high subcooling) is not accurate, and time-consuming to implement within a computer program. The accuracy of the CHF look-up table has been continuously improved by Canadian and Russian researchers over the last 28 years as more data became available.

Researchers at the Atomic Energy of Canada Limited (AECL), Chalk River, Ontario, Canada and the Institute of Physics and Power Engineering (IPPE), Obninsk, Russia combined their CHF databases and

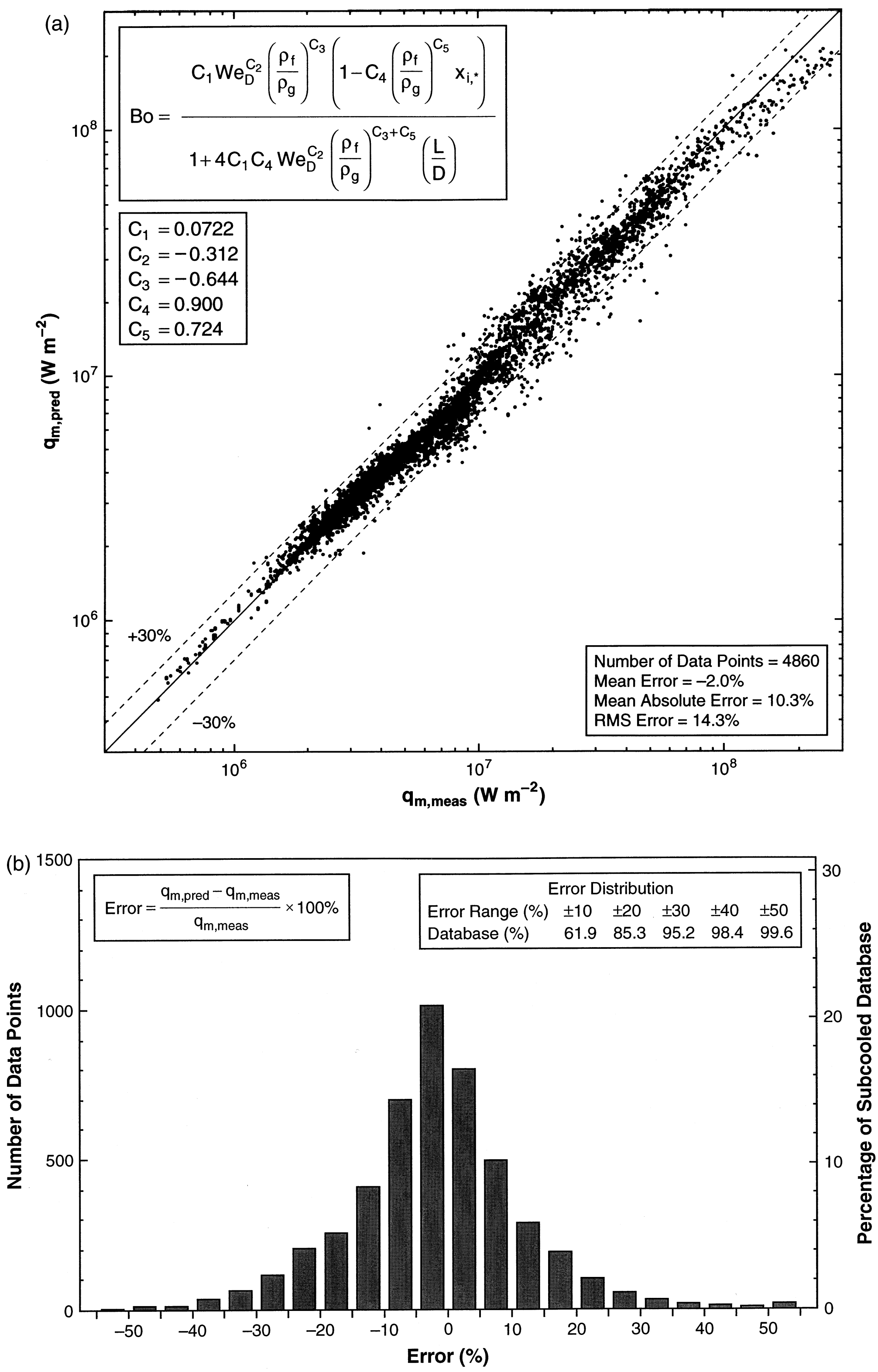


Fig. 5. Assessment of the optimized, inlet conditions, subcooled CHF correlation: (a) predicted vs. measured critical heat flux and (b) histogram of prediction errors.

proposed a unified CHF look-up table [163] based on 22,946 CHF data points. This CHF look-up table is the most recent and is utilized in several popular nuclear reactor thermal hydraulic computer programs. The table provided CHF values for an 8 mm diameter tube at 20 discrete values of mass velocity, 21 values of pressure, and 23 values of outlet quality (9420 total entries with 3360 of those in the subcooled region) covering ranges of 0 to 8000 kg m^{-2} s^{-1}, 1 to 200 bar, and −0.5 to 1.0, respectively. CHF values for tube diameters other than 8 mm were obtained from

$$\frac{q_m}{q_{m,*}} = \left(\frac{0.008}{D}\right)^{0.5}, \tag{16}$$

where $q_{m,*}$ is the CHF value from the look-up table and D is in meters. Above a diameter of 25 mm, the right-hand side of Eq. (16) was replaced with 0.6, independent of diameter. Below a diameter of 3 mm, Eq. (16) should be utilized with caution. In an independent assessment of this CHF look-up table, Baek et al. [165] obtained an RMS error of 36.7% using the direct substitution method advocated by the present authors [153] and others [155,160]. Baek et al. also determined that RMS error varied significantly throughout the range of local conditions (mass velocity, pressure, and outlet quality). In addition, many regions within the CHF look-up table did not have experimental data from which the table could be developed or tested. The accuracy of the table was indeterminate in these regions where CHF values in the table must have been estimated and not firmly based on experimental data.

The authors of the present study ascertained the accuracy of the subcooled region of the CHF look-up table [163] using the subcooled CHF database. Table 6 compares the mean error, mean absolute error, and RMS error of the CHF look-up table [163] with those

Table 6
Comparison of Groeneveld et al. [163] CHF look-up table with the optimized, inlet and outlet conditions, subcooled CHF correlations

Study	Inlet conditions	Outlet conditions	Adjustable constants[a]	Restriction	No. of data points	Mean error (%)	Mean absolute error (%)	RMS error (%)
Groeneveld et al. [163]		●	3360	Subcooled CHF database	4860	[b]	[b]	[b]
				[c]	3405	23.6	37.5	72.5
				$7 \leq D \leq 9$ mm[c]	1089	−4.7	13.1	16.7
				$D > 3$ mm, $L/D > 80$[c]	1200	5.6	14.2	28.0
				$D \leq 3$ mm[c]	437	40.2	55.5	82.3
				$L/D \leq 80$[c]	2148	29.4	46.6	83.0
Present study (see Table 4)	●		5	Subcooled CHF database	4860	−2.0	10.3	14.3
				[c]	3405	−2.3	9.0	12.5
				$7 \leq D \leq 9$ mm[c]	1089	−5.1	9.2	13.5
				$D > 3$ mm, $L/D > 80$[c]	1200	0.1	4.7	6.0
				$D \leq 3$ mm[c]	437	−3.3	13.8	17.5
				$L/D \leq 80$[c]	2148	−3.9	11.3	14.9
Present study (see Table 4)		●	5	Subcooled CHF database	4860	−2.1	22.3	31.6
				[c]	3405	−2.0	23.3	33.2
				$7 \leq D \leq 9$[c] mm	1089	−10.7	20.1	28.1
				$D > 3$ mm, $L/D > 80$[c]	1200	1.2	14.6	19.7
				$D \leq 3$ mm[c]	437	4.1	40.5	54.7
				$L/D \leq 80$[c]	2148	−6.6	26.0	34.4

[a] Adjustable constants refer to those constants which the authors manipulated in order to increase the accuracy of their correlation or look-up table.

[b] CHF look-up table cannot predict CHF for 1455 data points (30% of the subcooled CHF database) which have mass velocity, perssure, or outlet quality outside of the ranges for which CHF values are given in the table.

[c] Parametric range of Groeneveld et al. [163] CHF look-up table: $G \leq 8 \times 10^3$ kg m^{-2} s^{-1}; $1 \times 10^5 \leq P < 3 \times 10^5$ N m^{-2} and $x_o \geq -0.15$; $3 \times 10^5 \leq P < 10 \times 10^5$ N m^{-2} and $x_o \geq -0.2$; $10 \times 10^5 \leq P < 30 \times 10^5$ N m^{-2} and $x_o \geq -0.3$; $30 \times 10^5 \leq P \leq 200 \times 10^5$ N m^{-2} and $x_o \geq -0.5$..

of the optimized, inlet and outlet conditions correlations developed in the present study (see Table 4). One of the two main disadvantages of a look-up table becomes immediately apparent from Table 6; the look-up table can not provide a prediction when mass velocity, pressure, or outlet quality are outside of the ranges for which CHF values are given in the table. Hence, the look-up table can not predict CHF for 30% of the subcooled CHF database, while the present correlations offer predictions for all data within the database. The other main disadvantage of the table is that it requires 3360 entries for predicting subcooled CHF within a relatively small parametric range (see footnote in Table 6) compared with the five adjustable constants and large parametric range (see Table 4) of the present correlations. Error values are shown in Table 6 for the parametric range of the look-up table as well as four other carefully chosen conditions which further limit this parametric range. The mean absolute error (37.5%) and RMS error (72.5%) of the subcooled region of the look-up table are much higher than those of both correlations evaluated within the parametric range of the table. Also, the high mean error (23.6%) of the look-up table indicates that CHF is often considerably overpredicted. Recall that the look-up table provides CHF values for an 8 mm diameter tube and requires a supplemental equation for other diameters. Thus, the much improved accuracy of the look-up table for diameters near 8 mm is expected. This may also indicate that Eq. (16) does not correctly represent the effect of diameter on CHF. Furthermore, the table was developed using only CHF data with $D > 3 \times 10^{-3}$ m and $L/D > 80$. Relatively larger errors are observed outside of these ranges. The outlet conditions correlation (see Table 4), even with the inclusion of near-saturated data ($x_o > -0.05$) for which it was not recommended, is more accurate than the look-up table except where data are limited to diameters between 7 and 9 mm, the range for which the look-up table is most accurate. The inlet conditions correlation (see Table 4) is quite superior to the look-up table for all conditions tested in the present study.

5.3. Dimensional representation of CHF correlations

The obvious advantage of the CHF look-up table over an empirical correlation is that, for a given diameter, mass velocity, pressure, and outlet quality, CHF can be determined from the look-up table without knowledge of the thermophysical properties. This advantage was nullified by reformulating the optimized, nondimensional correlations from the present study into dimensional equations. In doing so, the saturated thermophysical properties were combined into terms which could be represented as a function of pressure. Fig. 6 shows a dimensional representation of both the inlet and outlet conditions correlations (see Table 4). For a given pressure, values of the three thermophysical property terms are determined from the graph and CHF calculated using either the correlation based on heated length and inlet quality or the one based on outlet quality. This procedure is valid for pressures of 7–220 bar. Thus, the effort required to calculate CHF with the correlations is the

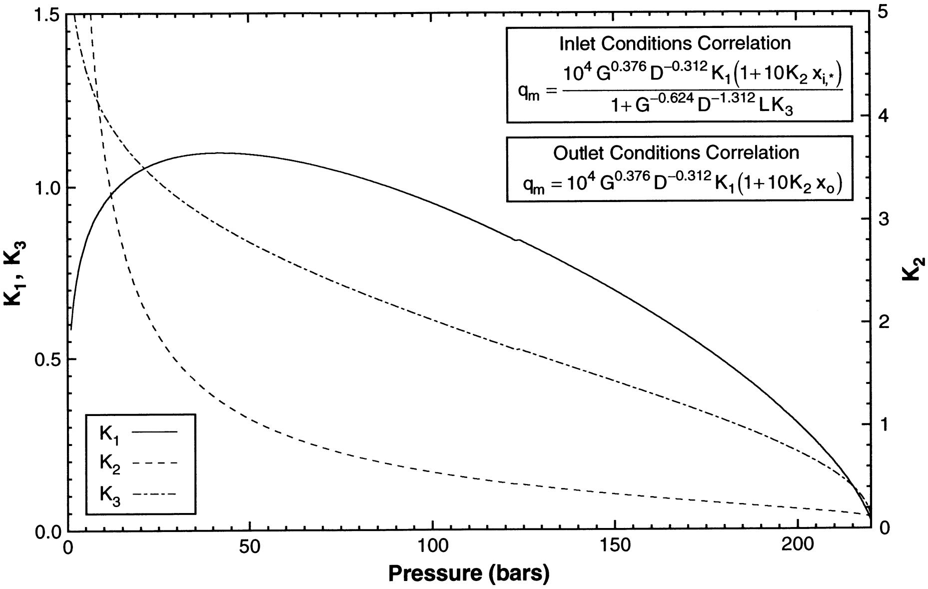


Fig. 6. Dimensional representation of the optimized, inlet and outlet conditions, subcooled CHF correlations.

same as that with the look-up table, the main difference being the higher accuracy of the correlations (see previous section).

6. Conclusions

An exhaustive literature search identified over 100 subcooled CHF correlations for water flow in a uniformly heated round tube. The accuracy of the latest versions of these correlations was ascertained using the PU-BTPFL CHF database [1] which contains the largest volume of subcooled CHF data of any database available in the literature. In response to the many inaccurate and inordinately complex correlations, the present authors formulated two nondimensional correlations containing only five constants and whose unique functional form was determined without using a statistical analysis but rather using the parametric trends observed in less than 10% of the subcooled CHF data. Ultimately, the goal of the present study was the recommendation of a superior correlation. Key findings are as follows:

1. The optimized, inlet conditions, subcooled CHF correlation developed in the present study (see Table 4) was by far the most accurate correlation, having mean absolute and RMS errors of 10.3% and 14.3%, respectively, using the entire subcooled CHF database. Also, the accuracy of the correlation did not vary significantly within the parametric range of the correlation. This correlation based on upstream conditions (diameter, length, mass velocity, pressure, and inlet quality) is recommended for water flow in a tube having a uniform axial heat flux.
2. The optimized, outlet (local) conditions, subcooled CHF correlation developed in the present study (see Table 4) was the most accurate correlation based on outlet conditions. The mean absolute error and RMS error were 18.5% and 27.7%, respectively, using the subcooled CHF database with the exclusion of the near-saturated data ($x_o > -0.05$) for which the correlation is not recommended. Correlations based on local conditions (diameter, mass velocity, pressure, and outlet quality) can be applied to water flow in a tube having a nonuniform axial heat flux profile.
3. Initially, the constants appearing in the correlations were methodically determined from the parametric trends exhibited in a small subset of the subcooled CHF database. Optimization of the constants using all of the subcooled CHF data reduced the mean absolute and RMS errors of the inlet conditions correlations by only 15% and 11%, respectively. Reoptimization of the constants, when additional subcooled CHF data become available, is not expected to produce an appreciable increase in accuracy. Superiority of the correlations is attributed to the systematic development of the functional form of the correlation from the CHF parametric effects.
4. The subcooled region of the most recent CHF look-up table [163] developed by Canadian and Russian researchers was considerably less accurate than both the optimized, inlet and outlet conditions, subcooled CHF correlations developed in the present study. Other disadvantages of the look-up table include: smaller parametric range within the subcooled region, indeterminate accuracy in regions without CHF data, and thousands of adjustable constants when implemented in computer codes.

Acknowledgements

The authors are grateful for the support of the Office of Basic Energy Sciences of the U.S. Department of Energy (Grant No. DE-FG02-93ER14394.A003). Financial support for the first author was also provided in the form of the Link Foundation Energy Fellowship and the Ingersoll-Rand Fellowship.

References

[1] D.D. Hall, I. Mudawar, Critical heat flux (CHF) for water flow in tubes — I. Compilation and assessment of world CHF data, International Journal of Heat and Mass Transfer 43 (2000) 2573–2604.

[2] H. Buchberg, F. Romie, R. Lipkis, M. Greenfield, Heat transfer, pressure drop, and burnout studies with and without surface boiling for de-aerated and gassed water at elevated pressures in a forced flow system, in: Preprints of Papers — Heat Transfer and Fluid Mechanics Institute, Stanford University Press, Stanford, CA, 1951, pp. 177–191.

[3] F.C. Gunther, Photographic study of surface-boiling heat transfer to water with forced convection, Transactions of the American Society of Mechanical Engineers 73 (1951) 115–123.

[4] W.H. Jens, P.A. Lottes, Analysis of heat transfer, burnout, pressure drop, and density data for high-pressure water, ANL-4627, Argonne National Laboratory, Argonne, IL, 1951.

[5] H.L. McGill, W.L. Sibbitt, Heat transfer and pressure drop of water flowing in a small tube, ANL-4603 (Part I), Argonne National Laboratory, Argonne, IL, 1951.

[6] H.M. Epstein, J.W. Chastain, S.L. Fawcett, Heat transfer and burnout to water at high subcritical pressures, BMI-1116, Battelle Memorial Institute, Columbus, OH, 1956.

[7] R.H. Hoe, L.A. Senghaus, Correlation of subcooled and quality burnout data for cylindrical tubes and rectangular ducts, in: J.E. Viscardi (Ed.), Reactor Heat Transfer Progress No. 12, NDA-31(Del.), Nuclear Development Corporation of America, White Plains, NY, 1956.

[8] P. Griffith, The correlation of nucleate boiling burnout data, ASME Paper 57-HT-21, 1957.

[9] J. Longo, Jr., A statistical investigation of subcooled burnout with uniform and locally peaked heat fluxes, KAPL-1744, Knolls Atomic Power Laboratory, Schenectady, NY, 1957.

[10] W.R. Gambill, N.D. Greene, Boiling burnout with water in vortex flow, Chemical Engineering Progress 54 (10) (1958) 68–76.

[11] S.J. Green, B.W. LeTourneau, M. Troy, Forced circulation uniform flux burnout studies for high-pressure water, ASME Paper 59-HT-25, 1959.

[12] R.L. Menegus, Burnout of heating surfaces in water, DP-363, E.I. du Pont de Nemours and Co., Wilmington, DE, 1959.

[13] G. Sonnemann, A method of correlating burnout heat flux data, Nuclear Science and Engineering 5 (1959) 242–247.

[14] L. Bernath, A theory of local-boiling burnout and its application to existing data, Chemical Engineering Progress Symposium Series 56 (30) (1960) 95–116.

[15] A.A. Ivashkevich, Critical heat flows in the forced flow of liquid in channels, Atomnaya Énergiya 8 (1960) 51–54; Soviet Journal of Atomic Energy 8 (1960) 44–47.

[16] R.T. Jacobs, J.A. Merrill, The application of statistical methods of analysis for predicting burnout heat flux, Nuclear Science and Engineering 8 (1960) 480–496.

[17] P.I. Povarnin, S.T. Semenov, An investigation of burnout during the flow of subcooled water through small-diameter tubes at high pressures, Teploenergetika 7 (1) (1960) 79–85; AEC-tr-5602, US Atomic Energy Commission.

[18] D.A. Labuntsov, Critical thermal loads in forced motion of water which is heated to a temperature below the saturation temperature, Atomnaya Énergiya 10 (1961) 523–525; Soviet Journal of Atomic Energy 10 (1961) 516–518.

[19] Z.L. Miropol'skii, M.E. Shitsman, The critical heat flux for boiling water in tubes, Atomnaya Énergiya 11 (1961) 515–521; Soviet Journal of Atomic Energy 11 (1961) 1166–1173.

[20] K. Torikai, M. Hori, Y. Ouchi, The surface boiling burnout in a channel, Nihon-Genshiryoku-Gakkai Shi (Journal of the Atomic Energy Society of Japan) 3 (1961) 333–337.

[21] W.J. Levedahl, Two regimes of burnout (DNB) correlated with steam energy flow for uniformly-heated channels, Nuclear Science and Engineering 14 (1962) 201–203.

[22] S. Levy, Prediction of the critical heat flux in forced convection flow, GEAP-3961, General Electric Co., San Jose, CA, 1962.

[23] I. Michiyoshi, R. Matsumoto, Prediction of burnout heat flux of forced convection, Nihon-Genshiryoku-Gakkai Shi (Journal of the Atomic Energy Society of Japan) 4 (1962) 224–231.

[24] A.P. Ornatskii, A.M. Kichigin, Critical heat loads in high-pressure boiling of underheated water in small diameter tubes, Teploenergetika 9 (6) (1962) 44–47; ORNL-tr-107, Oak Ridge National Laboratory, Oak Ridge, TN, 1964.

[25] Y.-P. Chang, Some possible critical conditions in nucleate boiling, ASME Journal of Heat Transfer 85 (1963) 89–100; ASME Paper 62-HT-37.

[26] W.R. Gambill, Generalized prediction of burnout heat flux for flowing, subcooled, wetting liquids, Chemical Engineering Progress Symposium Series 59 (41) (1963) 71–87.

[27] M.E. Shitsman, On the method of calculation of burnout heat fluxes for forced convection boiling of water, Teploenergetika 10 (8) (1963) 76–78; AEC-tr-6290, US Atomic Energy Commission.

[28] L.S. Tong, H.B. Currin, A.G. Thorp II, New correlations predict DNB conditions, Nucleonics 21 (5) (1963) 43–47.

[29] R.J. Weatherhead, Nucleate boiling characteristics and the critical heat flux occurrence in subcooled axial-flow water systems, ANL-6675, Argonne National Laboratory, Argonne, IL, 1963.

[30] A.N. Ryabov, B.F. Berzina, A survey of the experimental data on critical heat loads with forced flow of a cooling fluid in cylindrical tubes, Teploenergetika 11(2) (1964) 81–87; Thermal Engineering 11(2) (1964) 107–113.

[31] L.S. Shtokolov, An attempt to generalize the data on critical heat fluxes in liquid boiling at high flow speeds, Zhurnal Prikladnoi Mekhaniki i Tekhnicheskoi Fiziki 5 (1) (1964) 134–136.

[32] R.H. Wilson, J.K. Ferrell, Correlation of critical heat flux for boiling water in forced circulation at elevated pressures, Chemical Engineering Progress Symposium Series 60 (47) (1964) 118–125.

[33] B.A. Zenkevich, On the effect of subcooled water flow velocity on burnout heat fluxes, Inzhenerno-Fizicheskii Zhurnal 7 (7) (1964) 43–46.

[34] J. Griffel, C.F. Bonilla, Forced-convection boiling burnout for water in uniformly heated tubular test sections, Nuclear Structural Engineering 2 (1965) 1–35.

[35] A.P. Ornatskii, L.S. Vinyarskii, Heat transfer crisis in a forced flow of underheated water in small-bore tubes, Teplofizika Vysokikh Temperatur 3 (1965) 444–451; High Temperature 3 (1965) 400–406.

[36] B.C. Skinner, C.S. Loosmore, Subcooled critical heat flux for water in round tube, M.S. Thesis, Massachusetts Institute of Technology, Cambridge, MA, 1965.

[37] L.S. Tong, Prediction of departure from nucleate boiling for an axially non-uniform heat flux distribution, Journal of Nuclear Energy 21 (1967) 241–248.

[38] L.S. Tong, Boundary-layer analysis of the flow boiling crisis, International Journal of Heat and Mass Transfer 11 (1968) 1208–1211.

[39] L.F. Glushchenko, Correlation of experimental data on critical heat fluxes in subcooled boiling, Teplofizika i Teplotekhnika (15) (1969) 125–129; Heat Transfer —

Soviet Research 2(1) (1970) 139–143; International Chemical Engineering 10 (1970) 219–222.

[40] A.P. Ornatskii, L.F. Glushchenko, E.M. Maevskii, Critical heat flux in steam generating tubes in the region of low subcooling and steam content, Teploenergetika 18(8) (1971) 74–76; Thermal Engineering 18(8) (1971) 106–109.

[41] A.N. Vasil'yev, P.L. Kirillov, Study of the heat transfer crisis associated on sudden boiling inception in liquids in small-diameter channels, Heat Transfer — Soviet Research 3 (1) (1971) 36–43.

[42] K.M. Becker, D. Djursing, K. Lindberg, O. Eklind, C. Österdahl, Burnout conditions for round tubes at elevated pressures, in: G. Hetsroni, S. Sideman, J.P. Hartnett (Eds.), Progress in Heat and Mass Transfer, vol. 6, Pergamon Press, Oxford, UK, 1972, pp. 55–73.

[43] R.W. Bowring, A simple but accurate round tube, uniform heat flux, dryout correlation over the pressure range 0.7–17 MN/m^2 (100–2500 psia), AEEW-R 789, United Kingdom Atomic Energy Authority, Winfrith, UK, 1972.

[44] J.C. Purcupile, S.W. Gouse, Jr., Reynolds flux model of critical heat flux in subcooled forced convection boiling, ASME Paper 72-HT-4, 1972.

[45] S.Y. Ahmad, Fluid to fluid modeling of critical heat flux: a compensated distortion model, International Journal of Heat and Mass Transfer 16 (1973) 641–662.

[46] W.T. Hancox, W.B. Nicoll, On the dependence of the flow-boiling heat transfer crisis on local near-wall conditions, ASME Paper 73-HT-38, 1973.

[47] E.J. Thorgerson, D.H. Knoebel, J.H. Gibbons, A model to predict convective subcooled critical heat flux, ASME Journal of Heat Transfer 96 (1974) 79–82.

[48] L.L. Levitan, F.P. Lantsman, Investigating burnout with flow of a steam-water mixture in a round tube, Teploenergetika 22(1) (1975) 80–83; Thermal Engineering 22(1) (1975) 102–105.

[49] L.S. Tong, A phenomenological study of critical heat flux, ASME Paper 75-HT-68, 1975.

[50] V.A. Chernobai, Model for heat-transfer crisis for water boiling in pipes, Teplofizika Vysokikh Temperatur 18 (1980) 1046–1050; High Temperature 18 (1980) 797–801.

[51] A.L. Koba, Y.D. Kozhelupenko, N.S. Peretyaka, G.F. Smirnov, V.N. Sviridov, Burnout with boiling under conditions of forced motion in capillaries, Teploenergetika 27(6) (1980) 73–74; Thermal Engineering 27 (1980) 355–357.

[52] B.R. Bergel'son, A.D. Leongardt, A.P. Potapov, V.A. Sherstnev, Critical heat inputs in tubes under conditions of boiling with subcooling and low pressures, Teploenergetika 28(4) (1981) 11–14; Thermal Engineering 28 (1981) 204–207.

[53] W. Hebel, W. Detavernier, M. Decreton, A contribution to the hydrodynamics of boiling crisis in a forced flow of water, Nuclear Engineering and Design 64 (1981) 433–445.

[54] A.A. Ivashkevich, A semiempirical formula for critical heat flux with boiling of subcooled water in a tube, Teploenergetika 28(5) (1981) 66–67; Thermal Engineering 28 (1981) 303–304.

[55] I.P. Smogalev, Calculation of critical heat fluxes with flow of subcooled water at low velocity, Teploenergetika 28(4) (1981) 14–17; Thermal Engineering 28 (1981) 208–211.

[56] A.P. Sapankevich, Generalization of experimental data on heat-transfer crisis in pipes, Inzhenerno-Fizicheskii Zhurnal 44 (1983) 894–902; Journal of Engineering Physics 44 (1983) 595–602.

[57] F. Inasaka, H. Nariai, Critical heat flux and flow characteristics of subcooled flow boiling in narrow tubes, JSME International Journal 30 (268) (1987) 1595–1600.

[58] M.M. Shah, Improved general correlation for critical heat flux during upflow in uniformly heated vertical tubes, International Journal of Heat and Fluid Flow 8 (1987) 326–335.

[59] B.P. Avksentyuk, Critical heat fluxes with forced flow of subcooled and saturated liquids, Teploenergetika 35(12) (1988) 43–46; Thermal Engineering 35 (1988) 694–697.

[60] R.D. Boyd, Subcooled water flow boiling experiments under uniform high heat flux conditions, Fusion Technology 13 (1988) 131–142.

[61] W.R. Gambill, T. Mochizuki, Advanced neutron source design: burnout heat flux correlation development, Transactions of the American Nuclear Society 57 (1988) 298–300.

[62] I.I. Gromova, V.I. Esikov, V.N. Smolin, Calculation of the heat-transfer crisis in boiling in tubular fuel elements on the basis of a control experiment, Atomnaya Énergiya 69 (1990) 219–222; Soviet Atomic Energy 69 (1990) 828–832.

[63] M. Siman-Tov, W.R. Gambill, W.R. Nelson, A.E. Ruggles, G.L. Yoder, Thermal-hydraulic correlations for the advanced neutron source reactor fuel element design and analysis, in: Y.A. Hassan, L.E. Hochreiter (Eds.), Nuclear Reactor Thermal-Hydraulics, ASME HTD-Vol. 190, 1991, pp. 63–78.

[64] A.A. Vasil'yev, The boiling crisis and permissible heat flux densities in forced-convection pipe flows of water, Promyshlennaia Teplotekhnika 14(4–6) (1992) 61–65; Heat Transfer Research 25 (1993) 439–444.

[65] M. Caira, G. Caruso, A. Naviglio, Prediction of CHF in subcooled flow boiling, in: M. Courtland, J.M. Delhaye (Eds.), Proceedings of the Sixth International Topical Meeting on Nuclear Reactor Thermal Hydraulics: NURETH-6, Commissariat a l'Energie Atomique, Grenoble, France, vol. 2, 1993, pp. 825–832.

[66] G.P. Celata, M. Cumo, A. Mariani, Assessment of correlations and models for the prediction of CHF in water subcooled flow boiling, International Journal of Heat and Mass Transfer 37 (1994) 237–255.

[67] C.L. Vandervort, A.E. Bergles, M.K. Jensen, An experimental study of critical heat flux in very high heat flux subcooled boiling, International Journal of Heat and Mass Transfer 37 (suppl. 1) (1994) 161–173.

[68] M. Caira, G. Caruso, A. Naviglio, A correlation to predict CHF in subcooled flow boiling, International

Communications in Heat and Mass Transfer 22 (1995) 35–45.

[69] G. Caruso, Personal Communication, University of Rome, Department of Nuclear Engineering and Energy Conversion, Rome, Italy, February 26, 1996.

[70] A.E. Hechanova, M.S. Kazimi, J.E. Meyer, A framework for critical heat flux prediction in high heat flux, high subcooling components, in: R.J. Cochran, R.E. Hogan, A.M. Khounsary, M.A. Ebadian, M. Kaviany, R.W. Douglass, L.C. Burmeister, J.E. O'Brien, R.L. Mahajan, T.S. Chen, W.J. Bryan, T. Chopin, L.W. Sawnson (Eds.), Proceedings of the ASME Heat Transfer Division, vol. 1, ASME HTD-Vol. 317-1, 1995, pp. 127–132.

[71] C. Lombardi, A formal approach for the prediction of the critical heat flux in subcooled water, in: R.C. Block, F. Feiner (Eds.), Proceedings of the 7th International Meeting on Nuclear Reactor Thermal-Hydraulics: NURETH-7, NUREG/CP-0142, vol. 4, US Nuclear Regulatory Commission, Washington, DC, 1995, pp. 2506–2518.

[72] R. Pernica, J. Cizek, General correlation for prediction of critical heat flux ratio in water cooled channels, in: R.C. Block, F. Feiner (Eds.), Proceedings of the 7th International Meeting on Nuclear Reactor Thermal-Hydraulics: NURETH-7, NUREG/CP-0142, vol. 4, US Nuclear Regulatory Commission, Washington, DC, 1995, pp. 2636–2653.

[73] T. Jafri, T.J. Dougherty, B.W. Yang, Local and non-local correlations for critical heat flux at low and medium pressures, in: F.B. Cheung, B.W. Yang, J.R. Riznic, J. Seyed-Yagoobi, Y.A. Hassan, J.H. Kim, S. Paolucci, K.D. Kihm, P.H. Oosthuizen (Eds.), Proceedings of the ASME Heat Transfer Division, vol. 3, ASME HTD-Vol. 334, 1996, pp. 229–238.

[74] Y. Kabata, R. Nakajima, K. Shioda, Enhancement of critical heat flux for subcooled flow boiling of water in tubes with a twisted tape and with a helically coiled wire, in: A.S. Rao, R.B. Duffey, D. Elias (Eds.), Proceedings of the ASME/JSME 4th International Conference on Nuclear Engineering 1996:, ICONE-4, vol. 1-pt. B, American Society of Mechanical Engineers, New York, 1996, pp. 639–646.

[75] V.V. Yagov, V.A. Puzin, L.A. Sukomel, The approximate model for critical heat flux under subcooled flow boiling conditions, in: G.P. Celata, P. Di Marco, A. Mariani (Eds.), 2nd European Thermal-Sciences and 14th UIT National Heat Transfer Conference 1996, vol. 1, Edizioni ETS, Pisa, Italy, 1996, pp. 483–490.

[76] Y.A. Zeigarnik, A.I. Klimov, A.G. Rotinov, B.A. Smyslov, Some experimental results on burnout in subcooled water flow boiling, Thermal Engineering 44 (1997) 184–191.

[77] J. Boscary, M. Araki, J. Schlosser, M. Akiba, F. Escourbiac, Dimensional analysis of critical heat flux in subcooled water flow under one-side heating conditions for fusion application, Fusion Engineering and Design 43 (1998) 147–171.

[78] D.D. Hall, I. Mudawar, Ultra-high critical heat flux (CHF) for subcooled water flow boiling — II: high-CHF database and design equations, International Journal of Heat and Mass Transfer 42 (1999) 1429–1456.

[79] D.D. Hall, I. Mudawar, Critical heat flux (CHF) for water flow in tubes, vol. III, subcooled CHF correlations, Purdue University, Boiling and Two-Phase Flow Laboratory, West Lafayette, IN.

[80] D.D. Hall, Critical heat flux in subcooled flow boiling, Ph.D. Thesis, Purdue University, West Lafayette, IN, 1999.

[81] V.N. Tramontini, M.L. Greenfield, G.C. Wong, R.P. Lipkis, H.I. Leon, R.K. Breeze, G.S. Arbuthnot, W.L. Martin, P. Wiener, A. Auerbach, R.E. George, J.R. Hall, F.E. Romie, B.R. Mead, A.G. Guibert, G.H. Zizicas, B. Bussell, H. Buchberg, R. Bromberg, L.M.K. Boelter, Final report on studies in boiling heat transfer, COO-24, U.S. Atomic Energy Commission, 1951.

[82] R.J. Hoe, J.H. Helve, S3G/S4G design criteria and analysis, KAPL-M-RES-50, Knolls Atomic Power Laboratory, Schenectady, NY, 1957.

[83] W.R. Gambill, N.D. Greene, A preliminary study of boiling burnout heat fluxes for water in vortex flow, ORNL CF-58-4-56, Oak Ridge National Laboratory, Oak Ridge, TN, 1958.

[84] T.W. Hunt, H.S. Jacket, J.D. Roarty, J.E. Zerbe, An investigation of subcooled and quality burnout in circular channels, WAPD-LSR(IM)-1, Westinghouse Electric Corp., Pittsburgh, PA, 1955.

[85] H.S. Jacket, J.D. Roarty, J.E. Zerbe, Investigation of burnout heat flux in rectangular channels at 2000 psia, WAPD-A1W(IM)-3, Westinghouse Electric Corp., Pittsburgh, PA, 1955.

[86] H.S. Jacket, J.D. Roarty, J.E. Zerbe, Investigation of burnout heat flux in rectangular channels at 2000 psia, Transactions of the American Society of Mechanical Engineers 80 (1958) 391–401.

[87] R.C. Cunningham, J.E. Zerbe, Review of thermal design criteria for pressurized water reactors at 2000 psia, WAPD-SFR-Rs-444, Westinghouse Electric Corp., Pittsburgh, PA, 1956.

[88] R.A. DeBortoli, S.J. Green, B.W. LeTourneau, M. Troy, A. Weiss, Forced-convection heat transfer burnout studies for water in rectangular and round tubes at pressures above 500 psia, WAPD-188, Westinghouse Electric Corp., Pittsburgh, PA, 1958.

[89] G. Sonnemann, Correlation of burnout data, WAPD-TH-160, Westinghouse Electric Corp., Pittsburgh, PA, 1956.

[90] L. Bernath, Prediction of heat transfer burnout, Chemical Engineering Progress Symposium Series 52 (18) (1956) 1–6.

[91] A.A. Ivashkevich, The critical thermal flow and the coefficient of heat transfer in the conditions of forced motion of boiling liquid in the pipes, Teploenergetika 8 (10) (1961) 74–79.

[92] P.I. Povarnin, S.T. Semenov, Investigation into boiling crisis of water heated below the temperature of saturation when flowing at high velocity in pipes, Teploenergetika 6 (4) (1959) 72–79.

[93] W.J. Levedahl, Application of steam energy flow to

reactor design, Transactions of the American Nuclear Society 5 (1962) 149–150.

[94] A.P. Ornatskii, A.M. Kichigin, An investigation of the dependence of critical thermal loading on weight velocity, underheating and pressure, Teploenergetika 8 (2) (1961) 75–79;.

[95] A.P. Ornatskii, Critical heat loads and heat transfer for a forced flow of water in tubes in the region of superhigh pressures (175–220 atm), Teploenergetika 10 (3) (1963) 66–69 AEC-tr-6401, US Atomic Energy Commission, 1963.

[96] L.S. Tong, H.B. Currin, A.G. Thorp, New DNB (burnout) correlations, WCAP-1997, Westinghouse Electric Corp., Pittsburgh, PA, 1962.

[97] L.S. Tong, H.B. Currin, F.C. Engel, DNB (burnout) studies in an open lattice core, vol. I, WCAP-3736 (Vol. I), Westinghouse Electric Corp., Pittsburgh, PA, 1964.

[98] R.J. Weatherhead, Heat transfer, flow instability, and critical heat flux for water in a small tube at 200 psia, ANL-6715, Argonne National Laboratory, Argonne, IL, 1963.

[99] R.H. Wilson, J.K. Ferrell, Correlation of critical heat flux for boiling water in forced circulation at elevated pressures, BAW-168, Babcock and Wilcox Co., Lynchburg, VA, 1961.

[100] B.A. Zenkevich, V.I. Subbotin, Critical heat loadings in forced flow of water heated below boiling, Atomnaya Énergiya 3(8) (1957) 149–151; Soviet Journal of Atomic Energy 3 (1957) 915–920; Journal of Nuclear Energy, Part B: Reactor Technology 1 (1959) 134–136.

[101] V.I. Subbotin, B.A. Zenkevich, O.A. Sudnitsyn, V.I. Krotov, O.L. Peskov, Critical heat fluxes for water in forced convection up to boiling point in pipes at 140–220 atm, in: N.A. Dollezhal' (Ed.), Issledovaniya teplootdachi k paru i vode kipyashchei v trubakh pri vysokikh davleniyakh (Investigations of Heat Transfer to Steam and Water Boiling in Pipes at High Pressures), Atomizdat, Moscow, Russia, 1958, pp. 95–119.

[102] B.A. Zenkevich, Similitude relations for critical heat loading in forced liquid flow, Atomnaya Énergiya 4(1) (1958) 74–77; Soviet Journal of Atomic Energy 4 (1958) 89–94; Journal of Nuclear Energy, Part B: Reactor Technology 1 (1959) 137–140.

[103] B.A. Zenkevich, The correlation of the experimental data on critical heat loads in forced flow of water heated below the boiling temperature, Atomnaya Énergiya 6(2) (1959) 169–173; Soviet Journal of Atomic Energy 6 (1959) 95–97; Journal of Nuclear Energy, Part B: Reactor Technology 1 (1959) 130–133.

[104] G.V. Alekseev, B.A. Zenkevich, O.L. Peskov, N.D. Sergeev, V.I. Subbotin, Burn-out heat fluxes under forced water flow, in: Third U.N. International Conference on the Peaceful Uses of Atomic Energy, A/CONF.28/P/327a, International Atomic Energy Agency, Vienna, Austria, 1964, pp. 295–304.

[105] J. Griffel, Forced-convection boiling burnout for water in uniformly heated tubular test sections, Eng.Sc.D. Thesis, Columbia University, New York. NYO-187-7, U.S. Atomic Energy Commission, 1965.

[106] L.S. Tong, Heat transfer in water-cooled nuclear reactors, Nuclear Engineering and Design 6 (1967) 301–324.

[107] L.S. Tong, An evaluation of the departure from nucleate boiling in bundles of reactor fuel rods, Nuclear Science and Engineering 33 (1968) 7–15.

[108] L.S. Tong, F.E. Motley, J.O. Cermak, Scaling law of flow-boiling crisis, in: U. Grigull, E. Hahne (Eds.), Heat Transfer 1970: Fourth International Heat Transfer Conference, vol. 6, Elsevier, Amsterdam, 1970 (paper B 6.12).

[109] L.F. Glushchenko, E.M. Maevsky, On the methods of treatment and comparison of the data on critical heat fluxes, Teplofizika i Teplotekhnika 22 (1972) 82–87.

[110] R.V. Macbeth, Burn-out analysis. Part I: a burn-out correlation for water in round and rectangular channels uniformly heated at various pressures with forced convection, AEEW-R 117, United Kingdom Atomic Energy Authority, Winfrith, UK, 1961.

[111] R.V. Macbeth, Burn-out analysis. Part II: the basic burnout curve, AEEW-R 167, United Kingdom Atomic Energy Authority, Winfrith, UK, 1963.

[112] R.V. Macbeth, Burn-out analysis. Part III: the low velocity burnout regime, AEEW-R 222, United Kingdom Atomic Energy Authority, Winfrith, UK, 1963.

[113] R.V. Macbeth, Burn-out analysis. Part IV: application of a local conditions hypothesis to world data for uniformly heated round tubes and rectangular channels, AEEW-R 267, United Kingdom Atomic Energy Authority, Winfrith, UK, 1963.

[114] R.V. Macbeth, The burn-out phenomenon in forced-convection boiling, in: T.B. Drew, G.R. Cokelet, J.W. Hoopes, Jr., T. Vermeulen (Eds.), Advances in Chemical Engineering, vol. 7, Academic Press, New York, 1968, pp. 207–293.

[115] B. Thompson, R.V. Macbeth, 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, Winfrith, UK, 1964.

[116] D.H. Lee, An experimental investigation of forced convection boiling in high pressure water. Part IV. Large diameter tubes at about 1600 psi, AEEW-R 479, United Kingdom Atomic Energy Authority, Winfrith, UK, 1966.

[117] J.C. Purcupile, L.S. Tong, S.W. Gouse, Jr., Refrigerant-water scaling of critical heat flux in round tubes — subcooled forced-convection boiling, ASME Journal of Heat Transfer 95 (1973) 279–281.

[118] E.J. Thorgerson, Hydrodynamic aspects of the critical heat flux in subcooled convection boiling, Ph.D. Thesis, University of South Carolina, Columbia, SC, DPST-69-327, E.I. du Pont de Nemours and Co., Wilmington, DE, 1969.

[119] V.E. Doroshchuk, L.L. Levitan, F.P. Lantsman, Investigations into burnout in uniformly heated tubes, ASME Paper 75-WA/HT-22, 1975.

[120] V.E. Doroshchuk, L.L. Levitan, F.P. Lantsman,

Recommendations for calculating burnout in a round tube with uniform heat release, Teploenergetika 22(12) (1975) 66–70; Thermal Engineering 22(12) (1975) 77–80.

[121] B.R. Bergel'son, Burnout under conditions of subcooled boiling and forced convection, Teploenergetika 27(1) (1980) 58–61; Thermal Engineering 27 (1980) 48–50.

[122] W. Hebel, W. Detavernier, Critical heat transfer rate to flowing cooling water, Kerntechnik 19 (5) (1977) 228–232.

[123] H. Nariai, F. Inasaka, T. Shimura, Critical heat flux of subcooled flow boiling in narrow tube, in: P.J. Marto, I. Tanasawa (Eds.), Proceedings of the 1987 ASME–JSME Thermal Engineering Joint Conference, vol. 5, American Society of Mechanical Engineers, New York, 1987, pp. 455–462.

[124] F. Inasaka, H. Nariai, Critical heat flux of sub cooled flow boiling with water, in: U. Müller, K. Rehme, K. Rust (Eds.), Proceedings of the Fourth International Topical Meeting on Nuclear Reactor Thermal-Hydraulics: NURETH-4, vol. 1, G. Braun, Karlsruhe, Germany, 1989, pp. 115–120.

[125] F. Inasaka, H. Nariai, Critical heat flux of subcooled flow boiling for water in uniformly heated straight tubes, Fusion Engineering and Design 19 (1992) 329–337.

[126] F. Inasaka, H. Nariai, Evaluation of subcooled critical heat flux correlations for tubes with and without internal twisted tapes, in: Proceedings of the Fifth International Topical Meeting on Reactor Thermal Hydraulics: NURETH-5, vol. 4, American Nuclear Society, La Grange Park, IL, 1992, pp. 919–928.

[127] F. Inasaka, H. Nariai, Critical heat flux of subcooled flow boiling with water for high heat flux application, in: A.M. Khounsary (Ed.), High Heat Flux Engineering II, Society of Photo-Optical Instrumentation Engineers, Bellingham, WA, 1993, pp. 328–339. Proceedings of SPIE — The International Society of Optical Engineering, vol. 1997.

[128] F. Inasaka, H. Nariai, Evaluation of subcooled critical heat flux correlations for tubes with and without internal twisted tapes, Nuclear Engineering and Design 163 (1996) 225–239.

[129] H. Nariai, F. Inasaka, Critical heat flux of subcooled flow boiling with water, with application to high heat flux components, Fusion Engineering and Design 9 (1989) 245–249.

[130] H. Nariai, F. Inasaka, Critical heat flux and flow characteristics of subcooled flow boiling with water in narrow tubes, in: O.C. Jones, I. Michiyoshi (Eds.), Dynamics of Two-Phase Flows, CRC Press, Boca Raton, FL, 1992, pp. 689–708.

[131] F. Inasaka, Critical heat flux of subcooled flow boiling in water under uniform heating conditions, Papers of Ship Research Institute 30 (4) (1993) 1–69.

[132] M.M. Shah, A generalized graphical method for predicting CHF in uniformly heated vertical tubes, International Journal of Heat and Mass Transfer 22 (1979) 557–568.

[133] B.P. Avksentyuk, V.V. Ovchinnikov, Burnout model for pool and forced flow boiling, in: G.P. Celata, R.K. Shah (Eds.), Two-Phase Flow Modelling and Experimentation, vol. 2, Edizioni ETS, Pisa, Italy, 1995, pp. 1205–1210.

[134] V.N. Smolin, S.V. Shpanskii, V.I. Esikov, T.K. Sedova, Method of calculating burnout in tubular fuel rods when cooled by water and a water–steam mixture, Teploenergetika 24(12) (1977) 30–35; Thermal Engineering 24(12) (1977) 29–34.

[135] M. Caira, G. Caruso, A. Naviglio, Requirements of high heat flux for fusion reactor components: revised models and correlations predict critical heat flux in subcooled flow boiling, in: ANS Proceedings: 1993 National Heat Transfer Conference, American Nuclear Society, La Grange Park, IL, 1993, pp. 383–390.

[136] G.P. Celata, M. Cumo, A. Mariani, CHF in highly subcooled flow boiling with and without turbulence promoters, in: European Two-Phase Flow Group Meeting, Stockholm, Sweden, Paper C1, 1992.

[137] G.P. Celata, M. Cumo, A. Mariani, Burnout in highly subcooled water flow boiling in small diameter tubes, International Journal of Heat and Mass Transfer 36 (1993) 1269–1285.

[138] G.P. Celata, M. Cumo, A. Mariani, Experimental results on high heat flux burnout in subcooled flow boiling, Energia Nucleare 10 (1) (1993) 46–57.

[139] G.P. Celata, Recent achievements in the thermal hydraulics of high heat flux components in fusion reactors, Experimental Thermal and Fluid Science 7 (1993) 263–278.

[140] M. Cumo, Subcooled flow boiling CHF at high liquid velocity, in: Heat Transfer: 3rd UK National Heat Transfer Conference Incorporating 1st European Conference on Thermal Sciences, vol. 1, Hemisphere, New York, 1992, pp. 15–33.

[141] T.M. Jafri, Analysis of critical heat flux for vertical round tubes, Ph.D. Thesis, Columbia University, New York, 1993.

[142] T. Jafri, T.J. Dougherty, B.W. Yang, Correlation of critical heat flux data for uniform tubes, in: R.C. Block, F. Feiner (Eds.), Proceedings of the 7th International Meeting on Nuclear Reactor Thermal-Hydraulics: NURETH-7, NUREG/CP-0142, vol. 4, U.S. Nuclear Regulatory Commission, Washington, DC, 1995, pp. 3197–3217.

[143] V.V. Yagov, V.A. Puzin, Burnout under conditions of forced flow of subcooled liquid, Teploenergetika 32(10) (1985) 52–54; Thermal Engineering 32 (1985) 569–572.

[144] V.V. Yagov, V.A. Puzin, A.A. Kudryavtsev, Investigation of the boiling crisis and heat transfer in dispersed-film boiling of liquids in channels, Heat Transfer — Soviet Research 19 (1) (1987) 1–8.

[145] V.V. Yagov, The mechanism of the heat transfer crisis with saturated and subcooled liquid boiling in tubes, Teploenergetika 39 (5) (1992) 16–22; Thermal Engineering 39 (1992) 235–241.

[146] Y.A. Zeigarnik, N.P. Privalov, A.I. Klimov, Critical heat flux with boiling of subcooled water in rectangular channels with one-sided supply of heat,

Teploenergetika 28 (1) (1981) 48–51; Thermal Engineering 28 (1981) 40–43.

[147] Y.A. Zeigarnik, A.I. Klimov, I.V. Maslakova, Limiting parameters for a system of cooling, utilizing the boiling of strongly subcooled water, Teploenergetika 32 (12) (1985) 55–59; Thermal Engineering 32 (1985) 690–693.

[148] Y.A. Zeigarnik, Critical heat flux and pressure drop under forced convection boiling of subcooled water: experimental data, in: G.F. Hewitt (Ed.), Heat Transfer 1994: Proceedings of the Tenth International Heat Transfer Conference, vol. 7, Institution of Chemical Engineers, Rugby, UK, 1994, pp. 581–586.

[149] M.B. Bowers, High heat-flux dissipation using small diameter channels, Ph.D. thesis, Purdue University, West Lafayette, IN, 1994.

[150] I. Mudawar, M.B. Bowers, Parametric study of ultra-high CHF in highly subcooled water flow inside small diameter tubes, in: J.C. Chen, Y. Fujita, F. Mayinger, R. Nelson (Eds.), Convective Flow Boiling, Taylor and Francis, Washington, DC, 1996, pp. 117–122.

[151] I. Mudawar, M.B. Bowers, Ultra-high critical heat flux (CHF) for subcooled water flow boiling — I: CHF data and parametric effects for small diameter tubes, International Journal of Heat and Mass Transfer 42 (1999) 1405–1428.

[152] D.D. Hall, I. Mudawar, Critical heat flux (CHF) for water flow in tubes, vol. I, compilation and assessment of world CHF data, Purdue University, Boiling and Two-Phase Flow Laboratory, West Lafayette, IN, 1998.

[153] D.D. Hall, I. Mudawar, Evaluation of subcooled critical heat flux correlations using the PU-BTPFL CHF database for vertical upflow of water in a uniformly heated round tube, Nuclear Technology 117 (1997) 234–247.

[154] M.E. Nissley, A.J. Friedland, R.P. Knott, Considerations for comparing CHF correlations, in: H. Kakihana, N. Todreas, Y.Y. Hsu, R. Kiyose, J. Wakabayashi, C. Chiu, H. Nariai, T. Kobori, A. Inoue, J. Chao (Eds.), Proceedings of Second International Topical Meeting on Nuclear Power Plant Thermal Hydraulics and Operations, Atomic Energy Society of Japan, Tokyo, Japan, 1986, pp. 9–13.

[155] P. Bricard, A. Souyri, Understanding and modelling DNB in forced convective boiling: a critical review, in: G.P. Celata, R.K. Shah (Eds.), Two-Phase Flow Modelling and Experimentation 1995, vol. 2, Edizioni ETS, Pisa, Italy, 1995, pp. 843–851.

[156] G.P. Celata, On the application method of critical heat flux correlations, Nuclear Engineering and Design 163 (1996) 241–242.

[157] D.C. Groeneveld, On the definition of critical heat flux margin, Nuclear Engineering and Design 163 (1996) 245–247.

[158] P. Hejzlar, N.E. Todreas, Consideration of critical heat flux margin prediction by subcooled or low quality critical heat flux correlations, Nuclear Engineering and Design 163 (1996) 215–223.

[159] P. Hejzlar, N.E. Todreas, Response to contributors' letters and technical notes, Nuclear Engineering and Design 163 (1996) 273–279.

[160] M. Siman-Tov, Application of energy balance and direct substitution methods for thermal margins and data evaluation, Nuclear Engineering and Design 163 (1996) 249–258.

[161] F. Mayinger, O. Schad, E. Weiss, Investigation into the critical heat flux in boiling water, Final report, Maschinenfabrik Augsburg–Nürnberg Aktiengesellschaft, Nürnberg, West Germany, 1966; EURAEC-1811, United States–European Atomic Energy Community Joint Research and Development Program; EUR-3347.e, European Atomic Energy Community, 1967.

[162] V.E. Doroshchuk, F.P. Lantsman, Selecting magnitudes of critical heat fluxes with water boiling in vertical uniformly heated tubes, Teploenergetika 17 (12) (1970) 17–19; Thermal Engineering 17(12) (1970) 18–21.

[163] D.C. Groeneveld, L.K.H. Leung, P.L. Kirillov, V.P. Bobkov, I.P. Smogalev, V.N. Vinogradov, X.C. Huang, E. Royer, The 1995 look-up table for critical heat flux in tubes, Nuclear Engineering and Design 163 (1996) 1–23.

[164] P.L. Kirillov, Heat-transfer crisis in channels, Atomnaya Énergiya 80 (1996) 370–379; Atomic Energy 80 (1996) 348–357.

[165] W.-P. Baek, H.-C. Kim, S.H. Chang, An independent assessment of Groeneveld et al.'s 1995 CHF look-up table, Nuclear Engineering and Design 178 (1997) 331–337.