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A GENERALIZED GRAPHICAL METHOD FOR PREDICTING CHF IN UNIFORMLY HEATED VERTICAL TUBES

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Abstract—A general correlation is presented for calculating CHF in vertical tubes during subcooled and saturated boiling. The correlation has been compared to 1271 data points from more than 30 sources and found to have a mean deviation of 15%, with 90% of data within ±30%. Data include water, potassium, freons, benzene, ammonia, parahydrogen, and nitrogen. Reduced pressure range is 0.0012 to 0.94, mass flux from 6 to 24 300 kg/m² s, critical quality from −2.6 to +0.96, and inlet quality from −3.0 to positive values.*

NOMENCLATURE

A_c, cross-sectional area of tube $= \pi D^2/4$;
Bo, boiling number, defined by equation (1);
C_p, specific heat of liquid;
CHF, critical heat flux;
D, ID of tube;
Fr, liquid Froude number $= G^2/(\rho_L^2 g D)$;
g, acceleration due to gravity;
G, total mass flux or velocity $= W/A_c$;
H_{cr}, enthalpy of liquid or liquid–vapor mixture at the location where CHF occurred;
H_{in}, enthalpy of liquid–vapor mixture at inlet;
H_{SAT}, enthalpy of saturated liquid;
k, thermal conductivity of liquid;
L_{cr}, distance between the section where CHF occurs and the entrance section;
Pe, Peclet number $= GDC_p/k$;
p_r, reduced pressure;
p, absolute pressure;
q_{cr}, critical heat flux;
Re, Reynolds number $= GD/\mu_L$;
W, total mass (vapor + liquid) flow per unit time;
x_{cr}, critical vapor quality $= (H_{cr} - H_{SAT})/\lambda$;
x_{in}, inlet vapor quality $= (H_{in} - H_{SAT})/\lambda$;
Y, correlating parameter for CHF, defined by equation (3).

Greek symbols

λ, latent heat of vaporization;
μ, dynamic viscosity;
γ, $\dfrac{\partial(\rho_L/\rho_G)}{\partial p}$;
ψ_{CHF}, Ahmad's correlating parameter, defined by equation (2).

Subscripts

L, for liquid;
G, for vapor;
x, at $x_{cr} = x$;
0, at $x_{cr} = 0$.

INTRODUCTION

PERHAPS no topic in heat transfer has been subject to more research in recent years than critical heat flux (CHF) in flow boiling. Among the reasons for this intensive research has been the development of nuclear reactors and power plants for space vehicles. Many geometries such as plain tubes, annuli, tubes with inserts, rod bundles etc. are of practical interest. This paper is concerned only with upflow in plain vertical tubes with approximately uniform heat flux. Furthermore, only single-component fluids and essentially pulsation-free flows are considered.

The most important objective of these researches has been to develop techniques for predicting the CHF. A very large number of predictive techniques has been proposed, many of which have been listed and discussed by Tong [1], Rohsenow [2], and most recently by Bergles [3]. Some of the proposed techniques are based on mechanistic analysis of physical models. While such basic approaches are very desirable, these have as yet not yielded generally applicable solutions. The majority of the available solutions are equations intended for only one fluid, mostly water, in a limited range of parameters. Notable examples of such equations are those proposed by Thompson and MacBeth [4] and Doroshuk *et al.* [5]. Very few attempts at developing correlations which apply to a wide variety of fluids have been made. Only two comparatively successful attempts are known to this author. These are the correlation of Bernath [7] and Gambill [6]. Both of these apply only to subcooled boiling CHF. No well-verified general correlation for the positive quality region could be found.

It will clearly be desirable to have a predictive technique which applies to a wide variety of fluids in both subcooled and positive quality regions and a

*Copies of Fig. 3(a–c) printed on graph paper are obtainable from the author.

wide range of pressures, tube diameters and flow rates. The new correlation developed satisfies a large amount of data for 11 diverse fluids in tubes of diameters ranging from 0.6 to 38 mm, absolute pressures from 0.02 to 19.6 MN/m^2, temperatures from -248 to 789 C, and mass velocities from 6 to 24 300 kg/m^2 s.

The objective of this paper is to present the correlation developed, explain its use, and explore its applicability and validity through comparison with experimental data. So that the correlation may be viewed in the proper perspective, some other predictive techniques have also been briefly discussed.

CORRELATING PARAMETERS

Experiments have shown that mass velocity, diameter, length, pressure, inlet subcooling, vapor quality, and properties of fluid are the major factors affecting CHF. Hence a very large number of dimensionless groups can be formed. For example, Barnett [8] has identified 14 dimensionless groups on which the CHF may possibly depend. It was felt that probably only a few of the many possible dimensionless groups have a significant effect. The choice of these groups was made on the basis of previous experience, examination of experimental data, and trial and error.

A group including the heat flux was first sought. Even a cursory examination of data shows that there is some relation between CHF and mass flux. This suggests the boiling number defined as,

$$Bo = q_{cr}/(G\lambda). \tag{1}$$

The author had earlier used the boiling number successfully for saturated boiling [9] and subcooled boiling [10] heat-transfer correlations. Furthermore, Ahmad [11] and Dix [12] have used this parameter in fluid to fluid modelling with good results.

The search was then confined to finding parameters on which Bo depends. Among the parameters tried were Re, $Re \cdot Fr^{0.4}$, and ψ_{CHF}, the parameter introduced by Ahmad [11] which is defined as,

$$\psi_{CHF} = \left(\frac{GD}{\mu_L}\right)\left(\frac{\gamma^{1/2}\mu_L}{D\rho_L^{1/2}}\right)^{2/3}\left(\frac{\mu_L}{\mu_G}\right)^{1/8}. \tag{2}$$

None of these were found to be satisfactory over the entire range of data. Eventually, a parameter Y was defined as,

$$Y = PeFr^{0.4}(\mu_L/\mu_G)^{0.6}. \tag{3}$$

The parameter Y was found to be the most satisfactory. Other parameters that were found to be significant are L_{cr}/D, x_{in}, x_{cr}, and p_r as described later.

The process through which Y was arrived at is now briefly described. Examination of data showed that Bo decreases with increasing velocity as well as increasing diameter. Thus a dimensionless group containing the product of G and D appeared suitable. Re is one such group which has been widely used in heat-transfer correlations. Plots of Bo against Re showed that the exponent of D should be about 0.6 and not 1. Fr has been used in several correlations, for example that by Ortanskii *et al.* [15]. The function $ReFr^{0.4}$ contains $D^{0.6}$. Plotting Bo vs $ReFr^{0.4}$ resulted in satisfactory correlation of almost all water data. However, most of the data for halocarbon refrigerants were much lower than the correlation through the water data. As the thermal conductivity of water is much higher than that of halocarbon refrigerants, this discrepancy appeared to be due to the effect of thermal conductivity. Re was then replaced by Pe. Plots of Bo vs $(PeFr^{0.4})$ showed much better correlation. However, the lines through data for various fluids still differed by about 30%. This deviation was found to be related to μ_L/μ_G. Through some more trial and error, the exponent of μ_L/μ_G was fixed at 0.6 and thus the parameter Y was finally arrived at. The choice of μ_L/μ_G was suggested by its use in several correlations, such as that of Ahmad [11].

It is interesting to compare the parameters Y and ψ_{CHF}. Equation (3) may be written as,

$$Y = G^{1.8}D^{0.6}\left(\frac{C_p}{k\rho_L^{0.8}g^{0.4}}\right)\left(\frac{\mu_L}{\mu_G}\right)^{0.6}. \tag{4}$$

Equation (2) may be written as,

$$\psi_{CHF}^{1.8} = G^{1.8}D^{0.6}\left(\frac{\gamma^{0.6}}{\rho_L^{0.6}\mu_G^{0.225}\mu_L^{0.375}}\right). \tag{5}$$

Thus the two parameters are identical in G and D and differ only in the property function.

DEVELOPMENT OF THE CORRELATION

The development of a correlation involves two major steps. Firstly, the significant dimensionless parameters have to be identified. Secondly, their relationship has to be determined. The selection of the two major parameters Y and Bo has been discussed in the foregoing. Some other steps in the development of the correlation and identification of other dimensionless parameters are now discussed.

The data of Doroshuk *et al.* [5] were primarily used in the early phase of development as these are tabulated in a very convenient form and cover a wide range of pressures, flow rates, and qualities. The boiling number at zero vapor quality was plotted against Y as shown in Fig. 1. It is seen that pressure appears to have no effect at lower values of Y but becomes significant at higher values of Y. Data from other sources for water and other fluids for $Y > 10^6$ generally agreed with the data of Doroshuk *et al.* [5] and Fig. 1 was suitably modified to give the best fit to data from all sources.

The ratio Bo_x/Bo_0 was plotted against Y, again using the data of Doroshuk *et al.* The final correlation arrived at after considering all data is shown in Fig. 3(c). For $p_r < 0.6$, Bo_x/Bo_0 was found to be a function of Y alone while at higher pressures, p_r also became a parameter.

As the local condition hypothesis is widely accepted, it was expected that for all values of Y, Bo

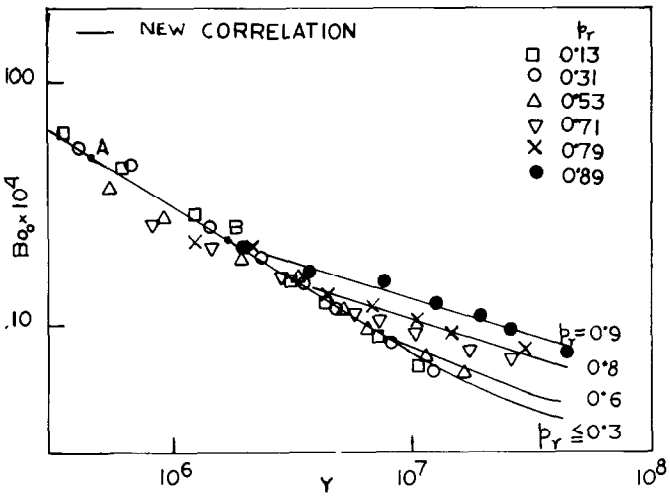

FIG. 1. Analysis of the data of Doroshuk *et al.* [5] for water in 8 mm tubes at zero vapor quality.

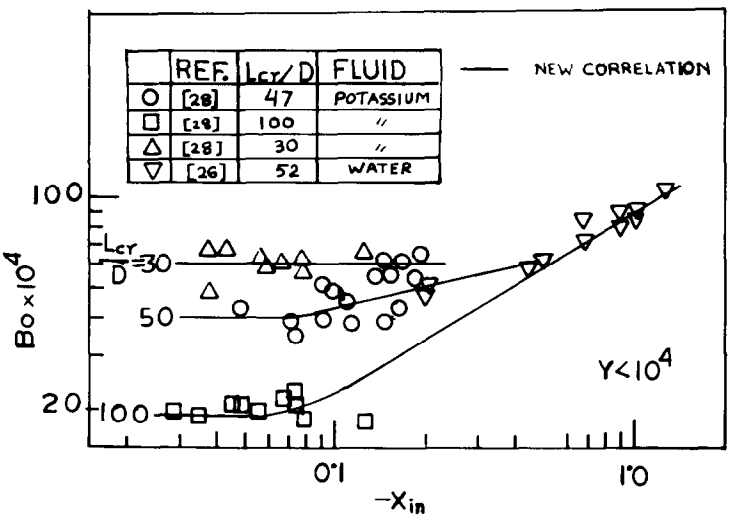

FIG. 2. Analysis of CHF data at low values of Y.

would be a function of only p_r, Y, and x_{cr} as long as L_{cr}/D is not too small. However, analysis of data at $Y < 3 \times 10^5$ showed that as Y becomes smaller, Bo tends to decrease with increasing L_{cr}/D. Furthermore, it was found that for $Y < 10^4$, Y has no perceptible influence and x_{cr} does not directly control the CHF. Instead, x_{in} and L_{cr}/D alone determine the boiling number. Some of the data for $Y < 10^4$ are shown in Fig. 2.

Data between $Y = 10^4$ and 10^6 often showed conflicting trends. Some of the data for benzene [16] and nitrogen [17] essentially follow the line AB in Fig. 1. Some of the data such as those of Staub [18] for R-22 indicate that longer L_{cr}/D decreases Bo as Y falls to around 10^6. On the other hand, some of the data of Stevens *et al.* [32] and Lee and Obertelli [25] are well above the line AB in Fig. 1. The correlating curves drawn are those that satisfy the majority of data.

THE FINAL CORRELATION

The proposed correlation is shown in Figs. 3(a)–(c). Figures 3(a) and (c) apply to $Y > 10^5$ while Fig. 3(b) applies to $Y < 10^5$. Figure 3(a) provides the value of Bo_0, the boiling number at zero vapor quality. Figure 3(c) provides the value of Bo_x/Bo_0 where Bo_x is the boiling number at a critical vapor quality x. Thus the value of the boiling number at a vapor quality x for $Y > 10^5$ is calculated by multiplying Bo_0 from Fig. 3(a) by the value of Bo_x/Bo_0 from Fig. 3(c). For $Y < 10^5$, Fig. 3(b) directly yields the value of Bo for the prescribed x_{in} and L_{cr}/D. Thus the knowledge of x_{cr} is not needed for calculating the boiling number when $Y < 10^5$.

It will be noted that in Fig. 3(a) and (c), p_r appears as a parameter. Most researchers have preferred to use ρ_G/ρ_L instead of p_r. The present author used ρ_G/ρ_L in correlations for saturated and subcooled boiling heat-transfer coefficients [9, 10] but found p_r more suitable for correlating film condensation heat-transfer coefficients [33]. For deciding which one to use here, the relation between p_r and density ratio for several fluids was studied. It was found that for data analyzed here, the prediction will virtually be the same whichever of the two parameters is used. The study of $p_r - \rho_G/\rho_L$ relation indicates that for p_r

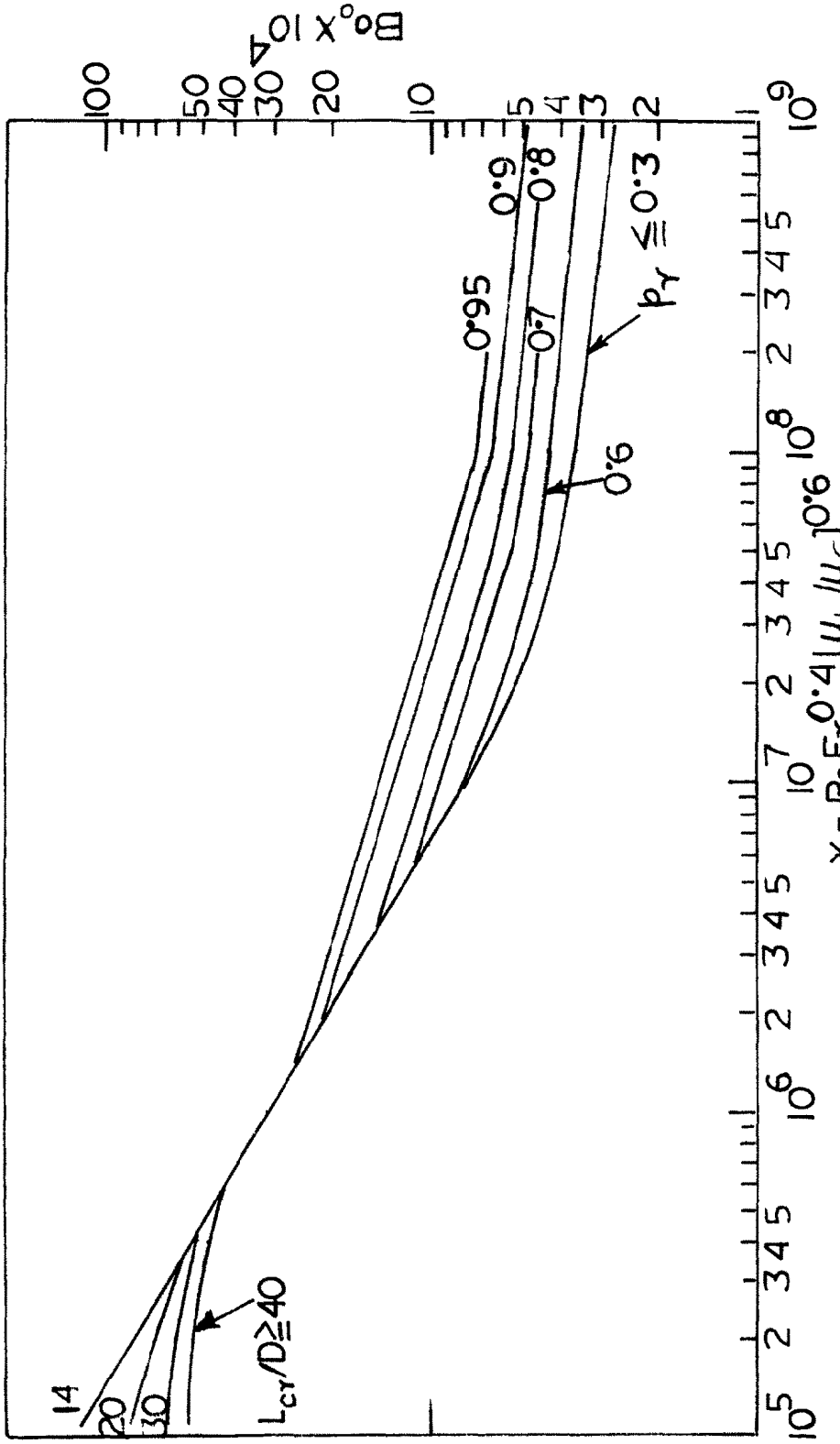

FIG. 3(a). Part 1 of the new correlation. Boiling number at $x_{cr} = 0$ for $Y > 10^5$.

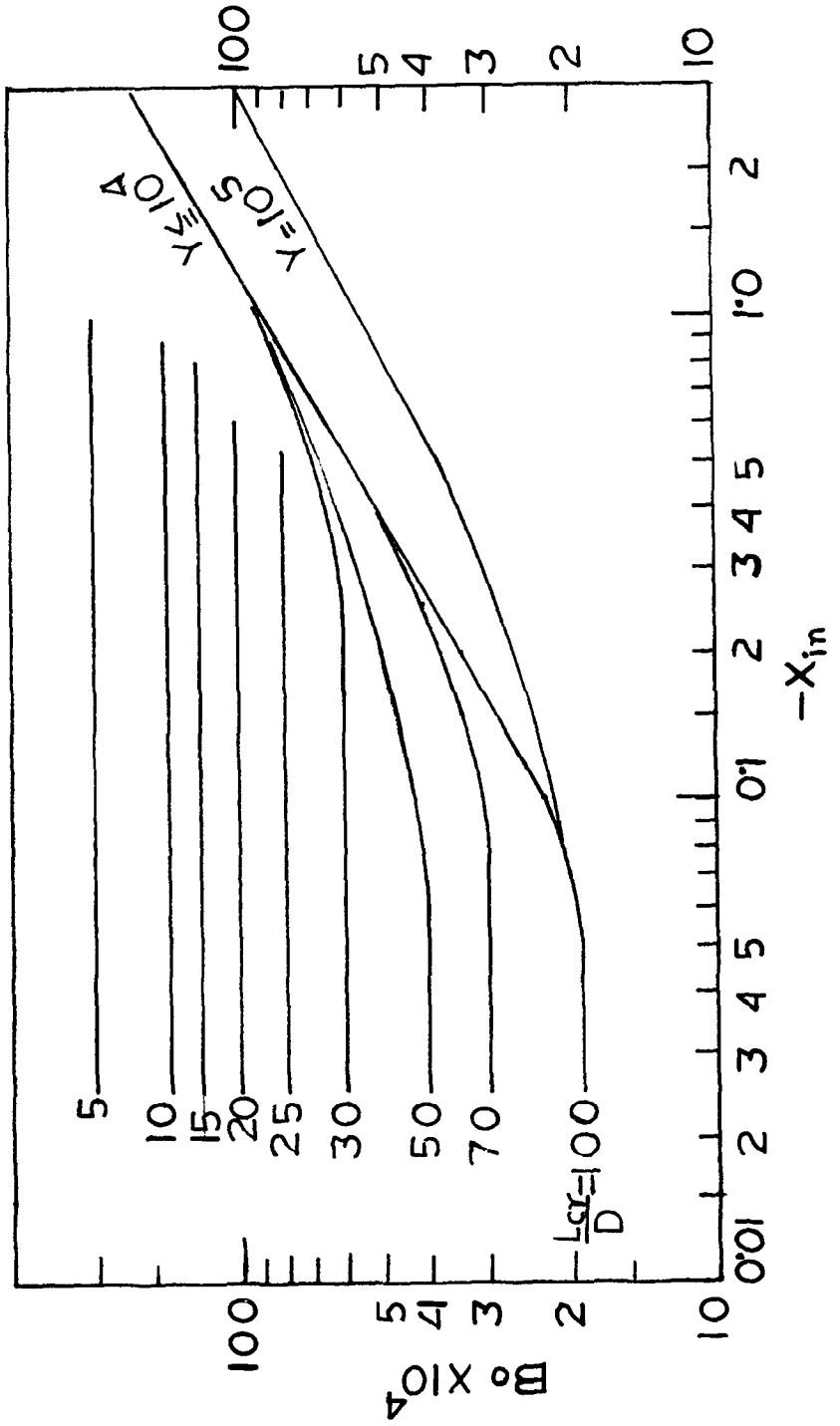

FIG. 3(b). Part 2 of the new correlation. Boiling number for $Y < 10^5$.

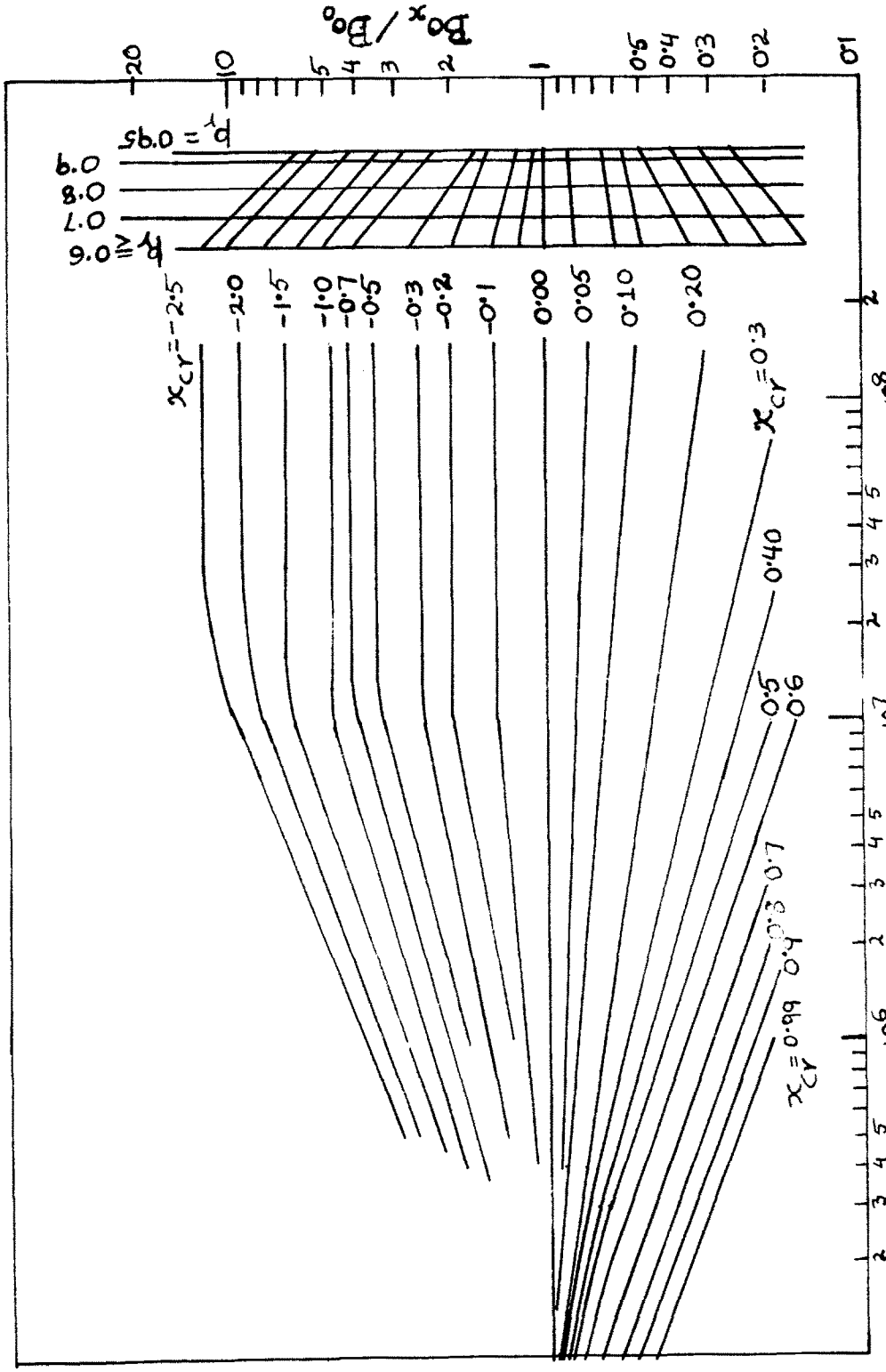

FIG. 3(c). Part 3 of the new correlation. Ratio of boiling number at $x_{cr} = x$ to the boiling number at $x_{cr} = 0$.

> 0.9, the predictions with the two parameters could be significantly different. As only 3 data points for $p_r > 0.9$ were available and all were for the same fluid, ammonia, which one is the better choice could not be determined. As p_r is easier to calculate, it was used.

SELECTION OF DATA

The experimental data used to develop and verify the proposed correlation are listed in Table 1 along with the range of important dimensional and dimensionless parameters. The data of Dix [12], Watson *et al.* [13], Bergles [14], and Ortanskii [15] have been obtained by reading the actual data points shown in the graphs in these references. The data of Pokhvalov [16] and Pappel [17] have also been read from graphs but the values have been taken from the mean curves through the data points. All other data are from tabulations.

Table 1 lists 1271 data points while the number available in the references is much greater. Hence elaboration of the basis of data selection is desirable. Where a reference provided a large amount of data, samples representative of the range of parameters covered were taken at random. This was done to keep calculation effort to within reasonable limits, especially as all calculations have been done manually. Some of the data have been eliminated for reasons other than saving calculation effort. All data points in [4] rejected by Thompson and MacBeth were not considered. Even among the data accepted by them, in a few cases it was found that the data in some samples were too low. Such data are test No. 245.01–257.01 of Table 6, 1.07–6.07 of Table 1, and 4.07–10.07 of Table 13. It is interesting that the data of test No. 245.01–257.01 of Table 6 are also well below the Thompson and MacBeth correlation. In fact the prediction of the present correlation and the Thompson and MacBeth correlation are in good agreement and both are on the average about 175% of the measured values.

Staub [18] has provided data at reduced pressures of 0.125, 0.175, 0.23 and 0.41. Among these, data at p_r of 0.23 are exceptionally low. As data at both higher and lower pressures are fairly well correlated, it was felt that those at p_r of 0.23 represent premature burnouts and were discarded. Pokhvalov [16] has presented data at p_r of 0.013, 0.06, 0.18, 0.32 and 0.76. Most of the data with p_r of 0.013 and 0.06 and low mass velocities are very low. Pokhvalov has reported pulsations at low flow rates. Hence premature burnouts were suspected at the two lower pressure levels and data for these pressures were not considered.

In the tabulations provided by Lewis [19] for nitrogen and parahydrogen, only those runs listed as "maximum or near maximum critical heat flux" were considered. Runs listed merely as "transition" were not considered as they appear to be premature burnouts.

Hoffman's experiments [20] were carried out in two different test sections. The 22 mm test section was heated in a way that would not have produced uniform heat flux. Data from this section were therefore discarded. The other test section was an 8.2 mm tube with the total length to diameter ratio of 135. Data have been reported for heated length to diameter ratio of 45 to 71. However, the heater arrangement was such that the actual heated length would have been longer than that reported, the error being greater for the shorter heated length. Hence only the data for L_{cr}/D of 71 were considered.

Individual data points have not been eliminated even when they depart widely from the trend shown by other data points in the set. For example, in the data of Percupile *et al.* [24] at p_r of 0.4, two data points have deviations of 102 and 64% while all other data points are within 19%. These runs have been retained in Table 1 even though premature burnout is suspected.

PROPERTY DATA

Properties of R-11, R-12, R-22, R-113, R-114, and ammonia were taken from [21]. Properties of water were taken from [22]. Properties of nitrogen, parahydrogen, benzene, and potassium were taken from [23]. All properties have been evaluated at the saturation temperature.

RESULTS OF COMPARISON WITH DATA

The results of comparison of experimental data with the proposed correlation are included in Table 1. The mean deviation for all data points is 15%. Ninety per cent of the data are within $\pm 30\%$ while 96.7% of the data are within $\pm 40\%$. Deviation of a data point is defined as,

$$\text{Deviation} = \frac{(\text{Predicted } Bo - \text{Measured } Bo)}{\text{Measured } Bo} \quad (6)$$

DISCUSSION OF RESULTS

The range of parameters covered in each data set is given in Table 1 and the complete range of parameters covered for all data is summarized in Table 2. The data analyzed are from 20 references. Furthermore [5], [26], and [30] are in fact compilations of data from many sources. Reference [30] alone contains data from 12 independent experimental studies. Thus the data analyzed are from more than 30 independent sources.

Data include 11 different fluids, namely water, R-11, R-12, R-22, R-113, R-114, benzene, ammonia, parahydrogen, nitrogen and potassium. Those fluids differ very widely in their properties. Furthermore, the data cover a very wide range of tube diameters, flow rates and pressures. Thus the results suggest that this correlation may be applicable to a wide range of parameters.

This correlation is intended only for uniformly heated tubes and most of the analyzed are for uniformly heated tubes. However, in the data of Aladyeev *et al.* [28], the ratio of maximum to mean

Table 1. Summary of data analyzed to develop and verify the proposed correlation

Source	Fluid	D mm	L_{cr}/D	p_r	G kg/m^2 s	q_{cr} MW/m^2	x_{in}	x_{cr}	$Y \times 10^{-3}$	No. of Data points	Mean Dev. %	No. of Data with dev. $> 30\%$	No. of Data with dev. $> 40\%$
Doroshuk *et al.* [5]	water	8.0	187	0.13	750	0.40	*	−0.83	355	493	11.2	32	7
		0.89	385		5000	11.60		+0.70					
Firstenberg *et al.* [30]	water	3.0	50	0.0047	49	0.47	−0.60	+0.38	2	20	13.6	2	1
			50	0.0770	598	3.5	−0.40	+0.79	206				
		4.6	52	0.031	13	0.12	−0.26	+0.72	0.09	20	11.8	0	0
			52	0.031	92	0.98	−0.05	+0.98					
		24.0	24	0.0047	19	0.16	−0.16	+0.41	1.5	18	9.5	0	0
				0.0047	41	0.69	−0.16	+0.82	5.7				
DeBortoli *et al.* [26]	water	3.0	50	0.15	60	0.47	−0.53	+0.71	2.1	20	9.5	1	0
			50	0.15	304	2.96	−0.06	+0.94	40				
		5.7	109	0.15	2670	2.4	−1.20	−0.40	1490	17	19.1	0	0
			109	0.62	10610	11.9	−0.31	+0.06	63840				
		4.6	52	0.62	38	0.23	−1.07	+0.76	2.3	17	5.5	0	0
			52	0.62	85	0.85	−0.21	+1.07	92				
		4.7	64	0.62	283	0.66	−0.84	−0.05	85	17	25.4	7	2
			64	0.62	1411	3.28	−0.64	+0.67	1530				
		1.9	80	0.86	1845	2.55	−1.25	−0.29	3784	15	9.6	0	0
			80	0.86	3500	4.54	−0.73	−0.08	11963				
Matzner [29]	water	12.8	151	0.31	931	1.68	−0.77	−0.00	815	22	22.3	6	5
			151	0.31	18590	8.11	−0.04	+0.56	178650				
		24.0	26	0.31	637	3.20	−0.26	−0.01	676	12	12.0	0	0
					9540	8.00	−0.05	+0.28	90273				
		37.5	52	0.31	678	2.36	−0.45	−0.15	678	18	9.7	0	0
			52	0.31	7517	6.65	−0.05	+0.26	7517				
Thompson and MacBeth [4]	water	10.2	74	0.15	1841	3.92	−0.44	−0.20	7565	18	15.6	3	2
			74	0.47	9900	9.30	−0.04	+0.15	59764				
Lee and Obertelli [25]	water	19.8	31	0.56	407	1.29	−0.31	+0.17	284	9	28.0	5	1
			46	0.56	543	2.01	−0.10	+0.40	476				
		5.6	38	0.18	1018	7.25	−0.20	+0.04	512	6	42.6	5	1
			38	0.18	4070	8.06	−0.04	+0.51	6393				
Bergles [14]	water	0.58	25	0.0093	3040	13.9	−0.24	−0.04	1147	6	17.0	2	0
			25	*0.0093*	*6080*	*24.9*	*−0.14*	−0.04	3984				
		1.2	25	0.0093	3026	11.3	−0.24	−0.12	1763	25	32.0	10	0
			25	0.0093	24288	59.6	−0.10	+0.04	79695				

Ortanskii *et al.* [15]	water	2.9	30	0.13	1500	4.8	−1.06	−0.15	914	29	25.8	5	0
			150	0.44	3000	17.6	+0.06	+0.40	2340				
		5.8	55	0.44	1500	2.6	−0.81	−0.02	1394	10	14.4	0	0
			55	0.44	1500	7.2	+0.04	+0.25	1394				
		4.0	55	0.44	1500	3.0	−0.92	−0.01	1119	8	20.6	0	0
			55	0.44	1500	8.3	−0.00	+0.30	1119				
		8.0	55	0.44	1500	2.8	−0.71	−0.04	1679	7	7.6	0	0
			55	0.44	1500	6.1	−0.13	+0.18	1679				
Watson *et al.* [13]	water	37.8	145	0.84	407	0.25	−0.74	−0.08	1380	32	17.6	10	2
			145	0.84	2035	0.79	+0.23	+0.47	25000				
Noel [30]	ammonia	5.9	14	0.10	480	5.5	−2.98	−2.63	358	40	15.7	1	0
			14	0.94	23338	32.2	−0.08	−0.03	388621				
Pokhvalov [16]	benzene	5.0	16	0.18	69	0.35	−1.68	0.00	18	39	26.8	10	6
			16	0.76	10000	1.1	−0.02	0.00	158600				
Pappel *et al.* [17]	N_2	12.8	24	0.10	117	0.16	−0.46	+0.34	84	37	20.7	3	2
			24	0.49	2659	0.82	−0.08	+0.92	26200				
Lewis *et al.* [19]	N_2	14.1	22	0.10	21	0.03	−0.02	+0.48	4	11	12.4	1	1
			29	0.10	73	0.17	−0.01	+0.93	36				
	para-hydrogen	14.1	4	0.26	6	0.02	0.00	+0.42	4	38	9.1	0	0
			29	0.26	17	0.06	0.00	+0.90	101				
Steven *et al.* [32]	R-12	9.6	33	0.31	509	0.05	−0.27	+0.00	671	56	24.0	9	2
			269	0.31	2035	0.31	−0.04	+0.83	8134				
Percupile *et al.* [24]	R-11	12.5	90	0.40	1481	0.27	−1.20	−0.62	4275	35	17.7	7	4
			90	0.56	8806	1.26	−0.65	−0.15	106000				
Dix [12]	R-114	12.9	71	0.26	733	0.01	−0.30	+0.02	1539	44	18.1	5	0
			150	0.33	1696	0.02	−0.11	+0.49	7250				
Coeffield *et al.* [27]	R-113	10.2	75	0.27	1289	0.14	−1.12	−0.54	4400	38	11.2	0	0
			75	0.61	5603	1.12	−0.11	+0.02	56718				
Staub [18]	R-22	10.2	151	0.12	495	0.10	−0.29	+0.23	413	21	21.2	4	3
			151	0.41	1256	0.19	−0.02	+0.79	2979				
Hoffman and Krakoviak [20]	K	8.2	71	0.0052	104	0.69	+0.01	+0.32	0.05	14	29.0	4	4
			71	0.0073	199	0.96	+0.05	+0.86	0.30				
Aladyev *et al.* [28]	K	4.0	30	0.0012	65	0.27	−0.17	+0.50	0.013	39	7.3	0	0
			100	0.0110	334	1.70	−0.03	+0.78	0.182				
		6.0	46	0.0064	38	0.41	−0.19	+0.46	0.005	20	14.4	0	0
			100	0.0110	252	1.01	−0.03	+0.96	0.149				
Total, all data										1271	15.0	132	45

*Subcooled to positive quality inlet. Actual x_{in} not known.

Table 2. Complete range of parameters over which the correlation has been verified

Fluids	Water, R-11, R-12, R-22, R-113, R-114, ammonia, benzene, potassium, parahydrogen, nitrogen
D, mm	0.58–37.8
p, MN/m^2	0.023–19.6
Temp. °C	−248–789
G, kg/m^2 s	5.6–24 300
q_{cr}, MW/m^2	0.028–32.2
L_{cr}/D	4.5–385
p_r	0.0012–0.94
x_{cr}	−2.6–0.96
x_{in}	−2.98–positive qualities
Y	5–388 621 000

heat flux varied from 1 to 1.5. As all their data are well correlated, it appears that this correlation could be applied to somewhat nonuniform heat flux distribution.

RECOMMENDATIONS FOR APPLICATION

The results of comparison of this correlation with experimental data have been presented in the foregoing. The reader is invited to reach his own conclusion as to its reliability and utility on the basis of the evidence presented here as well as comparison with other data. This author recommends this correlation in the range of parameters covered in Table 2. Caution must be exercised regarding the following points.

1. For $Y < 10^5$, the correlation has not been tested for $p_r > 0.62$.
2. There is considerable scatter in data between $Y = 10^4$ to 10^6. Hence in this range it is advisable to also check with other methods.
3. There are only 3 data points for $p_r > 0.89$ and $x_{cr} < -0.83$, all from the tests by Noel [31].
4. As pointed out by Doroshuk *et al.* [5], burnout can occur due to purely hydrodynamic reasons. In such a burnout, critical heat flux has no meaning. Predictions of burnout quality should then be made with correlations suitable for this purpose.

OTHER PREDICTIVE TECHNIQUES

As was stated in the introduction, most of the available predictive techniques apply only to a single fluid in a certain range of parameters. We will discuss here only those techniques which apply to more than one fluid.

Perhaps the first to present a general predictive technique was Bernath [7]. The correlation presented by him is dimensional and applies only to subcooled CHF. Bernath correlated the data for flow in plain tubes, tubes with inserts, and annuli. The fluids included were water, ammonia and diphenyl. Good accuracy was reported. However, for the data analyzed by Gambill [6], the Bernath correlation predicted 46% of the water data to within 30% and 60% of the water to within 40%. Hence the Bernath method does not appear to be very accurate.

Gambill [6] presented a correlation for subcooled CHF which was based on the assumption that the critical heat flux in flow boiling is the sum of the pool boiling critical heat flux and the heat flux removed by single phase convection. Data analyzed included plain tubes, tubes with inserts, annuli, rectangular channels and rod bundles. For plain tubes, fluids analyzed were water, hydrazine, ammonia, nitrogen tetroxide and ethylene glycol. Seventy two per cent of the water data were predicted to within 30%. For selected water data, 86% were within 30%. For fluids other than water, 80% of the accepted data were within 30%. However according to Bergles [14], the predictions of the Gambill correlation were very much lower than his data for water in small diameter tubes. As shown in Table 1, these data are satisfactorily correlated by the present correlation.

As far as plain tubes are considered, this correlation has been verified with much more varied data than the Gambill and Bernath correlations. Indeed, the other two do not apply to positive quality burnout at all. Hence one can feel more confident in using this correlation than other general correlations. However for water, specialized correlations such as that by Thompson and MacBeth are likely to be significantly more accurate.

CONCLUDING REMARKS

The curves in Figs. 3(a)–(c) probably do not represent the optimum for minimum deviation. To optimize much a wide range of data by hand calculations is difficult. Once an accuracy of 30% was achieved for 90% of the data, further attempts at minimizing the deviations were not made. It is suggested that the correlation be optimized through computer analysis of larger samples of data. Specially needing attention is the region from $Y = 10^4$ to 10^6. Analysis of more data for x_{cr} less than -0.83 and p_r greater than 0.89 is also needed for confirming/modifying the correlation in this range. Careful study of data for $p_r > 0.9$ is required to determine if ρ_G/ρ_L may be preferable to p_r as a correlating parameter.

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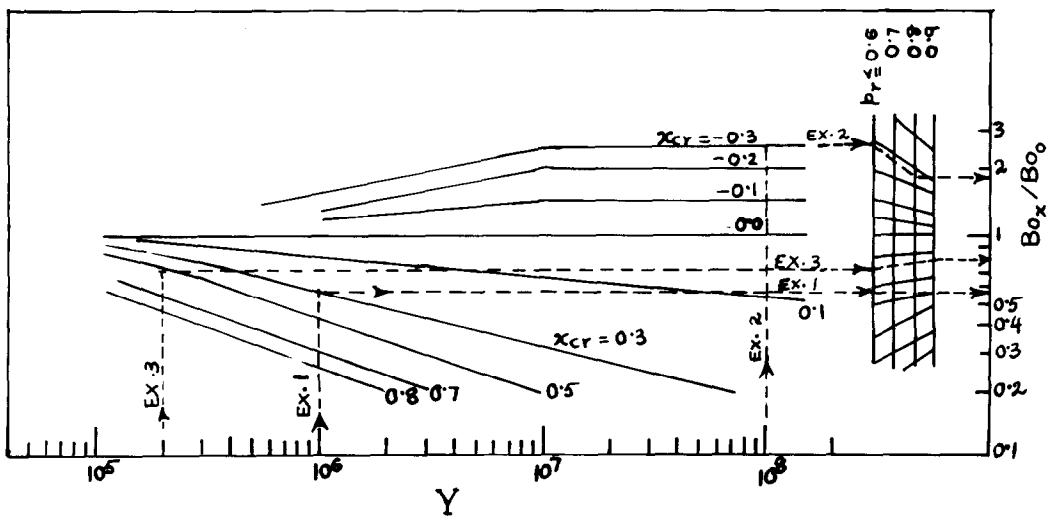

FIG. 4. Reproduction of part of Fig. 3(c) to illustrate the solution of some examples.

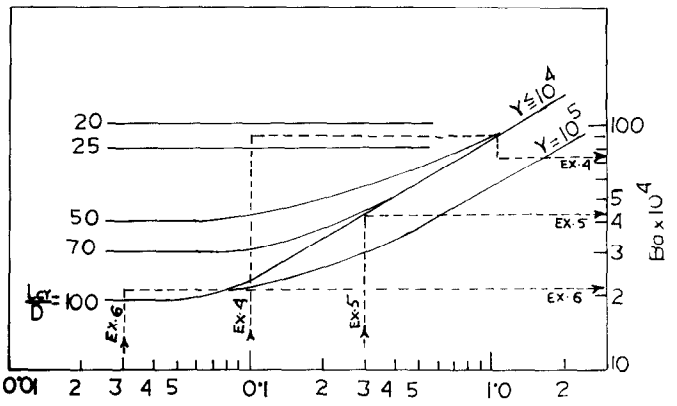

FIG. 5. Reproduction of part of Fig. 3(b) to illustrate the solution of some examples.

APPENDIX

Use of the correlation

Use of the correlation is explained through a few solved examples. Reading Fig. 3(a) is straightforward. Figures 3(b) and (c) are somewhat more complicated. Hence parts of Figs. 3(b) and (c) have been reproduced in Figs. 4 and 5 and the solutions to the examples plotted on them.

Example 1.

$Y = 10^6$, $L_{cr}/D > 14$, $p_r = 0.30$, $x_{cr} = 0.30$.

From Fig. 3(a) it is noted that L_{cr}/D and p_r have no influence. Bo_0 is read to be 31×10^{-4}. Figure 3(c) is redrawn in Fig. 4 and the correlation shown on it by dotted lines. As p_r is less than 0.6, it has no influence. Bo_x/Bo_0 is read to be 0.56. Thus predicted $Bo_x = 0.56 \times (31 \times 10^{-4}) = 17.4 \times 10^{-4}$.

Example 2.

$Y = 10^8$, $L_{cr}/D > 14$, $p_r = 0.8$, $x_{cr} = -0.3$.

From Fig. 3(a), $Bo_0 = 5.6 \times 10^{-4}$. As shown in Fig. 4, $Bo_x/Bo_0 = 1.9$. Hence $Bo_x = 1.9(5.6 \times 10^{-4}) = 10.6 \times 10^{-4}$.

Example 3.

$Y = 2 \times 10^5$, $L_{cr}/D = 30$, $x_{cr} = 0.53$, $p_r = 0.9$.

Figure 3(a) yields $Bo_0 = 61 \times 10^{-4}$.

Figure 3(c) yields $Bo_x/Bo_0 = 0.78$.

$Bo_x = 0.78(61 \times 10^{-4}) = 47.6 \times 10^{-4}$.

Example 4.

$Y = 5 \times 10^4$, $L_{cr}/D = 22$, $x_{in} = -0.10$.

Figure 3(b) gives $Bo = 74 \times 10^{-4}$.

Example 5.

$Y = 3 \times 10^3$, $L_{cr}/D = 75$, $x_{in} = -0.3$.

Figure 3(b) yields $Bo = 43 \times 10^{-4}$.

Example 6.

$Y = 0.1$, $x_{in} = -0.03$, $L_{cr}/D = 90$.

Figure 3(b) gives $Bo = 22 \times 10^{-4}$.

In Examples 1–3, it has been assumed that x_{cr} is known. In many practical problems, L_{cr}/D and x_{in} are fixed and x_{cr} is not known. In such cases, Bo_x and x_{cr} have to be determined iteratively through use of this correlation together with the heat balance equation which may be written as,

$$x_{cr} = 4(L_{cr}/D)Bo_x + x_{in}. \tag{7}$$

A value of x_{cr} is first assumed and Bo_x calculated using Figs. 3(a) and (c). Equation (7) is then used to calculate x_{cr}. If the calculated x_{cr} does not equal the assumed value, a new value of x_{cr} is assumed and the calculations repeated till equation (7) is satisfied. Generally, the number of iterations required to reach adequate convergence does not exceed 5.

UNE METHODE GRAPHIQUE GENERALE POUR PREDIRE LE CHF DANS DES TUBES VERTICAUX UNIFORMEMENT CHAUFFES

Résumé—Une formule générale est présentée pour calculer le CHF dans des tubes verticaux pendant l'ébullition sous-refroidie et saturée. La formule est comparée aux 1271 points expérimentaux provenant de plus de 30 sources et elle respecte un écart moyen de 15%, avec 90% des points à ±30%. Les données concernent l'eau, le potassium, les Freon, le benzène, l'ammoniac l'hydrogène et l'azote. Le domaine de pression réduite s'étend de 0,0012 à 0,94, le flux massique varie de 6 à 24,3 kg/m² s, la qualité critique de −2,6 à +0,96 et la qualité à l'entrée de −3,0 jusqu'aux valeurs positives.

EINE VERALLGEMEINERTE GRAFISCHE METHODE ZUR BESTIMMUNG DER KRITISCHEN WÄRMESTROMDICHTE IN GLEICHMÄSSIG BEHEIZTEN, SENKRECHTEN ROHREN

Zusammenfassung—Es wird eine allgemeingültige Gleichung zur Berechnung der kritischen Wärmestromdichte in senkrechten Rohren beim unterkühlten und gesättigten Sieden angegeben. Die Gleichung wurde mit 1271 Meßpunkten aus über 30 Quellen verglichen; die mittlere Abweichung war 15%, 90% aller Meßwerte lagen innerhalb ±30%.

Die Meßwerte gelten für Wasser, Natrium, Freone, Benzol, Ammoniak Parawasserstoff und Stickstoff. Der Bereich des reduzierten Drucks lag zwischen 0,0012 und 0,94, die Massenstromdichte zwischen 6 und 23 300 kg/m² s, der kritische Dampfgehalt zwischen −2,6 und +0,96 und der Dampfgehalt im Eintrittsquerschnitt zwischen −3,0 und positiven Werten.

ОБОБЩЕННЫЙ ГРАФИЧЕСКИЙ МЕТОД РАСЧЁТА КРИТИЧЕСКОГО ТЕПЛОВОГО ПОТОКА В РАВНОМЕРНО НАГРЕВАЕМЫХ ВЕРТИКАЛЬНЫХ ТРУБАХ

Аннотация — Представлена обобщенная зависимость для расчёта критического теплового потока при кипении с недогревом и насыщенном кипении в вертикальных трубах. Проведенное сравнение зависимости с 1271 экспериментальной точкой более чем из 30 источников показало, что среднее отклонение не превышает 15%, а 90% данных находится в пределах ±30%. Использовались данные для воды, калия, фреонов, бензола, аммиака, параводорода и азота. Диапазон приведенных давлений составлял 0,0012–0,94, поток массы — от 6 до 24 300 кг/м²сек, критическое весовое теплосодержание — от 2,6 до +0,96, а теплосодержание на входе — от −3,0 до положительных значений.