Improved general correlation for critical heat flux during upflow in uniformly heated vertical tubes

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An improved version of the author's earlier correlation for CHF in vertical tubes is presented. It is compared with data that include 23 fluids (water, refrigerants, cryogens, chemicals, and liquid metals), tube diameters 0.315 to 37.5 mm, tube length 1.3 to 940 times diameter, mass flux 4 to 29 051 kg/m^{2}s, reduced pressures 0.0014 to 0.96, inlet quality -4 to $+0.85$, and critical quality -2.6 to $+1$. These data, from 62 independent sources, are also compared with Katto's general correlation and those of Bowring for water and Subbotin for helium. The present correlation shows much better agreement with data.

Keywords: *CHF, burnout, tubes, boiling, liquids, prediction*

Introduction

The prediction of critical heat flux (CHF) is of great importance in the design and analysis of heat exchangers, since exceeding the CHF always results in inefficient heat transfer and can also result in complete failure with catastrophic consequences such as in nuclear reactors. For this reason, a tremendous amount of research has been done on this subject. Much of it has been devoted to CHF during upflow in uniformly heated vertical tubes. The reason for this emphasis is that many heat exchangers are of this type, and the solutions for this case can be extended to other situations such as nonuniform heat flux and rod bundles.

The research in this field has been reviewed, among others, by Collier,[1] Rohsenow,[2] Hewitt,[3] and Katto.[4] A good many predictive techniques have been proposed for CHF during upflow in uniformly heated vertical tubes. Among these, only two have been demonstrated to be in agreement with experimental data for many fluids covering a wide range of parameters. One of these is the correlation developed by Katto and co-workers.[4,5,6] The other is the correlation of Shah.[7] This paper is mainly concerned with the latter.

The Shah correlation[7] was verified with data for 11 fluids that included water, refrigerants, chemicals, cryogens, and potassium. The data covered a very wide range of parameters, including critical qualities from -2.6 to $+0.96$. Satisfactory agreement with the Shah correlation has been reported by Lazarek and Black[8] with their R-113 data and by Katto and Yokoya[9] with their high-pressure R-12 data. Despite its agreement with such a wide range of data, this correlation has the following limitations and shortcomings:

1. For $Y < 10^5$, the correlation cannot be used for $L_c/D > 100$ and $X_{IN} > 0$.
2. Considerable scatter was found in the range $Y = 10^5$ to 10^6.
3. The correlation for $Y > 10^5$ had not been tested for $L_c/D > 385$ and < 14.
4. The correlation had not been tested with data for helium, which has the lowest normal boiling point of all fluids and is today of great practical interest.
5. The correlation is in graphical form, which though convenient for hand calculations, is not suitable for computerized calculations.

Research was undertaken to overcome these shortcomings and limitations. The improved correlation presented here shows adequate agreement with a wide variety of data that include 23 fluids (water, halocarbon refrigerants, chemicals, liquid metals, helium and other cryogens), L_c/D from 1.3 to 940, tube diameters from 0.315 to 37.5 mm, reduced pressures from 0.0014 to 0.96, mass flux from 3.9 to 29 051 kg/m^{2}s, inlet quality from -4 to $+0.85$, and critical quality from -2.6 to $+1$. These data, from 62 independent sources, are correlated with a mean deviation of 16%. The correlation is given in graphical as well as equation form, permitting both manual and computerized calculations.

In order that the present correlation may be viewed in perspective, the same data have also been compared with three other predictive techniques, which are probably the best of their kinds. These are the general correlation of Katto *et al.*,[4,5,6] the correlation of Bowring[10] for water, and the correlation of Subbotin *et al.*[11] for helium. The present correlation performed significantly better.

In the following sections, the improved Shah correlation is presented followed by its comparison with world data together with the other correlations mentioned earlier. The results are discussed and applicable ranges of the present and other predictive techniques are identified.

The improved Shah correlation

As does the original correlation,[7] the improved correlation consists of two correlations, namely, the upstream condition correlation (UCC) and the local condition correlation (LCC). In the UCC, the CHF at a location depends on the upstream conditions, namely, inlet subcooling and distance from inlet. In the LCC, CHF depends only on the local quality, except for very short tubes. These are presented now, and are followed by the procedure for determining which one to use.

Upstream condition correlation (UCC)

The UCC is expressed by the following equation:

$$Bo = 0.124\left(\frac{D}{L_E}\right)^{0.89}\left(\frac{10^4}{Y}\right)^n (1 - X_{IE}) \qquad (1)$$

When $Y \leqslant 10^4$, $n = 0$ for all fluids. When $Y > 10^4$, n is given by the following relations:

For helium (at all values of Y),

$$n = \left(\frac{D}{L_E}\right)^{0.33} \qquad (2)$$

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For all fluids other than helium,

$$Y \leqslant 10^6, \quad n=\left(\frac{D}{L_E}\right)^{0.54} \tag{3}$$

$$Y > 10^6, \quad n=\frac{0.12}{(1-X_{IE})^{0.5}} \tag{4}$$

The effective length and effective inlet quality are defined as

$$\text{When } X_{IN} \leqslant 0, \quad L_E=L_c \text{ and } X_{IE}=X_{IN} \tag{5}$$

$$\text{When } X_{IN} > 0, \quad L_E=L_B \text{ and } X_{IE}=0 \tag{6}$$

For uniformly heated tubes, the boiling length L_B is given by

$$\frac{L_B}{D}=\frac{X_c}{4Bo}=\frac{L_c}{D}+\frac{X_{IN}}{4Bo} \tag{7}$$

Figure 1 shows the UCC for $Y < 10^4$ and $X_{IN} < 0$.

The local condition correlation (LCC)

The LCC is expressed by the following relation:

$$Bo=F_E \cdot F_x \cdot Bo_0 \tag{8}$$

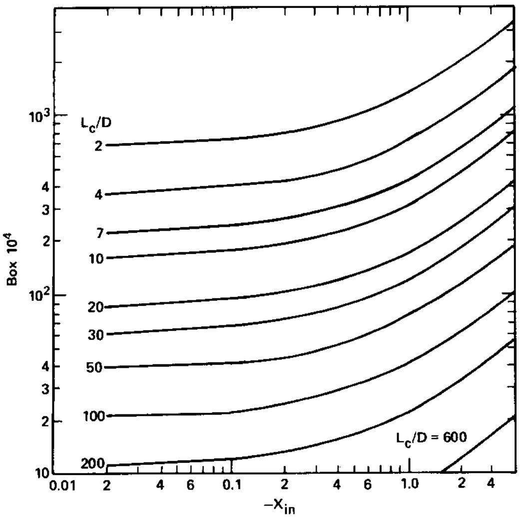

Figure 1 Graphical representation of the present upstream condition correlation (UCC) at $Y \leqslant 10^4$

F_E is the entrance effect factor given by

$$F_E=1.54-0.032\left(\frac{L_c}{D}\right) \tag{9}$$

If Eq. (9) gives $F_E < 1$, use $F_E=1$.

Bo_0 is the boiling number at $X_c=0$ and is calculated by the following equations:

$$Bo_0=15Y^{-0.612} \tag{10}$$

$$Bo_0=0.082Y^{-0.3}(1+1.45p_r^{4.03}) \tag{11}$$

$$Bo_0=0.0024Y^{-0.105}(1+1.15p_r^{3.39}) \tag{12}$$

The correct Bo_0 is the highest of the values given by the above three equations.

At $X_c > 0$, F_x is given by the following equations:

$$F_x=F_3\left[1+\frac{(F_3^{-0.29}-1)(p_r-0.6)}{0.35}\right]^c \tag{13}$$

When $p_r \leqslant 0.6$, $c=0$
When $p_r > 0.6$, $c=1$

$$F_3=\left(\frac{1.25\times 10^5}{Y}\right)^{0.833x_c} \tag{14}$$

At $X_c < 0$, F_x is calculated by the following equations:

$$F_x=F_1\left[1-\frac{(1-F_2)(p_r-0.6)}{0.35}\right]^b \tag{15}$$

When $p_r \leqslant 0.6$, $b=0$

When $p_r > 0.6$ $b=1$

$$\text{When } Y \leqslant 1.4\times 10^7, \quad F_1=1+0.0052(-X_c^{0.88})Y^{0.41} \tag{16}$$

When $Y > 1.4\times 10^7$, use Eq. (16) with $Y=1.4\times 10^7$.

$$\text{When } F_1 \leqslant 4, \quad F_2=F_1^{-0.42} \tag{17}$$

$$\text{When } F_1 > 4, \quad F_2=0.55 \tag{18}$$

Choice between UCC and LCC

For helium, UCC is always used. For all other fluids, the following selection criteria apply:

(a) $Y \leqslant 10^6$, use the UCC.
(b) $Y > 10^6$, use the correlation that gives the lower value of Bo. The only exception to this rule is that the UCC is used when

$$L_E > \frac{160}{p_r^{1.14}} \tag{19}$$

Notation

Bo	Boiling number $=q_c/(Gi_{FG})$
Bo_0	Bo at $X_c=0$
Bo_x	Bo at $X_c=X$
C_{PL}	Specific heat of liquid at constant pressure
D	Inside diameter of tube
F_E	Entrance effect factor
F_x	$=Bo_x/Bo_0$
Fr	Froude number $=G^2/(\rho_L{}^2 gD)$
G	Mass velocity
g	Acceleration due to gravity
i_{FG}	Latent heat of vaporization
k_L	Thermal conductivity of liquid
L_B	Boiling length (axial distance between $X=0$ and $X=X_c$)
L_c	Axial distance between tube entrance and location of boiling crisis
L_E	Effective length of tube, Eqs. (5) and (6)
n	Exponent of Y, Eq. (1)
p_r	Reduced pressure
Pe	Peclet number $=GDC_{PL}/k_L$
q_c	Critical heat flux
X	Vapor quality
X_c	X at location of CHF
X_{IE}	Effective inlet quality, Eqs. (5) and (6)
X_{IN}	Inlet quality
Y	Shah's correlating parameter $=$ Pe $\text{Fe}^{0.4}(\mu_L/\mu_G)^{0.6}$
μ	Dynamic viscosity
ρ	Density
σ	Surface tension

Subscripts

G	Vapor
L	Liquid

Abbreviations

CHF	Critical heat flux
LCC	Local condition correlation
MIPD	Monoisopropyl diphenyl
UCC	Upstream condition correlation

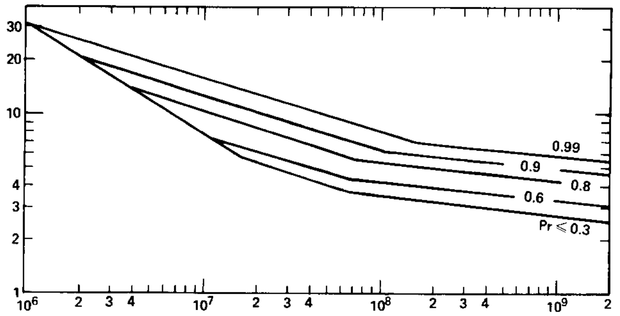

Figure 2 Graphical representation of the present local condition correlation (LCC), part 1: value of boiling number at $X_c=0$

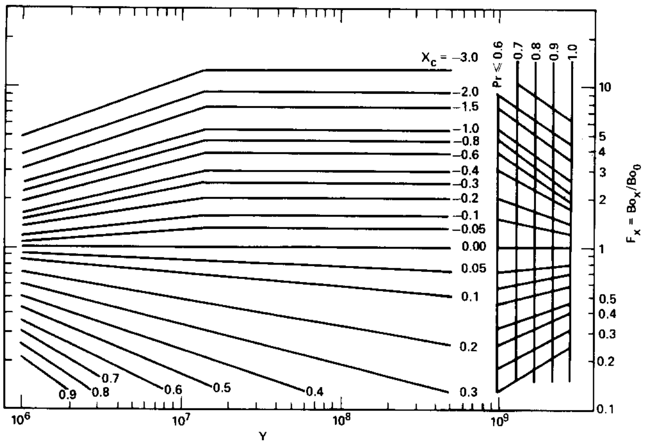

Figure 3 Graphical representation of the present local condition correlation (LCC), part 2: ratio of boiling numbers at $X_c=X$ and $X_c=0$

Manual calculations with the present correlation

The upstream condition correlation (UCC) is simple enough for direct use without any graphical aid. If desired, Figure 1 may be used for $Y<10^4$ and $X_{IN}<0$.

Figures 2 and 3 represent the equations for F_x and Bo_0 in the local condition correlation. The method of using these graphs is the same as that for using Figures 3(a) and 3(c) in Shah.[7] Bo_0 is obtained from Figure 2, F_x from Figure 3, and F_E is calculated with Eq. (9). Bo is then calculated with Eq. (8).

The choice between UCC and LCC is made as explained before. Use of this method shows that when $Y>10^6$, the applicable correlation is always LCC is $L_c/D<100$.

As is apparent from the foregoing discussion, manual calculations with the present correlation are more laborious than with the original Shah correlation. Still, the labor involved is far less than that with the Katto correlation or with most of the other better correlations.

Summary of the development work

Simple equations were fitted to the curves for $Y>10^6$ in Figures 3(a) and 3(c) of Shah.[7] These are Eqs. (10)–(18) and are plotted here in Figures 2 and 3.

The original UCC (Figure 3(b) of Shah[7]) had not been tested for $X_{IN}>0$. Such data were analyzed in two ways. First, this figure was replotted with inlet quality on linear scale and the curves extrapolated to positive qualities. This approach was not successful. The use of boiling length was next attempted. This approach was successful and has been adopted.

Equation (1) was obtained using Figure 3(b) of Shah[7] together with data beyond its range. The value of n in Eq. (1) for helium was found to be different from that for other fluids. For this reason, efforts were made to obtain and analyze as much helium data as possible.

Values of n for fluids other than helium indicated the following relation:

$$n=\text{function}\left(\frac{L_E}{D}, X_{IN}, p_r, Y\right) \tag{20}$$

Several equations were tried; the best of these are Eqs. (3) and (4), which have been adopted.

Study of data for very short tubes together with high Y indicated an entrance effect similar to that during single phase flow. Data for very small L_c/D together with high Y were collected and analyzed. Equation (9) resulted from this analysis.

Intense efforts were made to determine the boundary between the UCC and LCC. For helium, it was found that the UCC applies at all values of Y. For other fluids, it was found that only the UCC applies at $Y<10^6$. At higher Y, it was seen that the true value of Bo is generally the smaller of the Bo given by the UCC and LCC. A few data points at high p_r and L_E/D departed from this rule as indicated by Eq. (19). The selection rules were established accordingly. Some data disagreed with these rules but did not give any satisfactory alternative.

Efforts were made to develop a single equation representing the boundary between UCC and LCC. Several formulas were developed, the simplest among these is that the UCC applies if

$$\frac{L_E}{D}>\frac{Y}{10^4} \tag{21}$$

However, Eq. (21) and other similar formulas gave results inferior to those obtained by the method finally adopted.

Data analysis

Data search and selection

To thoroughly test and further develop the original correlation, efforts were made to obtain data in the range beyond the range of data it was developed from. As in Shah,[7] only data for single-component fluids obtained under stable, pulsation-free conditions were considered. Only data for burnout of the first kind (X_c < limiting quality) were considered. The additional data collected include 12 new fluids, very long tubes (L_c/D from 300 to 940), very short tubes (L_c/D from 1.3 to 10) together with high Y and positive inlet qualities (up to 0.85). Further, data were sought in the ranges in which the original database had too few data points. These include very small diameter tubes, ($D<2$ mm), $X_c<-0.83$, $Y=10^5$ to 10^6, and high pressures (specially at $Y<10^5$).

It became apparent at an early stage that the correlation was erratic when compared with helium data. Hence intense efforts were made to find and analyze helium data. Several publications do not give the data in analyzable form. The figures in Petukhov *et al.*[13] are too blurred to be read accurately, and inlet quality is not known. The data of Babii and Pavlov[14] and Pavlov *et al.*[78] for natural circulation systems were not accepted, since these were obtained under unstable conditions; besides, the mass velocities are not known accurately. The data of Hildebrandt could not be analyzed, since L_c and X_c are not given.

During the search for small tube diameter data, those in Tables 1 and 3 of Thompson and Macbeth[15] for diameters of 1.02 and 1.14 mm were examined. Most of these are well below the present correlation as well as the Katto correlation. Despite their ready availability, these have not been included in any of

Table 1 Verified range of the Bowring correlation for water

p (bar)	2–190
D (m)	2–45
L (m)	0.15–3.7
G (kg/m^{2}s)	136–18 600

Table 2 Verified range of the Subbotin *et al.* correlation for helium

p (bar)	12–
G (kg/m^{2}s)	80–320
X_c	-0.25–$+1.0$

the more successful correlations such as those of Biasi *et al.*[85] and Bowring.[10] These data therefore appear to be premature burnouts, and these sets were rejected. However, tabulations of these data are included in Shah.[82] Where the sources gave a large amount of data, samples representative of the total range were taken at random. Individual data points from a set were not deleted even when they appeared to be erroneous.

Besides the new data collected during this study, the intention was to reevaluate all the original database. Among these, the data of Doroschuk *et al.*[17] could not be analyzed, since the tube lengths for individual data points are not known. This is a rather strange situation, since the original LCC was based largely on these data, and the present LCC at $Y > 10^6$ is essentially the same. All the other data sets in Shah[7] were analyzed, though the total number of data points was reduced by taking data points at larger steps of parameters. A couple of data from Bergles[16] were deleted, since that paper indicates they are inapplicable.

Correlations tested

Besides the present correlation, three others have also been tested. These were chosen because they appear to be the best available.

The most verified general predictive technique is the Katto correlation.[5] Katto *et al.* have further tested this correlation in several publications[6,9,52,65] and made modifications to it. The Katto-Ohno version[6] appears to be the most improved form and was originally selected for evaluation. However, the present data analysis showed it to greatly underpredict data at positive inlet qualities, even predicting negative heat fluxes. When boiling length was used at positive inlet qualities through Eqs. (5) and (6), satisfactory results were obtained. It was decided to use the Katto-Ohno correlation with L_B when $X_{IN} > 0$. It is felt this is the best version of the Katto correlation.

Many correlations have been presented that apply exclusively to water. The better ones among these include those by Bowring,[10] Doroschuk *et al.*,[17] Biasi *et al.*,[85] and Thompson and Macbeth.[15] Among these, Bowring's seems to be the most verified and was therefore selected. Table 1 lists the verified range of this correlation.

Several correlations applicable exclusively to helium have been proposed. These include those by Giarratano *et al.*,[50] Keilin *et al.*,[51] Petukhov *et al.*,[13] and Subbotin *et al.*[11] The correlation of Subbotin *et al.*[11] appears to be the most verified, since it is said to agree with data from four sources besides their own data. It was therefore selected for evaluation. Table 2 lists the correlation's verified range as stated by Subbotin *et al.*

Property data

All the correlations tested use properties at the saturation temperature. For helium, all properties were taken from McCarty.[18] For refrigerants, the prime source of data was the ASHRAE Handbook.[19] For other fluids, the prime data source was Vargaftik.[20] These two sources were not sufficient to provide all needed data, and hence several other sources were also used. Where no data could be found, predictions and extrapolations were done using the simpler of the methods recommended by Gambill.[21] Property data obtained by these methods are tabulated in Shah.[82]

Properties of hydrazine are from Yaws *et al.*,[22] this being the only source found. This shows a very rapid rise in liquid specific heat with increasing pressure at pressures well below the critical. This does not appear reasonable; thus Noel's data[23] for CHF at higher pressures were not analyzed.

It is well known that on heating, N_2O_4 decomposes to form NO_2, and the process requires addition of heat.[24] To analyze the CHF data for N_2O_4, it was assumed it is completely converted to NO_2 at the burnout point. Therefore, all properties used were for NO_2, taken from Yaws *et al.*[25] Further, an effective latent heat was used that was obtained by adding the heat of decomposition of N_2O_4 to the latent heat of NO_2.

Assumptions and approximations in data analysis

For some of the data sets analyzed, the publications did not give all the information needed for analysis. In these cases, assumptions were made that appear to be reasonable and consistent with other material in those publications. The data of Ogata and Sato[27] were obtained with L_c/D of 53.2 and 26.6; a value of 53.2 was used in analysis, since the actual L_c/D for individual data points is not known. This assumption causes underprediction of up to 10% for the shorter length when the present correlation is used.

In the data of Petukhov *et al.*[28] and Grigoriev *et al.*,[29] inlet subcooling is not known. $X_{IN} = 0$ was assumed except where this assumption resulted in exit quality greater than 1. In these cases, a slight inlet subcooling was assumed.

The data of Cumo and Palmieri[77] for $L_c/D = 1.33$ are represented graphically in terms of a simple correlation. Data were extracted from this figure assuming the flow rate, subcooling, and pressures during these tests were in the range of their tests on longer tubes.

One may question why the data with incomplete information were not simply discarded. The reason is that data for these parameters are scarce, and their analysis with reasonable assumptions provides valuable information on the reliability of the tested correlations.

Results of data analysis

Tables 3–6 summarize the results of data analysis. Complete tabulations of all data analyzed are given in Shah.[82]

$$\text{Deviation} \equiv \frac{q_P - q_M}{q_M} \tag{22}$$

where q_P is the predicted CHF, and q_M is the measured CHF.

$$\text{Mean deviation} = \frac{\text{sum of absolute values of deviations}}{\text{number of data points}} \tag{23}$$

$$\text{Average deviation} = \frac{\text{sum of actual values of deviations}}{\text{number of data points}} \tag{24}$$

Study of these tables show the present correlation performed reasonably well for all fluids under all conditions. The Katto correlation gave large deviations with subcooled burnout data and helium data. The correlations of Subbotin *et al.* and Bowring performed satisfactorily in their own verified ranges (Tables 1 and 2) but gave large deviations for data outside these ranges.

For all the 1443 data points analyzed (from 62 independent sources and for 23 fluids), the mean deviation of the present correlation is 16%, whereas that of the Katto correlation is 22.3%. Hence the present correlation appears to be the best general predictive technique, since no well-verified general correlation other than that of Katto *et al.* is known.

Discussion

All discussions pertain to the present correlation except where others are specifically mentioned.

Table 3 Comparison of the data for water with the correlations of Shah, Katto, and Bowring

Source	D (mm)	L_c/D	p_r	G (kg/m^{2}s)	q_c (MW/m^2)	x_{IN}	x_c	$Y/10^4$	No. of data pts.	Mean deviation (%)		
										Shah	Katto	Bowring
Waters *et al.* [48]	11.2	326.0	0.467	6690	2.0	−0.71	−0.00	3200	12	19.3	19.2	14.3
				9320	5.1	−0.06	+0.29	5700				
Chojnowski [43]	32.0	238.1	0.815	682	0.25	−0.64	+0.17	230	10	10.7	6.3	23.9
				1462	0.83	−0.08	+0.40	900				
Bergles [16]	0.58	25.0	0.0093	6070	15.0	−0.22	−0.04	430	3	24.3	56.8	63.0
					25.0	−0.15						
	1.19	25.0	0.0093	3035	11.0	−0.23	−0.12	190	15	23.9	27.3	68.0
				24255	45.0	−0.07	+0.01	2900				
Maaulbetsch and Griffith [46]	1.19	26.1	0.0093	3022	7.6	−0.21	−0.00	190	11	20.6	22.8	57.6
		100.0		6057	20.0	−0.15	+0.28	660				
Wurtz [38]	10.0	402.0	0.316	1000	0.35	−0.47	+0.38	80	15	8.9	8.9	8.2
		800.0		2500	1.6	0.00	+0.79	410				
Ornatskii *et al.* [45]	2.9	54.8	0.44	1500	2.6	−1.05	−0.03	92	18	14.5	7.1	14.1
	8.0	55.1			9.6	−0.03	+0.27	170				
Firstenberg *et al.* [35]	3.0	25.5	0.0047	13	0.11	−1.11	−0.46	0.019	47	10.8	23.3	22.2
	23.9	66.7	0.623	9864	13.0	−0.03	+0.97	5100				
De Bortoli *et al.* [31]	1.9	21.0	0.156	38	0.23	−2.34	−1.15	0.21	72	14.7	16.5	8.6
	10.3	365.4	0.935	10596	12.0	−0.06	+0.98	14000				
Thompson [15] ref. 4	10.3	74.0	0.156	3713	3.9	−0.47	−0.20	760	18	15.7	16.9	6.5
			0.467	9892	10.0	−0.04	+0.15	6000				
Lee [33]	5.6	31.0	0.176	406	0.93	−0.31	+0.14	34	31	18.1	12.2	7.5
	19.8	359.6	0.560	4214	8.1	−0.01	+0.85	700				
Matzner [36]	23.6	25.8	0.31	637	2.1	−0.45	−0.19	59	30	8.8	17.4	6.9
	37.5	52.1		9661	7.5	−0.05	+0.28	7900				
Swenson [37]	10.5	174.2	0.623	677	0.63	−0.52	+0.18	66	5	27.4	12.1	5.0
				1761	0.97	−0.09	+0.15	370				
Lee and Morris [34]	10.0	338.7	0.31	2016	1.3	−0.24	+0.26	290	5	10.6	2.0	3.9
				4088	1.7	−0.03	+0.42	1100				
Becker [32]	3.9	125.0	0.0209	100	0.4	−0.48	+0.40	1.1	23	9.5	9.9	4.6
	10.0	792.2	0.167	1631	5.9	−0.13	+1.0	170.0				
Hewitt and Kearsey [41]	12.6	72.5	0.31	1355	0.31	+0.01	+0.33	160.0	13	16.4	20.9	33.1
		290.0		2710	1.7	+0.73	+0.80	550.0				
Hewitt [40]	6.2	940.0	0.31	1350	0.5	−4.00	−0.03	100.0	12	8.9	9.0	5.1
				4070	3.4	−0.04	+0.75	750.0				
Becker [42]	10.0	200.0	0.81	500	0.15	−1.12	−0.04	67.0	41	12.0	11.9	25.5
		500.0	0.904	7000	3.5	−0.16	+0.73	16000.0				
Watson *et al.* [44]	37.8	145.1	0.84	406	0.22	−0.79	−0.08	140.0	24	14.2	11.9	36.3
				2032	0.79	+0.21	+0.42	2500				
Styrikovich *et al.* [47]	8.0	7.5	0.443	750	0.8	−0.78	−0.52	49	19	18.4	17.9	22.1
		188.0			8.5	+0.81	+0.90					
Tolubinsky [70]	4.0	15.0	0.030	3157	8.1	−0.19	−0.10	350	3	49.9	70.4	23.4
				4510	10.0	−0.16		660				
All data	0.58	7.5	0.0047	13	0.11	−4.00	−1.15	0.019	427	14.5	16.2	18.6
	37.8	940.0	0.935	24255	45.0	+0.81	+0.97	16000.0				

Table 4 Comparison of the data for helium with the correlations of Shah, Katto, and Subbotin *et al.*

Source	D (mm)	L_c/D	p_r	G (kg/m^{2}s)	q_c (kW/m^2)	x_{IN}	x_c	$Y/10^4$	No. of data pts.	Mean deviation (%)		
										Shah	Katto	Subbotin
Katto and Yokoya [52]	1.0	25.0	0.87	10	0.11	−0.53	−0.17	1.5	56	17.6	28.3	92.9
		200.0		71	3.2	+0.32	+0.98	72.0				
Deev *et al.* [55]	1.63	30.0	0.465	92	2.0	−0.39	−0.02	29	13	14.8	9.8	8.6
		106.7		305	6.4	+0.16	+0.35	160				
Keilin *et al.* [51]	2.0	25	0.533	39	3.0	0.00	+0.45	8.1	2	26.0	3.9	35.9
					3.4	+0.13	+0.53					
Ogata and Sato [27]	1.09	53.2	0.566	79	1.8	−0.80	−0.16	21	5	20.7	30.6	17.1
			0.890	178	3.4	−0.01	+0.29	110				
Johannes [54]	2.12	140.0	0.490	60	1.3	−0.18	+0.20	16	10	10.2	27.9	23.1
			0.668	240	2.7	−0.04	+0.57	230				
Giarratano *et al.* [50]	2.13	6.0	0.49	45	1.6	−0.30	−0.23	9.7	22	23.1	69.5	26.9
		42.0	0.89	630	6.9	0.00	+0.37	23.0				
Romonov *et al.* [49]	0.47	21.3	0.452	22	1.3	0.00	+0.12	1.0	10	33.8	53.2	125.6
		54.9		275	4.2		+0.64	94.0				
Petukhov *et al.* [28]	0.8	37.5	0.44	60	0.89	0.00	+0.16	8.4	8	5.5	34.6	117.0
		193.8		270	5.9		+0.57	130.0				
Grigoriev *et al.* [29]	0.67	194.0	0.43	25	0.57	−0.01	+0.73	1.2	4	15.2	12.6	725.9
				62	1.2	0.00	+1.0	7.6				
Beliakov *et al.* [53]	4.05	5.0	0.527	20	0.6	0.00	+0.02	3.4	37	15.9	25.0	26.4
		34.0	0.791	200	4.9	+0.80	+0.84	440.0				
All data	0.47	5.0	0.43	10	0.11	−0.00	−0.23	1.0	167	17.8	32.7	74.0
	4.05	194.0	0.89	630	5.9	+0.80	+1.00	440.0				

Table 5 Comparison of the data for various fluids with the correlations of Shah and Katto

Source	Fluid	D (mm)	L_c/D	p_r	G (kg/m^{2}s)	q_c (kW/m^2)	x_{IN}	x_c	$Y/10^4$	No. of data pts.	Mean deviation (%)	
											Shah	Katto
Percupile	R-11	12.5	9.0	0.404	1480	0.27	−1.17	−0.61	390	22	14.4	17.2
et al. [59]				0.560	8797	1.1	−0.60	−0.18	10000			
Merilo and	R-12	5.3	194.3	0.25	1600	0.04	−0.36	+0.03	270	73	10.4	11.0
Ahmad [61]			575.0	0.368	8100	0.36	+0.03	+0.55	5500			
Katto and	R-12	3.0	333.3	0.83	3000	0.055	−0.99	−0.13	1000	15	5.6	21.5
Yokoya [9]					9000	0.35	−0.03	+0.37	7200			
Katto and	R-12	10.0	90.0	0.475	121	0.016	−0.59	−0.08	5.1	35	10.1	8.0
Ohno [6]				0.83	2010	0.19	0.00	+0.86	850			
Katto and	R-12	5.0	50.0	0.475	770	.08	−0.63	−0.25	130	27	19.7	10.0
Ashida [65]				0.83	6630	0.82	0.00	+0.28	5800			
Steven	R-12	9.6	33.6	0.26	508	0.054	−0.28	−0.12	449	33	11.3	8.0
et al. [60]			268.5		2032	0.31	−0.04	+0.85	600			
Groeneveld	R-12	7.8	176.9	0.254	1330	0.04	−0.19	+0.02	250	24	22.2	11.9
[62]					8100	0.28	+0.40	+0.57	6400			
Barnett and	R-21	6.7	75.5	0.142	467	0.064	−0.37	−0.03	33	80	14.3	13.0
Wood [58]		16.1	306.5	0.267	2358	0.47	−0.04	+0.96	920			
Staub [63]	R-22	10.2	151.9	0.125	494	0.083	−0.29	+0.24	42	21	8.9	7.2
				0.41	1255	0.19	−0.02	+0.82	290			
Nishikawa	R-22	13.0	153.8	0.84	200	0.015	−1.38	−0.22	19	37	23.7	26.6
et al. [66]				0.962	1300	0.092	+0.06	+0.59	570			
Coeffield	R-113	10.2	74.7	0.27	1287	0.14	−1.04	−0.54	440	32	10.3	17.1
et al. [64]				0.61	5596	0.56	−0.11	+0.02	6400			
Lazarek and	R-113	3.5	40.0	0.035	270	0.11	−0.58	+0.30	10	13	26.2	27.8
Black [8]				0.120	740	0.30	−0.02	+0.81	75			
Koizumi	R-113	10.0	41.1	0.089	1410	0.018	+0.61	+0.65	440	5	23.2	20.6
et al. [56]			141.2			0.049		+0.66				
Weede and	R-113	17.3	5.1	0.0604	2107	0.4	−0.50	−0.43	1300	21	16.9	36.7
Dhir [83]			26.5		6322	0.85	−0.15	−0.05	9300			
Dix [57]	R-114	10.0	45	0.262	439	0.066	−0.48	−0.00	53	51	19.4	20.4
		14.1	145	0.44	3902	0.22	−0.05	+0.78	2700			
Cumo and	O-terphenyl	5.0	1.3	0.055	1713	0.66	−2.07	−1.19	1400	33	25.2	61.1
Palmieri [77]		10.0	100.0	0.123	6970	3.5	−0.31	−0.29	14000			
Pokhvalov	Benzene	5.0	16.0	0.185	70	0.34	−1.73	0.00	1.8	33	17.6	29.7
et al. [69]				0.76	10000	1.0	−0.03		17000			
Sterman	Benzene	10.0	10.0	0.0406	3304	1.7	−0.42	−0.34	3000	8	9.3	56.5
et al. [68]					10320	3.8	−0.15	−0.13	23000			
Sterman	MIPD	10.0	10.0	0.073	3128	1.2	−0.83	−0.73	4900	9	17.6	66.6
et al. [68]				0.29	9708	4.9	−0.33	−0.27	38000			
Shlykov	MIPD	10.0	15.0	0.073	3092	0.87	−2.89	−2.47	4600	23	25.5	70.3
et al. [73]				0.29	6680	4.3	−0.07	−0.01	22000			
Sterman	Diphenyl	10.0	10.0	0.0334	3316	1.3	−0.84	−0.76	3500	9	15.2	50.1
et al. [79]					7200	4.1	−0.10	−0.07	14000			
Hauptman	CO_2	6.04	175.0	0.28	1355	0.32	−0.10	+0.19	180	6	17.5	6.5
et al. [80]					3387	0.39		+0.48	940			
Noel [67]	Ammonia	5.89	14.0	0.103	480	3.4	−2.98	−2.62	36	35	11.3	35.9
				0.93	23306	16.0	−0.07	−0.03	39000			
Noel [23]	Hydrazine	5.89	19.7	0.07	271	2.4	−1.04	−0.81	14	10	33.1	101.0
				0.117	18835	27.0	−0.41	−0.32	25000			
Birdseye	N_2O_4	4.57	13.5	0.102	3871	1.8	−0.46	−0.42	1400	36	17.1	25.7
[26]		4.72	13.9	0.408	26840	12.0	−0.05	+0.00	44000			
Tolubinsky	Ethanol	4.0	15.0	0.103	3751	3.0	−0.40	−0.30	3300	3	24.9	37.3
[70]						5.0	−0.20	−0.14				
Tolubinsky	Acetone	4.0	15.0	0.139	3605	3.1	−0.29	−0.19	1500	1	15.0	26.7
[70]												
Tolubinsky	Benzene	4.0	15.0	0.134	3959	2.4	−0.59	−0.42	2300	3	40.0	9.2
[70]						3.8	−0.30	−0.19				
Gambill and	Ethylene	6.32	48.1	0.0187	5637	6.5	−0.74	−0.51	8300	4	19.1	5.0
Bundy [81]	Glycol		52.1	0.0840	29051	20.0	−0.50	−0.25	72000			
Lewis	Para-	14.1	4.0	0.268	4	0.020	−0.04	+0.42	0.41	19	20.4	13.5
et al. [71]	Hydrogen		26.2		23	0.067	+0.03	+0.83	10.0			
Lewis	Nitrogen	14.1	29.0	0.101	26.7	0.028	−0.11	+0.00	0.36	11	16.4	10.9
et al. [71]					55.2	0.081	0.00	+0.86	3.6			
Grigoriev	Nitrogen	0.32	101	0.029	40	0.013	−0.01	+0.72	0.13	7	8.4	12.7
et al. [29]			413		620	0.08	0.00	+1.00	3.0			
Katto and	Nitrogen	1.0	200	0.065	109	0.022	−0.05	+0.85	1.1	6	13.0	8.0
Yokoya [52]					328	0.078	−0.01	+0.99	5.3			
Pappel	Nitrogen	12.8	23.8	0.101	118	0.082	−0.46	−0.33	8.2	37	16.5	15.7
et al. [72]				0.490	2656	0.43	0.43	−0.08	2600			
Aladyev	Potassium	4.0	30	0.0014	38	0.27	−0.19	+0.54	0.0006	34	11.7	18.5
et al. [76]		6.0	100	0.0076	333	1.7	−0.04	+1.00	0.026			
Bond and	Potassium	10.7	39.5	0.0875	75.6	0.17	+0.08	+0.59	0.0066	11	17.6	19.8
Converse [74]		19.3	71.2		301.0	0.71	+0.77	+0.91	0.056			

Table 5 (continued)

Source	Fluid	D (mm)	L_c/D	p_r	G (kg/m^{2}s)	q_c (kW/m^2)	x_{IN}	x_c	$Y/10^4$	No. of data pts.	Mean deviation (%) Shah	Mean deviation (%) Katto
Hoffman [75]	Potassium	8.25	71.0	0.0062	104	0.69	−0.37	+0.34	0.0048	14	28.9	37.2
					286	0.96	+0.10	+1.00	0.030			
Fisher [30]	Rubidium	7.1	42.1	0.0095	253	0.16	+0.14	+0.45	0.0009	8	34.3	40.9
				0.0440	732	0.76	+0.63	+0.80	0.063			
All data		0.32	1.3	0.0014	4	0.013	−2.98	−2.62	0.0006	849	16.3	23.3
		19.3	575.5	0.962	29051	27.0	+0.77	+1.00	72000			

Table 6 Summary of the results of data analysis

Fluid	Data range	No. of data	Correlation of	Deviation (%) Mean	Deviation (%) Average	No. of data with deviation >30%
Water	All data	427	Shah	14.4	−0.9	40
			Katto	16.1	+3.1	51
			Bowring	18.6	−9.6	86
Water	Verified range of Bowring corr. (Table 1)	251	Shah	14.4	−0.3	20
			Katto	14.1	−3.2	17
			Bowring	11.7	−3.9	19
Helium	All data	167	Shah	17.8	−2.6	29
			Katto	32.7	+29.3	73
			Subbotin	74.0	+54.2	74
Helium	Verified range of Subbotin corr. (Table 2)	67	Shah	20.3	+7.9	18
			Katto	25.3	+22.1	25
			Subbotin	22.3	−3.5	21
All fluids	$X_c<0$	397	Shah	16.9	−2.1	56
			Katto	30.7	+21.8	141
All fluids	$X_c \geqslant 0$	1046	Shah	15.4	−3.2	129
			Katto	18.8	+11.8	187
All fluids	All data	1443	Shah	16.0	−2.9	185
			Katto	22.3	+14.6	328

Helium correlation

At $Y > 10^4$, the present correlation for helium is different from that for other fluids, and it predicts lower CHF than the correlation for other fluids. This difference raises several concerns and questions. Is the general correlation lacking some significant parameter that is causing this discrepancy with helium data? Since the behavior of helium differs from the general correlation, could the behavior of some other fluid be also different? The final resolution of these questions must await additional data for helium and hitherto untested fluids. However, helium is unique in that its normal boiling point is lower than that of any other fluid. Hydrogen is the fluid with the second lowest normal boiling point, and its data are in agreement with the general correlation and so are data for 21 other fluids ranging from cryogens to liquid metals.

That low CHF can be caused by flow instabilities and pulsations is well known (see, for example, Mishima *et al.*[12]). Hence the possibility that most of the helium data may be premature burnouts needs careful examination.

Dissociating fluids

Heating of nitrogen tetraoxide causes its dissociation to nitrogen dioxide. The data of Birdseye[26] for this fluid were analyzed assuming complete dissociation, using an effective latent heat that is the sum of the latent heat of NO_2 and the heat needed for the dissociation of N_2O_4. This procedure resulted in satisfactory agreement with the correlation.

As noted by Shlykov *et al.*,[73] MIPD also has a tendency to dissociate at higher temperatures. Virtually all of their data show adequate agreement except those at near zero subcooling, which are high. This suggests a method of analysis similar to that used with N_2O_4 might have been successful.

The general applicability of this method for dissociating fluids needs further evaluation and refinement. For now, it is to be considered applicable only to nitrogen tetraoxide under the conditions of Birdseye's tests.

Entrance effect factor

At high values of Y, it was found that the CHF of very short tubes is higher than that in longer tubes at the same local conditions. Cumo and Palmieri[77] and Bergles,[16] among others, have also noted such entrance effects. Indeed, the correlation of Gambill[84] for subcooled burnout indicates the entrance effects during CHF are the same as in single-phase flow.

The predictions of Eq. (9) are lower than required to give the best fit to all data. It was felt prudent to be conservative, since the analysis of many of the data for very short tubes cannot be fully relied on owing to problems such as lack of reliable property data and dissociation of fluids. Therefore, further research is needed using stable fluids whose properties are fully established.

Reliability of the correlation

Let us first examine some data sets that have high deviations from the present correlation.

Table 7 Complete range of data analyzed

Fluids	Water, R-11, R-12, R-21, R-22, R-113, R-114, ammonia, hydrazine, N_2O_4, MIPD, CO_2, helium, nitrogen, hydrogen, acetone, benzene, diphenyl, ethanol, ethylene glycol, o-terphenyl, potassium, rubidium
D (mm)	0.32–37.8
p_r	0.0014–0.962
G (kg/m^{2}s)	4–29 051
q_c (kW/m^2)	0.11–45 000
L_c/D	1.3–940
X_{IN}	−4.0–+0.81
X_c	−2.6–+1.0
Y	6–720 000 000

The mean deviation of Noel's hydrazine data[23] is 33.1%. This is largely because of two data points at low velocities that have deviations of +95.8 and +124.2%. The deviations of these data points with the Katto correlation are +259% and +295%. Hence these data appear to be premature burnouts.

The data of Tolubinsky and Matorin[70] for water are overpredicted by about 50%. The Katto correlation overpredicts these data by 70%. Data in the same range from other sources are satisfactorily correlated. Hence these data are not representative and are probably incorrect. The data of Toluninsky and Matorin[70] for benzene are underpredicted by about 40%. However, data for this fluid from two other sources covering a wider range of parameters are satisfactorily predicted.

Study of deviations for all data analyzed shows no consistent trends except for the underpredictions for very short tubes with high values of Y, as was discussed earlier. Other than that, there is no tendency for increased deviations at extreme values of dimensional or nondimensional parameters. The fluids analyzed represent extreme variations of chemical structures and properties. Only helium was found to behave differently from other fluids, and possible reasons for this have been discussed earlier. The remaining 22 fluids include cryogens, refrigerants, rocket propellents, complex organic compounds, water, and liquid metals. It would therefore appear reasonable to infer that the correlation is likely to be reliable for all fluids over the range of parameters covered by the data analyzed. This range is so wide that it envelopes the range of virtually all published data.

Other correlations

Detailed study and evaluation of other correlations was beyond the scope of this project. Some features and trends readily apparent from data analysis are noted below.

The Katto correlation, as given by Katto and Ohno,[6] greatly underpredicts the data for high positive inlet qualities. This fault was rectified here by the use of boiling length at positive inlet qualities. The results reported here are for this improved version. The Katto correlation is erratic at $X_c < 0$. It generally overpredicts such data. Indeed, Katto and Ohno[6] had indicated it may not be successful at deeply subcooled conditions. Katto[4] presented the Katto-Ohno correlation using boiling length at all values of inlet quality and restricted its use to $X_c > 0$. It is also erratic with helium, generally overpredicting the data. It also tends to greatly overpredict the data for very small L_c/D coupled with high Y. Thus the data of Cumo and Palmieri[77] at L_c/D of 1.3 are overpredicted by several hundred percent, and the data of Weede and Dhir[83] at L_c/D of 5.1 are overpredicted by about 80%.

The Bowring correlation[10] for water was found to have very large deviations beyond its original verified range given in Table 1. Even within this range, it was found to greatly underpredict data at positive inlet qualities. The Subbotin *et al.*[11] correlation for helium worked fairly well within the range of Table 2. Beyond this range very large deviations were found.

Recommendations for use

Present correlation

Tables 3–5 list the ranges of data for various fluids over which the present correlation has been tested. Table 7 lists the complete range of data for all fluids. No limitations to the applicability of the correlation were discovered. The recommendations for its use are as follows:

1. For helium, use only in the range of parameters in Table 4.
2. For all other stable fluids, use in the range of parameters in Table 7.
3. It may be used for nitrogen tetraoxide by the method described earlier. Applicability of this method to other dissociating fluids is subject to verification.

Other correlations

The other correlations are reliable in the following ranges:

> The Katto-Ohno correlation (using boiling length at $X_{IN} > 0$) for all fluids other than helium in the range $X_c > 0$ and $L_c/D > 17$
>
> Bowring correlation for water only in the range of Table 1, and then only if $X_{IN} < 0$
>
> Subbotin *et al.* correlation for helium only in the range of Table 2

Areas for further research

1. Further study the transition between the local condition and upstream condition correlations. This includes efforts to refine the transition criteria and study of phenomena associated with this transition. It is plausible that there may be an intermediate regime between the UCC and LCC.
2. Further study the entrance effects in the local condition correlation regime and refinement of the entrance effect formula, Eq. (9).
3. Further study CHF with helium. Why are helium data overpredicted by correlations that fit data for all other fluids? Is it due to instabilities or to some other phenomena?
4. Further study CHF with dissociating fluids. Can the method used here for correlating N_2O_4 data be applied to other dissociating fluids?

Concluding remarks

The improved Shah correlation for CHF in uniformly heated vertical tubes presented here has been shown to agree with experimental data, including all types of fluids over a range of parameters that covers the extremes in world data. Comparing the same data with Katto's general correlation showed it to be unreliable for helium and for subcooled burnout. Comparing the data with the best specialized correlations for water and helium showed the present correlation to be more reliable. Hence it may be concluded that the improved correlation presented here is considerably more reliable than other predictive techniques and is usable over the entire range of parameters covered by world data. It should therefore be of considerable value in the design and analysis of heat transfer equipment and processes.

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