Available online at www.sciencedirect.com
SCIENCE DIRECT®

International Journal of Heat and Mass Transfer 49 (2006) 1058–1072

International Journal of HEAT and MASS TRANSFER

www.elsevier.com/locate/ijhmt

Correlation of critical heat flux for flow boiling of water in mini-channels

W. Zhang [a,1], T. Hibiki [b,2], K. Mishima [b,*], Y. Mi [c]

[a] Graduate School of Energy Science, Kyoto University, Kyoto 606-8317, Japan
[b] Research Reactor Institute, Kyoto University, Kumatori, Sennan, Osaka 590-0458, Japan
[c] En'Urga Inc., 1291 Cumberland Avenue, West Lafayette, IN 47906, USA

Received 26 May 2005
Available online 18 November 2005

Abstract

In view of practical significance of a correlation of critical heat flux (CHF) in the aspects of engineering design and prediction, this study is aiming at evaluation of existing CHF correlations for flow boiling of water with available databases taken from small-diameter tubes, and then development of a new, simple CHF correlation. Available CHF databases in the literature for flow boiling of water in small-diameter tubes ($0.33 < D_h < 6.22$ mm) are collected, covering wide parametric ranges. Three correlations by Bowring, Katto and Shah are evaluated with the CHF data for saturated flow boiling, and three correlations by Inasaka–Nariai, Celata et al. and Hall–Mudawar evaluated with the CHF data for subcooled flow boiling. The Hall–Mudawar correlation and the Shah correlation seem to be the most reliable tools for CHF prediction in the subcooled and saturated flow boiling regions, respectively. In order to avoid the defect of predictive discontinuities often encountered when applying previous correlations, a simple, nondimensional, inlet conditions dependent CHF correlation for saturated flow boiling has been formulated. Its functional form is determined by the application of the artificial neural network and parametric trend analyses to the collected database. Superiority of this correlation has been verified by the database. The new correlation has a mean deviation of 16.8% for this collected databank, smallest among all tested correlations. Compared to many inordinately complex correlations, this new correlation consists only of a single equation.

Keywords: Critical heat flux; CHF; Flow boiling; Mini-channel; Small diameter

1. Introduction

In order to meet increased demands for dissipating high heat fluxes from plasma-facing components in a nuclear fusion reactor, solid targets of a high power accelerator, high performance electronic chips and compact heat exchangers, development of new cooling technologies has been under way for the last two decades. Mini-channel cooling technologies have attracted considerable attention in recent years. However, the definition of mini-channel has not been clearly and strictly established in the literature although many related studies have been done. Based on engineering practice and application areas employing these channels, Kandlikar [1] proposed the following limit of mini-channel by hydraulic diameter: $200\ \mu m \leqslant D_h \leqslant 3$ mm. However, for compact heat exchanges, Mehendale et al. [2] gave a relatively loose definition in terms of hydraulic diameter: $1\ mm \leqslant D_h \leqslant 6$ mm. Thus, this study will focus on the channels with diameters ranging roughly from 200 μm to 6 mm, called small-diameter channels afterwards. There are many practical merits of the application of small-diameter channels such as high heat transfer coefficients, small thermal resistances between the device and coolant, reduced inventory requirements, low capital cost

* Corresponding author. Tel.: +81 724 51 2449; fax: +81 724 51 2637.
E-mail addresses: wzzhang@post3.rri.kyoto-u.ac.jp (W. Zhang), hibiki@rri.kyoto-u.ac.jp (T. Hibiki), mishima@rri.kyoto-u.ac.jp (K. Mishima).
1 Tel.: +81 724 51 2449; fax: +81 724 51 2637.
2 Tel.: +81 724 51 2373; fax: +81 724 51 2461.

0017-9310/$ - see front matter © 2005 Elsevier Ltd. All rights reserved.
doi:10.1016/j.ijheatmasstransfer.2005.09.004

Nomenclature

A'	parameters in empirical correlations
Bo	boiling number, $q_c/(h_{fg}G)$
C, C'	parameters in empirical correlation
C_1–C_5	parameters in empirical correlation
c_p	specific heat capacity
D_h	hydraulic equivalent diameter of flow channel
f_1–f_2	parameters in correlation
Fr	liquid Froude number, $G^2/\rho_f^2 g D_h$
G	mass flux
g	gravitational acceleration
h_{fg}	latent heat of evaporation
Δh_{in}	inlet subcooling
K	inlet subcooling parameter
k	thermal conductivity
L	heated length
p	pressure
p_{cr}	critical pressure
p_r	reduced pressure, p/p_{cr}
Pe	Peclet number, $GD_h c_{pf}/k_f$
Pr	Prandtl number
q_c	critical heat flux
q_{co}	critical heat flux for zero inlet subcooling
Re	Reynolds number, GD_h/μ_f
T	temperature
ΔT	temperature difference
We_D	Weber number, $G^2 D_h/(\sigma\rho_f)$
We_L	Weber number, $G^2 L/(\sigma\rho_f)$
x_{eq}	thermodynamic equilibrium quality
Y	parameter in Shah's correlation, $PeFr^{0.4}(\mu_f/\mu_g)^{0.6}$

Greek symbols

ζ_1–ζ_8	parameters of correlation
μ	dynamic viscosity
ξ	intercept of linear equation
ρ	density
σ	surface tension
ψ	parameter in empirical correlation
ς	empirical parameter

Subscripts

cal	calculational value
exp	experimental value
f	saturated liquid
fg	difference between saturated liquid and vapor
g	saturated vapor
in	channel inlet
o	channel outlet
sat	saturated state
sub	subcooling
Tong	corresponding parameter in Tong's correlation

Mathematical symbol

fn	function

and compact physical size. In order to dissipate higher heat fluxes with small-diameter channels while maintaining practical limits on the surface temperature of device and pressure drop, flow boiling is an optimum option to be applied as compared to single-phase flow. Forced convective flow boiling can achieve extremely high heat transfer coefficients at the cost of small wall temperature rises. The wall temperature's magnitude is generally determined by the saturation properties of the cooling fluid. However, the limiting factor for most forced convective boiling is the critical heat flux (CHF). CHF refers to the heat transfer limit causing a sudden decrease in the heat transfer coefficient and possible catastrophic failure of a device in which evaporation or boiling is occurring. For a heat flux-controlled system, exceeding the CHF can lead to a sudden large increase in the wall temperature, which, for most coolants, can lead to a catastrophic system failure. The ability to predict the CHF is therefore of vital importance to the safety of flow boiling system.

CHF generally occurs at the channel outlet. According to whether the bulk fluid at channel outlet is subcooled (represented by $x_{eq,o} < 0$) or not when CHF occurs, flow boiling CHF can be classified as either *subcooled CHF* or *saturated CHF*. For the subcooled CHF, several theories have been proposed to explain its mechanism: intense boiling causes the boundary layer separation from the heated wall and the resulting stagnant liquid depletion [3,4], bubble crowding within the boundary layer inhibits liquid replenishment near the wall surface [5], and dryout of a liquid sublayer beneath vapor blankets causes the appreciable rise of local wall temperature [6]. For the saturated CHF, the liquid film dryout near the channel outlet is widely regarded as the trigger mechanism [7]. At low flow rates in small-diameter tubes this type of CHF may be prone to occur due to the thinner liquid film thickness.

As the transport process behind the flow boiling CHF is extremely complex, CHF prediction relies heavily on empirical correlations derived from experimental CHF databases. Traditional flow boiling CHF correlations may not be suitable to predict CHF in small-diameter channels since the databases from which they were derived may not include enough databases taken from small-diameter channels and thus the accurate effect of channel dimension on CHF may not be reflected. Therefore, the applicability of existing CHF correlations to small-diameter channels should be carefully examined in detail. Although many analytical and experimental studies [14–28] related to flow boiling CHF in small-diameter channels have been performed for the past decades, in the current status of this subject, sufficient, systematic and accurate databases are still unavailable to understand CHF in small-diameter channels, and a reliable CHF correlation applicable to a wide range of parameters for small-diameter channels has not been developed yet. For this purpose, the present study is aiming at providing a literature survey and evaluation of existing CHF correlations with available experimental databases for flow boiling CHF in small-diameter channels, and then developing a CHF correlation based on the databases. The newly obtained correlation will be verified with the collected database covering wide ranges of experimental conditions.

2. Previous analytical and experimental works

2.1. Existing CHF correlations

2.1.1. Existing correlations for saturated CHF

In what follows, some well known existing correlations which could be used to predict the saturated flow boiling CHF will be reviewed briefly.

There are many correlations in the literature that apply exclusively to water. Among them, Bowring's correlation [8,9] seems to one of the most verified and convenient to use. The correlation is dimensional and expressed by the following equation:

$$q_c = \frac{A' + 0.25 D_h G \Delta h_{in}}{C' + L}, \tag{1}$$

where q_c is critical heat flux in W/m^2, Δh_{in} is inlet subcooling in J/kg, D_h and L are tube diameter and length in m, respectively, G is mass flux in kg/m^2 s, and A' and C' are functions. This correlation was derived from data covering the following parameter ranges: $0.2 < p_o < 19$ MPa, $2 < D_h < 45$ mm, $150 < L < 3700$ mm, and $136 < G <$ 18,600 kg/m^2 s.

Katto's correlation [10,11] is one of the most verified general predictive correlations. On the presumption that the hydrodynamic condition is responsible for CHF and with the aid of the vectorial dimensional analysis, Katto [10] found the following functional form to correlate flow boiling CHF data when the inlet subcooling is zero for the uniformly heated tubes:

$$\frac{q_{co}}{G \cdot h_{fg}} = \text{fn}\left(\frac{\rho_g}{\rho_f}, We_L, \frac{L}{D_h}\right), \tag{2}$$

where $We_L = G^2 L/(\rho_f)$. A large amount of experimental CHF data for many test fluids taken from many sources were analyzed and correlated in four distinct main regimes called the L-, H-, N-, and HP-regimes. Considering that in many cases a linear relationship between CHF and inlet subcooling enthalpy holds, inlet subcooling was taken into account as follows:

$$q_c = q_{co}(1 + K \Delta h_{in}/h_{fg}), \tag{3}$$

where K was determined empirically from the data for each regime. Katto et al. have further tested and improved this correlation in several subsequent publications. The Katto–Ohno version [11] appears to be the most improved and recent one, and thus will be selected for evaluation in this study.

Shah presented initially in graphical form [12] and later also in equation form [13] a general correlation of CHF for subcooled and saturated boiling in vertical tubes. Shah's final correlation consists in essence of two correlations, namely, the upstream conditions correlation (UCC) and the local conditions correlation (LCC). The UCC covers the situation where CHF at a location depends on the upstream conditions, e.g., inlet subcooling and distance from tube inlet. The LCC relates CHF to the local quality, except for very short tubes. The UCC and LCC were expressed by the following equations, respectively:

Upstream condition correlation (UCC):

$$\frac{q_c}{G \cdot h_{fg}} = \text{fn}\left(\frac{L}{D_h}, Y, x_{eq,in}\right), \tag{4}$$

Local condition correlation (LCC):

$$\frac{q_c}{G \cdot h_{fg}} = \text{fn}\left(\frac{L}{D_h}, Y, x_{eq,o}, p_r\right), \tag{5}$$

where $Y = PeFr^{0.4}(\mu_f/\mu_g)^{0.6}$, Peclet number $Pe = GD_h c_{pf}/k_f$, liquid Froude number $Fr = G^2/\rho_f^2 g D_h$, and reduced pressure $p_r = p/p_{cr}$. This correlation was verified with a wide variety of data which included 23 fluids (water, halocarbon refrigerants, chemicals, liquid metals, helium and other cryogens), L/D_h from 1.3 to 940, D_h from 0.315 to 37.5 mm, reduced pressures from 0.0014 to 0.96, mass fluxes from 3.9 to 29,051 kg/m^2 s, inlet qualities from −4 to +0.85, and outlet qualities from −2.6 to +1. All data from 62 independent sources were correlated with a mean deviation of 16%.

However, the above correlations are quite complex having many equations, many constants, or conditional statements for switching over equations, which bring about severe discontinuities in magnitude at each boundary between the adjoining two equations. In view of this, the present study aims to develop a simple, nondimensional correlation consisting of a single equation with as few constants as possible for saturated CHF.

2.1.2. Existing correlations for subcooled CHF

In what follows, some existing correlations for the subcooled CHF will be briefly reviewed.

Using the concept of boundary layer separation from a permeable flat plate with gas injection, Tong [4] proposed a CHF correlation as follows:

$$q_c = C \frac{G \cdot h_{fg}}{Re^{0.6}}, \tag{6}$$

where the Reynolds number is defined as $Re = GD_h/\mu_f$. By comparing Eq. (6) to the experimental CHF data of water taken under pressures as high as 6.9–13.8 MPa, Tong determined the parameter C in Eq. (6) as a function of the exit thermal equilibrium quality:

$$C = 1.70 - 7.43x_{\mathrm{eq,o}} + 12.22x_{\mathrm{eq,o}}^2. \tag{7}$$

Tong's correlation agreed with the data within ±25% for pressures higher than 7.0 MPa.

Inasaka and Nariai [14] modified the parameter C using CHF data at pressures ranging from 0.1 to 7 MPa as follows:

$$\frac{C}{C_{\mathrm{Tong}}} = 1 - \frac{52.3 + 80x_{\mathrm{eq,o}} - 50x_{\mathrm{eq,o}}^2}{60.5 + (10p_{\mathrm{o}})^{1.4}}, \tag{8}$$

where C_{Tong} is the parameter C in Eq. (7), and p_{o} is outlet pressure in MPa. Eq. (6) combined with this modified parameter C is referred to as the Inasaka–Nariai correlation afterwards in this study for the convenience of narration. Inasaka and Nariai verified that this correlation could predict CHF within ±20% in the ranges of following parameters: $0.1 < p < 20$ MPa, $2 < D_{\mathrm{h}} < 20$ mm, $30 < L < 2000$ mm, $1300 < G < 20{,}000$ kg/m^2 s, $-0.46 < x_{\mathrm{eq,o}} < -0.001$, and $2 < q_{\mathrm{c}} < 18$ MW/m^2. About 430 data points in all were used to verify this correlation.

Celata et al. [15] also modified Tong's correlation, Eq. (6), on the parameter C, together with a slight modification of the Reynolds number power, in order to give a more accurate prediction in the range of pressures below 5.0 MPa. The modified correlation is

$$Bo = \frac{C}{Re^{0.5}}, \tag{9}$$

where $Bo = q_{\mathrm{c}}/(G \cdot h_{\mathrm{fg}})$, and C is a function of both outlet pressure, p_{o}, and quality, $x_{\mathrm{eq,o}}$.

The modified correlation was verified using a total of 1865 data points covering wide parametric ranges: $0.1 < p_{\mathrm{o}} < 8.4$ MPa, $0.3 < D_{\mathrm{h}} < 25.4$ mm, $0.1 < L < 0.61$ m, $2 < G < 90.0$ Mg/m^2 s, and $90 < \Delta T_{\mathrm{sub,in}} < 230$ K. The modified correlation presented a root-mean-square error of 21.2% in the CHF prediction of all 1865 data points. Celata et al. concluded that the modified correlation is the best correlation compared to other three existing correlations in their assessment of correlations and models for the prediction of subcooled CHF. This modified Tong correlation is referred to as the Celata correlation in this study for the convenience of narration.

Hall and Mudawar [16] provided a comprehensive review of the current state of the knowledge of subcooled CHF for water flow boiling in channels, and designed a statistical correlation with five parameters based on almost all available subcooled CHF databases in the literature:

$$Bo = \frac{C_1 We_{\mathrm{D}}^{C_2} (\rho_{\mathrm{f}}/\rho_{\mathrm{g}})^{C_3} \lfloor 1 - C_4 (\rho_{\mathrm{f}}/\rho_{\mathrm{g}})^{C_5} x_{\mathrm{eq,in}} \rfloor}{1 + 4C_1 C_4 We_{\mathrm{D}}^{C_2} (\rho_{\mathrm{f}}/\rho_{\mathrm{g}})^{C_3+C_5} (L/D_{\mathrm{h}})}, \tag{10}$$

where the Weber number $We_{\mathrm{D}} = G^2 D_{\mathrm{h}}/(\rho_{\mathrm{f}}\sigma)$, $C_1 = 0.0722$, $C_2 = -0.312$, $C_3 = -0.644$, $C_4 = 0.900$, and $C_5 = 0.724$. The correlation was developed using a total of 4860 data points and predicted CHF with a root-mean-square error of 14.3% in the following parametric ranges: $0.1 < p_{\mathrm{o}} < 20$ MPa, $0.25 < D_{\mathrm{h}} < 15.0$ mm, $2 < L/D_{\mathrm{h}} < 200$, $300 < G < 30{,}000$ kg/m^2 s, $-2.00 < x_{\mathrm{eq,in}} < 0.00$, and $-1.00 < x_{\mathrm{eq,o}} < 0.00$.

2.2. Existing experimental work on mini-channels

In what follows, some recent flow boiling CHF experiments on small-diameter tubes will be reviewed briefly.

Nariai et al. [17] conducted CHF experiments of water for subcooled flow boiling at nearly ambient pressure in vertical narrow tubes with the inner diameters from 1 to 3 mm and lengths from 10 to 100 mm in the range of mass fluxes from 7000 to 20,000 kg/m^2 s. The CHF data were compared with four existing empirical correlations, showing that on the whole the agreement was unsatisfactory. Then, with the object of experimentally clarifying the effect of tube diameter on CHF in the quality region and explaining the discontinuities of CHF characteristics between the subcooled and quality region, Nariai et al. [18] performed an experiment on the flow boiling CHF in narrow tubes with 1–3 mm inner diameters using water under ambient pressure as a testing fluid. Subsequently, Inasaka and Nariai [19] experimented on the CHF of water under pressures from 0.3 to 1 MPa in a tube of 3 mm diameter and 100 mm in length.

In order to meet the needs of fusion reactor technology which calls for a knowledge of heat transfer under very high heat loading conditions, Celata et al. performed a series of experimental and analytical works on subcooled flow boiling CHF in small-diameter channels. Celata et al. [20] conducted experiments of flow boiling CHF with water at pressures from 0.1 to 2.2 MPa, mass fluxes from 2000 to 33,500 kg/m^2 s in vertical tubes with 2.5, 4.0 and 5.0 mm diameters. The heated length is 0.1 m, the subcooling at the locations of CHF ranging from 15 to 120 K. Their data were compared with eight existing correlations, revealing general inadequacies in CHF prediction. Subsequently, Celata et al. [21] conducted an experimental study of subcooled CHF with water at pressures of 0.6–2.5 MPa, masses fluxes from 11,000 to 40,000 kg/m^2 s and outlet subcooling from 50 to 136 K in a vertical tube of 2.5 mm diameter ($L/D_{\mathrm{h}} = 40$). The obtained CHF data were compared with six existing empirical correlations, including the Tong correlation modified by themselves [15] and three mechanistic models. The good agreement was obtained by their modified Tong correlation. Then, Celata et al. [22] discussed the relationship between the CHF and tube diameter based on the existing experimental data.

Lezzi et al. [23] performed an experiment on CHF for forced convection boiling of water in a horizontal capillary tube with the inner diameter of 1 mm and L/D_{h} approximately equal to 250, 500, and 1000 at low mass fluxes from 800 to 2700 kg/m^2 s and pressures from 1.9 to 7.2 MPa. In many cases the exit qualities were high and the CHF was reached through liquid film dryout. They reported that their CHF data agreed well with predictions by Katto's correlation [11].

Vandervort et al. [24] studied experimentally flow boiling CHF in tubes with diameters of 0.3–2.7 mm, L/D_h from 2.0 to 50.0 in a wide range of mass fluxes from 5000 to 40,000 kg/m^2 s, exit subcooling from 313 to 408 K, and exit pressures from 0.2 to 2.2 MPa. A complicated statistical correlation was developed based on their obtained data and compiled data.

Roach et al. [25] experimentally investigated saturated flow boiling CHF in four channels, all 16 cm in length. Two uniformly heated channels are circular and their diameters are 1.17 and 1.45 mm, respectively, and the other two represent flow channels in a micro-rod bundle with a triangular array, having 1.131 mm hydraulic diameter. The tested parametric ranges were as follows: mass fluxes from 250 to 1000 kg/m^2 s, exit pressures from 0.344 to 1.043 MPa, and inlet temperatures from 322 to 346 K. They reported that the Bowring correlation [8] could predict their data with reasonable accuracy.

Since most of CHF data have been obtained at high pressures, it necessitates accumulating data and investigating the effect of various factors on CHF at a relatively low pressure, under which some cooling systems may operate. In view of this, Kureta [26] conducted experiments with water under the atmospheric pressure in tubes with inner diameters ranging from 1.0 to 6.0 mm, L/D_h from 1 to 113, inlet water subcooling $\Delta T_{sub,in}$ from 0 to 90 K, and mass fluxes G from 0 to 19,740 kg/m^2 s. The highest CHF reached in his experiment was 158 MW/m^2. His subcooled CHF data were compared with the modified Tong correlations proposed by Inasaka and Nariai [14] and Celata et al. [15], respectively. The data were under-predicted by both of the modified correlations, especially for channels with very short heated section.

Mudawar and Bowers [27] conducted an experiment on ultra-high critical heat flux for subcooled water flow boiling in narrow tubes with diameters from 0.406 to 2.54 mm, L/D_h from 2.4 to 34.1 over a wide range of mass fluxes from 5000 to 134,000 kg/m^2 s, inlet temperatures from 18 to 70 °C, and outlet pressures from 0.25 to 17.2 MPa. The highest CHF value, 276 MW/m^2, heretofore for uniform heating in the literature was reached in their tests. Subsequently, Hall and Mudawar [28] developed a subcooled CHF correlation for high heat flux flow boiling, through examining parametric trends exhibited by a small fraction of the database. The correlation had a root-mean-square error of 19.5% for all collected databases, lowest among the correlations they tested.

3. Results and discussion

3.1. Collected CHF Database for flow boiling in mini-channels

Available datasets for flow boiling CHF of water in small-diameter tubes are shown in Table 1. There are 13 collected datasets in all. Only taking data for tube diameters less than 6.22 mm, and then eliminating duplicate data and those not meeting the heat balance calculation, the

Table 1
Collected database for flow boiling CHF of water in small-diameter tubes

Symb.	Reference	No. of data (sat[a])	D_h [mm]	L/D_h [–]	p_o [MPa]	G [kg/m^2 s]	$x_{eq,in}$ [%]	$x_{eq,o}$ [%]	$q_{c,exp}$ [MW/m^2]
○	Thompson and Macbeth [29]	1149 (779)	1.02–5.74	11.7–792	0.103–19.0	13.0–1.57×10^4	−235 to −0.031	−44.8 to 99.9	0.113–21.4
◁	Lowdermilk et al. [31]	449 (445)	1.30–4.78	25.0–250	0.101–0.690	27.1–3.42×10^4	−29.1 to −0.032	−3.02 to 99.1	0.167–41.6
▷	Becker et al. [30]	306 (306)	3.93–6.07	164.8–382	1.13–6.97	470–5.45×10^3	−67.5 to −23.4	0.086–96.7	1.59–5.66
⊟	Griffel [32]	70 (59)	6.22	147	6.89–10.3	1.85×10^3–1.39×10^4	−91.4 to −6.38	−7.07 to 30.4	2.60–7.81
⬡	Nariai et al. [17,18]	209 (54)	1.00–3.00	3.33–50.0	0.101–1.05	4.30×10^3–2.99×10^4	−31.5 to −3.07	−18.3 to 5.55	4.50–66.1
⊖	Inasaka and Nariai [19]	29 (0)	3.00	33.3	0.290–1.05	4.30×10^3–2.99×10^4	−31.5 to −12.5	−18.3 to −3.99	7.30–44.5
▽	Inasaka [33]	95 (3)	1.00–3.00	3.17–50.4	0.101	6.71×10^3–2.09×10^4	−15.6 to −6.66	−13.2 to 1.10	4.64–67.0
□	Celata et al. [21]	78 (0)	2.5	40	0.585–2.61	1.12×10^4–4.00×10^4	−46.1 to −18.7	−35.6 to 0.6	1.21–60.6
⬠	Vandervort et al. [24]	210 (19)	0.330–2.67	1.66–26.2	0.131–2.28	5.03×10^3–4.18×10^4	−28.2 to −1.91	−22.6 to 28.4	4.60–124
⊖	Lezzi et al. [23]	87 (87)	1.00	239–975	1.90–7.20	7.76×10^2–2.74×10^3	−64.4 to 0	64.3–0.976	0.285–2.36
◇	Kureta [26]	930 (736)	1.00–6.00	1.00–113	0.101	5.33–1.91×10^3	−17.2 to −0.032	−14.6 to 99.5	0.0935–158
◈	Roach et al. [25]	51 (51)	1.13–1.45	110–141	0.336–1.04	256–1.04×10^3	−27.9 to −13.1	36.2–97.4	0.860–3.70
△	Mudawar and Bowers [27]	174 (0)	0.406–2.54	2.36–34.2	0.250–17.2	5.00×10^3–1.34×10^5	−189 to −11.7	−175 to −6.23	9.40–276
Total (13 databases)		3837 (2539)	0.330–6.22	1.00–975	0.101–19.0	5.33–1.34×10^5	−235 to 0	−175 to 99.9	0.0935–276

[a] Numbers in parentheses denoting data points for saturated flow boiling CHF.

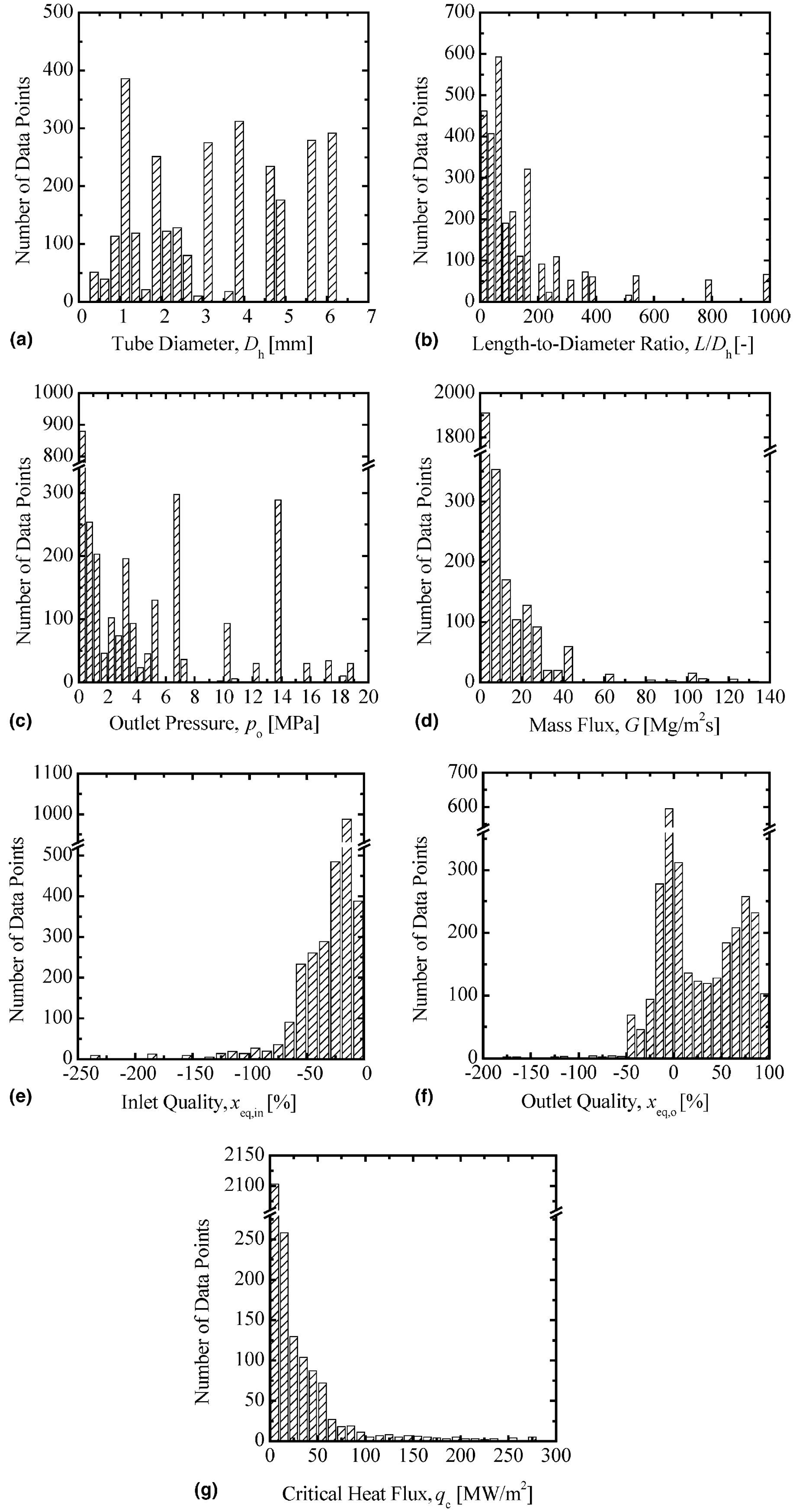

Fig. 1. Distribution of parameters in collected database: (a) tube diameter, (b) length-to-diameter ratio, (c) outlet pressure, (d) mass flux, (e) inlet quality, (f) outlet quality, and (g) critical heat flux.

collected database is reduced to a total of 3837 data points (2539 points for saturated CHF, and 1298 points for subcooled CHF), covering a wide range of parameters, such as outlet pressures from 0.101 to 19.0 MPa, mass fluxes from 5.33 to 1.34×10^5 kg/m^2 s, critical heat fluxes from 0.094 to 276 MW/m^2, and hydraulic diameters of channels from 0.330 to 6.22 mm, length-to-diameter ratios from 1.00 to 975, inlet qualities from −2.35 to 0, and outlet thermal equilibrium qualities from −1.75 to 1.00.

Fig. 1(a)–(g) shows the statistics of the collected database over the entire range of parameters including diameter, heated length-to-diameter ratio, pressure, mass flux, inlet subcooling, outlet subcooling and critical heat flux. Bar charts are shown for each parameter. The height of a bar represents the number of data points contained within the range of the parameter corresponding to the width of the bar. In some cases, when the height of a bar is very high, a break of axis is employed to make the other bars visible. From Fig. 1(a), the data numbers distribute almost evenly in the entire range of diameter from 0.330 to 6.22. From Fig. 1(b)–(g), most of the data are located in the range of low heated length-to-diameter ratios (L/D_h from 0 to 200), low outlet pressures (below 1 MPa), mass fluxes from 0 to 10 Mg/m^2 s, high inlet quality from −0.5 to 0, outlet quality around zero and critical heat fluxes below 20 MW/m^2.

3.2. Evaluation of existing correlations with collected data

3.2.1. Evaluation of correlations for saturated CHF

Among various existing correlations for saturated flow boiling CHF available in the literature, there are the following three frequently referenced in the literature: the correlations by Bowring [8], Katto and Ohno [11], and Shah [13]. Here an extensive comparison is made for these existing correlations with the collected dataset.

The comparison results with each database are tabulated in Table 2. As utilized by Shah [13], the mean deviation, whose definition is given below the table, is used as a measure of predictive accuracy. The underlined figures are the smallest among the mean deviations predicted by the three existing correlations for saturated CHF. For saturated CHF, Shah's correlation has a total mean deviation of 20.6% for all saturated CHF data, smallest among the three existing correlations, and presents the smallest mean deviations for six datasets among the total ten. The second is the Katto correlation having a slightly higher total mean deviation of 26.4% and the two smallest mean deviations. Finally, the Bowring correlation gives a total mean deviation of 29.3% and the two smallest mean deviations. Although all of the three correlations work very well for some old databases, e.g., those by Thompson and Macbeth [29], by Becker et al. [30] and by Griffel [32], they behave unsatisfactorily for some recent databases. Moreover, since each of these existing correlations consists of many equations and empirical constants, discontinuities or large deviations of the CHF prediction from the corresponding experimental data are often encountered when switching over the adjoining equations. This defect makes these correlations unreliable to be applied in some parameter regions although they may appear to work well in total for the whole dataset.

Figs. 2–4 compared graphically the predicted CHF values by Bowring's correlation, Katto's correlation and Shah's correlation with the experimental values,

Table 2
Assessment of CHF correlations for flow boiling of water

Reference	No. of data (sat.)	Databases						
		Mean deviation[a] [%]						
		Correlations for saturated CHF				Correlations for subcooled CHF		
		Bowring's [8]	Katto's [11]	Shah's [13]	New correl.	Inasaka–Nariai's [14]	Celata et al.'s [15]	Hall–Mudawar's [16]
Thompson and Macbeth [29]	1149 (779)	**12.3**	15.2	12.6	17.8	18.7	21.8	7.68
Lowdermilk et al. [31]	449 (445)	32.4	21.9	15.7	**11.2**	30.3	13.2	32.7
Becker et al. [30]	306 (306)	**5.51**	7.14	10.0	11.5			
Griffel [32]	70 (59)	5.61	5.47	**4.43**	17.2	4.48	21.3	5.97
Nariai et al. [17,18]	209 (54)	73.8	35.7	**21.8**	29.0	16.4	31.4	17.8
Inasaka and Nariai [19]	29 (0)					9.25	17.1	7.48
Inasaka [33]	95 (3)	81.2	37.1	**14.3**	38.3	18.9	28.0	21.7
Celata et al. [21]	78 (0)					23.2	28.7	14.8
Vandervort et al. [24]	210 (19)	82.5	16.9	42.9	**16.7**	17.3	24.6	29.6
Lezzi et al. [23]	87 (87)	32.3	**7.84**	15.3	9.40			
Kureta [26]	930 (736)	52.5	51.9	37.9	**20.2**	42.7	47.0	35.6
Roach et al. [25]	51 (51)	18.6	33.5	**16.4**	18.0			
Mudawar and Bowers [27]	174 (0)					83.5	38.7	18.8
Total (13 databases)	3837 (2539)	29.3	26.4	20.6	**16.8**	30.5	30.1	19.2

[a] Mean deviation defined as $(1/N)\sum|(q_{c,exp} - q_{c,cal})/q_{c,exp}| \times 100\%$, a bold figure denoting the smallest of mean deviations predicted by four correlations including a new correlation, and an underlined figure being the smallest except for the new correlation.

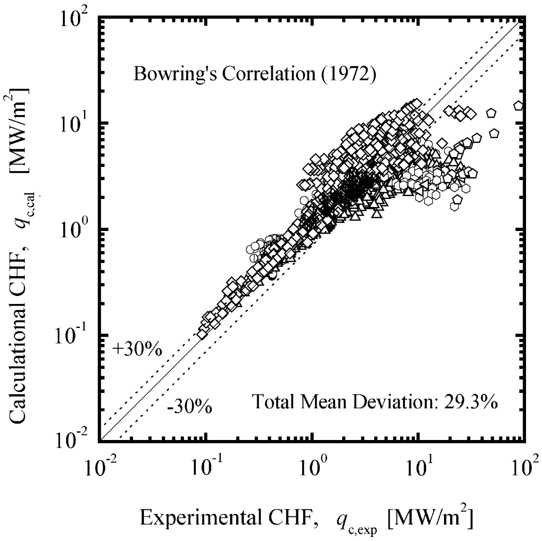

Fig. 2. Evaluation of Bowring's correlation with saturated CHF data.

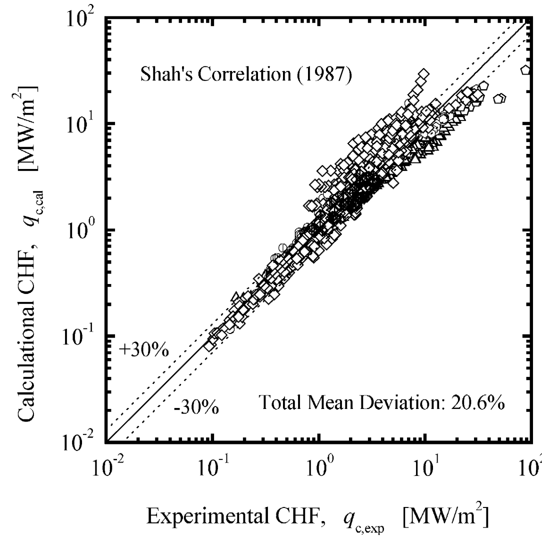

Fig. 4. Evaluation of Shah's correlation with saturated CHF data.

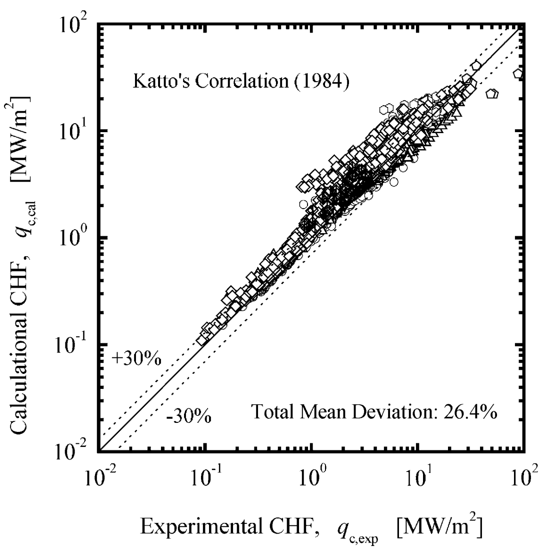

Fig. 3. Evaluation of Katto's correlation with saturated CHF data.

respectively. Symbols for each dataset are depicted in Table 1. For low CHF values, shown in Fig. 2, the Bowring correlation correlated generally well the experimental CHF values, although there is a slight over-prediction. For high CHF values, however, the Bowring correlation fails to correlate the experimental CHF values. A large scatter of predictions can be observed and many of them tend to deviate systematically from the experimental values. Fig. 3 shows the behavior of Katto's correlation. Although the correlation correlates all the data successfully within a relatively small scatter, it seems that there exist some slight over-predictions for most of the CHF data. Fig. 4 shows the evaluation of Shah's correlation. For low CHF values, the predictions by the Shah correlation have a very small scatter and most are centered within the error band of ±30%. For high CHF values, the Shah correlation tends to predict CHF with some scatter.

3.2.2. Evaluation of correlations for subcooled CHF

Here presented is an assessment of three correlations for subcooled flow boiling CHF: one is a statistical correlation by Hall and Mudawar [16], the other two are modified Tong correlations (one by Inasaka and Nariai [14], and another by Celata et al. [15]). It should be mentioned that the Inasaka–Nariai and Celata et al. correlations are local conditions correlations (LCC). These two correlations require a prior knowledge of local quality (i.e., thermodynamic equilibrium quality) at CHF to predict CHF values. Since the local quality is a dependent parameter and unknown, the heat balance equation, which needs upstream information, e.g., inlet quality, is used in this study to obtain the local quality. Therefore, our evaluation method for the Inasaka–Nariai and Celata et al. correlations is a HBM (heat balance condition method). This method gives better evaluation than the DSM (direct substitution method) according to Inasaka [33].

The comparison results are also tabulated in Table 2. The mean deviation is used as an indicator of predictive accuracy as well. Underlined figures in the table are the smallest mean deviations. In all, Hall–Mudawar's correlation presented the best predictive accuracy with a total mean deviation of 19.2%, smallest among the three correlations. For a total of 10 datasets of subcooled CHF, this correlation provides the smallest mean deviations of five datasets, most among the three existing correlations for subcooled CHF. For six databases by Thompson and Macbeth, Griffel, Nariai et al., Inasaka and Nariai, Celata et al., and Mudawar and Bowers, the Hall–Mudawar correlation predicts the CHF with the mean deviations less than 20%, three of them even less than 10%. The correlation by Celata et al. has a total mean deviation of 30.1% for all subcooled CHF data, and the smallest mean deviation for one dataset. The Inasaka–Nariai correlation predicts the CHF with a total mean deviation of 30.5% for all data, a little larger than that by the Celata correlation.

However, four mean deviations are lowest for all 10 datasets. Through further examination of the mean deviations, it can be found the Inasaka–Nariai correlation works satisfactorily for many datasets except for the two datasets, one by Kureta and another by Mudawar and Bowers.

Figs. 5–7 illustrate graphically the comparison of the calculated CHF values by Inasaka–Nariai's correlation, Celata et al.'s correlation and Hall–Mudawar's correlation, respectively, to experimental CHF values. Symbols for each dataset are represented in Table 1. As shown in Fig. 5, the Inasaka–Nariai correlation correlates the experimental CHF with some scatter and tends to over-predict the data for high CHF values. Fig. 6 shows the prediction behavior of the Celata correlation. For low CHF values, the correlation predicted the experimental data with a relatively large scatter. For high CHF values, it tends to under-predict the CHF, although with a small scatter of prediction. Fig. 7 shows the performance of Hall–Mudawar's correlation. All the data are correlated satisfactorily with a relatively small scatter. From the figure, no systematic deviations of prediction from the experimental data can be observed.

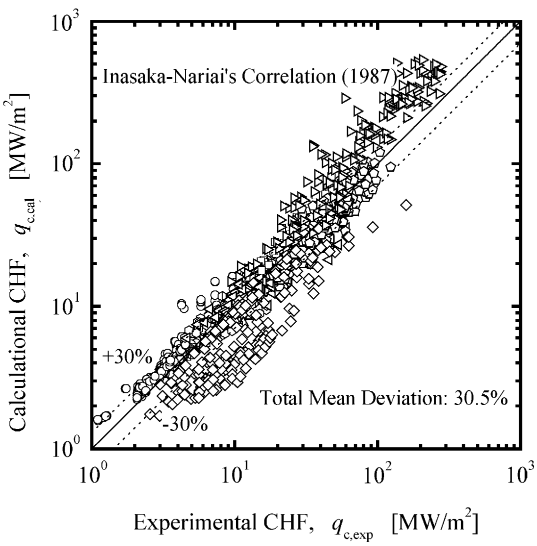

Fig. 5. Assessment of Inasaka–Nariai's correlation with subcooled CHF data.

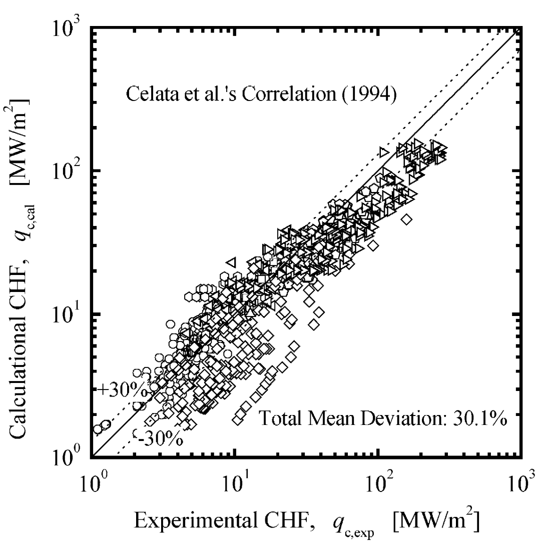

Fig. 6. Assessment of Celata et al.'s correlation with subcooled CHF data.

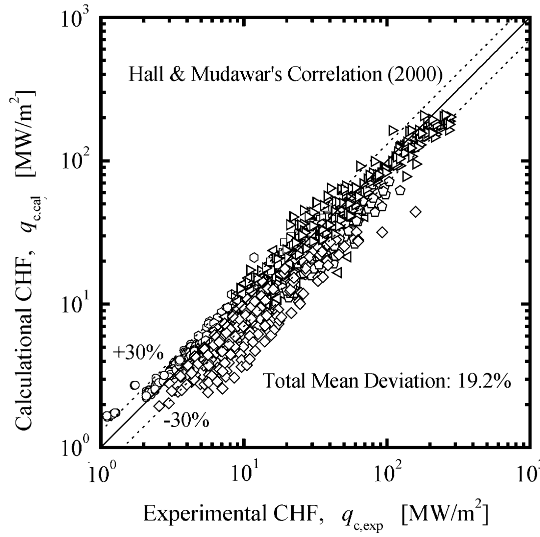

Fig. 7. Assessment of Hall–Mudawar's correlation with subcooled CHF data.

3.3. Development of CHF correlation for saturated flow boiling in mini-channels

3.3.1. Determination of nondimensional numbers

Six variables (or their alternatives) are often considered as CHF experimental parameters. They are channel diameter, D_h, heated length, L, mass flux, G, pressure, p, inlet thermal equilibrium quality, $x_{eq,in}$, and outlet thermal equilibrium quality, $x_{eq,o}$. As they should agree with the heat balance equation, therefore there are only five independent variables relating to the CHF in experiments. Generally, a CHF correlation is classified as either an inlet conditions correlation based on inlet independent variables such as inlet enthalpy and heated length, or a local (or outlet) conditions correlation based on a dependent variable such as outlet quality. Although the outlet conditions correlations are more useful in nuclear engineering since they can satisfactorily account for separate effects, such as axial flux distributions and spacer grids in reactor, this study will focus on developing an inlet conditions correlation for the reason that all the collected data in this study are from experiments in which the uniform heat flux is employed, and inlet conditions correlations are usually more successful to correlate CHF data from uniform heat flux experiments than outlet condition correlations.

Through combining physical properties with CHF experimental parameters, CHF correlations can be expressed in nondimensional forms. However, there exist many functional forms to correlate CHF in the literature. For instance, for the relation between CHF and mass flux, Tong [4], Katto [10], Shah [12] and Groeneveld et al. [34] employed different nondimensional numbers. Here selections of nondimensional numbers are made on the basis of the application of an advanced information processing technique, the artificial neural network (ANN). The ANN has the capability to learn complex relationships from a set of associated input-outs [35]. It has been verified that the backpropagation neural network (BPN), one of simple but powerful ANNs, could provide a powerful alternative to current techniques for estimating and analyzing the CHF [36]. The applicability of ANN to predict CHF was also verified in this study. The ANN indeed could predict this collected database with high accuracy, such as a total mean deviation as small as 8.83%. However, due to lack of transparency and insight into the physical mechanism of CHF, this study is aiming at applying ANN not to predict CHF directly but to select nondimensional numbers which have significant effects on CHF prediction. Since any functional relationship can be approximated by a BPN if its sigmoid layer has enough neurons [35], an architecture-fixed BPN (layer and neuron numbers fixed) may be utilized to pick out a set of nondimensional numbers which can well correlate CHF. One set of nondimensional numbers have been found based on ANN as follows:

$$Bo = \mathrm{fn}(L/D_\mathrm{h}, We_\mathrm{D}, \rho_\mathrm{g}/\rho_\mathrm{f}, x_\mathrm{eq,in}). \tag{11}$$

Since Katto [10], based on the dimensional analysis, showed that CHF could be correlated by using similar nondimensional numbers (Weber number, We_L, defined based on the channel heated length L instead of the diameter D_h), and Groeneveld et al. [34] utilized Weber number (We_D), density ratio ($\rho_\mathrm{g}/\rho_\mathrm{f}$), and local thermal equilibrium quality ($x_\mathrm{eq,o}$) to successfully develop a nondimensional CHF look-up table, therefore it is determined that the nondimensional numbers in Eq. (11) are used to develop a CHF correlation in this study.

3.3.2. Determination of functional form

Since the mass flux has a significant effect on the CHF, it would be better to draw the plot of Bo versus We_D as a first step to analyze the relationship between the CHF and mass flux. Fig. 8 shows the tendency of Bo against We_D with L/D_h as a parameter under atmospheric pressure. The data used are taken from Thompson and Macbeth [29], Lowdermilk et al. [31], Nariai et al. [17,18], and Kureta [26]. From the figure, it can be observed that for low values of We_D, Bo keeps almost constant. For high values of We_D, however, a linear relationship between Bo and We_D appears to hold. Two asymptotic equations were found based on CHF mechanisms. At low values of We_D, it may be presumed that dryout of an annular liquid film flowing along the tube wall is mainly responsible for the occurrence of CHF in this regime, and therefore a correlation form similar to the equation for a condition of the complete exhaustion of liquid at the tube exit with a uniform heat flux

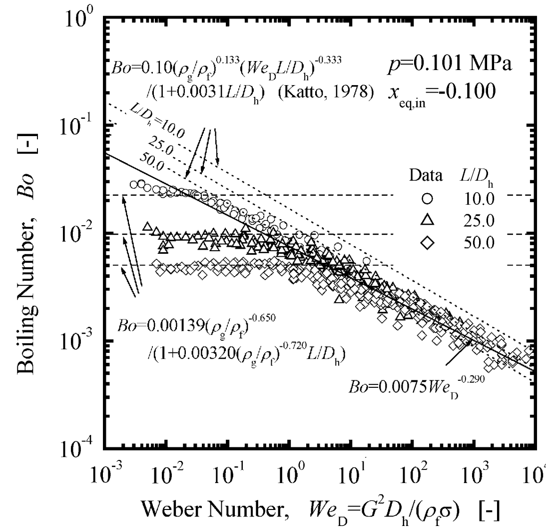

Fig. 8. Tendency analysis under atmospheric pressure.

should be valid in this regime [10]. This regime may belong to the L-regime as proposed by Katto [10]. It is found that the following equation may predict the CHF in this regime:

$$Bo = 0.00139(\rho_\mathrm{g}/\rho_\mathrm{f})^{-0.65}/\lfloor 1 + 0.0032(\rho_\mathrm{g}/\rho_\mathrm{f})^{-0.72}L/D_\mathrm{h}\rfloor. \tag{12}$$

For high values of We_D, since the relationship between Bo and We_D is almost linear on a log–log scale, therefore the following preliminary equation may work for this case:

$$Bo = 0.0075We_\mathrm{D}^{-0.29}. \tag{13}$$

The predictions by Katto's equation [10] for the H-regime are also presented in the figure. To check the validity of the above two simple equations, data taken under the pressure of 7.00 MPa are plotted in Fig. 9. It shows that Eq. (12) also works for this case, however, the coefficient and exponent in Eq. (13) should be slightly modified from

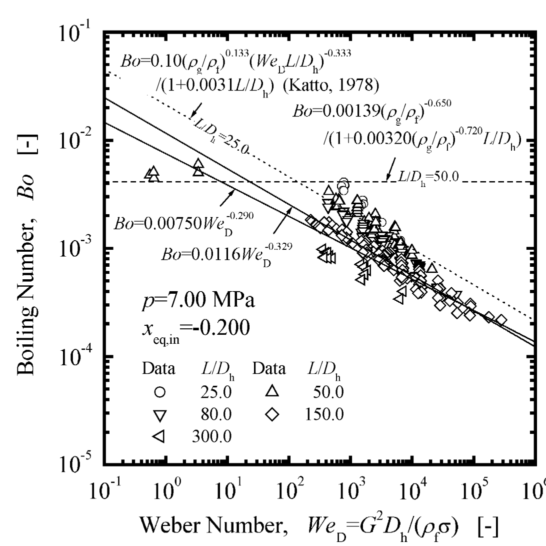

Fig. 9. Tendency analysis under pressure of 7.00 MPa.

0.00750 and −0.29 to 0.0116 and −0.329, respectively, for data of $L/D_h = 150$. Therefore, a much more accurate correlation is desirable and ought to be developed subsequently in place of Eq. (13).

From Fig. 9, it can be observed that there is a small dependency of Bo on L/D_h. At the fixed We_D, Bo decreases with increase of L/D_h. To check this dependency, data is plotted in the figure of the ratio of Bo to $We_D^{-0.329}$ as a function of L/D_h, as illustrated in Fig. 10. It should be mentioned here that only the data of exit qualities less than 0.4 are used in Figs. 10–12 because such data may all fall into the H-regime and could be based on to develop the more accurate correlation for the H-regime. Under the pressure of 7.00 MPa, the relationship between the ratio of Bo to $We_D^{-0.329}$ and L/D_h is nearly linear on a log–log scale for fixed inlet qualities, as shown in Fig. 10(c). In other words, the ratio of Bo to $We_D^{-0.329}$ is nearly proportional to $L/D_h^{-0.45}$. This relationship holds as well for data taken under other two pressures (3.00 and 14.0 MPa, see Fig. 10(b) and (d)), and may be assumed to be valid under atmospheric pressure although there exists some scatter, as shown in Fig. 10(a). Fig. 10 illustrates that there also exists an inlet quality dependency. Thus, the above ratio ($Bo/We_D^{-0.329}$) is further divided by $L/D_h^{-0.45}$, and then data are plotted in the figure of the new ratio, i.e., $Bo/(We_D^{-0.329}L/D_h^{-0.45})$, versus the inlet quality, $x_{eq,in}$. The results are illustrated in Fig. 11. It could be observed that a linear relationship holds between the new ratios and the inlet qualities, and the values of the slope of the linear equation are almost the same and may be fixed to a constant of −0.0015 for the four cases of pressure. The values of the intercept, ξ, of the linear equation vary with pressure and can be determined under the four different pressures, as illustrated in Fig. 12. It is a function of pressure as follows:

$$\xi = 0.155(\rho_g/\rho_f)^{0.240}. \tag{14}$$

Therefore, a new equation for the H-regime can be concluded as follows:

$$Bo = \varsigma \cdot We_D^{-0.329}(L/D_h)^{-0.450} \cdot [0.155(\rho_g/\rho_f)^{0.240} - 0.0015x_{eq,in}], \tag{15}$$

where ς is a constant of 1 according to the above deduction. However, since only a small part of data in the H-regime was utilized to find the above functional form of the correlation, its coefficients can be further improved by use of the regression method based on all the data in the H-regime. Thus, ς may be set to a constant of 1.38.

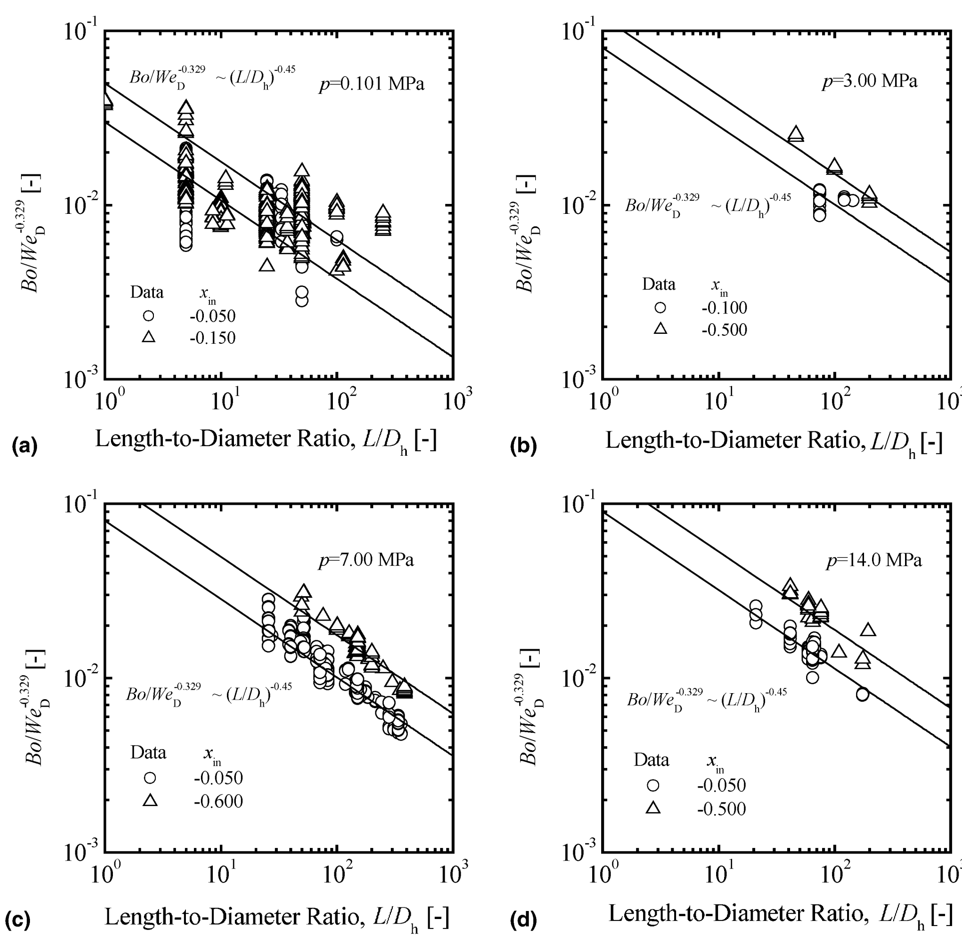

Fig. 10. Determination of length-to-diameter dependency under pressures of (a) 0.101 MPa, (b) 3.00 MPa, (c) 7.00 MPa and (d) 14.0 MPa.

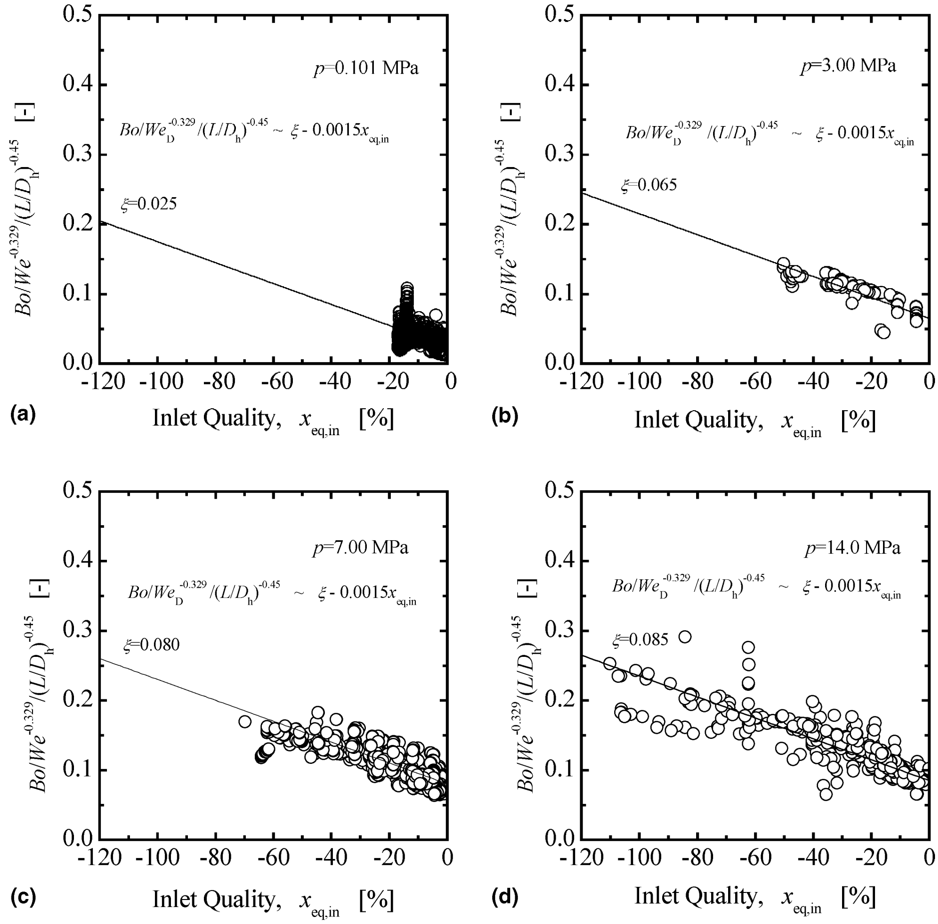

Fig. 11. Determination of inlet quality dependency under pressures of (a) 0.101 MPa, (b) 3.00 MPa, (c) 7.00 MPa, and (d) 14.0 MPa.

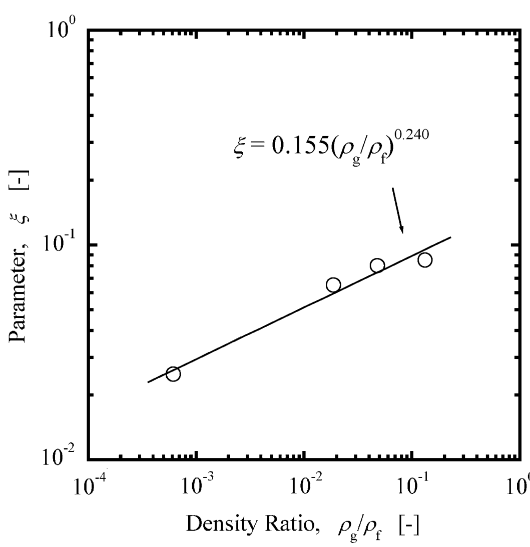

Fig. 12. Determination of parameter in linear equation.

If taking the minimum between Eqs. (12) and (15), one yields

$$Bo = \min(\text{Eq. (12), Eq. (15)}). \quad (16)$$

All the CHF data with $D_h < 6.22$ mm and $x_{eq,o} > 0$ can be predicted by the above equation with the total mean deviation of 22.1%. Further, it was found that the following function form may predict the whole tendency of Bo against We_D in all the regimes, as shown in Fig. 8,

$$Bo = f_1(We_D + f_2)^{\zeta_1}, \quad (17)$$

where f_1 and f_2 may be constants or functions of ρ_g/ρ_f, L/D_h, and $x_{eq,in}$, and ζ_1 may be deemed as a constant close to the exponent of We_D, -0.329, in Eq. (15). Since Eq. (17) should reach the two asymptotic equations, Eqs. (12) and (15), for low and high values of We_D, respectively, therefore it can be reasonably assumed that the following functions are valid for f_1 and f_2, respectively:

$$f_1 = \zeta_2(L/D_h)^{\zeta_3}\lfloor\zeta_4(\rho_g/\rho_f)^{\zeta_5} - x_{eq,in}\rfloor, \quad (18)$$

$$f_2 = \zeta_6(L/D_h)^{\zeta_7}(\rho_g/\rho_f)^{\zeta_8}. \quad (19)$$

By applying the regression method, eight parameters, ζ_1–ζ_8, can be determined and therefore the following new simple equation for saturated CHF may be concluded:

$$Bo = 0.0352[We_D + 0.0119(L/D_h)^{2.31}(\rho_g/\rho_f)^{0.361}]^{-0.295} \cdot (L/D_h)^{-0.311}[2.05(\rho_g/\rho_f)^{0.170} - x_{eq,in}]. \quad (20)$$

3.4. Comparison of new correlation with saturated CHF data

In this section, the new CHF correlation, Eq. (20) will be evaluated by the collected database for the saturated CHF tabulated in Table 1. Table 2 shows in detail the comparison results of the new correlation with the three existing correlations by Bowring [8], Katto and Ohno [11] and Shah [13] for each dataset. Bold figures in the table denote the smallest of mean deviations predicted by four correlations including the newly developed one. From the table, the new correlation works the best for three datasets, by the smallest mean deviations. For a total of 10 datasets for saturated CHF, seven of them are predicted within the mean deviation of 20%. In all the new correlation has the total mean deviation of 16.8% for this collected database taken from small-diameter channels, smallest among the four correlations. Fig. 13 further compares the new correlation with the experimental data graphically. CHF values predicted by the new correlation are plotted against their corresponding experimental values. From the figure, it can be observed that the values of CHF spanning almost three orders of magnitude are well predicted within the error bars of ±30%, and no systematic deviation occurs. Fig. 14 illustrates that the tendencies of Bo against We_D could be smoothly and well predicted by the new correlation for a variety of length-to-diameter ratios (L/D_h from 5.0 to 200). The data used are taken from Thompson and Macbeth [29], Lowdermilk et al. [31], Nariai et al. [17,18], and Kureta [26]. Therefore, the new, simple correlation overcomes the defects of predictive discontinuities often encountered when applying existing correlations. Fig. 15 showed the evaluation of the new correlation with the data by Lowdermilk et al. [31] in the plot of CHF versus mass flux. For different channel diameters (D_h of 1.30, 3.12 and 4.78 mm), the predictions by the new correlation agree well with the data in the whole range of $x_{eq,o}$ from 0 to 1.

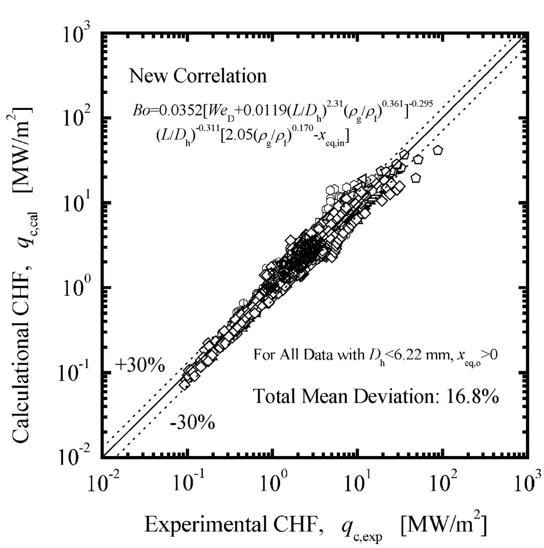

Fig. 13. Evaluation of new correlation with all data for saturated CHF.

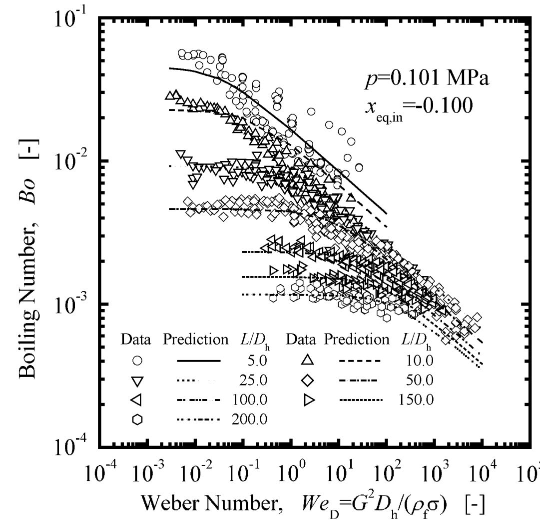

Fig. 14. Comparison of new CHF correlation with data taken under atmospheric pressure.

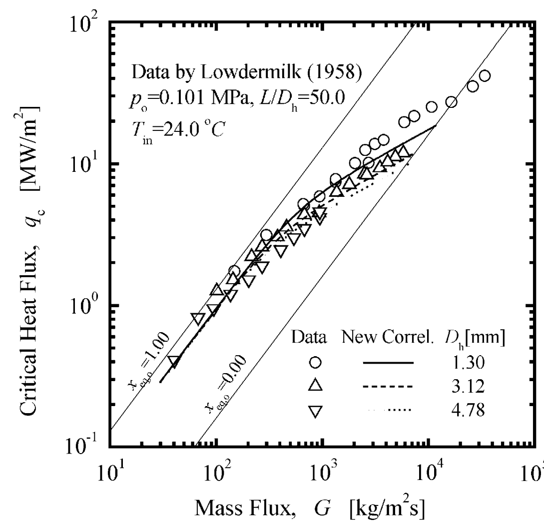

Fig. 15. Verification of new CHF correlation by Lowdermilk's data.

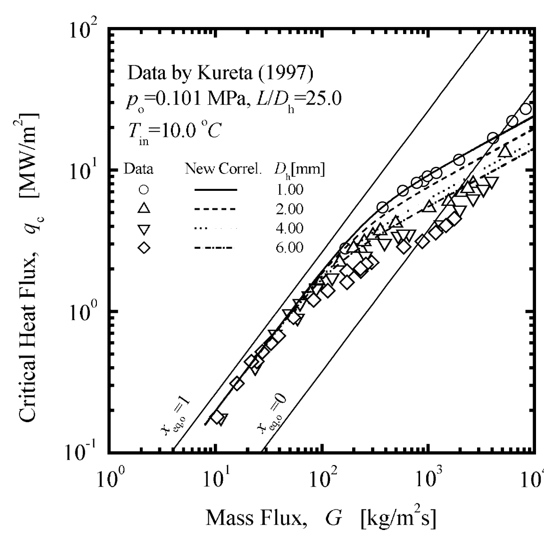

Fig. 16. Verification of new CHF correlation by Kureta's data.

Fig. 16 showed the further evaluation of the new correlation with the data by Kureta [26]. For channel diameters ranging from 1.00 to 6.00 mm, the predictions by the new correlation also agree with the tendencies of the data in the wide range of $x_{eq,o}$ from 0 to 1.

4. Conclusions

In view of practical importance of a CHF correlation for flow boiling in the aspects of engineering design and prediction, this study reviewed some existing correlations and experimental studies related to saturated and subcooled flow boiling CHF of water in small-diameter tubes, and collected an extensive CHF database under a variety of experimental conditions, and developed a new simple saturated CHF correlation for small-diameter tubes. The detailed conclusions could be drawn as follows:

(1) An extensive comparison of the existing correlations with the collected database demonstrates that for the saturated CHF region Shah's correlation correlated the data best, and for the subcooled CHF region Hall–Mudawar's correlation is the most reliable approach to CHF prediction for this collected database and may be recommended for prediction of subcooled CHF in small-diameter tubes.
(2) The dominant nondimensional numbers for CHF correlation can be determined based on the artificial neural network. Through the parametric tendency analysis of the existing data, a new, simple correlation is developed for saturated CHF in small-diameter tubes. In sharp contrast to other correlations, this new, dimensionless CHF correlation consists only of a single equation, avoiding the defects of predictive discontinuities often encountered when applying existing correlations.
(3) The new CHF correlation presents the satisfactory predictive accuracy for this collected databank covering wide ranges of parameters. The total mean deviation is 16.8%, smallest among all tested correlations in this study. It may be recommended for use to predict CHF of saturated flow boiling in small-diameter tubes.

At present, the new CHF correlation developed in this study may not be suitable to predict CHF for the cooling channels under circumferentially and/or axially nonuniform heating conditions. Further study is desirable to introduce some correction factors to this correlation or develop a new mechanism-based correlation for such channels.

For subcooled flow boiling CHF in mini-channels, the Hall–Mudawar correlation may be deemed as one of the best prediction tools so far since it was based on almost all available subcooled CHF databases in the literature and presents satisfactory predictive accuracies. Our database contains only about 1300 data points, less than one third of the Hall–Mudawar database (4860 data points), and only one new dataset (Kureta's dataset). Further work to collect datasets from the literature is needed. Therefore, this study did not develop a new CHF correlation for subcooled flow boiling. In addition, since the Hall–Mudawar correlation is a statistical correlation, it may be desirable to develop a mechanism-based CHF correlation for subcooled flow boiling in the future. Mechanism-based CHF correlations may be applied in many cases, e.g., cooling channels under circumferentially and/or axially nonuniform heating conditions.

Acknowledgements

The authors would like to express their sincere appreciation to Dr. M. Kureta (JAERI) for providing his valuable datasets, and Drs Y. Saito (Kyoto Univ.) as well as X. Shen (Kyoto Univ.) for their kind helps. One of the authors (W. Zhang) gratefully acknowledges the support of Japanese Government Scholarship.

References

[1] S.G. Kandlikar, Fundamental issues related to flow boiling in minichannels and microchannels, Exp. Therm. Fluid Sci. 26 (2002) 389–407.
[2] S.S. Mehendale, A.M. Jacobi, R.K. Shan, Fluid flow and heat transfer at micro- and meso-scales with application to heat exchanger design, Appl. Mech. Rev. 53 (7) (2000) 175–193.
[3] S.S. Kutateladze, A.I. Leont'ev, Some applications of the asymptotic theory of the turbulent boundary layer, in: Proceedings of the Third International Heat Transfer Conference, vol. 3, American Institute of Chemical Engineers, New York, 1966, pp. 1–6.
[4] L.S. Tong, Boundary-layer analysis of the flow boiling crisis, Int. J. Heat Mass Transfer 11 (1968) 1208–1211.
[5] J. Weisman, B.S. Pei, Prediction of critical heat flux in flow boiling at low qualities, Int. J. Heat Mass Transfer 26 (1983) 1463–1477.
[6] C.H. Lee, I. Mudawar, A mechanistic critical heat flux model for subcooled flow boiling based on local bulk flow conditions, Int. J. Multiphase Flow 14 (1988) 711–728.
[7] G.F. Hewitt, N.S. Hall-Taylor, Annular Two-phase Flow, Pergamon Press, New York, 1970.
[8] 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, 1972.
[9] N.E. Todreas, M.S. Kazimi, Nuclear Systems I, Hemisphere Press, New York, 1990.
[10] Y. Katto, A generalized correlation of critical heat flux for the forced convection boiling in vertical uniformly heated round tubes, Int. J. Heat Mass Transfer 21 (1978) 1527–1542.
[11] Y. Katto, H. Ohno, An improved version of the generalized correlation of critical heat flux for the forced convective boiling in uniformly heated vertical tubes, Int. J. Heat Mass Transfer 27 (1984) 1641–1648.
[12] M.M. Shah, A generalized graphical method for predicting CHF in uniformly heated vertical tubes, Int. J. Heat Mass Transfer 22 (1979) 557–568.
[13] M.M. Shah, Improved general correlation for critical heat flux during upflow in uniformly heated vertical tubes, Int. J. Heat Fluid Flow 8 (1987) 326–335.
[14] F. Inasaka, H. Nariai, Critical heat flux and flow characteristics of subcooled flow boiling in narrow tubes, JSME Int. J. 30 (1987) 1595–1600.

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

[16] D.D. Hall, I. Mudawar, Critical heat flux (CHF) for water flow in tubes—II. Subcooled CHF correlations, Int. J. Heat Mass Transfer 43 (2000) 2605–2640.

[17] H. Nariai, F. Inasaka, T. Shimura, Critical heat flux of subcooled flow boiling in narrow tube, ASME-JSME Thermal Eng. Joint Conf. Proc. 5 (1987) 455–462.

[18] H. Nariai, F. Inasak, K. Uehara, Critical heat flux in narrow tubes with uniform heating, Heat Transfer—Jpn. Res. 18 (1989) 21–30.

[19] F. Inasaka, H. Nariai, Critical heat flux of subcooled flow boiling with water, Proc. NURETH-4 1 (1989) 115–120.

[20] G.P. Celata, M. Cumo, G.E. Farello, A. Mariani, Preliminary remarks on high heat flux CHF in subcooled water flow boiling, Heat Technol. 8 (1990) 20–42.

[21] G.P. Celata, M. Cumo, A. Mariani, Burnout in highly subcooled water flow boiling in small diameter tubes, Int. J. Heat Mass Transfer 36 (1993) 1269–1285.

[22] G.P. Celata, M. Cumo, A. Mariani, H. Nariai, F. Inasaka, Influence of channel diameter on subcooled flow boiling burnout at high heat fluxes, Int. J. Heat Mass Transfer 36 (1993) 3407–3410.

[23] A.M. Lezzi, A. Niro, G.P. Beretta, Experimental data on CHF for forced convection water boiling in long horizontal capillary tubes, in: G.F. Hewitt (Ed.), Heat Transfer 1994: Proceedings of the Tenth International Heat Transfer Conference, vol. 7, Institution of Chemical Engineers, Rugby, United Kingdom, 1994, pp. 491–496.

[24] C.L. Vandervort, A.E. Bergles, M.K. Jensen, An experimental study of critical heat flux in very high heat flux subcooled boiling, Int. J. Heat Mass Transfer 37 (1994) 161–173.

[25] G.M. Roach Jr., S.I. Abdel-Khalik, S.M. Ghiaasiaan, M.F. Dowling, S.M. Jeter, Low-flow critical heat flux in heated microchannels, Nucl. Sci. Eng. 131 (1999) 411–425.

[26] M. Kureta, Critical heat flux for flow boiling of water in small diameter tubes under atmospheric pressure, doctoral thesis, Kyoto University, 1997, (in Japanese).

[27] 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, Int. J. Heat Mass Transfer 42 (1999) 1405–1428.

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

[29] 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.

[30] K.M. Becker, G. Hernborg, M. Bode, O. Eriksson, Burnout data for flow of boiling water in vertical round ducts, annuli and rod clusters, AE-177, Aktiebolaget Atomenergi, Stockholm, Sweden, 1965.

[31] W.H. Lowdermilk, C.D. Lanzo, B.L. Siegel, Investigation of boiling burnout and flow stability for water flowing in tubes, NACA TN 4382, National Advisory Committee for Aeronautics, Washington, DC, 1958.

[32] J. Griffel, Forced convection boiling burnout for water in uniformly heated tubular test sections, USAEC Report NYO 187-7, TID-4500, 1965.

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

[34] D.C. Groeneveld, S.C. Cheng, T. Doan, AECL-UO critical heat flux look-up table, Heat Transfer Eng. 7 (1986) 46–62.

[35] Y.H. Pao, Adaptive Pattern Recognition and Neural Networks, Addison-Wesley, USA, 1989.

[36] G.H. Su, K. Fukuda, D. Jia, K. Morita, Application of an artificial neural network in reactor thermo-hydraulic problem: prediction of critical heat flux, J. Nucl. Sci. Tech. 39 (2002) 564–571.