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A GENERAL CORRELATION FOR CRITICAL HEAT FLUX IN ANNULI

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Abstract – A general correlation for prediction of critical heat flux in vertical annuli is presented. It has been verified with over 800 data points for four fluids and found to have a mean deviation of 14%. Data include cylindrical and non-cylindrical annuli with internal heating, external heating, and heating on both sides. Range of parameters covered includes reduced pressures from 0.017 to 0.9, mass flux from 100 to 16 000 kg/m^2 s, inlet quality from − 3.1 to 0.00, critical quality from − 2.8 to + 0.74, annular gap from 0.5 to 11.1 mm, and heated tube diameter from 1.5 to 96.5 mm.

NOMENCLATURE

Bo, boiling number, $q_{cr}/G\lambda$;
Bo_1, boiling number at $Y \leq 10^4$;
C_p, specific heat of liquid;
D, diameter of surface on which CHF occurs;
D_i, diameter of inner tube of annulus;
D_O, diameter of outer tube of annulus;
D_{hp}, equivalent diameter of annulus based on the heated perimeter, defined by equation (5);
f_1, a function;
f_2, a function;
f_3, a function;
F_1, multiplier in equation (8), given by Fig. 2;
F_2, multiplier in equation (8), given by Fig. 3;
Fr, Froude number;
g, acceleration due to gravity;
G, mass velocity, i.e. mass flow per unit area per unit time;
k, thermal conductivity of liquid;
L, axial distance between entrance and the location where CHF occurs;
Pe, Peclet number;
p_r, reduced pressure;
X_{in}, inlet quality, may be positive or negative;
X_{cr}, critical quality, i.e. quality at the location where CHF occurs, may be positive or negative;
Y, CHF correlating parameter, defined by equation (3) and (4);
q_{cr}, critical heat flux.

Greek symbols

ρ, density of liquid;
μ_L, dynamic viscosity of liquid;
μ_G, dynamic viscosity of vapor;
λ, latent heat of vaporization;
δ, annular gap width, $= (D_O - D_i)/2$.

INTRODUCTION

PREDICTION of critical heat flux (CHF) in annular channels is of much practical interest. This is evident from the fact that a large number of experimental studies on CHF in annuli have been carried out and many techniques for predicting CHF have been proposed. Tong [1], Rosenhow [2], Collier [3], Hsu and Graham [4], among others, have listed and discussed many of the available predictive techniques. 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 dimensional equations intended for only one fluid, most commonly water, in a limited range of parameters. Perhaps the best known correlation of this kind is that by Barnett [5] which applies to water in plain cylindrical annuli at 6.9 MN/m^2. Very few attempts at developing correlations which apply to a variety of fluids and over a wide range of parameters have been made. Only two comparatively successful attempts are known to this author. These are the correlations of Bernath [6] and Gambill [7]. Both of these apply only to subcooled boiling CHF. No well verified general correlation for the positive quality region could be found.

The primary objective of the author was to develop a correlation for internally heated cylindrical annuli with uniform heat flux which would apply to a wide variety of fluids and a wide range of parameters. The correlation developed correlates 639 data points for internally heated annuli with a mean deviation of 11.4%, with 93% of the data within ± 30%. Hence the primary objective has been fulfilled to a considerable extent. The correlation developed has also been compared with data for other geometries with fairly good results. The other geometries explored are cylindrical annuli with external heating and two-sided heating, and a heated tube in a square channel. Considering all geometries, the correlation has been verified with data for four fluids covering reduced pressures from 0.017 to 0.9, mass flux from 100 to 15 780 kg m^{2}s, critical qualities from − 2.8 to + 0.74, clearance from 0.5 to 11 mm, and heated tube diameters from 1.5 to 96.5 mm.

Only plain annuli without any heat-transfer enhancement devices such as turbulaters or stripper rings were considered. All data are for uniform heat flux though in the case of annuli heated on both sides the heat flux on the two sides was different. Furthermore, only pulsation-free, stable upflow data for single component fluids were considered.

The objective of this paper is to present the correlation developed, explain its use, and explore its validity and applicability 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.

CORRELATION FOR TUBES

The starting point for the development of the correlation for annuli was the author's correlation for CHF in uniformly heated tubes [8]. That correlation is in graphical form. In functional form, it may be expressed by the following two equations:

$$\text{For } Y < 10^4,\ Bo = f_1(X_{\text{in}}, L/D) \tag{1}$$

$$\text{For } Y > 10^5,\ Bo = f_2(X_{cr}, Y, p_r). \tag{2}$$

The parameter Y is defined as follows:

$$Y = Pe\, Fr^{0.4}(\mu_L/\mu_G)^{0.6} \tag{3}$$

On substituting the values of Pe and Fr, equation (3) becomes:

$$Y = \left(\frac{GDC_p}{k}\right)\left(\frac{G^2}{\rho^2 gD}\right)^{0.4}(\mu_L/\mu_G)^{0.6}. \tag{4}$$

Thus for high values of Y, the boiling number Bo is a function of Y, the critical quality X_{cr}, and reduced pressure p_r, but independent of L/D provided L/D is not too small. For low values of Y, Bo is a function of inlet quality X_{in} and the length to diameter ratio L/D, and is independent of Y. This correlation was verified with data for 11 fluids covering a wide range of pertinent parameters.

DEVELOPMENT OF CORRELATION FOR ANNULI

Determining geometrical factors

Experience has shown that heat-transfer correlation for tubes can be applied to annuli by replacing the tube diameter by a suitably defined equivalent diameter of annulus. Hence the first approach taken was to apply the tube CHF correlation of [8] to the annulus data with a suitably defined equivalent diameter. The most widely used equivalent diameter is the hydraulic diameter D_{HYD} defined as:

$$D_{\text{HYD}} = \frac{4 \times \text{Flow area}}{\text{Wetted parameter}}. \tag{5}$$

Substitution of hydraulic diameter in place of tube diameter did not provide satisfactory correlation.

Another way to define equivalent diameter is to base it on the heated perimeter. The equivalent diameter thus defined, D_{hp}, is given by:

$$D_{hp} = \frac{4 \times \text{Flow area}}{\text{Heated perimeter}}. \tag{6}$$

In the next attempt, D_{hp} was substituted for D in equation (4) as well as in L/D and the tube CHF correlation applied to the data. Agreement was again unsatisfactory.

In the next attempt, the diameter used in equation (4) was the diameter of the heated tube and L/D was replaced by L/D_{hp}. The application of tube CHF correlation then showed some agreement with experimental data even though the scatter was considerable. It was found that even at high values of Y, the critical heat flux is affected by inlet subcooling and the length to diameter ratio. However, it was established that the D in equation (4) has to be the diameter of the heated tube as data for tube diameters from 1.5 to 96 mm were made to converge through this definition of D. Furthermore, the use of L/D_{hp} instead of L/D was also established.

FURTHER DEVELOPMENT

Even with these geometrical factors, the tube correlation did not adequately satisfy the data for annuli. Hence a completely new correlation had to be developed. To proceed with this development, it was assumed that the boiling number at $Y < 10^4$, Bo_1, is a function of X_{in} and L/D_{hp} alone and is independent of Y, X_{cr}, and p_r.

$$Bo_1 = f_3(X_{\text{in}}, L/D_{hp}). \tag{7}$$

Only a limited number of data were available for $Y < 10^4$ but they supported this assumption. For $Y > 10^4$, experimental data indicated that the boiling number could be expressed as:

$$Bo = F_1 F_2 Bo_1. \tag{8}$$

F_1 is a function of Y, Bo_1, p_r and F_2 is a function of Y and X_{cr}. As extensive data were available only for internally heated cylindrical annuli, the correlation was optimized exclusively with the data for this geometry. The correlation has been developed entirely in graphical form as it was not found possible to express it in terms of simple mathematical equations.

THE CORRELATION

The correlation finally arrived at through several iterations is shown in Figs 1–3.* Figure 1 gives Bo_1, the boiling number for $Y < 10^4$. Figure 2 gives F_1; Fig. 3 gives F_2. In Fig. 2 it is noted that the reduced pressure p_r has an effect only when it exceeds 0.35 and then also only at higher values of Y. In Fig. 3, it is noted that $F_2 = 1$ for positive X_{cr}. Furthermore, $F_2 = 1$ for $Y \leq 10^6$ for any value of X_{cr}, positive or negative. Only at negative X_{cr} and $Y > 10^6$ is F_2 greater than 1.

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*Full-size copies of Figs. 1–3 plotted on graph paper along with notes clarifying the use of this correlation are obtainable from the author.

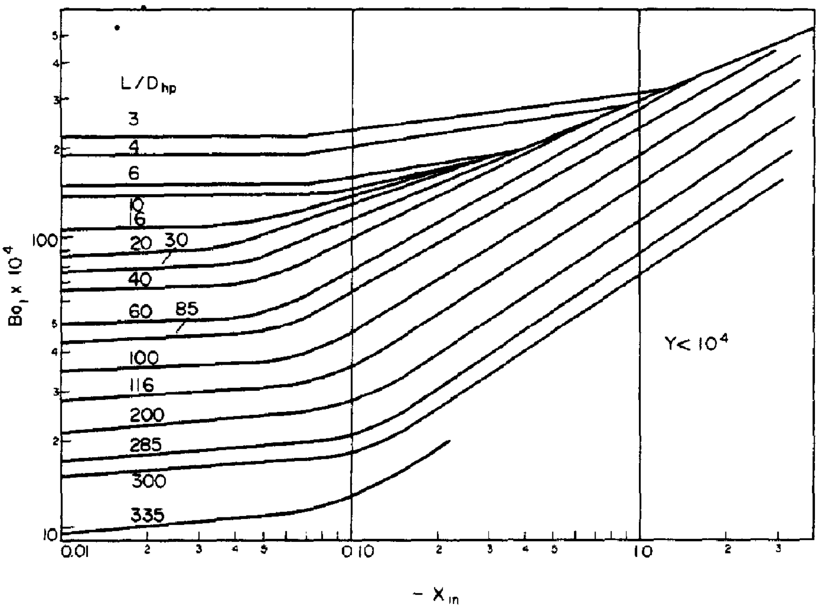

FIG. 1. Part 1 of the correlation. Boiling number for $Y < 10^4$.

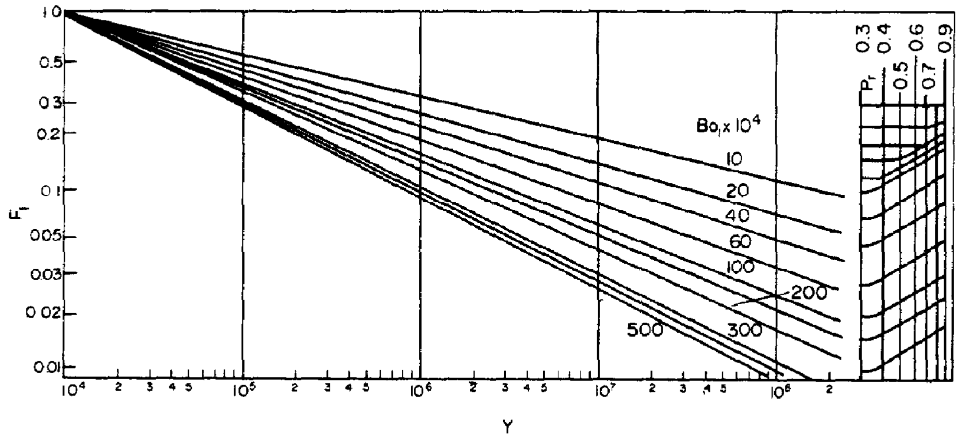

FIG. 2. Part 2 of the correlation. Multiplier F_1 for $Y > 10^4$. $F_1 = 1$ when $Y < 10^4$.

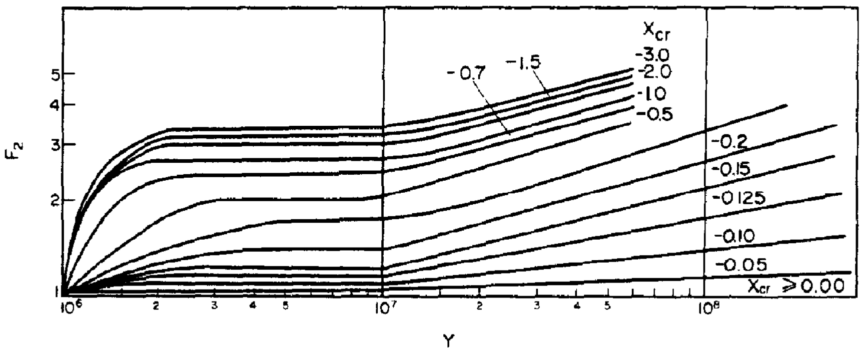

FIG. 3. Part 3 of the correlation. Multiplier F_2 for $Y > 10^6$. $F_2 = 1$ when $Y \leq 10^6$ for all values of X_{cr}. $F_2 = 1$ when $X_{cr} \geq 0$ for all values of Y.

USE OF THE CORRELATION

1. Calculate Y using equation (4). For internally heated annuli, D is the diameter of inner tube and for externally heated annuli it is the diameter of outer tube. For annuli heated on both sides, D is the diameter of the tube on which CHF occurs.

2. Calculate D_{hp} with equation (6). For annuli heated on both sides, heated perimeter used is that of the tube on which CHF occurs.

3. Calculate Bo_1 using Fig. 1. If $X_{in} > -0.01$, use the value of Bo_1 at $X_{in} = -0.01$ (this is discussed later).

In many practical problems, X_{cr} is not known. In such cases, this correlation has to be used together with the heat balance equation and Bo and X_{cr} determined iteratively. Of course if $Y < 10^6$, $F_2 = 1$ for all values of X_{cr} and hence no iterations are required. A few solved examples are given in the Appendix to fully clarify the application of this correlation.

SELECTION OF DATA

The data used to develop and verify this correlation are listed in Tables 1 and 2 along with the range of important dimensional and dimensionless parameters. Table 1 contains data for internally heated cylindrical annuli while Table 2 contains data for other geometries. The data of Tolubinsky *et al.* [12, 14], Alekseev *et al.* [10], Jansen *et al.* [13], Moeck *et al.* [15] and Bertoletti *et al.* [27], have been extracted from graphs in these references. All other data are from tabulations. It is to be noted that [5] is a compilation of data from 8 independent sources.

Table 1 and 2 list a total of 826 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 the calculation effort within reasonable limits. In the tabulations provided by Knoebbel *et al.* [9], those data marked by them as unreliable were not considered. Core and Sato [18] have provided data for water, diphenyl, monoisopropyl, diphenyl, polyphenyl mixtures, and santowax R. Reliable property data for monoisopropyl diphenyl and santowax R were not available and hence their CHF data were not analyzed. Polyphenyl mixture data were not analyzed as only single component fluids were considered. Furthermore, the data of Noyes and Lurie [20] for sodium have not been included for reasons discussed later. No data have been discarded because of large deviation from the correlation, even when they disagreed with other data points in the data set.

PROPERTY DATA

Properties of water were taken from [21]. Properties of R-12 were taken from [23]. Properties of heavy water (deuterium oxide) and diphenyl are from [22]. The viscosity of diphenyl vapor was calculated by the Bromley and Wilke equation as given in [24].

COMPARISON OF DATA WITH CORRELATION

The result of comparison of data with the correlation of Figs. 1–3 are given in Tables 1 and 2. The 639 data points for internally heated cylindrical annuli are correlated with a mean deviation of 11.4%, with 93% of the data being within 30% of the correlation, and 98.4% of the data within 40% of the correlation. The 122 data points for externally heated annuli are correlated with a mean deviation of 25.6%, 62% of the data being within 30% and 84% of the data within 40% of the correlation. There were only 34 data points for annuli heated on both sides and these have a mean deviation of 16.5%. There was only one data set for non-circular geometry and its mean deviation is 18.9%. The 826 data points for all geometries are correlated with a mean deviation of 14%, with 88% of the data within 30% and 96.2% of the data within 40%.

Deviation of a data point has been defined as follows:

$$\text{Deviation} = \frac{\text{Predicted value}-\text{measured value}}{\text{Measured value}} \tag{9}$$

Mean deviation of a data set is the sum of absolute deviations of individual data points, divided by the total number of data points.

LIQUID METAL CHF

Only one set of data for liquid metal in annulus could be found. These are the data of Noyes and Lurie [20] for sodium in an annulus. Rohsenow [2] considers the Noyes and Lurie experiments to have suffered from severe flow instabilities that caused premature burnouts. Nevertheless, these data were compared with the present correlation. The test section used by Noyes and Lurie was 686 mm long with a 50 mm long heater inserted at its end. If the CHF reported are considered to be based on the 50 mm heater length, the data are much lower than predictions. If reported CHF are considered to be based on the total 686 mm length, there is reasonable agreement with the correlation. Noyes and Lurie did not state on which length they based the CHF. The normal practice is to base the heat flux on the heater length.

As the author's correlation for CHF in tubes was found to be in good agreement with potassium data [8], and as the annulus and tube correlations are very much alike for $Y < 10^4$, it seems unlikely that this correlation would fail completely for liquid sodium. The explanation for this lack of agreement is most probably the flow instability pointed out by Rohsenow [2]. A definite conclusion regarding the applicability of this correlation to liquid metals can be reached only after analyzing reliable data under stable flow conditions.

DISCUSSION OF RESULTS

Considering the data for cylindrical internally heated annuli alone, the degree of agreement with the correlation can be considered quite satisfactory. The data cover heater diameters from 1.5 to 96.5 mm, annular gaps between 0.5 and 11.1 mm, and L/D_{hp} from 3.7 to 335. Reduced pressures range from 0.017 to 0.90, mass flux from 100 to 15 780 kg/m^{2}s, inlet qualities from $-$ 2.6 to 0.00 and critical qualities from $-$ 1.7 to + 0.74. The mean deviation for this wide range of parameters is 11.4 %, with 93 % of the 639 data points being within ± 30 %.

The deviation of the data for externally heated annuli is much greater, about 26 %. As was noted earlier these data were not used in developing the correlation. It could be that the correlation for external heating is somewhat different from that for internally heated annuli. This could not be investigated as sufficiently varied data for externally heated annuli were not available. However, there could be other causes for the larger deviations. Ortanskii *et al.* [17] experimented with annular gaps of 1, 1.5 and 2 mm. It was stated that the main series of tests was conducted at 1.5 mm gap. The tabulated data were analyzed on this assumption. It is however possible that those tabulations also contain data for other gap widths. This may explain the wider deviations of some of the data points. Furthermore, the diphenyl used in the experiments of Core and Sato [18] was not pure and its composition may have varied from test to test. Finally, the property data of even pure diphenyl are not fully reliable. Hence the question whether a modified correlation is required for externally heated annuli cannot be decided on the basis of data analyzed. The degree of agreement obtained is not excellent but is good enough for reasonable estimates of CHF.

Regarding annuli heated on both sides, only 34 data points from two sources were available. In both series of tests, CHF occurred on the inner tube. In the data of Tolubinsky *et al.* [12], the heat flux on the external tube was 60–90 % of the CHF on inner tube. In the data of Bertoletti *et al.* [26], the external heat flux was 10–40 % of the CHF on the inner tube. While these are satisfactorily correlated, it cannot be inferred that the general validity of this method for two-sided heating has been fully established. More varied data need to be analyzed before any definite conclusion can be reached.

The fact that the data of Larsen *et al.* [19] for a square channel are well correlated encourages one to believe that this correlation may be generally applicable to non-cylindrical annuli. Again, it would be inappropriate to reach a final conclusion on the basis of only one data set. Comparison with more varied data must be carried out to verify (or reject) this hypothesis.

Effect of annular gap

Many opinions have been expressed about the effect of annular gap width on the CHF. Some of these are compared with the results of the present data analysis. Moeck *et al.* [15] concluded that the CHF is maximum at a gap of 4 mm. Gambill [7] found that his correlation grossly over-predicted the CHF when the gap became less than 2 mm. Tolubinsky *et al.* [27] concluded that the CHF is independent of gap width provided it is greater than 1 mm but CHF decreases sharply when the gap becomes less than 1 mm.

The present correlation shows agreement with data for gap widths ranging from 11.1 to 0.5 mm. No maxima was found at 4 mm as had been noted by Moeck *et al.* [15]. The explanation for this discrepancy may be that Moeck *et al.* did not consider all pertinent parameters in carrying out their comparison.

A large number of data at gaps of 1.5 and 1.6 mm show good agreement with the present correlation. However, the mean deviation for the 14 data points at 0.5 mm gap is 31 %. Among these data points, those at a pressure of 14.6 MN/m^2 show deviation of 45–78 %. The data at both higher and lower pressures are within ± 30 %. This would suggest some error in reporting such as a typographical error. In any case, a mean deviation of 31 % is not large enough to conclude that the correlation is inapplicable at 0.5 mm gap.

Efforts were made to obtain more data at gap widths less than 1 mm. Unfortunately, the data that were found did not give all pertinent parameters. In the data of Tolubinsky *et al.* [28], the tube diameter is not known. In the data analyzed by Gambill [7], the tube length is not known. Hence neither could be compared with the present correlation.

In conclusion, it may be stated that the applicability of this correlation has been well established at gap widths of 1.5 mm and larger. Applicability down to 0.5 mm width is probable but requires confirmation from more data. For gaps smaller than 0.5 mm, applicability needs to be determined through data analysis. The applicability to small gaps may be limited to higher pressures as postulated by Gambill [7].

Application to positive inlet qualities

The inlet quality for the data analyzed here varied from $-$ 3.1 to 0.00. No data for positive inlet qualities were available. Hence the question of applicability to two-phase inlet conditions arises. Figure 1 cannot shed any light on this question as in it X_{in} is plotted on a logarithmic scale. In Fig. 4, part of Fig. 1 is redrawn on a semi-logarithmic scale. Figure 4 indicates that Bo_1 would in most cases continue to decrease as inlet quality passes from negative to positive values. The actual correlating curves for positive inlet qualities have to be determined through data analysis. The use of Fig. 4 to predict boiling number at positive inlet qualities is not recommended.

Effect of heater material

Tables 1 and 2 list the heater tube material for several of the data sets. For other data sets, this information was not readily available. Attempts to get

Table 1. Internally heated cylindrical annulus data analyzed and results of comparison with the present correlation

Ref.	Material	D_i (mm)	δ (mm)	D_{hp} (mm)	$\frac{L}{D_{hp}}$	Fluid	p_r	G $\left(\frac{\mathrm{kg}}{\mathrm{m}^2\mathrm{s}}\right)$	q $\left(\frac{\mathrm{MW}}{\mathrm{m}^2}\right)$	$-X_{in}$	X_{cr}	$Y \times 10^{-3}$	No. of data points	RMS error	Mean dev. (%)	No. of data points with dev.	
																> 30%	> 40%
[12]	ss	9	2	9.8	10.2	water	0.68	500	2.3	2.60	− 1.70	410	43	14.3	10.6	4	0
					41		0.90	1000	9.8	0.44	+ 0.30	4742					
[13]	—	9.5	6.4	42.4	42	water	0.19	2279	2.6	0.15	− 0.03	3034	10	5	4.0	0	0
							0.44		4.5	0.03	+ 0.11	3865					
		13.7	4.3	22.3	116	water	0.19	1520	1.2	0.43	+ 0.15	1820	16	4.4	3.4	0	0
							0.49		3.0	0.03	+ 0.25	2318					
[14]	ss	1.5	0.5	2.7	50	water	0.66	500	1.5	1.60	0.00	130	14	38.6	31.3	5	4
					165		0.90	2000	3.5	0.36	0.00	5444					
		1.5	4.0	58.7	3.7	water	0.53	100	2.3	0.82	− 0.39	5	35	12.6	8.8	1	0
					5.6			200	4.8	0.08	+ 0.35	18					
[9]	ss	12.7	4.8	26.2	23.3	Heavy	0.017	5128	13.8	0.37	− 0.23	17644	9	8.8	7.2	0	0
						water		15780	19.9	0.19	− 0.15	127276					
		19.0	3.9	19.1	32.3	Heavy	0.02	9634	8.8	0.26	− 0.17	65949	7	4.9	2.8	0	0
						water		14925	20.2	0.11	− 0.07	144315					
		12.7	4.8	26.2	23.3	water	0.017	4206	3.8	0.15	− 0.10	13060	14	27.5	24.0	5	3
								13568	11.3	0.04	− 0.02	102693					
		54.0	4.2	18.1	33.5	water	0.02	4342	4.2	0.41	− 0.15	30444	6	10.4	8.8	0	0
								13297	12.3	0.12	− 0.06	230396					
		52.1	5.6	24.6	20.5	water	0.017	4478	4.6	0.12	− 0.14	31947	12	17.1	13.8	1	0
								13568	12.0	0.04	− 0.02	240240					
	Al	19.0	3.9	19.1	32.3	water	0.02	4341	4.7	0.27	− 0.13	16404	16	14.0	12.0	0	0
								13161	13.6	0.07	− 0.04	120980					
		25.4	4.1	19.0	32	water	0.02	4410	7.1	0.25	− 0.13	20160	4	14.5	12.7	0	0
								8819	10.4	0.11	− 0.06	70396					
		19.0	3.9	19.1	32.3	Heavy	0.02	1628	5.8	0.32	− 0.12	2688	5	20.9	20.0	0	0
						water		9878	13.9	0.17	− 0.08	68988					
[10]	—	12.0	1.5	6.7	14.8	water	0.18	388	2.4	0.93	− 0.36	271	97	21	17.4	13	3
					59.0		0.90	3888	3.7	0.00	+ 0.10	29620					
[5]	—	76.3	1.6	6.6	284	water	0.31	651	0.5	0.33	+ 0.07	1256	36	11.6	8.0	1	0
								6648	2.1	0.03	+ 0.53	81992					
		9.5	6.3	42.3	42	water	0.31	719	2.1	0.41	− 0.04	429	53	14.6	10.1	6	0
					65			2293	4.8	0.02	+ 0.29	3461					
		12.7	6.3	38.1	16	water	0.31	275	3.4	0.54	− 0.11	91	63	14.5	11.0	2	0
					24			8331	4.7	0.00	+ 0.26	41465					
		9.5	11.1	96.3	18.5	water	0.31	190	1.7	0.46	+ 0.01	65	20	16.9	14.1	0	0
								1520	4.4	0.04	+ 0.35	2744					
		12.7	3.2	15.9	57.6	water	0.31	2795	2.8	0.31	− 0.06	5876	23	16.9	13.3	2	0
								8412	4.7	0.02	+ 0.11	42697					

[15]	—	96.5	1.6	6.5	287	water	0.31	687 6784	0.5 1.9	0.29 0.02	+ 0.08 + 0.50	1551 97821	30	10.0	6.7	1	0
[26]	—	15.0	5.0	26.7	61	water	0.23	1100 2200	1.5 2.6	0.14 0.00	+ 0.07 + 0.20	1100 3829	8	18.6	15.5	1	0
[16]	—	15.9	2.5	11.8	335*	R-12	0.20 0.26	892 2231	0.03 0.09	0.24 0.02	+ 0.19 + 0.37	1748 9537	60	8.3	6.5	0	0
[11]	Ni chrome V	22.2	4.1	21.4	85	R-12	0.15 0.40	132 3256	0.04 0.53	0.37 0.03	− 0.06 + 0.74	61 20035	58	14.8	9.5	3	2
Total all data		1.5 96.5	0.5 11.1	6.5 96.3	3.7 335	R-12 H_2O, D_2O	0.107 0.90	100 15780	0.03 20.0	2.6 0.00	− 1.70 + 0.74	5 240240	639	16.0	11.4	45	12

*Actual $L/D_{hp} = 310$. Increased to 335 to account for the heating stub at the entrance.
ss is abbreviation for stainless steel.

Table 2. Results of analysis of the data for annular channels other than internally heated cylindrical annulus

Ref.	Heater material	D_i (mm)	δ (mm)	D_{hp} (mm)	$\frac{L}{D_{hp}}$	Fluid	p_r	G $\left(\frac{\text{kg}}{\text{m}^2\text{s}}\right)$	q $\left(\frac{\text{MW}}{\text{m}^2}\right)$	$-X_{in}$	X_{cr}	$Y \times 10^{-3}$	No. of data points	RMS error	Mean dev. (%)	No. of data points with dev. 30%	40%
17*	1Cr 18Ni–9Ti	13.0	1.5	5.3	18.8	water	0.11 0.84	499 2496	1.7 9.4	1.22 0.04	− 0.97 + 0.16	229 12600	86	33.5	27	33	12
18*	304ss	4.8	3.4	9.7	30.0	water	0.079	1452 6391	2.4 8.4	0.04 0.03	− 0.15 − 0.02	1491 21613	4	25.1	18.5	1	1
						diphenyl	0.15 0.66	2091 3840	0.3 2.8	3.15 0.04	− 2.85 0.00	256 53603	32	28.8	22.8	12	7
12†	ss	9	2.0	9.8	10.2 41	water	0.68 0.90	500 1000	2.3 5.0	2.6 1.2	− 1.6 − 0.8	1358 4742	19	17.8	13.9	1	1
26†	—	15	5	26.7	61.2	water	0.23	1100 2200	1.5 2.6	0.14 0.00	+ 0.08 + 0.30	1100 3829	15	21.3	19.9	1	0
19‡	Hasteloy	8.1	—	18.1	39.3	water	0.50 0.72	667 4111	2.0 4.9	0.50 0.06	− 0.15 + 0.23	438 14092	31	22.1	18.9	6	0
													187	28.6	22.4		

*Cylindrical annulus, outer tube heated.
†Cylindrical annulus, both tubes heated. CHF on inner tube.
‡Heated tube in an unheated square channel.
ss = stainless steel.

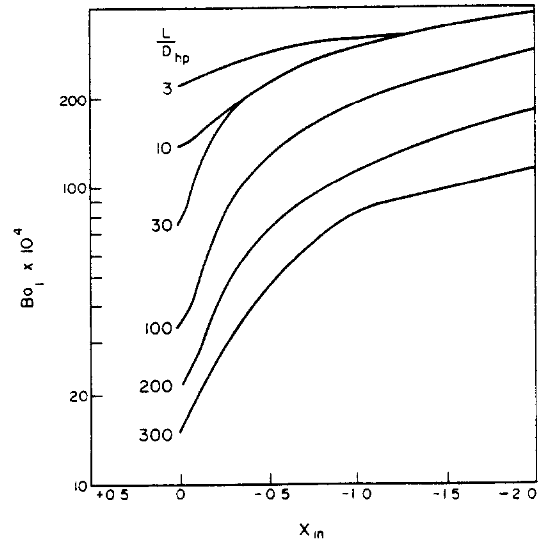

FIG. 4. The correlation of Fig. 1 plotted on semi-logarithmic scale.

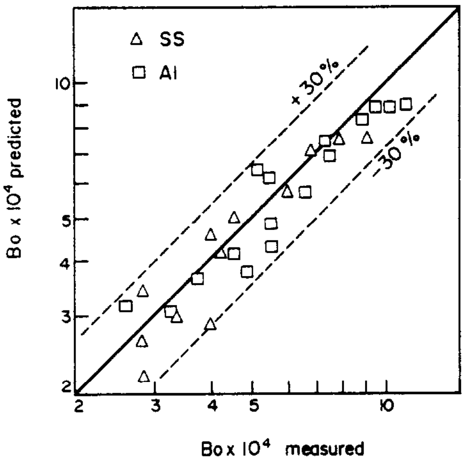

FIG. 5. Comparison of the present correlation with data of Knoebbel *et al.* [9] for water in aluminium and stainless steel annuli.

this information were not made as the available data did not show a relation between heater material and accuracy of prediction, as is discussed in the following.

Knoebbel *et al.* [9] carried out tests with both stainless steel and aluminium heaters. They reached the conclusion that the CHF is higher with aluminium heaters than with stainless steel. Figure 5 shows the comparison of some of their light water data with the present correlation. While some of the aluminium heater data are higher than this correlation, so are some data for stainless steel heater. Furthermore, Barnett [5] developed his CHF correlation with data from eight independent series of experiments which must have included a variety of heater materials. Yet Barnett has not made any mention of having found any effect of material. Also considering the other data included in Tables 1 and 2, the author feels that the present correlation can be used for any commercially produced plain metallic tubes.

RECOMMENDATIONS FOR APPLICATION

The results of data analysis have been presented in Tables 1 and 2. The reader is invited to draw his own conclusions regarding the validity and range of applicability of this correlation, based on the evidence presented here and through comparison with other data. The author recommends its use in the range of parameters covered in Table 3 with the following cautionary notes:

1. The correlation has been verified only for Newtonian non-metallic fluids. Application to metallic fluids or non-Newtonian fluids should not be made until verification with data for such fluids has been done.
2. This correlation has been thoroughly verified only for internally heated cylindrical annuli with annular gaps 1.5 mm and larger. Results of comparison with 0.5 mm gap data are marginal.
3. For geometries other than internally heated annuli, the results of data analysis are encouraging but not conclusive.
4. For $Y < 10^4$, only a few data points have been analyzed, all at $p_r = 0.53$ and small L/D_{hp}. Hence much caution should be exercised in application where $Y < 10^4$.

OTHER PREDICTIVE TECHNIQUES

As noted earlier, most of the available predictive techniques are dimensional equations applicable to only one fluid over a limited range of parameters and in a particular geometry. We will discuss here only those techniques which apply to a variety of fluids.

Perhaps the first to present a general predictive technique was Bernath [6]. His method is applicable to subcooled CHF only but is intended for all geometries. For plain annuli, Bernath compared his correlation with diphenyl and water data with good

Table 3. Complete range of data for which the correlation has been verified

Fluid	Water, deuterium oxide, R-12, diphenyl
Geometry	Vertical upflow in concentric annuli with internal, external, and two-sided heating. Also heated tube inside unheated square channel
Heater tube diameter	1.5–96.5 mm
δ	0.5–11.1 mm
D_{hp}	5.3–96.3 mm
L/D_{hp}	3.7–335
G	100–15 780 kg/m²s
Pressure	0.2–19.9 MN/m²
p_r	0.017–0.90
Saturation temperature	23–482°C
X_{in}	− 3.1–0.00
X_{cr}	− 2.8– + 0.74
Y	5000–240 240 000

results. However, for the data analyzed by Gambill [7], the Bernath correlation predicted only 46 % of the data within ± 30 %. Hence the Bernath method does not appear to be very accurate.

Gambill [7] presented a correlation for subcooled CHF which was based on the assumption that the critical heat flux in flow boiling is the sum of pool boiling critical heat flux and the heat flux removed by single phase convection. The wall temperature at CHF is calculated by the curve used in the Bernath correlation [6]. The Gambill correlation was intended to apply to all geometries. For annuli, Gambill compared his correlation with data for water, diphenyl, and monoisopropyl diphenyl. The data points which were well below the prediction were rejected on the assumption that they were premature burnouts. The maximum reduced pressure for water data was 0.22, considerably lower than 0.9 for the data analyzed here. The 201 selected water data had a deviation of 14.7 %. The 44 selected data for the other two fluids had a mean deviation of 20.5 %. Furthermore, Gambill found that his correlation greatly over-predicts the CHF when the annular gap is less than 2 mm. At 0.5 mm gap, a maximum deviation of 522 % was found. The present correlation gave a mean deviation of 31 % for the 14 data points at 0.5 mm gap. Thus the present correlation has been found to be satisfactory over a wider range of parameters and its accuracy is seen to be comparable to that of the Gambill correlation, despite the fact that no data were rejected in the present analysis.

Ahmed and Groeneveld [25] have presented a dimensionless correlation which shows good agreement with Barnett's data [5] for water at p_r of 0.31 and that of Ahmed and Groeneveld [11] for R-12 at p_r between 0.15 and 0.4. All data were for internally heated cylindrical annuli. The reported results are very encouraging but the range of data analyzed is not wide enough to consider it as having been verified for general applicability.

Based on the available evidence as discussed above, the author considers the present correlation preferable to other general correlations. However for water in a limited range of parameters, specialized correlations such as that of Barnett [5] may be preferable because of their reported better accuracy.

SUMMARY AND CONCLUSION

1. A general graphical correlation for predicting CHF in annular channels has been developed. It has been thoroughly verified over a wide range of parameters for internally heated cylindrical annuli of annular gaps 1.5 mm and larger.

2. The correlation shows reasonably good agreement with data for other geometries among which are externally heated cylindrical annuli, cylindrical annuli heated on both sides, and heated rod in a square channel.

3. The correlation has been verified only for Newtonian non-metallic fluids. Data analysis is needed to determine its applicability to other fluids.

4. Further data analysis is needed to determine the applicability to very thin annular gaps. More data also need to be analyzed to fully establish the validity of this correlation for geometries other than cylindrical internally heated annuli, and also for $Y < 10^4$.

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UNE FORMULATION GENERALE DU FLUX THERMIQUE CRITIQUE DANS UN ESPACE ANNULAIRE

Résumé – On présente une formule générale pour prévoir le flux thermique critique dans un espace annulaire vertical. Elle a été vérifiée sur 800 points expérimentaux pour quatre fluides et la déviation moyenne est de 14%. Les données incluent les anneaux cylindriques et non cylindriques avec chauffage interne, ou externe, ou sur les deux cotés. Le domaine de variation des paramètres couvre des pressions réduites de 0,017 à 0,9, des flux massiques de 100 à 16 000 kg/m^2 s, des qualités d'entrée de − 3,1 à 0,00, des qualités critiques de − 2,8 à +0,74, des espaces annulaires de 0,5 à 11,1 mm et des diamètres de tube chauffé de 1,5 à 96,5 mm.

EINE ALLGEMEINE KORRELATION FÜR DIE KRITISCHE WÄRMESTROMDICHTE IN RINGRÄUMEN

Zusammenfassung – Zur Vorausbestimmung der kritischen Wärmestromdichte in senkrechten Ringräumen wird eine allgemeine Korrelation angegeben. Sie wurde an über 800 Meßpunkten für 4 Fluide geprüft, wobei sich eine mittlere Abweichung von 14% ergab. Die Werte beinhalten Messungen an zylindrischen und nichtzylindrischen Ringräumen mit innerer, äußerer und beidseitiger Beheizung. Der Parameter-Bereich ist: normierte Drücke von 0.017 bis 0.9; Massenstromdichten von 100 bis 16 000 kg/m^2 s; Eintritts-Massen-Dampfgehalte von −3.1 bis 0.00; kritische Massen-Dampfgehalte von −2.8 bis +0.74; Spaltweiten von 0.5 bis 11.1 mm; Durchmesser der beheizten Rohre von 1.5 bis 96.5 mm.

ОБОБЩЕННАЯ ЗАВИСИМОСТЬ ДЛЯ КРИТИЧЕСКОГО ТЕПЛОВОГО ПОТОКА В КОЛЬЦЕВЫХ КАНАЛАХ

Аннотация — Предложена обобщенная зависимость для расчета критического теплового потока в вертикальных кольцевых каналах. Ее справедливость была проверена на более чем 800 точках для четырех жидкостей, и обнаружено, что среднее отклонение не превышало 14%. Использовались данные для цилиндрических и нецилиндрических кольцевых каналов с внутренним, внешним и двусторонним подводом тепла. Рассматриваемые параметры менялись в следующих диапазонах: приведенное давление 0,017–0,9, плотность потока массы от 100 до 16 000 кг/м^{2}с, паросодержание на входе от −3,1 до 0,00, критическое паросодержание от −2,8 до 0,74, кольцевой зазор в пределах 0,5–11,1 мм и диаметр нагреваемой трубы от 1,5 до 96,5 мм.