A General Predictive Technique for Heat Transfer during Saturated Film Boiling in Tubes

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A simple predictive technique for heat transfer during film boiling in tubes is presented. This technique is based on the two-step model and consists of a graphic correlation for nonequilibrium quality and an equation for liquid droplet cooling at high pressures. It has been developed from and verified with data for water, nitrogen, para-hydrogen, R-113, methane, and propane. The range of data includes equilibrium qualities from 0.1 to 2.9, pressures from 1.4 to 215 bar, reduced pressures from 0.01 to 0.97, mass flux from 30 to 3442 kg/m^2 s, tube diameters from 2.5 to 14.9 mm, heat flux from 0.012 to 2.1 MW/m^2, and wall temperatures from 81 to 1112 K. For all 722 data points analyzed, heat transfer coefficients based on actual vapor temperatures are correlated with a root-mean-square error of 15%.

INTRODUCTION

Many practical heat exchangers involve operation under postdryout conditions. Examples are cryogenic coolers, refrigerant evaporators, once-through steam boilers, and nuclear reactors after the postulated loss-of-coolant accident. Numerous experimental and theoretical studies of postdryout heat transfer have been carried out, their most important objective being to provide information for prediction of heat transfer rates. Postdryout heat transfer includes subcooled and saturated fluids in the transition and film boiling regimes. In this paper, only saturated fluids in the film boiling regime are considered.

Because of the practical importance of this problem, a large number of predictive techniques for heat transfer estimation have been proposed. Most of the early correlations were modifications of single-phase heat transfer equations. These took no account of the physical phenomena involved and completely ignored the possibility of thermodynamic nonequilibrium. Well-known examples of such correlations are those of Groeneveld [1] and Miropoloskiy [2]. Both of these correlations, although dimensionless, are intended only for water, as indeed are most others. Such correlations have only a limited range of validity and their applicability to other fluids is unlikely.

Researchers at the Massachusetts Institute of Technology (M.I.T.) and the U.K. Atomic Energy Authority (U.K. AEA) independently developed the so-called two-step model of film boiling, according to which heat is first transferred from the heated wall to vapor and then from the vapor to liquid drops. Starting from the dryout point, calculations are carried out successively over short lengths of the tube downstream of the dryout point. Some of the more refined models also include the effects of droplet-wall interaction. Such calculation techniques have been presented by, among others, Bennet et al. [3], Forslund and

Rohsenow [4], Hynek et al. [5], and Koizumi et al. [6]. The difficulty with this approach is that many of the fundamental data needed for such calculations are either unavailable or very tentative. Hence a number of empirical factors and equations whose general validity is questionable must be used. Thus this fundamental approach has not as yet yielded reliable general predictive techniques. In addition, calculations by this method are very tedious.

Recently, predictive techniques have been presented by Chen et al. [7], Groeneveld and Delorme [8], Saha and co-workers [9, 10], and Jones and Zuber [11]. These are generally consistent with the physical phenomena involved and are comparatively easy to use for practical calculations. The Jones-Zuber correlation has been verified with data for nitrogen and water. The other three correlations have been verified with water data only.

It is clear from the foregoing discussion that although a number of good predictive techniques for water have been published, no verified predictive technique applicable to a wide variety of fluids has been available until now. Presented here is a simple dimensionless correlation consistent with physical phenomena that has been verified over a very wide range of parameters for six fluids: water, nitrogen, hydrogen, R-113, methane, and propane. The experimental data correlated include tube diameters from 2.5 to 14.9 mm, absolute pressures from 1.4 to 215 bar, reduced pressures from 0.01 to 0.97, mass flux from 30 to 3442 kg/m^2 s, wall temperatures from 81 to 1112 K, and equilibrium vapor qualities from 0.1 to 2.9. The heat transfer coefficients (based on nonequilibrium vapor temperatures) for the 722 data points analyzed are correlated with a root-mean-square (rms) error of less than 15%.

This paper presents the new correlation and explores its validity and applicability through comparison with experimental data. So that the correlation may be veiwed in the proper perspective, some other predictive techniques are also briefly discussed.

PHYSICAL MODEL FOR THE CORRELATION

At the outset, it was decided to confine this correlation to equilibrium vapor qualities of 10% or higher. The physical model assumed for the development of the correlation is as follows:

1. Flow consists entirely of liquid droplets dispersed in the vapor stream.
2. At the dryout point there is complete thermodynamic equilibrium between vapor and liquid. This assumption is common to virtually all analyses, including [4–6, 8–11].
3. At low to moderate reduced pressures, the effects of liquid droplet-wall interaction are negligible. Heat is convected from the vapor to liquid droplets.
4. At high reduced pressures, cooling of the wall by liquid droplets becomes significant, as shown by Bailey et al. [12]. Heat is then removed from the wall through convection by vapor as well as by direct impingement of liquid droplets.
5. Heat transfer by radiation is negligible.

THE CORRELATION

The correlation was developed through the analysis of data for film boiling of six fluids.

1. The total heat flux q_w removed from the wall is expressed by

$$q_w = q_c + q_{dc} = F_{dc} h_g (T_w - T_g) \tag{1}$$

2. The actual vapor temperature T_g is calculated by the following basic heat balance equation:

$$\frac{x_E - x_A}{x_A} i_{fg} = \int_{T_{\mathrm{sat}}}^{T_g} c_{pg}\, dT = i_g - i_{g\,\mathrm{sat}} \tag{2}$$

3. At the dryout point x_A and x_E are assumed equal. Downstream of the dryout point, the following relations apply:

For Bo $\leqslant 4.5 \times 10^{-4}$,

$$x_A = x_E \tag{3}$$

For Bo $> 4.5 \times 10^{-4}$,

$$x_A = \mathrm{fn}(x_{\mathrm{cr}}, x_E, \mathrm{Fr}_L) \tag{4}$$

The functional relation of Eq. (4) is expressed graphically in Fig. 1. This is used together with estimated x_{cr} to determine x_A, as explained later. Table 1 lists the coordinates for the correlation of Fig. 1. This ensures that accurate interpolations can be made for any intermediate values of Fr_L.

4. The droplet cooling factor F_{dc} for water is given by

$$F_{dc} = 1.5 x_A^{0.14} \tag{5}$$

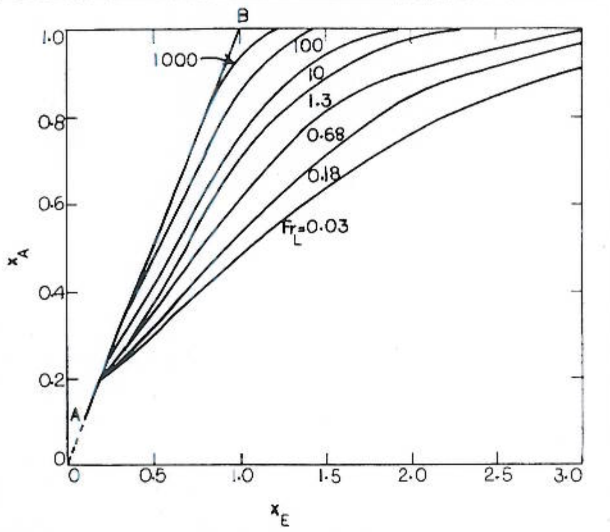

Figure 1 The new correlation for x_A. Locate x_{cr} on line AB and join tangentially to Fr_L curve.

Equation (5) applies provided $p_r > 0.8$ and $x_A \geqslant x_{cr} + 0.30$. Otherwise, $F_{dc} = 1$.

There were not sufficient high-pressure data for fluids other than water to determine F_{dc}. For fluids other than water, $F_{dc} = 1$ is assumed until a better estimate can be developed.

5. The vapor heat transfer coefficient h_g is calculated by using a single-phase correlation appropriate to the fluid and prevalent conditions, with the void fraction calculated on the assumption of equal liquid and vapor velocities.

CALCULATION OF ACTUAL QUALITY

The steps for calculating x_A by using Fig. 1 are as follows:

1. Calculate Fr_L and x_{cr}. The latter is calculated with appropriate correlations. If $x_{cr} < 0.1$, assume $x_{cr} = 0.1$.
2. Locate x_{cr} on the equilibrium line AB.
3. If this point is below the intersection of the Fr_L curve with line AB, x_A is directly read along the Fr_L curve.
4. If this point is above the intersection of the Fr_L curve and line AB, draw a tangent to the Fr_L curve from the x_{cr} point on line AB. x_A is then read along the tangent, and from the point of contact with the Fr_L curve onward along this curve.

To illustrate these simple steps, the following two cases are shown in Fig. 2.

1. $Fr_L = 1.3, x_{cr} = 0.10$
2. $Fr_L = 10, x_{cr} = 0.60$

To interpolate for Fr_L values, it is suggested that the data of Table 1 be plotted with Fr_L on a logarithmic scale. Use of log-log paper results in straight lines but it makes accurate reading of x_A values difficult. Hence use of semilog paper would generally be preferable. Figure 3 shows the correlation on semilog paper.

CALCULATION OF h_g

The majority of single-phase heat transfer equations are of the following form:

$$Nu = a\, Re^b\, Pr^c \tag{6}$$

Table 1 The Values of x_A for Various Values of x_E and Fr_L According to the Correlation Shown in Fig. 1[a]

	x_E															
Fr_L	0.2	0.4	0.6	0.8	1.0	1.2	1.4	1.6	1.8	2.0	2.2	2.4	2.6	2.8	3.0	3.2
0.03	0.2	0.260	0.340	0.410	0.480	0.540	0.595	0.655	0.710	0.760	0.800	0.830	0.857	0.890	0.910	0.936
0.10		0.270	0.350	0.430	0.515	0.580	0.650	0.715	0.765	0.820	0.853	0.880	0.905	0.925	0.950	0.975
0.18		0.275	0.365	0.450	0.540	0.610	0.680	0.750	0.800	0.850	0.880	0.900	0.925	0.945	0.970	0.995
0.60		0.300	0.410	0.510	0.610	0.710	0.780	0.840	0.875	0.900	0.930	0.940	0.960	0.980	0.995	1.000
1.30		0.320	0.457	0.580	0.710	0.800	0.860	0.910	0.950	0.980	1.000	1.000	1.000	1.000	1·000	
4.00		0.340	0.465	0.605	0.740	0.825	0.893	0.940	0.970	1.000						
10.00		0.350	0.485	0.630	0.760	0.855	0.920	0.962	0.990							
20.00		0.360	0.500	0.650	0.795	0.880	0.940	0.980	1.000							
40.00		0.370	0.525	0.680	0.820	0.910	0.980	1.000								
100.00		0.390	0.560	0.720	0.860	0.942	1.000									
300.00		0.400	0.600	0.760	0.905	0.985										
1000.00				0.800	0.940	1.000										

[a] The last entry in a column also applies to the blank spaces below it.

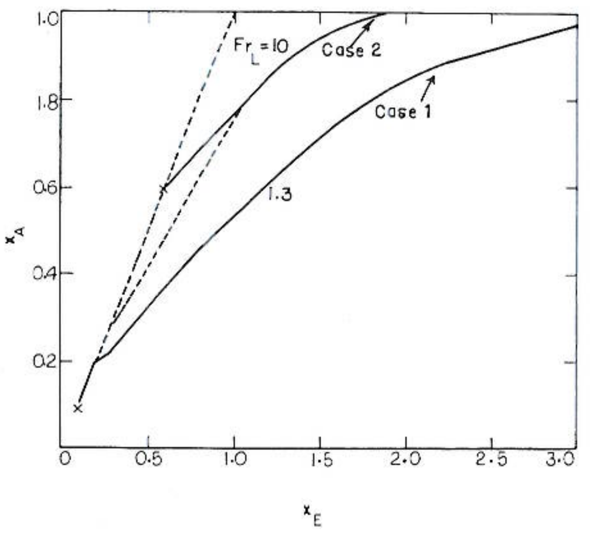

Figure 2 Prediction of x_A for two cases. Predicted x_A is read along solid lines.

Such equations apply outside the entrance region whose boundary is generally taken as $L/D < 30$. As pointed out by Rohsenow and Hartnett [13], no single set of values for a, b, and c applies over the entire range of parameters. However, the following equation, generally known as the Dittus-Boelter equation, has been found to fit the data for many fluids over a wide range:

$$\mathrm{Nu} = 0.023\ \mathrm{Re}^{0.8}\ \mathrm{Pr}^{0.4} \tag{7}$$

For actual vapor quality x_A and void fraction α, Eq. (7) yields the following expression for h_g:

$$h_g \frac{D}{k} = 0.023 \left(\frac{GDx_A}{\mu\alpha}\right)^{0.8} \mathrm{Pr}^{0.4} \tag{8}$$

Dittus and Boelter developed this equation from data for moderate wall-to-fluid temperature differences and recommended that properties be evaluated at the bulk fluid temperature. Others have suggested the use of properties at the film temperature (mean of wall and fluid temperature) in the same or similar equations.

In the early developmental phase of this correlation, calculations were done with Eq. (8) by using both bulk and film temperatures. For water at especially high pressures the use of film properties gave less scatter. For other fluids, properties at the bulk temperature gave better correlation. In the final data analysis, data for nitrogen, R-113, propane, and methane were analyzed by using Eq. (8) with fluid properties evaluated at the bulk temperature.

Groeneveld and Delorme [8], when developing their correlation for film boiling of water, tried nine single-phase heat transfer correlations. They found minimum deviation with the Hallader equation, which may be written as [13a]

$$h_g \frac{D}{k_f} = 0.00834 \left(\frac{GDx_A}{\mu_f\alpha}\right)^{0.8774} \mathrm{Pr}_f^{0.6112} \tag{9}$$

Equation (9) was found to give less scatter than Eq. (8) with film properties, and hence Eq. (9) was used here for the final data analysis. However, the deviations with Eq. (8) were only a little larger.

For hydrogen vapor, no generally accepted correlation is available. Barrow and Morris [14] listed more than a dozen equations. Their predictions differ from one another by up to several hundred percent. Most of the data of Hendricks et al. [15]

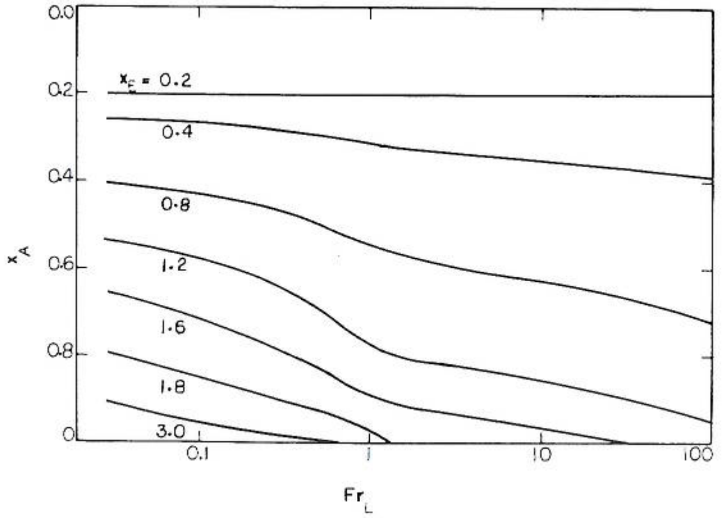

Figure 3 The correlation of Fig. 1 and Table 1 plotted on semilog paper to illustrate the method for interpolating for Fr_L.

for $L/D > 30$ were correlated to within -20 and $+40\%$ using x_A from Fig. 1 and Eq. (8) with bulk temperature properties. However, for virtually all the data of [16], the heat transfer coefficients so predicted were much larger than the measurements. The only noticeable difference between the data of [15] and [16] is that those of the former are for pressures less than 4.6 bar whereas those of the latter are for pressures greater than 5.1 bar. The possibility that the correlation of Fig. 1 was inapplicable to hydrogen was considered. However, this hypothesis could not explain the discrepancy; for many of the data points of [16], no reasonable assumption regarding the value of x_A would reconcile the measured and predicted heat transfer coefficients.

Investigation of the reason for the wide discrepancy between the many correlations for hydrogen vapor single-phase heat transfer and the development of a unified predictive technique would be a major research project in itself. Such an effort could not be carried out within the scope of this study. Hence equations that satisfy the hydrogen film boiling data of [15] and [16] were developed.

The majority of the equations for hydrogen vapor heat transfer are of the following form:

$$\mathrm{Nu} = aF_{\mathrm{ent}}\,\mathrm{Re}^b\,\mathrm{Pr}^c\left(\frac{T_g}{T_w}\right)^d \tag{10}$$

where F_{ent} is the entrance correction factor. The most common values of b, c, and d are, respectively, 0.8, 0.4, and 0.55. By using these values, the following equations were developed:

For $p < 4.6$ bar,

$$h_g\frac{D}{k_f} = 0.046F_{\mathrm{ent}}\left(\frac{GDx_A}{\mu_f\alpha}\right)^{0.8}\mathrm{Pr}_f^{0.4}\left(\frac{T_g}{T_w}\right)^{0.55} \tag{11}$$

For $p > 5.1$ bar,

$$h_g\frac{D}{k_f} = 0.0276F_{\mathrm{ent}}\left(\frac{GDx_A}{\mu_f\alpha}\right)^{0.8}\mathrm{Pr}_f^{0.4}\left(\frac{T_g}{T_w}\right)^{0.55} \tag{12}$$

It is interesting to note that the equations used by Chi [17-19] for correlating his postcritical heat flux hydrogen data had values of a as 0.0205, 0.023, and 0.031, but were otherwise exactly the same as Eq. (11) and (12) for long tubes.

The entrance correction factor F_{ent} is expressed by the following equations:

For $L/D \leqslant 30$,

$$F_{\mathrm{ent}} = 8.53\left(\frac{L}{D}\right)^{-0.63} \tag{13}$$

For $L/D \geqslant 30$,

$$F_{\mathrm{ent}} = 1 \tag{14}$$

To summarize, h_g has been calculated as follows:

For water, the Hallader equation [13a], Eq. (9), with film temperature properties
For hydrogen, Eqs. (11)-(14)
For other fluids, the Dittus-Boelter equation, Eq. (8), with bulk fluid properties

ESTIMATION OF VOID FRACTION

With very small droplets suspended in high-velocity vapor, physical considerations suggest that there will be very little velocity slip between vapor and liquid. Through their mechanistic analysis, Koizumi et al. [6] found that the slip velocity in their R-113 data was 1 m/s or lower. Experimental studies of Cumo et al. [20] also indicated slip ratios close to 1. Hence it was decided to calculate the void fraction assuming zero velocity slip between the two phases, from which it follows that

$$\alpha = \frac{x_A\rho_l}{(1-x_A)\rho_g + \rho_l x_A} \tag{15}$$

REPRESENTATION OF CORRELATING ERRORS

In the literature deviation between data and correlation has been represented in many ways. Groeneveld and Delorme [8] calculated the deviations of their correlation for water by the following equation:

$$\text{Deviation} = \frac{\text{measured } T_w - \text{predicted } T_w}{\text{measured } T_w} \tag{16}$$

where T_w is in degrees Fahrenheit.

In some calculations such as reactor safety analysis, the only objective is to determine that the wall temperature does not exceed the safe limit. For such applications, Eq. (16) is adequate for representing the correlation error. However, for sizing of heat exchangers that operate with film boiling, the quantity of interest is the fluid-to-wall temperature difference or the heat transfer coefficient. A small error in wall temperature may mean a large error in heat transfer coefficient and in the heat transfer area required. To provide the most stringent test for the correlation, deviation is defined as

$$\text{Deviation} = \frac{\text{predicted } h_{TP} - \text{measured } h_{TP}}{\text{measured } h_{TP}} \tag{17}$$

h_{TP} is based on the actual gas temperature, i.e.,

$$h_{TP} = \frac{q_w}{T_w - T_g} \tag{18}$$

Wall temperature deviations were also calculated according to Eq. (16). To facilitate comparison with the results of Groeneveld and Delorme [8], T_w for water data was taken in Fahrenheit degrees. For other data, absolute temperatures were used.

COMPARISON OF CORRELATION WITH DATA

Efforts were made to obtain a wide range of data for as many fluids as possible. Data for six fluids, i.e., water, propane, methane, nitrogen, R-113, and para-hydrogen, were analyzed. The range of significant parameters covered for each data set and its rms deviations from the correlation are listed in Tables 2 and 3. Table 4 lists the complete range of parameters covered by all data analyzed. Figures 4–6 show the comparison of

Table 2 Results of Comparison of the New Correlation with Data for Film Boiling of Water

Source	Diameter, mm	$q \times 10^{-6}$, W/m^2	G, kg/m^2 s	Fr$_L$	x_E	p_r	T_w, K	No. of data points	rms error, %	
									T_w, °F	h_{TP}
Swenson et al. [21]	10.4	0.289 0.595	948 1355	41 83	0.10 1.00	0.93	650 772	58	2.8	8.8
Schmidt [25]	8.0	0.470	700	34	0.35 2.4	0.97	693 778	11	3.3	21.6
Herkenrath et al. [26]	5.0	0.720	1530	84	0.37 0.88	0.84	681 773	5	1.8	9.4
Bailey et al.[a] [12]	12.8	0.242 0.643	2000	109	0.40 0.60	0.81	639 711	10	1.3	12.9
Era[a] [27]	6.0	0.540 0.900	1100 2200	37 149	0.50 1.23	0.32	691 769	15	5.1	20.2
Bennet et al. [3]	12.6	0.441 1.833	379 5176	2 391	0.26 1.49	0.31	712 1112	80	4.9	12.2
Brevi and Cumo[a] [28]	5.9	0.079 0.428	2200	159	0.55 0.85	0.32	583 799	39	4.1	15.4
Bishop et al. [22]	2.54 5.08	0.891 1.921	1355 3387	207 1661	0.12 0.96	0.75 0.97	658 770	77	2.9	17.5
Ling et al. [29]	14.9	0.450 0.560	500	2 4	0.60 1.30	0.13 0.54	777 960	50	4.9	10.8
Janssen and Kervinen [30]	12.5	0.840	1016	15	0.71 0.88	0.32	797 858	9	2.1	4.7
Nijhawan et al.[a,b] [34]	14.1	0.22 0.29	30 43	0.007 0.015	0.23 0.38	0.01	668 885	13	15.0	17.4
Keeys et al.[c] [24]	12.7	0.040 0.140	680 272	7 108	0.25 0.70	0.31			d	d
All data	2.54 14.9	0.022 1.921	30 5176	0.007 1661	0.10 2.40	0.01 0.97	583 1112	367	4.1	14.6

[a] $\mathrm{Bo} < 4.5 \times 10^{-4}$ for all data points in this set.

[b] Only steady-state data considered.

[c] Nonuniform heat flux. All other data for uniform heat flux.

[d] Satisfactory agreement of x_A. See text.

Table 3 Results of Comparison of the New Correlation with Film Boiling Heat Transfer Data for Several Fluids Other Than Water

Source	Fluid	Diameter, mm	q, MW/m^2	G, kg/m^2 s	Fr$_L$	x_E	p_r	T_w, °R	No. of data points	rms error, %	
										T_w, °R	h_{TP}
Hendricks et al. [15]	para-H$_2$	7.95	0.374 1.518	718 1653	1,452 8,500	0.10 1.10	0.13 0.36	124 356	64	12.0	13.6
Hendricks et al. [16]	para-H$_2$	8.51	1.729 2.088	944 1549	3,219 15,165	0.10 1.64	0.37 0.93	125 554	35	15.2	16.7
		11.12	0.815 1.241	531 900	938 2,661	0.10 0.81	0.66 0.68	241 411	17	8.6	9.6
		12.87	0.718 1.190	326 644	276 1,069	0.10 1.35	0.56 0.75	280 515	40	10.1	11.2
		4.77	0.652 1.124	1964 3442	29,600 91,000	0.10 0.61	0.48 0.83	81 169	19	16.5	18.6
Koizumi et al.[a] [6]	R-113	10.0	0.021 0.084	542 1154	1.5 6.7	0.55 1.00	0.08	375 473	24	2.7	18.3
Forslund and Rohsenow [4]	N$_2$	8.2	0.015 0.079	95 257	0.18 1.32	0.10 2.90	0.05	222 611	80	9.8	12.4
Laverty and Rohsenow [31]	N$_2$	8.1	0.012 0.053	95 293	0.18 1.75	0.10 1.77	0.05	215 543	30	17.2	19.1
Hynek et al. [5]	N$_2$	10.2	0.022	45	0.033	0.3 2.3	0.05	319 569	18	18.5	25.4
	Methane	8.9	0.214	209	3.8	0.50 0.75	0.22	519 574	5	6.9	10.6
	Propane	8.9	0.397 0.561	251 652	3.0 20.5	0.19 1.75	0.24	722 933	23	10.8	14.3
All data		4.8 12.9	0.012 2.088	45 3442	0.033 91,000	0.10 2.90	0.05 0.93	81 933	355	12.3	15.3

[a] $\mathrm{Bo} < 4.5 \times 10^{-4}$ for some data points. $\mathrm{Bo} > 4.5 \times 10^{-4}$ for all other data sets.

measured and predicted wall temperature for some tests. Data of Swenson et al. [21], Bennet et al. [3], Bishop et al. [22], and Hendricks et al. [15, 16] were taken from tabulations. The rest of the data have been read from graphic representations. Where the references provided a large number of data, smaller samples representative of the range were taken at random. This was necessary to keep the calculation effort within reasonable limits as all calculations were done manually.

Table 4 Complete Range of Data Correlated

Fluid	Water, nitrogen, para-hydrogen, R-113, methane, propane
Tube ID, mm	2.5–14.9
p, bar	1.4–215
p_r	0.01–0.97
q, MW/m^2	0.012–2.1
G, kg/m^2 s	30–3442
x_E	0.10–2.9
Fr$_L$	0.033–91,000
T_w, K	81–1112

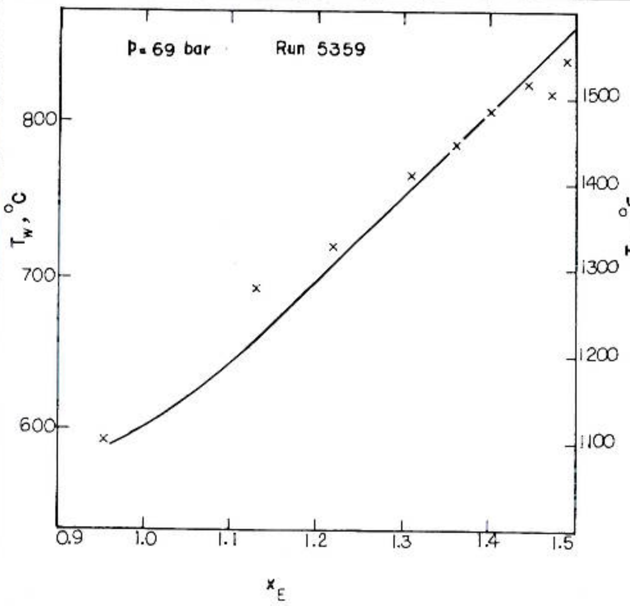

Figure 4 Data of Bennet et al. [3] for water compared with the present correlation. $G = 393$ kg/m^2 s, $q = 0.544$ MW/m^2.

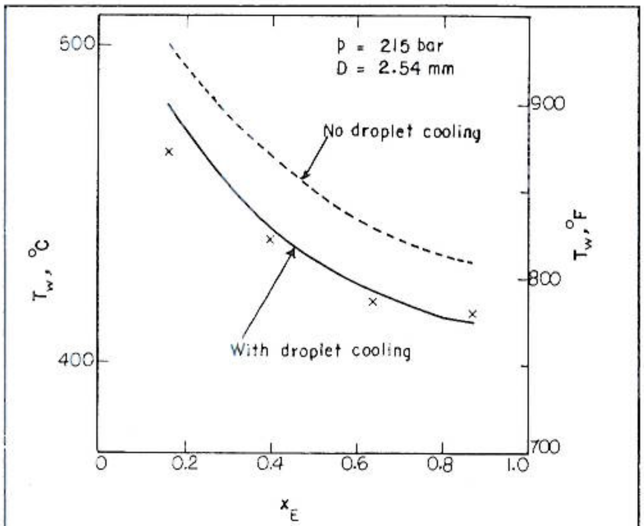

Figure 5 Comparison of the data of Bishop et al. [22] with the new correlation, with and without the droplet cooling effect. $G = 2022$ kg/m^2 s, $q = 1.47$ MW/m^2.

About three-fourths of the data points for hydrogen listed in Table 3 are for $L/D < 30$. Their deletion was considered in order to avoid complications resulting from entrance effects, but the loss of such a substantial part of the data did not seem desirable. Hence Eq. (13) was developed for the entrance correction factor F_{ent}. The data for other fluids contained very few points for $L/D < 30$. These generally agreed with Eq. (13), but F_{ent} was assumed equal to 1 for them.

Calculation of x_A from Fig. 1 requires the knowledge of x_{cr}. In most cases, this could be determined from the data themselves. Where it was not possible, x_{cr} was calculated by the Shah correlation [23].

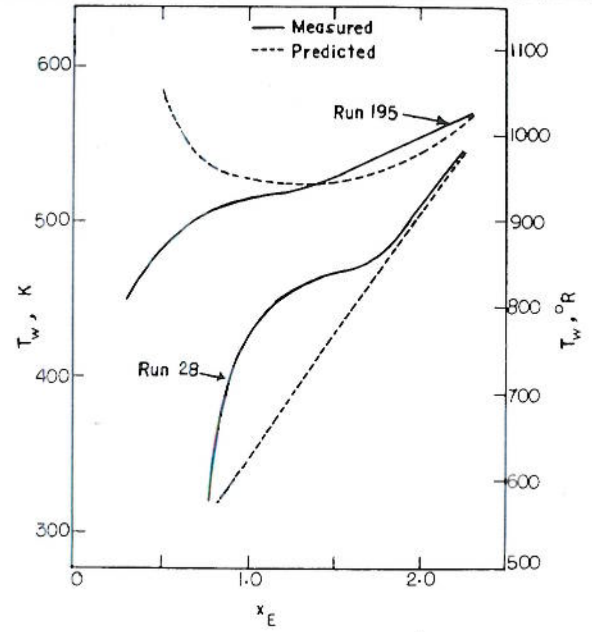

Figure 6 Comparison of the present correlation with the data of Hynek et al. [5] for nitrogen. The pressure, heat flux, and mass flux were almost identical for the two runs.

All the data listed in Tables 2 and 3 are for uniform heat flux except those of Keeys et al. [24] in which the heat flux decreased along the tube length according to a truncated cosine curve. The graphic representation of these data in the paper does not permit accurate comparison of wall temperatures. However, Keeys et al. showed the calculated x_A for three of their runs together with x_E. They used their calculated x_A in a single-phase correlation similar to Eq. (9) to predict wall temperatures with good results. The maximum difference between x_A calculated by Keeys et al. and those given by the present correlation was found to be 0.017. This indicates that agreement of wall temperatures would also be good. These data are therefore considered to have been satisfactorily correlated.

Table 2 lists 367 data points for water. The rms error of wall temperatures (in Fahrenheit degrees) for these data points is 4.1%. If wall temperatures were in absolute degrees, the rms error would be about 2%. The rms error of heat transfer coefficients is 14.6%. The predicted heat transfer coefficients are within ± 30% of the measurements for 97% of the data points. The data are from 11 independent sources and cover absolute pressures from 2.3 to 215 bar, tube diameters from 2.5 to 14.9 mm, heat flux from 0.02 to 1.921 MW/m^2, mass flux from 30 to 5176 kg/m^2 s, equilibrium qualities up to 2.4, and wall temperatures from 583 to 1112 K. Thus a very wide range and variety of data for water have been satisfactorily correlated.

Table 3 lists 355 data points for para-hydrogen, nitrogen, methane, propane, and R-113. The rms error of absolute wall temperatures is 12.3%. The rms error of heat transfer coefficients is 15.3%, with 95% of the data points within ± 30%. The range of data in Table 3 is also very wide, with reduced pressures ranging from 0.05 to 0.93, and equilibrium qualities from 0.1 to 2.9.

The complete range of data analyzed for all fluids is given in Table 4. The rms error in heat transfer coefficients for all the data analyzed is 15%.

DISCUSSION OF CORRELATION AND DATA ANALYSIS RESULTS

Tables 2, 3, and 4 show that this correlation satisfies a very wide range of data. Although these results can be viewed with considerable satisfaction, certain aspects of the correlation and data analysis require further discussion.

Low Boiling Numbers

According to this correlation, $x_E = x_A$ when $\mathrm{Bo} \leqslant 4.5 \times 10^{-4}$. All data in [12, 27, 34] are for $\mathrm{Bo} < 4.5 \times 10^{-4}$, and [3, 6, 21, 28] also contain some data for $\mathrm{Bo} < 4.5 \times 10^{-4}$. Bo may be interpreted as the nondimensional ratio of heat and mass flux. Thus it appears that if heat flux is low compared with mass flux, heat removed by vapor from the wall can be transferred to liquid droplets without significant vapor superheat.

Droplet Cooling

High-pressure data were available for only hydrogen and water. Because of the lack of any reliable single-phase heat transfer correlation for hydrogen, conclusions could be drawn only from water data. These showed that for pressures close to critical, wall temperatures calculated with this correlation assuming no droplet cooling were higher than the measured temperatures, as shown in Fig. 5. Although the error in wall temperatures was small, the resulting error in heat transfer coefficient was as much as 50%. This discrepancy was considered to be caused by cooling by liquid droplets. As the only reliable data available were for water, a general correlation for droplet cooling was not attempted. The water data were adequately correlated by Eq. (5). However, further study and refinement of this correlation is needed. Droplet cooling will probably increase gradually with reduced pressure rather than the sharp transition at $p_r \geqslant 0.8$ assumed here. Hydrogen data at high pressures also showed some indication of droplet cooling but the effect was not as pronounced. Hence F_{dc} was assumed equal to 1 for hydrogen, and the same is suggested for fluids other than water until a general solution is developed. This would require varied data for several fluids.

Application to Nonuniform Heat Fluxes

Although the rest of the data correlated are for uniformly heated tubes, those of Keeys et al. [24] are for nonuniform heat flux. The fact that these are well-correlated is very encouraging. However, analysis of more varied data is needed to fully establish its applicability to nonuniform heat flux conditions.

Choice of Single-Phase Heat Transfer Correlation

The accuracy of prediction depends on the choice of appropriate single-phase correlation. No single equation is known that is applicable to all fluids under all conditions. Hence for any particular application, an attempt should be made to select the most appropriate equation by means of a literature survey. If no guidance is obtainble from the literature, the best choice would be Eq. (7). The data analyzed here suggest that for $p_r < 0.3$, fluid properties at the bulk temperature are more appropriate. For $p_r > 0.3$, film temperature properties give a better correlation. Some guidance on this topic is obtainable from [13].

Equations (11) and (12), which were derived here for hydrogen, should be considered applicable only in the range of parameters actually covered in the tests of Hendricks et al. [15, 16]. The reason for the wide difference between the data of [15] and those of [16] is not clear. A difference in tube diameters, flow rates, heat fluxes, and T_g/T_w cannot explain this discrepancy. The only clear difference between the two data sources is in pressure. However, the maximum pressure for [15] is 4.6 bar whereas the minimum pressure for [16] is 5.1 bar. Such a sharp change in heat transfer over such a small pressure change is surprising. For these reasons, use of Eqs. (11) and (12) outside the range of data analyzed here is discouraged.

Estimation of Critical Quality

The critical quality must be known to estimate x_A with Fig. 1. If x_{cr} is less than 0.2, its actual value need not be known. Similarly, the actual value of x_{cr} need not be known as long as it is less than the quality at the intersection of the pertinent Fr_L curve and the equilibrium line *AB*. Many correlations for predicting critical quality are available, including one in [23]. The possibility of dryout caused by purely hydrodynamic reasons should also be considered. Very few correlations for such dryout are available. One example is that by Doroshchuk et al. [32].

COMPARISON WITH OTHER PREDICTIVE TECHNIQUES

Most of the early predictive techniques were modifications of single-phase heat transfer correlations. These completely ignored nonequilibrium effects. Many of these have been listed and reviewed by Groeneveld and Gardiner [33]. Such correlations are applicable only to the actual range of data from which they were derived. Discussed here are predictive techniques that account for nonequilibrium effects and are applicable to a reasonably wide range of parameters.

The mechanistic analysis techniques developed by M.I.T. and U.K. AEA have been valuable in providing understanding of the phenomena involved. However, in addition to their involving laborious calculations, the lack of reliable basic relations necessitates the incorporation of empirical correlation and factors that are valid for only a narrow range of parameters. For example, Hynek et al. [5] used an empirical factor K_1K_2 to account for the various unknowns in liquid droplet-heated wall interaction. The value of this parameter was found to vary by an order of magnitude for the data analyzed. For this reason the technique of Hynek et al. cannot be used with confidence for general predictive purposes. Similar difficulties are faced with most of such techniques.

Groeneveld and Delorme [8] presented a predictive technique assuming no liquid droplet cooling, and zero slip. The main feature of this technique is a correlation for determining nonequilibrium, which is in the form of equations that can be conveniently solved on computer. This correlation was developed from and verified with water data only. The rms error of wall temperatures (in degrees Fahrenheit) was 6.9%. The comparable rms error of the present correlation is significantly better at 4.1%. Most of the data points in the present analysis were also analyzed by Groeneveld and Delorme. Although the present correlation is intended only for $x_E \geqslant 0.1$, Groeneveld and Delorme considered their correlation applicable also to negative qualities and they correlated some such data. On the other hand, they did not analyze any nonuniform heat flux data, whereas the present correlation shows good agreement with the nonuniform heat flux data of Keeys et al. [24]. Applicability to nonuniform heat flux is of much practical interest. Finally, the present correlation has been verified for five fluids in addition to water, whereas the Groeneveld-Delorme correlation has been tested for water only.

The correlation of Saha et al. [9, 10] is fairly easy to use but was tested only with water data in the pressure range 29–70 bar. The correlation of Chen et al. [7] was also verified only with water data but these go up to a pressure of 195 bar. However, the minimum equilibrium quality considered was 0.5. Both of these correlations assumed no significant liquid droplet cooling of the wall.

Calculations with the Jones-Zuber correlation [11] are more complicated but its tested range is wider. They showed good agreement with the nitrogen data of [4] as well as with water data from several sources that go up to a pressure of 207 bar. An important point made by Jones and Zuber is that the magnitude of nonequilibrium depends on the critical quality. Hynek et al. [5] clearly demonstrated this through experiments in which for two test runs with almost identical heat and mass flux but different burnout quality, a vastly different relation between x_A and x_E was found. Figure 6 shows the data from these tests. The mass flux for runs 28 and 195 were respectively 44.7 and 42.0 kg/m^2 s, and the heat fluxes were 22,995 and 22,522 W/m^2. Pressure for both tests was about 1.4 bar. It is seen that the wall temperatures for both cases are reasonably well-predicted. Correlations of Chen et al. [7] and Groeneveld and Delorme [8] do not consider x_{cr} in predicting x_A. Hence these would fail for at least one of these two runs.

It is seen that the present correlation compares favorably with other predictive techniques in accuracy and has been verified with more varied data. The only disadvantage may be that the relation for x_A is in graphic form. Although this makes it more convenient for hand calculations, computer calculations are preferred for many applications. One way to use it for computer calculations would be to manually estimate x_A from Fig. 1 and feed the values to computer for further calculations. It also seems possible to express the correlation in terms of a few equations.

CONCLUSIONS

A simple general correlation for film boiling heat transfer in tubes at vapor qualities in excess of 0.1 has been presented. It has been verified with data for water, nitrogen, para-hydrogen, propane, methane, and R-113 over a very wide range of parameters including uniform and nonuniform heat flux. Although the correlation is empirical, it is consistent with generally accepted physical models. It compares favorably with other predictive techniques in accuracy, ease of calculation, and verified range of fluids and parameters. Hence it should be given serious consideration for practical calculations.

The correlation for nonequilibrium quality, Fig. 1, has been verified and therefore appears to be generally valid. Further research is needed to refine and generalize the droplet cooling part of the correlation. A thorough investigation of single-phase and film boiling heat transfer of hydrogen is needed. Analysis of additional data for other fluids over a wide range of pressures is needed for further verification and to determine the ranges for which film and bulk temperature fluid properties are appropriate.

NOMENCLATURE

a	multiplier in Eq. (10)
Bo	boiling number ($= q_w/Gi_{fg}$)
C_{pg}	specific heat of vapor at constant pressure
D	inside diameter of tube
Fr_L	Froude number ($= G^2/\rho_l^2 gD$)
F_{dc}	factor for enhancement resulting from liquid droplet-wall interaction, defined by Eq. (1)
F_{ent}	factor for enhancement resulting from entrance effects
g	acceleration caused by gravity
G	total mass flux, mass per unit area per unit time
h_g	heat transfer coefficient between vapor and tube wall
h_{TP}	two-phase heat transfer coefficient, defined by Eq. (18)
i_g	enthalpy of vapor at actual temperature
$i_{g\,\mathrm{sat}}$	enthalpy of saturated vapor
i_{fg}	latent heat of vaporization
k	thermal conductivity of vapor
L	distance from entrance
Nu	Nusselt number
p	absolute pressure
p_r	$= p/p_c$ where p_c is critical pressure
Pr	Prandtl number of vapor
q_w	total heat flux at inside surface of tube
q_c	heat flux removed from wall through convection by vapor
q_{dc}	heat flux removed from wall through liquid droplet cooling
Re	Reynolds number of vapor
T_w	temperature of wall
T_g	actual vapor temperature
T_{sat}	temperature of saturated vapor
x_E	vapor quality calculated by assuming thermodynamic equilibrium
x_A	actual vapor quality
x_{cr}	critical quality, i.e., quality at dryout
α	vapor void fraction
μ	dynamic viscosity of vapor
ρ_l	density of liquid
ρ_g	density of vapor

Subscript

f	evaluated at film temperature [$= (T_w + T_g)/2$]

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