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An Evaluation of Subcooled CHF Correlations and Databases For Research Reactors Operating at 1 to 50 bar Pressure

M. Kalimullah, E. E. Feldman, A. P. Olson, B. Dionne, J. G. Stevens, and J. E. Matos
GTRI Convert Program, Nuclear Engineering Division
Argonne National Laboratory
9700 S. Cass Ave., Argonne, IL 60439-4803 – USA

ABSTRACT

In order to recommend a critical heat flux (CHF) prediction method for use in research reactors, an evaluation of 12 newer CHF correlations published during the last 20 years was performed. The correlations were compared at six pressures: 1, 5, 10, 20, 30, and 50 bar. It is found that two authors, Hall and Mudawar[1,6] and Groeneveld et al.[2], have assembled all the CHF measured data from the world literature dating back to 1949, have checked each data point by heat balance for error, and have independently developed two world-class CHF databases, each containing nearly 32500 data points. Derived from each database, only two CHF prediction methods are based on all the measured CHF data in the world: the Hall-Mudawar inlet conditions correlation and the Groeneveld 2006 CHF table. Close agreement between these two is found. They are considered to be the most reliable subcooled CHF prediction methods. Comparison of the Groeneveld table with the Caira[19], Lombardi[20], and Sarma[18,41] correlations adds further confidence to the reliability of the two. Although these databases were developed for round tubes with uniform heat flux over the full wetted perimeter of the heated length, based on the works of Mishima[29] and Pioro[30] these prediction methods are applicable to non-circular geometry for subcooled water at velocities greater than about 2 m/s. In addition, Zhang[32] points out that a dimensionless CHF correlation is applicable with acceptable accuracy to channels with heating on only part of the wetted perimeter if the heated diameter (D_h) is used in place of the hydraulic diameter in the Weber number. Based on the work of Celata[28], Tanase et al.[26] and the Hall-Mudawar correlation, (i) the Groeneveld 2006 table is extended to a maximum mass flux (G) of 30,000 kg/m^2-s by multiplying the tabulated CHF at 8000 kg/m^2-s by a factor of $(G/8000)^{0.376}$, and (ii) the recommended diameter correction factor is $(0.008/D_h)^{0.312}$ where D_h is in meters.

1. Introduction

In research reactors, two phenomena limit the amount of heat transferred from the heated surface to the coolant: the onset of excursive flow instability (OFI) and the critical heat flux (CHF). The heated surface may melt if OFI or CHF occurs. The purpose of this work is to search and

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evaluate the newer CHF correlations published during the last 20 years, in order to find the most reliable subcooled CHF correlation(s) to use for thermal-hydraulic analysis of research reactors operating at pressures between 1 and 50 bar.

Three types of CHF prediction methods are available in the literature: (i) CHF correlations based on parametric trends and statistical analysis of measured CHF data. The number of subcooled CHF correlations exceeds 100, and the total number of correlations for subcooled and saturated CHF has exceeded 1000 over the past 50 years[1,2]; (ii) Mechanistic CHF models based on an assumed mechanism which leads to a set of equations for CHF that is parametrically fitted to measured CHF data. Chang and Baek (2003)[3] have reviewed three mechanistic models for subcooled CHF. The resulting set of equations is usually iterative, difficult to quickly implement in a thermal-hydraulic code, and therefore are not discussed here; and (iii) Look-up tables giving CHF at discrete values of the important determining parameters (coolant pressure, mass flux, and critical quality). The tables are obtained, by an evaluation process, from a large database of measured CHF data. In 1986 Groeneveld et al.[4] of the Atomic Energy of Canada Limited and the University of Ottawa (AECL-UO) published a CHF lookup table which was updated[5] in 1995 after the merger of the Canadian and Russian CHF databases. The 1995 lookup table was recently updated[2] in 2006 when more data had become available.

Chang and Baek (2003)[3] have reported in their review that the Purdue University-Boiling and Two Phase Flow Laboratory (PU-BTPFL) database[6] containing 32544 CHF data points (5544 subcooled CHF data and 27000 saturated CHF data) is the largest in the world. The Hall-Mudawar subcooled CHF correlation[1] is derived from this database. Another world-class CHF database is the combined database of the Atomic Energy of Canada, Limited (AECL), Canada and the Institute of Physics and Power Engineering (IPPE), Russia. This AECL-IPPE database, maintained at the University of Ottawa, contains 33,175 data points. The Groeneveld 2006 CHF look-up table[2] is derived from this database (using 24,781 data points and rejecting 8394 data points). All other CHF correlations are based on medium size (1000 to 3000 CHF data points) or smaller databases.

Using the 4860 acceptable, subcooled CHF data points in the PU-BTPFL database[6], Hall and Mudawar (2000)[1] assessed 82 subcooled CHF correlations, including the Bernath correlation[7], the Gambill correlation[8], the Groeneveld 1995 look-up table[5], the Labuntsov correlation[9], the Shah correlation[10], and four correlations of their own. They ranked the correlations in the order of increasing mean absolute error, and found that the Hall-Mudawar inlet conditions correlation Eq. (1), provided below in Section 4, had the smallest mean absolute error. The Bernath correlation developed using 374 CHF data points was ranked 43rd in this assessment. It has a mean error of 3.5 %, a mean absolute error of 31.1 %, and an RMS error of 43.3 % for the 3931 CHF data points of the PU-BTPFL database that are within the parametric range of the Bernath correlation.

Using 1298 subcooled CHF data points, Zhang et al. (2006)[11] evaluated the Inasaka-Nariai correlation[12], the Celata correlation[13], and Eq. (1), and found Eq. (1) to be the most reliable. The Japanese work of two decades on CHF in rectangular channels of research reactors has culminated into the Sudo-Kaminaga correlation (1998)[14]. It has three ranges of mass flux, and accounts for the CHF difference between upflow and downflow in the intermediate mass flux range. By comparing with 596 data points, Sudo and Kaminaga found that the measured CHF value was always more than 67 % of the calculated value (i.e., a maximum error of -33 %). Their database is much smaller than one of the world-class databases. Furthermore, Sudo and Kaminaga[15] have reported that their database contained excursive flow instability data mixed with CHF data.

Every CHF prediction method, in order to be reliable and useful, must be tested against a database (the larger the better) of measured CHF data. The prediction method having the smallest error when tested against the largest CHF database in the world is the most reliable. It is found that many of the successful prediction methods predict about 90 % of the measured data in the *author's* medium-sized CHF database (containing 1000 to 3000 data points), within an error of ±30 %. Only a few methods predict *all* the measured data in the medium-sized CHF database, within an error of ±50 %. For example, see Celata (1994)[16] and Liu et al. (2000)[17]. This gives an idea of the magnitude of the error. Therefore, a close agreement (within about 15%) between the Hall-Mudawar subcooled correlation and the Groeneveld 2006 CHF look-up table would mean that they are equally the most reliable.

2. Grouping of CHF Prediction Methods

CHF prediction methods may be classified into four groups based on the number of measured CHF data points utilized in developing them: (1) Group 1 contains CHF prediction methods based on practically all measured CHF data in the world. This group has only two prediction methods: the Hall-Mudawar subcooled CHF correlation derived from the PU-BTPFL database, and the Groeneveld 2006 CHF look-up table derived from the AECL-IPPE database. (2) Group 2 contains correlations based on 1000 to 3000 measured data points. For example, the Sarma (2006)[18] subcooled CHF correlation based on 3050 data points; the Caira[19] correlation based on 544 data points, reassessed later by him using 1887 data points; the Lombardi[20] correlation based on 2529 data points; and the Inasaka-Nariai[12] correlation based on about 430 data points, reassessed later by Zhang (2006)[11] using 1298 subcooled CHF data points. (3) Group 3 contains correlations based on 300 to 1000 measured CHF data points. For example, the Sudo-Kaminaga (1993)[15] correlation based on 596 data points; the Bernath (1960)[7] correlation based on about 374 data points; and Kureta (2002)[21] correlation based on 535 data points. (4) Group 4 contains correlations based on less than 300 measured CHF data points. For example, the Mirshak (1959)[22] correlation is based on 65 data points from a single source.

3. CHF Databases

Thompson and Macbeth[23] of the United Kingdom Atomic Energy Authority published in 1964 a CHF database of 4372 data points of which 3564 are considered acceptable by Hall and Mudawar[6]. Celata[24] of ENEA, Rome, Italy recently provided us the ENEA CHF database containing 1969 subcooled CHF data points. This database has CHF data from 25 sources, and covers the parameter range: $1 \leq P \leq 84$ bar, $2000 \leq G \leq 90{,}000$ kg/m^2-s, $0.3 \leq D_e \leq 25.4$ mm, $0.1 \leq L_h \leq 0.61$ m, $90 \leq \Delta T_{sub,i} \leq 230$ °C. Chang et al.[25] of the Korea Advanced Institute of Science and Technology have developed the KAIST CHF database for water flowing in uniformly heated vertical round tubes containing 15000 CHF data points compiled from worldwide sources. The two proprietary databases, the PU-BTPFL CHF database developed by Hall and Mudawar[6] and the AECL-IPPE database maintained by Groeneveld et al.[2], are the largest in the world today.

The PU-BTPFL database has measured CHF data for vertical upflow and horizontal flow of water in uniformly heated round tubes, collected from over 100 sources dating back to 1949. The CHF data was collected from the original sources so that the information in them could be used in assessing the data. A point-by-point assessment of the CHF database revealed that 7% of the data were unacceptable because these data were unreliable according to the original authors, unknowingly duplicated, or in violation of an energy balance. The parametric ranges of the 30,398 acceptable CHF data are:

$0.25 \le D \le 44.7$ mm,	$1.7 \le L_h/D \le 2484$,	$10 \le G \le 134{,}000$ kg/m^2-s,
$0.7 \le P \le 218$ bar,	$0 \le$ inlet subcooling ≤ 347 °C,	$-3.00 \le$ inlet quality ≤ 0.00
$0 \le$ exit subcooling ≤ 305 °C,	$-2.25 \le$ exit quality ≤ 1.00,	$0.05 \le$ CHF ≤ 276.0 MW/m^2

4. Hall-Mudawar Subcooled CHF Correlation

Hall and Mudawar (2000)[1] developed the form of the subcooled CHF correlation, Eq. (1), based on the parametric trends of some of the subcooled CHF data in the PU-BTPFL database[6], and then obtained the recommended set of values of the five constants (C_1 thru C_5) by nonlinear regression of Eq. (1) over the entire subcooled CHF database (4860 acceptable data points). Equation (1) is an Inlet Conditions Correlation (ICC). All saturated properties in Eq. (1) are evaluated at the exit pressure. The mean error of the correlation is –2.0 %, the mean absolute error is 10.3 %, and the RMS error is 14.3 % over the 4860 data points. Equation (1) although developed for tubes can be used for rectangular channels of research reactors at coolant velocities greater than about 2 m/s, as discussed in Section 6. See nomenclature.

$$\frac{q_c}{G\,h_{fg,o}} = \frac{C_1\left(\dfrac{G^2 D}{\rho_f\,\sigma}\right)^{C_2}\left(\rho_f/\rho_g\right)^{C_3}\left[1 - C_4\left(\rho_f/\rho_g\right)^{C_5} X_i^*\right]}{1 + 4\,C_1\,C_4\left(\dfrac{G^2 D}{\rho_f\,\sigma}\right)^{C_2}\left(\rho_f/\rho_g\right)^{C_3+C_5}\left(L_h/D_h\right)} \quad \text{where} \quad X_i^* = \frac{h_i - h_{f,o}}{h_{fg,o}} \qquad (1)$$

where $C_1 = 0.0722$, $C_2 = -0.312$, $C_3 = -0.644$, $C_4 = 0.900$, $C_5 = 0.724$
The range of application is:

$0.25 \le D \le 15$ mm ,	$6 \le L/D \le 200$,	$300 \le G \le 30{,}000$ kg/m^2-s ,
$1.0 \le P \le 200$ bar ,	$-2.0 \le X_i \le 0.0$,	$-1.0 \le X_o \le 0.0$

Equation (2) expresses the heat balance from the inlet to the outlet of the heated length. Using Eq. (2), Eq. (1) can be transformed into the Hall-Mudawar Outlet Conditions Correlation (OCC)[1], Eq. (3), which is applicable only if $X_o < -0.05$.

$$X_o = X_i^* + \frac{4\,L_h\,q_c}{D_h\,G\,h_{fg,o}} \qquad (2)$$

$$\frac{q_c}{G\,h_{fg}} = C_1\left(\frac{G^2\,D}{\rho_f\,\sigma}\right)^{C_2}\left(\rho_f/\rho_g\right)^{C_3}\left[1 - C_4\left(\rho_f/\rho_g\right)^{C_5} X_o\right] \tag{3}$$

5. Groeneveld 2006 Table for Predicting CHF

The combined work of Canadian and Russian researchers[2,5] has updated and improved the accuracy of a series of CHF lookup tables over 30 years as more data became available. The latest is the 2006 Groeneveld table which can be written as Eq. (4). On the right hand side, the first quantity $q_c(0.008, P, G, X_o)$ is tabulated, and is the CHF for a vertical 0.008-m-diameter water-cooled tube at mass flux G, exit pressure P, and exit equilibrium quality X_o. This table provides CHF values at 24 pressures, 20 mass fluxes, and 23 qualities, covering the range 1 to 210 bar pressure, 0 to 8000 kg/m^2-s mass flux, and -0.5 to 1.0 critical quality. The second factor accounts for the effect of tube diameter on CHF where the value of the exponent *n* was 1/3 in the 1986 table[4], was changed to 0.5 in 1995, and the same value (0.5) was published in 2006. However, based on the recent exhaustive work of Tanase et al. (2009)[26] (with Groeneveld as coauthor), the recommended value of *n* is 0.312 (see Section in 5.2).

$$q_c(D, P, G, X_o) = q_c(0.008, P, G, X_o)\left(\frac{0.008}{D}\right)^n \tag{4}$$

where D is the tube diameter. As discussed below, D is in general the heated diameter of the channel, given by (4 x flow area/heated perimeter). The RMS error reported by Groeneveld[2] for subcooled CHF is 14.7% if the 2006 table is used by the direct substitution method (DSM), and 7.1% if the table is used by the heat balance method (HBM).

5.1. Extension of Groeneveld Table to G > 8000 kg/m^2-s

The 2006 CHF table is limited to $G \leq 8000$ kg/m^2-s. The application of the 2006 table has been extended to $G > 8000$ kg/m^2-s, as follows. The subcooled CHF varies as G^{1+2C_2}, i.e., $G^{0.376}$ in the Hall-Mudawar correlation[1] Eq. (1), as $G^{0.4}$ in the Inasaka-Nariai correlation[12] Eq. (9), and as $G^{0.5}$ in the Celata correlation[13] Eq. (10). These three are outlet conditions correlations like the Groeneveld table. The recommended value of 0.376 for the exponent of G is the smallest (most conservative) of the three values, and is obtained from the most reliable subcooled CHF correlation[1], Eq. (1). To find CHF at a mass flux $G > 8000$ kg/m^2-s, the CHF at 8000 kg/m^2-s is multiplied by $(G/8000)^{0.376}$. As shown in Eq. (5), this extends the application of the 2006 CHF table to mass fluxes greater than 8000 kg/m^2-s.

$$q_c(D, P, G, X_o) = q_c(0.008, P, G, X_o)\left(\frac{0.008}{D}\right)^n \left\{\left(\frac{G}{8000}\right)^{0.376} \quad \text{if} \;\; G > 8000\right\} \tag{5}$$

The range of application is:

$3 < D < 25$ mm,	$L/D > 25$ for subcooled CHF,	$T_i > 0.01$ °C,
$1000 < G < 30{,}000$ kg/m^2-s ,	$L/D > 50$ for saturated CHF,	$-0.5 < X_o < 1.0$,
$1.0 \leq P \leq 210$ bar		

5.2. Diameter Effect on CHF Predicted by Groeneveld Table

Tanase et al. (2009)[26] derived new values of the exponent *n* in Eq. (4) by varying *n* until the RMS error of CHF reached its minimum. They calculated *n* for several ranges of pressure, mass flux, and quality. For the 1 to 140 bar pressure range, the new value is 0.4 for the mass flux range 250 to 3000 kg/m^2-s, and is 0.3 for the 3000 to 8000 kg/m^2-s. Tanase et al. then compared the new values and 9 other methods of diameter correction proposed in the literature over the years 1965 to 2009, by calculating each method's average error and RMS error using the AECL-UO CHF database. They also assessed the no correction option (n = 0), and established that a diameter correction is needed. In their conclusion, Tanase et al. note their reliance on the value n=0.33 proposed by Groeneveld et al. (1986)[4] and the value n=0.235 used in an earlier correlation by Hall-Mudawar (1999)[27]. They recommended an exponent in the range of 0.25 to 0.33 for subcooled CHF for mass fluxes > 250 kg/m^2-s.

Celata et al. (1996)[28] used their mechanistic model[16] to do a set of CHF calculations for subcooled water flowing in tubes of 0.5 to 32 mm diameter at a pressure of 50 bar, mass flux of 7500 kg/m^2-s, and a fixed heated length of 0.4 m (or a fixed $L_h/D = 20$ in another set of calculations). The water inlet temperature was changed from 20 to 200 °C in order to vary the exit quality (X_o) from -0.5 to -0.1. The ratio $(CHF)_D/(CHF)_8$ versus the diameter ratio D/8 was plotted for *fixed values of exit quality*. All the calculated points fell on the same curve, independently of the fixed exit quality chosen, and for each set of CHF calculations. By best fit through the points, they obtained the exponent n = 0.3, which agrees with Tanase's conclusion[26].

The exponent *n* equals the value of C_2 in the Hall-Mudawar CHF correlation, which is –0.312 in Eq. (1) and Eq. (3). Therefore, we recommend a diameter correction factor of $(0.008/D)^{0.312}$, reconciling the works of Hall-Mudawar[1], Tanase[26], and Celata[28]. The heated diameter (D_h) rather than the hydraulic diameter (D_e) should be used in making the diameter correction, as discussed in Section 7.

6. Applying the Hall-Mudawar CHF Correlation to a Non-circular Geometry

Using experimental CHF data at low velocity and pressure, Mishima et al.[29] studied the effect of channel geometry (circular, rectangular, and annular) on CHF. They concluded that (i) at *very low mass fluxes* ($G < G_{low}$), there is no difference in the behavior of CHF between different channel geometries; (ii) at intermediate mass fluxes ($G_{low} < G < G_{inter}$), the behavior of CHF in rectangular and annular geometries differs from that in a circular tube. The difference is mainly attributed to the amount of liquid flowing along the unheated wall perimeter existing in the rectangular and annular geometries; and (iii) at *high mass fluxes* ($G > G_{inter}$), the effect of channel geometry on CHF is small, and the CHF is correlated well by the subcooled-boiling CHF correlations for circular tubes.

The term '*high mass flux*' means a dimensionless mass flux $G^* > 220$ which is the lower limit of the mass flux range for the *subcooled-boiling* CHF curve plotted in Fig. 13 of Mishima et al.[29]. In terms of actual mass flux G, this criterion can be written as Eq. (6). Mishima et al. also use the term '*very low mass fluxes*' which means a dimensionless mass flux $G^* < 3$ which is the upper limit of the mass flux range for the flat part of the CHF curve in Fig. 13 of Mishima et al.[29]. In terms of actual mass flux G, this criterion can be written as Eq. (7).

High mass fluxes: $G > G_{inter} = 220\left\{\sigma \rho_g^2 (\rho_f - \rho_g) g\right\}^{0.25}$

$\approx$ 800 to 3400 kg/m^2-s for water at 1.0 to 30 bar (6)

Very low mass fluxes: $G < G_{low} = 3\left\{\sigma \rho_g^2 (\rho_f - \rho_g) g\right\}^{0.25}$

$\approx$12 to 50 kg/m^2-s for water at 1.0 to 30 bar (7)

Based on Mishima et al. (1987)[29] and Pioro et al. (1999)[30] summarized below, the Hall-Mudawar subcooled CHF correlation developed for circular tubes can be used at high mass fluxes in non-circular channels, e.g., the rectangular coolant channels of research reactors.

Pioro et al. (1999)[30] measured CHF of R-134a (a fluid used to simulate water) in four channel cross-section geometries (circular, rectangular, triangular, and dumb-bell shaped), and compared the measured CHF data of each geometry to the CHF predicted by the Groeneveld 1995 look-up table with the diameter correction $(0.008/D)^{0.5}$. Previous tests by Tain et al.[31] have shown that R-134a is an effective modeling fluid to simulate the CHF-behavior of water. The hydraulic diameter of the channels varied from 3.5 to 7.32 mm, the heated length varied from 0.45 to 1.5 m, the mass flux varied from 1000 to 3000 kg/m^2-s, and the pressure was 11.3 and 17 bar for R-134a (simulating water at 70 and 100 bar). Pioro et al. concluded that the circular tube CHF look-up table, after conversion to R-134a equivalent conditions and after applying the diameter correction, generally provides a good estimate of the CHF for all geometries investigated.

7. Effect of One-sided Heating in a Rectangular Channel

The heated diameter (D_h) rather than the hydraulic diameter (D_e) should be used in Hall-Mudawar CHF correlation Eq. (1). To verify this, Zhang et al. (2007)[32] conducted an assessment of all 17 existing *dimensionless* subcooled CHF correlations that could be used with acceptable accuracy for fluids other than water. He identified these correlations from among the hundreds compiled by Hall and Mudawar[33]. The assessment used a CHF database of dielectric coolant FC-72 liquid flowing in a horizontal rectangular channel (5.0 mm x 2.5 mm, heated from one 2.5-mm side), with velocity in the range of 0.3 to 8 m/s, outlet subcooling in the range of 10 to 32 °C, and an outlet pressure of 1.38 to 1.44 bar.

TABLE 1. Assessment of Hall-Mudawar Subcooled CHF Correlations for a Rectangular Channel and FC-72 Liquid Coolant

Rank	Subcooled CHF Correlation	Mean Error (%)	Mean Absolute Error (%)	RMS Error (%)
1	Eq. (1) with an earlier (1999) set of values of constants[27]:			
	based on D_h	-8.5	12.8	16.8
	based on D_e	11.4	18.8	21.8
2	Eq. (1) with the recommended set of values of constants:			
	based on D_h	-3.1	15.1	17.8
	based on D_e	26.3	27.8	33.8

As shown in Table 1, two Hall-Mudawar correlations, Eq. (1) with an earlier (1999) set of values of constants[27] and Eq. (1) with the recommended set of values of constants, achieved the smallest mean absolute error. The mean absolute error and RMS error were smaller when the channel heated diameter (D_h) rather than the hydraulic diameter (D_e) was used in the correlation. The RMS error of Eq. (1) using the recommended set of values of constants is 17.8 % in a rectangular channel with one-sided heating, compared to 14.3 % in circular tubes with full-perimeter heating. Zhang et al. concluded that this is because D_h better describes vapor formation and development in subcooled flow. This shows that Eq. (1) can be used to calculate CHF with acceptable accuracy in a rectangular channel with one-sided heating.

8. Recent Subcooled CHF Correlations

The Hall-Mudawar ICC and the following subcooled CHF correlations, developed or assessed during the last 20 years, are compared with the Groeneveld 2006 table.

8.1. Inasaka-Nariai Correlation (1987)

As summarized by Zhang et al. (2006)[11], Inasaka and Nariai[12] modified the parameter C_{Tong} in the Tong correlation[34], Eq. (8), and obtained Eq. (9) referred to as Inasaka-Nariai correlation.

$$\frac{q_c}{G\,h_{fg}} = \frac{C_{Tong}}{Re^{0.6}} \quad , \quad \text{where} \quad C_{Tong} = 1.76 - 7.433\,X_o + 12.222\,X_o^2 \quad \text{for } P \geq 70 \text{ bar} \tag{8}$$

$$\frac{q_c}{G\,h_{fg}} = \frac{C}{Re^{0.6}} \quad , \quad \text{where} \quad \frac{C}{C_{Tong}} = 1 - \frac{52.3 + 80\,X_o - 50\,X_o^2}{60.5 + P^{1.4}} + \quad \text{for } 1 \leq P \leq 70 \text{ bar} \tag{9}$$

Using a small CHF database of about 430 data points, Inasaka and Nariai found that Eq. (9) predicted CHF within ±20 % in the following range: $1 \leq P \leq 70$ bar, $1300 \leq G \leq 20{,}000$ kg/m^2-s , $2 \leq D_e \leq 20$ mm, $0.03 \leq L_h \leq 2.0$ m, $-0.46 \leq X_o \leq -0.001$, $2 \leq q_c \leq 18$ MW/m^2. Equation (9) was recently reassessed by Zhang et al. (2006)[11] using a medium size CHF database containing 1298 subcooled CHF data points, finding a mean deviation of 30.5 %. The range of the data used in the reassessment was: $1 \leq P \leq 190$ bar, $5.33 \leq G \leq 134{,}000$ kg/m^2-s, $0.33 \leq D_e \leq 6.22$ mm, $1 \leq L_h/D_e \leq 975$.

8.2. Celata Correlation (1994)

Celata et al.[24] also modified the Tong correlation, Eq. (8), in order to improve its accuracy at pressures below 50 bar, and obtained Eq. (10). The sign of the coefficient 0.986 in Eq. (11) for Ψ was positive as published[13] but has been *changed* here to negative based on the fact that CHF decreases with increasing exit quality X_o.

$$\frac{q_c}{G\,h_{fg}} = \frac{C}{Re^{0.5}} \quad \text{where} \quad C = (0.2164 + 4.74\,\text{x}\,10^{-3}\,P)\,\Psi \quad \text{for } 1 \leq P \leq 50 \text{ bar} \tag{10}$$

$$\text{where} \quad \Psi = \begin{cases} 1 & \text{if} \quad X_o < -0.1 \\ 0.825 - 0.986\,X_o & \text{if} \quad -0.1 < X_o < 0.0 \\ 1/(2 + 30\,X_o) & \text{if} \quad X_o > 0.0 \end{cases} \tag{11}$$

Using a medium size CHF database of 1865 data points, Celata et al. found that Eq. (10) had an RMS error of 21.2 %, and could predict 82.7 % of CHF data points within ±30 %, and 98.1 % of the data points within ±50 %. However, the correlation was reassessed later by Hall and Mudawar (2000)[1] using 4860 subcooled CHF data points, getting a RMS error of 50%.

8.3. Caira et al. Correlation (1995)

Caira et al.[19] developed a subcooled CHF correlation, Eq. (12), by regression analysis of 544 CHF data points. Caira et al. later used a database[16] of 1887 CHF data points to assess the correlation and obtained an RMS error of 19.5%, with 70% of the data points lying within the ±20% error band. Hall and Mudawar have assessed this correlation using 4860 subcooled CHF data points, getting an RMS error of 24.4% and ranking it to be the second most reliable of the 82 correlations assessed[1]. The range of the CHF data used in its development is: $1 \le P \le 84$ bar, $900 \le G \le 90{,}000$ kg/m^2-s , $0.3 \le D \le 25.4$ mm, $0.25 \le L_h \le 0.61$ m, and $0.3 \le T_i \le 242.7$ °C.

$$q_c = \frac{10829.55\,x10^{-3}\,D^{-0.0547}\,G^{0.713} + 0.1882\,x10^{-3}\,D^{-0.486}\,G^{0.462}\,(250\,\Delta h_{sub,i})^{0.978}}{1 + 0.1882\,D^{-1.2}\,G^{-0.36}\,L_h^{0.911}} \qquad (12)$$

In Eq. (12), the units of D, L_h, G, $\Delta h_{sub,i}$, and q_c are meter, meter, kg/m^2-s, kJ/kg, and kW/m^2, respectively. The signs of the constants 0.486, 1.2, and 0.36 were positive (due to typographical errors) in the original publication[19]. These errors have been corrected in Eq. (12) based on Hall and Mudawar's work[35].

8.4. Lombardi Correlation (1995)

Lombardi[20] developed a subcooled CHF correlation, Eq. (13), by regression analysis of 2529 measured CHF data points with an RMS error of 20.1 %. More than 1850 of the 2529 CHF data points were in the range 1 to 84 bar. The units used in Eq. (13) are: G in kg/m^2-s, the inlet enthalpy subcooling $\Delta h_{sub,i}$ in kJ/kg, L_h in m, D in m, ρ_f in kg/m^3, and the CHF q_c is obtained in kW/m^2.

$$q_c = \frac{0.25\,G\,\Delta h_{sub,i}}{L_h/D + 1.3\,G\,D^{0.4}/(2\,\rho_f)^{0.5}} \qquad (13)$$

The range of the CHF data utilized is: $1 \le P \le 84$ bar, $100 \le G \le 90{,}000$ kg/m^2-s , $0.3 \le D \le 37.5$ mm, $13 \le \Delta T_{sub,i} \le 338$ °C, and $0.0025 \le L_h \le 8.5$ m. Our own comparison of the correlation with the Groeneveld 2006 CHF table found that the correlation is applicable only if $L_h/D \ge 15$. Hall and Mudawar assessed this correlation using 4860 subcooled CHF data points of the PU-BTPFL CHF database, getting an RMS error of 29.1% and ranking it to be the third most reliable of the 82 correlations assessed[1].

8.5. Yagov et al. Correlation (1996)

Yagov et al.[36] have reported an outlet conditions correlation, Eq. (14), whose constants were adjusted to best fit the subcooled CHF data for $G \ge 500$ kg/m^2-s in a 1994 version of the Groeneveld look-up table based on the combined AECL-IPPE database (then containing 22046

CHF data points). The RMS difference between the correlation and the AECL-IPPE database reported by Yagov et al. is 11.9 % for the water pressure range of 15.3 to 162 bar.

$$q_c = \frac{q_{c,sat}}{1+X_o} + G\,C_{pf}\left(T_{sat}-T_o\right)\frac{f^*/2}{1-11\sqrt{f^*/2}} \tag{14}$$

where

$$q_{c,sat} = \begin{cases} \dfrac{0.011\,h_{fg}\left(\dfrac{\sigma^2\rho_g}{\nu_f\,D}\right)^{1/3}\left(Re^2\,F\,f^*\right)^{1/10}}{\left\{1+45000\left(\dfrac{\nu_f{}^2\,\rho_g}{\sigma D}\right)^{3/4}\left(\dfrac{Re^2\,f^*}{F^3}\right)^{1/4}\right\}^{1/3}} & , \quad 0.004 \le F < 0.7 \\[2ex] 0.001\,h_{fg}\left(\dfrac{\sigma^2\rho_g}{\nu_f\,D}\right)^{1/3}\left(Re^2\,F\,f^*\right)^{1/6} & , \quad F \ge 0.7 \end{cases} \tag{15}$$

$$F = \frac{h_{fg}\left(\nu_f\,\rho_g\right)^{3/2}}{\sigma\left(K_f T_{sat}\right)^{1/2}} \quad \text{and} \quad f^* = \frac{1}{\left\{1.58\ln(Re)-3.28\right\}^2} \tag{16}$$

Equation (14) as published by Yagov[36] has $|X_o|$ instead of X_o. The published equation was modified because CHF decreases as quality increases[2]. Using X_o instead of $|X_o|$ results in smaller RMS differences in our own evaluation (see Table 2). The correlation is found to be one of the reliable outlet conditions correlations.

8.6. Kureta-Akimoto Correlation (2002)

Kureta and Akimoto[21] did 128 CHF measurements for subcooled flow of water in one-side heated rectangular channels with atmospheric pressure at the channel exit where the CHF occurred. They varied the channel gap from 0.2 to 3.0 mm, the channel width from 7 to 22 mm, the heated width (P_h) from 5 to 20 mm, the heated length from 0.05 to 0.2 m, inlet temperature from 30 to 90 °C, and the mass flux from 846 to 15100 kg/m^2-s. Using these measurements with 407 CHF data points for other geometries, i.e., both-side heated narrow rectangular channel[37], half-circumference heated tube[38], and full-circumference heated tube[39,40] (a total of 535 CHF data points), Kureta and Akimoto developed a generalized CHF correlation, Eq. (17), whose application range is: $1.0 \le D_e \le 7.8$ mm, $0.25 \le P_h/P_w \le 1.0$, $9.5 \le L_h/D_h \le 500$, $1000 \le G \le 20000$ kg/m^2-s, $5 \le T_i \le 90$ °C, $-0.163 \le X_o \le 0.0099$, $1000 \le q_c \le 70000$ MW/m^2. Equation (17) with C_1 and C_2 given by Eq. (18) has a standard deviation of 45%.

$$\left(\frac{q_c}{G\,h_{fg}}\right)\left(\frac{G\,\nu}{\sigma}\right)^{0.5} = C_1(X_c + C_2) \tag{17}$$

$$C_1 = \left[6.9\left(\frac{P_h}{P_w}\right)^2 - 10\left(\frac{P_h}{P_w}\right) + 2 \right] x\, 10^{-3}$$

$$C_2 = -0.75\left(\frac{P_h}{P_w}\right)^2 + 0.9\left(\frac{P_h}{P_w}\right) - 0.28 \qquad (18)$$

Although based on a small database, the correlation has two useful features: (1) the development of the Kureta-Akimoto correlation emphasizes CHF data for channels of rectangular cross section which is the geometry of many research reactor coolant channels, and (2) the Kureta-Akimoto database is not mixed with excursive flow instability data as is the database of 596 data points used to develop the Sudo-Kaminaga correlation (1993, 1998)[15,14].

8.7. Sarma et al. Correlation (2006)

Sarma et al.[18,41] developed a subcooled CHF correlation, Eq. (19), by dimensional analysis of the CHF phenomena and heat balance, and determined the constants in the equation by regression analysis of 3050 measured CHF data points, getting a mean deviation of 17 %. It uses P in bar, D in meter, L_h in meter, liquid viscosity μ in Pa-s, mass flux G in kg/m^2-s, and h_{fg} in kJ/kg, giving q_c in kW/m^2. The liquid viscosity μ is evaluated at the inlet temperature if $P > 10$ bar, and at the saturation temperature if $P \leq 10$ bar. The range of application of the correlation determined by the CHF data used in its development and our own comparison with the Groeneveld 2006 CHF table and the Hall-Mudawar correlation is: $1 \leq P \leq 85$ bar, $1000 \leq G \leq 90{,}000$ kg/m^2-s , $1.0 \leq D \leq 10$ mm, $L_h/D \geq 15$, and $L_h \leq 1.17$ m. According to Eq. (19), the CHF increases with diameter as $D^{0.29}$. At constant G, P, T_i, and L_h, the CHF increases with increasing diameter[42,43] while at constant G, P, X_o, the CHF decreases with increasing diameter[2].

$$\frac{q_c D}{\mu h_{fg}} = 0.483\, Re^{0.62} \left(\frac{P D}{\mu h_{fg}^{0.5}}\right)^{0.17} \left(\frac{D}{L_h}\right)^{0.5} \qquad (19)$$

8.8. Shim et al. Subcooled and Saturated CHF Correlation (2006)

After a series of papers, Shim et al. (2006)[44] developed Eq. (20) to predict subcooled and saturated CHF of water in round tubes with uniform heat flux. They correlated CHF to the true mass fraction of steam (X_T) instead of to the thermodynamic equilibrium quality, by regression analysis of 8951 measured CHF data points. The true quality X_T is calculated using Eq. (22a), (22b), or (22c). The reported RMS error of Eq. (20) is 13.4%. The range of the CHF data utilized is: $1 \leq P \leq 206$ bar, $10 \leq G \leq 18{,}619$ kg/m^2-s , $1.02 \leq D \leq 44.7$ mm, $0.03 \leq L_h \leq 5$ m, $8.5 \leq L_h/D \leq 792$, $-609 \leq (h_i - h_f) \leq 1655$ kJ/kg, $-0.87 \leq X_o \leq 1.58$, and $0.11 \leq q_c \leq 21.4$ MW/m^2.

$$q_c\ (\text{kW/m}^2) = \frac{1000\,\alpha}{D^{K_1}} \exp\left[-\beta \left\{ G^{0.51} X_T^{\ 0.5} (1 + X_T^{\ 2})^{1.5} \right\}^{K_2} \right] \qquad (20)$$

$$\text{where}\quad \alpha = 0.8118 + 3.58831(P/P_c) - 4.07557(P/P_c)^2$$
$$\beta = 0.09897 - 0.58691(P/P_c) + 1.98084(P/P_c)^2 - 1.54275(P/P_c)^3$$
$$K_1 = -0.76648 + 0.33893(\ln G) - 0.02239(\ln G)^2 \qquad (21)$$
$$K_2 = 1.0027 - 0.16213\,X_T + 0.21796(X_T)^2$$

$$1 - X_o + X_{osv}(1 - X_T) = \left(\frac{X_o - X_T}{X_{osv}}\right)^{-X_{osv}} \text{(Jafri equation}^{45}\text{ for } X_T \quad \text{if } X_i < X_{osv}) \qquad (22a)$$

$$X_T = \frac{X_o - X_{osv}\exp\left(\frac{X_o}{X_{osv}} - 1\right)}{1 - X_{osv}\exp\left(\frac{X_o}{X_{osv}} - 1\right)} \quad \text{(Kroeger \& Zuber equation}^{46}\text{)} \qquad (22b)$$

$$X_T = X_o - X_{osv}\exp\left(\frac{X_o}{X_{osv}} - 1\right) \quad \text{(Levy equation}^{47}\text{)} \qquad (22c)$$

$$X_{osv} = -\frac{q}{St\,G\,h_{fg}}$$
$$St = \begin{cases} 455/Pe & \text{if} \quad Pe < 70000 \\ 0.0065 & \text{if} \quad Pe \geq 70000 \end{cases} \qquad \text{(Saha-Zuber equation)} \qquad (23)$$

$$X_o = X_i + \frac{4\,q\,L_h}{G\,D\,h_{fg}} \quad \text{(heat balance)} \qquad (24)$$

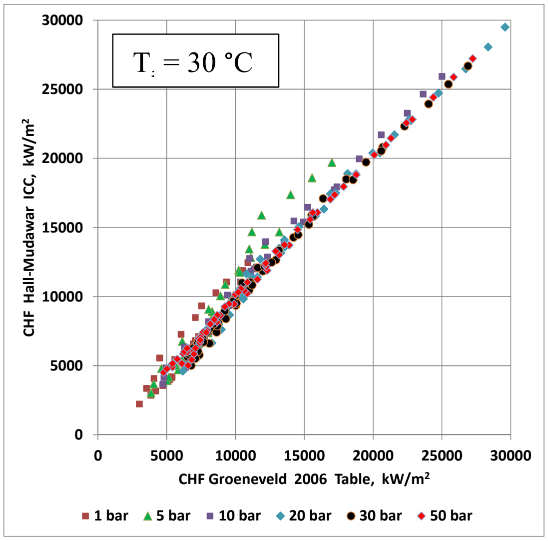
Shim et al. (2004)[45] had earlier developed a simpler correlation, Eq. (25), using the true mass fraction of steam (X_T) at channel exit, by regression analysis of 2562 measured CHF data points. The reported RMS error of Eq. (25) is 11.5%. The range of the CHF data utilized is: $10 \leq P \leq 70$ bar, $94 \leq G \leq 18{,}580$ kg/m^2-s , $1.14 \leq D \leq 37.5$ mm, $-0.21 \leq X_o \leq 1.09$, $0.10 \leq L_h \leq 5$ m, and $0.26 \leq q_c \leq 9.72$ MW/m^2.

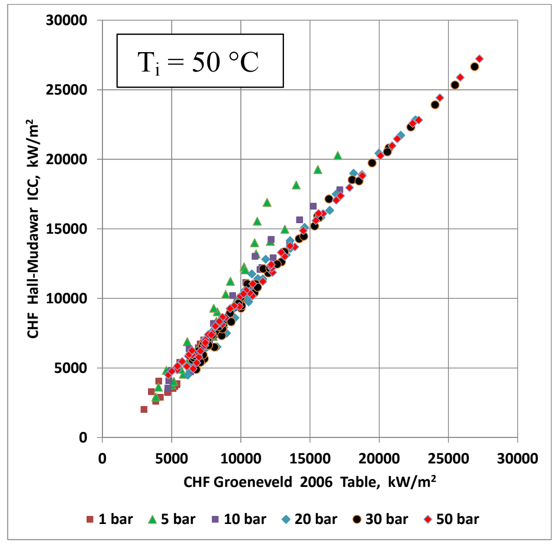
$$q_c\ (\text{kW/m}^2) = \frac{1000\,\alpha}{D^{0.5}}\exp\left\{-\beta\left(G\,X_T\right)^{0.5}\cosh(X_T)^2\right\}$$

$$(25)$$

$$\text{where}\quad \alpha = 0.334 + 7.681\left(P/P_c\right) - 12.42\left(P/P_c\right)^2$$
$$\beta = 0.06155 - 0.00664\left(P/P_c\right) + 0.13512\left(P/P_c\right)^2$$

To compare CHF prediction methods, we calculated CHF at 50 bar, in six ways, using Eq. (20) and Eq. (25) with X_T obtained from Eq. (22a), Eq. (22b) or Eq. (22c). The values of X_T obtained from the three equations are very close, with Eq. (22a) being in-between. We found an RMS difference of about 32% between the Groeneveld 2006 CHF table at 50 bar and Eq. (25) using X_T obtained from the three equations. We found an RMS difference of about 38% between the Groeneveld 2006 CHF table at 50 bar and Eq. (20) using X_T obtained from the three equations. The correlations give very low CHF values for highly subcooled flow with high mass flux.





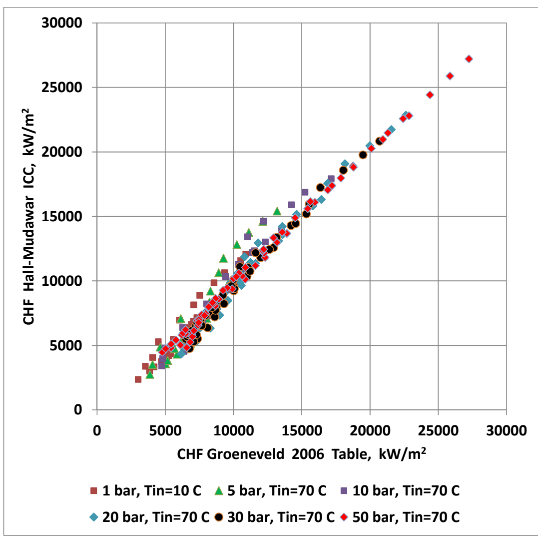


Fig. 1. Comparison of CHFs by Hall-Mudawar ICC and Groeneveld 2006 Table (D_h = 8mm)

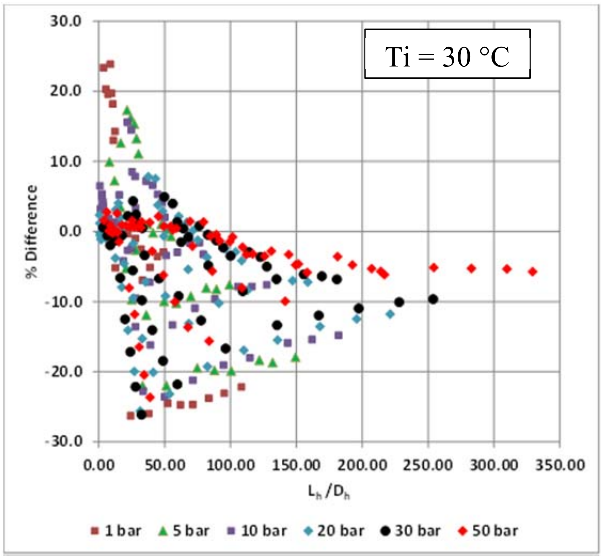
9. Comparison of CHF Prediction Methods

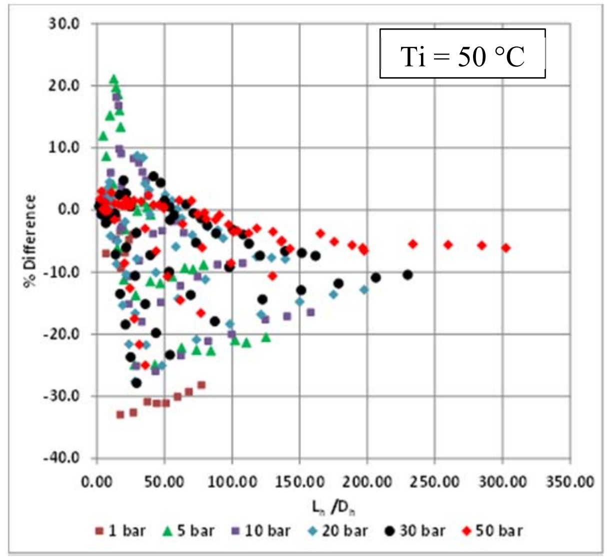
The 11 CHF correlations, Eqs. (1), (3), (9), (10), (12), (13), (14), (17), (19), (20), and (25), were compared with the values of CHF in the Groeneveld 2006 table for the reference 8-mm diameter tube, for 64 combinations of exit quality X_o and mass flux G (8 values of quality x 8 values of mass flux). The values of X_o are 0.0, -0.05, -0.1, -0.15, -0.2, -0.3, -0.4, and -0.5. The values of G are 1000, 2000, 3000, 4000, 5000, 6000, 7000, and 8000 kg/m^2-s. The comparisons were done on Excel spreadsheets (available on request) at six pressures (P), i.e., 1, 5, 10, 20, 30, and 50 bar. The coolant properties were obtained from Ref. 48.

It should be noted that the Groeneveld lookup table is a local/outlet conditions CHF prediction method using exit quality (X_o) whereas the Hall-Mudawar correlation Eq. (1), the Sarma correlation, the Ciara correlation, and the Lombardi correlation are inlet conditions correlations whose expressions contain the heated length L_h and the inlet temperature or inlet quality. In order to find the inlet temperature and the heated length corresponding to any tabulated CHF value in the Groeneveld table, a heat balance over the heated length, Eq. (26), was used for the tabulated value of CHF at the tabulated exit quality. The heat balance calculation provides a complete set of six thermal-hydraulic parameters (P, D_h, G, X_o, T_i, L_h), i.e., a *virtual CHF test*, for which different CHF correlations should be compared and be expected to give closely agreeing CHF values. The heated length was calculated assuming uniform heat flux and three reasonable values (30, 50, 70 °C) of the coolant inlet temperature. The approximation made in Eq. (26) implies ignoring the pressure difference between the heated length inlet and outlet.

$$L_h = \frac{\left(X_o - X_i^*\right) D_h\, G\, h_{fg,o}}{4 q_c} \cong \frac{\left(X_o - X_i\right) D_h\, G\, h_{fg,o}}{4 q_c} \qquad (26)$$

For $X_o < X_i$, Eq. (26) gives a negative heated length. It is impossible to get $X_o < X_i$ because in a CHF test heat is added to the coolant, and the quality increases from the inlet to exit. Equation (26) was used to calculate L_h for each of the 64 CHF values in the Groeneveld 2006 table at each of the three inlet temperatures. After discarding the negative values of L_h, the three values of L_h calculated for the three values of inlet temperature were used in the CHF comparison.





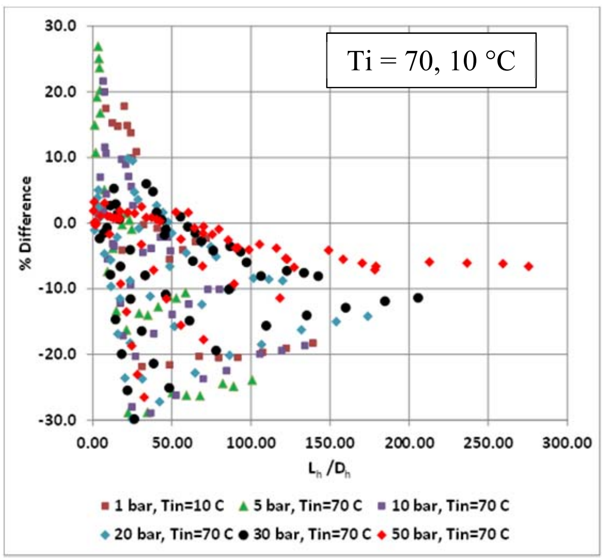
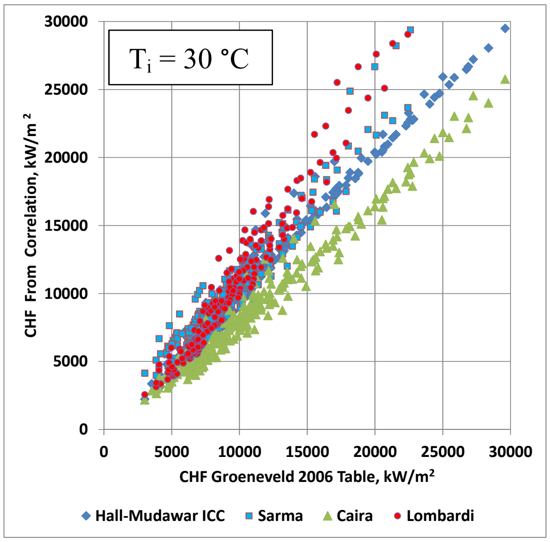
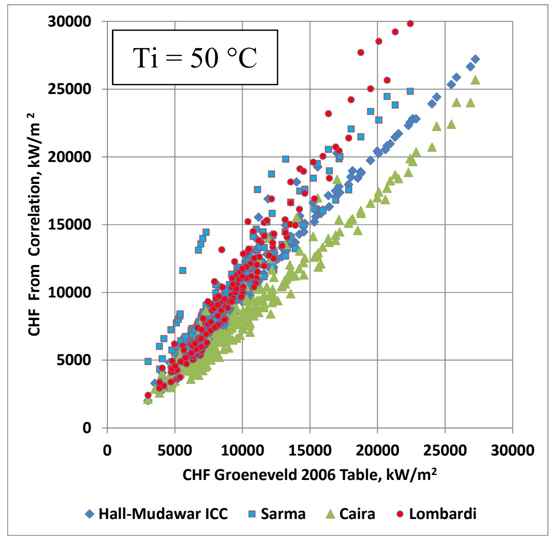


Fig. 2. Difference between CHFs by Hall-Mudawar ICC and Groeneveld 2006 Table versus L_h/D_h (D_h = 8 mm)

<u>H-M ICC Compared to Groeneveld 2006 Table:</u> The comparison between the Hall-Mudawar ICC (H-M ICC) and the Groeneveld 2006 table is vital because these are the only prediction methods based on all the CHF data available in the world. Their comparison is shown in Fig. 1 which shows a good agreement at different inlet temperatures (30, 50, and 70 °C) at all six pressures. Point-wise CHF differences between the H-M ICC and the Groeneveld 2006 table are plotted against L_h/D_h in Fig. 2 at different inlet temperatures for all six pressures. Figure 2 shows that the differences are larger at smaller L_h/D_h. The variation of the CHF difference with mass flux and exit quality were also plotted and studied. The RMS difference between the two prediction methods is 18% at 1.0 bar, is smaller at higher pressures, and is 7% at 50 bar. The maximum difference in CHF for $L_h/D_h > 15$ is 33%.

Having shown a good agreement for the standard 8-mm diameter tube, it should be noted that both prediction methods have the same diameter dependence (that recommended in Section 5.2). By varying the tube diameter from 3 to 24 mm, it was found that the percent difference between the Hall-Mudawar ICC and the Groeneveld 2006 table remains unchanged. Based on this overall good agreement, both methods are considered to be the most reliable in the 1 to 50 bar pressure range.





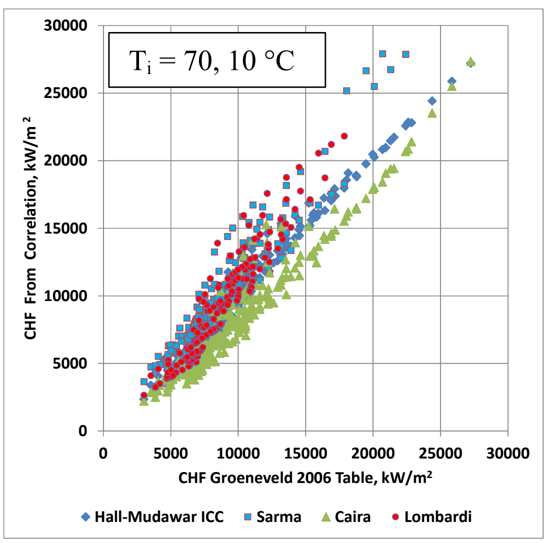


Fig. 3. Comparison of the Sarma, the Caira, the Lombardi, and the Hall-Mudawar ICC with Groeneveld 2006 Table (D_h = 8 mm)

Figure 3 compares the Groeneveld 2006 table and the H-M ICC with the Sarma, the Caira, and the Lombardi correlations. It adds further confidence to the reliability of the Groeneveld 2006 CHF table and the H-M ICC.

Assessment of Recent OCCs: The CHFs obtained from the Hall-Mudawar OCC, the Kureta-Akimoto, the Inasaka-Nariai, the Yagov, the Shim, and the Celata outlet conditions correlations were compared with the Groeneveld 2006 table at pressures 1, 5, 10, 20, 30, and 50 bar. The CHFs were also plotted against the Groeneveld 2006 table. The Kureta-Akimoto correlation usually gives higher CHF values than the Groeneveld table, and has the largest RMS differences, varying from 105 to 44 % as the pressure varies from 1 to 50 bar.

Table 2 summarizes the RMS difference between the Groeneveld 2006 table and each of the other 11 CHF correlations at the six pressures. At 1 bar, the Celata correlation is closer to the

Groeneveld table than the other six OCCs assessed. Over the 5 to 50 bar pressure range, Table 2 shows that among the seven OCCs assessed, the most reliable are the Hall-Mudawar OCC, the Yagov correlation, and the Inasaka-Nariai correlation.

TABLE 2. RMS Difference between a CHF Correlation and the Groeneveld 2006 Table for 8 mm Diameter Tube at 1 to 50 bar

CHF Correlation	Country of Origin	**% RMS Diff.** [a]					
		1 bar	5 bar	10 bar	20 bar	30 bar	50 bar
Hall-Mudawar Inlet Conditions Correlation	USA	18.0	15.4	12.3	10.8	9.9	6.9
Sarma Correlation	India	48.0	24.4	13.1	18.9	13.0	9.5
Caira Correlation	Italy	13.9	18.2	22.2	24.9	24.9	21.7
Lombardi Correlation	Italy	18.7	16.0	16.9	14.6	15.7	19.2
Yagov Eq. (14)	Russia	49.3[b]	27.4	20.7	12.8	8.4	16.7
Yagov Eq. (14) using $\|X_o\|$ instead of X_o	Russia	50.7	31.8	28.1	23.9	18.6	14.9
Hall-Mudawar Outlet Conditions Correlation	USA	19.7	23.6	18.6	19.2	19.5	15.7
Inasaka-Nariai Correlation	Japan	38.0	35.2	28.8	22.6	20.9	22.1
Shim Eq. (25) with X_T from Kroeger equation[46]	South Korea				40.5	32.9	32.1
Shim Eq. (20) with X_T from Kroeger equation	South Korea				48.0	38.2	38.6
Kureta-Akimoto Correlation	Japan	105.4	91.2	73.3	59.8	53.2	43.9
Celata Correlation	Italy	18.5	46.3	56.7	60.3	57.1	52.4

a. % Diff = (CHF Correlation – Groeneveld 2006 Table) as % of the CHF from the Groeneveld Table. The RMS difference was calculated by averaging (% difference)^1 at all three inlet temperatures.

b. The Yagov correlation is applicable only if the parameter F defined by Eq. (16) $\geq$ 0.004. However, F = 0.00018, 0.00100, 0.00238, 0.00579, 0.01045, and 0.0245 correspond to pressures of 1, 5, 10, 20, 30, and 50 bar, respectively. Therefore, the correlation is not strictly applicable in the shaded area at pressures 1, 5, and 10 bar because F < 0.004.

<u>Shim Correlation Compared to Groeneveld 2006 Table:</u> The CHF at 50 bar was calculated in six ways, using the Shim correlations Eq. (20) and Eq. (25) with the true quality (X_T) obtained from Eq. (22a), Eq. (22b) or Eq. (22c). The values of X_T obtained from the three equations are very close, with the Jafri equation, Eq. (22a), being in-between. The RMS difference is about 32% between the Groeneveld 2006 table at 50 bar and Eq. (25) using X_T obtained from the three equations. The RMS difference is about 38% between the Groeneveld 2006 table at 50 bar and Eq. (20) using X_T obtained from the three equations. Both Shim correlations give low CHF values (decreasing with increasing coolant mass flux, an incorrect trend) for highly subcooled flow with high mass flux. This is when CHF occurs before OFI. Shim et al.[53] are aware of the failure of their correlations in this condition.

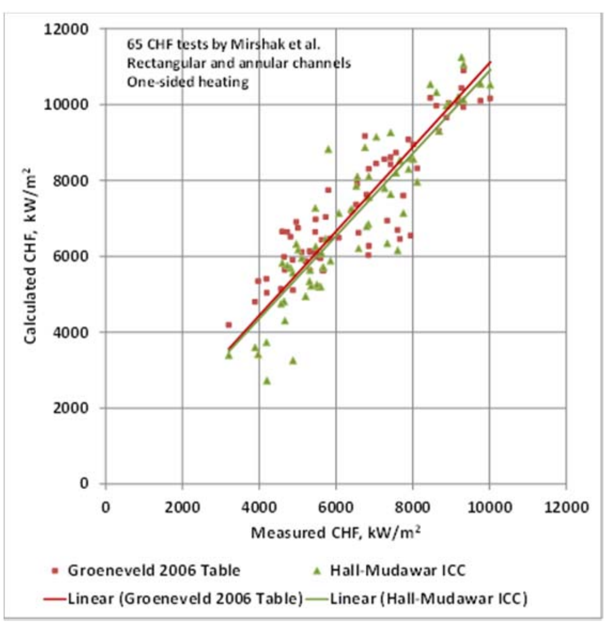


Fig. 4. Comparison of Eq. (1) and Eq. (5) to Mirshak's Measured CHF Data in Channels of Rectangular and Annular Cross Sections

10. Comparison to Mirshak's Measured CHF Data in Rectangular Channels

The extended Groeneveld 2006 CHF table, Eq. (5), and the Hall-Mudawar ICC, Eq. (1), were compared with all 65 measured CHF data of Mirshak et al. (1959)[22]. This comparison checks all three extension features of these prediction methods: the channel cross section is non-circular; only part of the wetted perimeter is heated; and the diameter is different from the standard 8 mm. A heat balance check of the data was not performed because the measured inlet temperatures are not reported. However, we compared the trends of the measured data with known correct trends[42,43], and found that three CHF data (Runs 1, 5 and 7) are too low, based on their comparison with Runs 14, 2 and 18, respectively.

A comparison of the measured and calculated CHF values is shown in Fig. 4 with each prediction method's trend-line passing through the origin. The calculated CHF data points of the Groeneveld table and Hall-Mudawar ICC are in close agreement. The RMS error over Mirshak's 65 CHF data points, of the Groeneveld 2006 table and the Hall-Mudawar ICC are 13.4% and 15.0%, respectively, about the same as their RMS error over the AECL-IPPE database or the PU-BTPFL database from which the prediction method was derived. In conclusion, the extended Groeneveld 2006 CHF table and the Hall-Mudawar ICC give acceptably accurate values of CHF for channels of rectangular and annular cross sections, with one-sided heating.

11. Concluding Remarks

Among the 12 CHF correlations compared, only two are derived using all the measured CHF data in the world: the Hall-Mudawar ICC and the Groeneveld 2006 table. The RMS difference between the two is 18%, 15.4%, 12.3%, 10.8%, 9.9%, 6.9% at the pressures 1, 5, 10, 20, 30, and 50 bar, respectively, and the maximum difference in CHF for $L_h/D_h > 15$ is 33%. Based on the close agreement between these two CHF prediction methods and on the fact that the other 10 methods have greater errors, each is considered to be the most reliable subcooled CHF prediction method in the 1 to 50 bar pressure range. Their comparison with the Sarma, the Caira, and the Lombardi correlations adds further confidence to their reliability.

A CHF multiplier of $(G/8000)^{0.376}$ at mass fluxes $G > 8000$ kg/m^2-s, and a diameter correction factor of $(0.008/D_h)^{0.312}$ is recommended in the Groeneveld 2006 table. The heated diameter (D_h) rather than the hydraulic diameter (D_e) should be used in making the diameter correction. The exponent of D_h is the value of C_2 ($C_2 = -0.312$) in Hall-Mudawar's recommended subcooled correlation, and the exponent of mass flux (G) equals $1+2C_2$. In the Hall-Mudawar ICC, the heated diameter (D_h) should be used in place of the hydraulic diameter in the Weber number.

The choice between the Hall-Mudawar ICC and the Groeneveld 2006 table may be based on other considerations: (1) The Groeneveld 2006 table provides both subcooled and saturated CHF whereas the Hall-Mudawar ICC provides only subcooled CHF. (2) The Hall-Mudawar ICC is derived assuming axially uniform heat flux and its application to the axially non-uniform heat flux present in research reactors involves an approximation. (3) The treatment of hot channel factors is straightforward based on the local conditions hypothesis when using the Groeneveld table or another outlet conditions correlation. Due to these considerations, the Groeneveld 2006 table may be preferred over the Hall-Mudawar ICC.

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NOMENCLATURE

A_f = Flow area of channel, m^2
C_{pf} = Specific heat of coolant at constant pressure, kJ/kg-°C
$(CHF)_D$ = Critical heat flux in a tube of diameter D, kW/m^2
$(CHF)_8$ = Critical heat flux in a 8 mm diameter tube, kW/m^2
D = Inner diameter of tube, m
$D_e = 4A_f/P_w$ = Hydraulic diameter of coolant channel, m
$D_h = 4A_f/P_h$ = Heated diameter of coolant channel, m
f* = Fanning friction factor
G = mass flux, kg/m^2-s
G^* = Non-dimensional mass flux = $G/\left\{\sigma\rho_g^2(\rho_f-\rho_g)g\right\}^{0.25}$
h_i = Enthalpy at inlet to the heated length, kJ/kg
h_o = Enthalpy at outlet of the heated length, kJ/kg
h_f = Enthalpy of saturated coolant at a given pressure, kJ/kg
h_g = Enthalpy of saturated vapor at a given pressure, kJ/kg
h_{fg} = Latent heat of vaporization at a given pressure, kJ/kg
$\Delta h_{sub} = h_f - h_i$ = Coolant subcooling in enthalpy, kJ/kg
K_f = Thermal conductivity of coolant, kW/m-°C
L_h = Heated length of channel, m
P = Pressure, bar
P_c = Critical pressure of water (221.2 bar)
P_w = Wetted perimeter of coolant channel, m
P_h = Heated perimeter of coolant channel, m
$Pe = GDC_{pf}/K_f$ = Peclet number
q_c = Critical heat flux, kW/m^2
$Re = GD_e/\mu$ = Reynolds number
St = Stanton number
T_i = Coolant temperature at channel inlet, °C
T_o = Coolant temperature at channel outlet, °C
T_{sat} = Saturation temperature, °C
T_b = Bulk temperature, °C
$\Delta T_{sub} = T_{sat} - T_b$ = Coolant subcooling in temperature, °C
X_i = Equilibrium quality at the inlet of heated length
X_o = Equilibrium quality at the outlet of heated length
X_{osv} = Equilibrium quality at onset of significant void (OSV defined by Saha-Zuber correlation)
X_T = True steam quality
μ = Viscosity of coolant, $N\text{-}s/m^2$
ν = Kinematic viscosity of coolant, m^2/s

σ = Surface tension, N/m

Subscripts

b = bulk coolant	e = equivalent hydraulic	
f = saturated liquid	fg = phase change from saturated liquid to saturated vapor	
g = saturated vapor	h = heated	
i = channel inlet	o = channel outlet	
p = constant pressure	sub = subcooling	w = heated wall

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