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GENERAL FEATURES OF CHF OF FORCED CONVECTION BOILING IN UNIFORMLY HEATED RECTANGULAR CHANNELS

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Abstract—For the critical heat flux (CHF) of forced convection boiling in uniformly heated rectangular channels fed with the subcooled liquid, existing experimental data are analyzed to derive a generalized correlation of the data on the same principle as in the author's preceding studies on CHF of forced convection boiling in tubes and annuli. In addition, experiments made under special conditions of very small l/d_{he}, where l is the heated length of channel and d_{he} the heated equivalent diameter, are also investigated to confirm that the CHF under such conditions is nearly equal to the CHF of forced convection boiling on heated plane surfaces in a parallel flow.

NOMENCLATURE

- b, width of rectangular cross-section [m];
- C, constant, equation (3);
- d_{he}, heated equivalent diameter [m];
- G, mass velocity [kg m^{-2} s^{-1}];
- H_{fg}, latent heat of evaporation [J kg^{-1}];
- ΔH_i, inlet subcooling enthalpy [J kg^{-1}];
- K, inlet subcooling parameter, equation (6);
- l, length of heated plate [m];
- q_c, critical heat flux [W m^{-2}];
- q_{c0}, basic critical heat flux (q_c for $\Delta H_i = 0$) [W m^{-2}];
- s, height of rectangular cross section [m], defined as s = real height for type A, and s = twice real height for type B in Fig. 1;
- w, width of heated plate [m].

Greek symbols

- δ, thickness of heated plate [m];
- ρ_l, density of liquid [kg m^{-3}];
- ρ_v, density of vapor [kg m^{-3}];
- σ, surface tension [N m^{-1}].

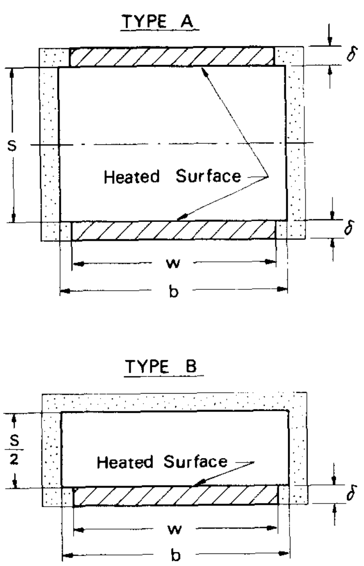

FIG. 1. Two types of rectangular cross-sections.

1. INTRODUCTION

FOR CRITICAL heat flux (CHF) in uniformly heated rectangular channels, Macbeth [1] presented an empirical correlation of water data, while many other studies assumed that the correlation proposed for CHF in round tubes could be used to predict CHF in rectangular channels. Recently, I have made studies of CHF in round tubes [2–7] and annuli [8, 9] to find a method capable of outlining the general framework of the above mentioned CHF. In this paper, therefore, the existing data of CHF in uniformly heated rectangular channels are analyzed to ascertain the general validity of the above method.

For rectangular channels with four side walls, overheating takes place in the corner of the cross-section near the exit end of the channel when all the side walls are heated. Accordingly this paper deals with the case of Fig. 1, where two facing side walls are equally heated in type A, while one side wall alone is heated in type B. The width of heated plate w is designed, in many cases, to be slightly shorter than that of rectangular cross-section b to avoid the danger of overheating in the corner. As for the height of rectangular cross-section, if the value of s is defined as shown in Fig. 1 for types A and B respectively, then the heated equivalent diameter d_{he} = (4 × flow area)/(heated perimeter) is given by the following equation in common for both type A and type B

$$d_{he} = 2sb/w. \qquad (1)$$

2. CRITICAL HEAT FLUX

2.1. *Data of* q_{c0}

Figure 2 shows examples of the relationship between

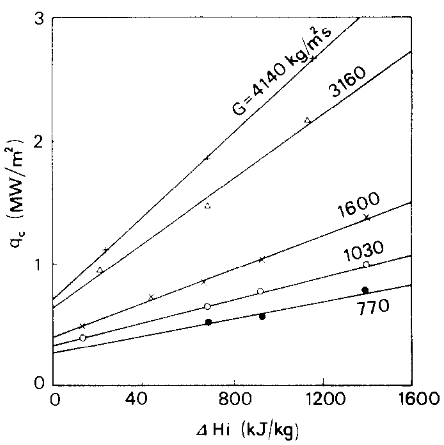

FIG. 2. Relationship between q_c and ΔH_i from the data of Troy [12]: water, p = 138 bar, l = 190 cm, s = 0.190 cm, b = w = 5.71 cm, and type A.

the critical heat flux q_c and the inlet subcooling enthalpy ΔH_i from the experimental data of Troy [12]. The basic critical heat flux q_{c0}, that is the value of q_c at $\Delta H_i = 0$, is readily determined from the relation such as shown in Fig. 2, and Table 1 lists the data sources and the experimental conditions for q_{c0} thus obtained. Among the data sources, however, Gambill and Bundy [13] give a data point of q_c for each set of separate values of G and ΔH_i, so that q_{c0} cannot be determined by the above method (see Section 2.4 for the indirect method to determine q_{c0}). The data of Tong, Efferding and Bishop [15] are also in the same form as above, but ΔH_i is kept near zero so that q_c can approximate to q_{c0}. In the experiment of Tippets [14], the thickness of heated plate δ is extremely small as 0.245 and 0.152 mm, accordingly the data for δ = 0.254 mm alone are adopted in Table 1 to avoid the effect of δ on CHF as much as possible. All the experimental studies listed in Table 1 are those made for vertical upward boiling flow except the experiment of Gambill and Bundy which was made for vertical downward boiling flow. The studies of Levy, Fuller and Niemi [16], Chernobay [17], and others based on experiments of the whole perimeter heating are excepted from Table 1.

2.2. *Generalized correlation of* q_{c0}

The data of q_{c0} obtained in the preceding section are classified by nominal values of l/d_{he}, and then plotted in Fig. 3 in the same dimensionless form as for tubes [5] and annuli [9]. According to Table 1, ρ_v/ρ_l takes magnitudes on the order of the value of saturated water at 69 bar (that is, $\rho_v/\rho_l = 0.048$), except the data of Tong, Efferding and Bishop [15], for which ρ_v/ρ_l is very small. Therefore, in the same manner as in the cases of tubes [5] and annuli [9], the data of [15] are corrected by multiplying q_{c0} by $[0.048/(\rho_v/\rho_l)]^{0.133}$ when plotted in Fig. 3.

Meanwhile, the straight lines (a), (b), (c) and (d) in Fig. 3 represent the following equations, respectively

Table 1. Summary of the collected data of q_{c0} and K

Source	Fluid	Type	l(cm)	s(cm)	b(cm)	w/b	l/d_{he}	$(\rho_v/\rho_l) \times 10^2$	$\sigma\rho_l/G^2l$	No. of data	δ(mm)
[11]	Water	A	15.2	0.257	2.54	0.880	26.1	3.67–13.6	2.80×10^{-5}–5.61×10^{-3}	10	1.27
[11]	Water	A	30.6	0.246	2.54	0.880	54.7	13.6	9.43×10^{-7}–3.11×10^{-4}	8	1.27
[11]	Water	A	30.6	0.127	2.54	0.880	106	2.61–13.6	3.06×10^{-6}–2.12×10^{-4}	8	1.27
[11]	Water	A	68.6	0.246	2.54	0.880	122	3.67–13.6	3.00×10^{-7}–8.53×10^{-5}	10	1.27
[11]	Water	A	68.6	0.150	2.54	0.880	201	3.67–13.6	3.02×10^{-6}–3.46×10^{-4}	7	1.27
[12]	Water	A	190	0.190–0.195	5.71	~1.0	487–500	6.16–13.6	1.24×10^{-7}–1.99×10^{-5}	9	—
[13]	Water	A	30.5–30.8	0.109–0.125	2.65–2.73	0.930–0.958	114–132	1.96–2.42	7.45×10^{-7}–1.03×10^{-6}	3*	1.52
[14]	Water	A	94.0	0.635	5.33	1.00	74.0	4.84	3.65×10^{-6}–5.97×10^{-5}	3	0.254
[14]	Water	A	94.0	1.27	5.33	1.00	37.0	4.84	1.43×10^{-5}–5.55×10^{-5}	2	0.254
[14]	Water	B	94.0	2.54	5.33	1.00	18.5	4.84	1.41×10^{-5}	1	0.254
[15]	R-113	B	63.5	1.27	6.03	~1.0	25.0	0.587–0.719	6.97×10^{-6}–1.28×10^{-4}	3	∞†

* Data for nickel test section.
† Very thick heated plate.

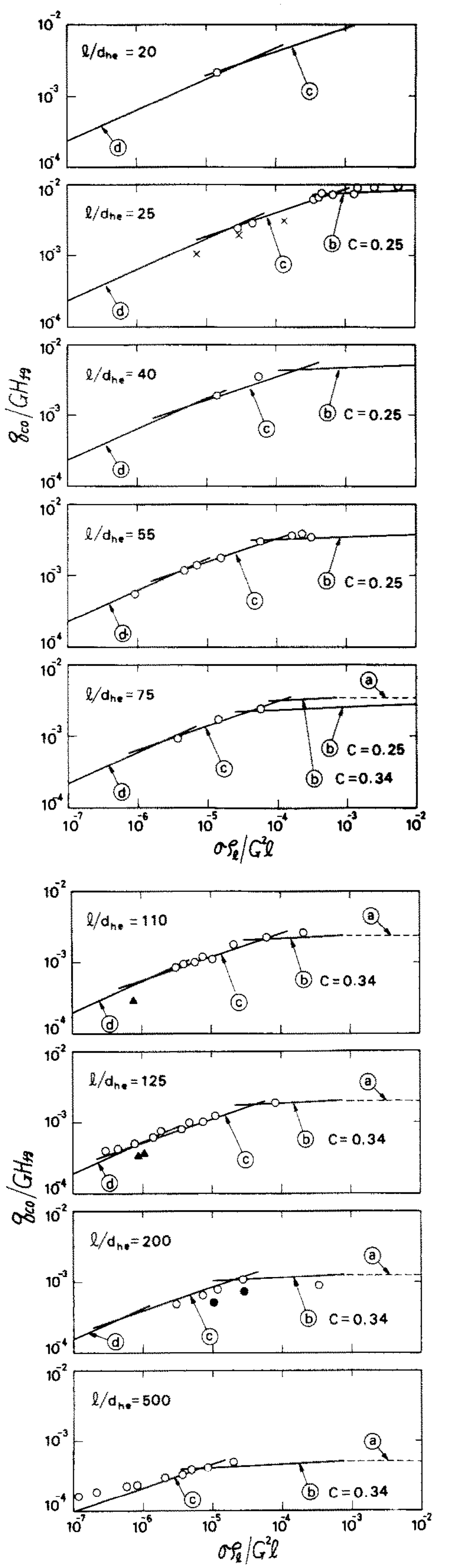

FIG. 3. Generalized graphic representation of q_{c0} data. (a) equation (2), (b) equation (3), (c) equation (4) with $\rho_v/\rho_l = 0.048$, (d) equation (5) with $\rho_v/\rho_l = 0.048$.

$$\text{(a)}\quad \frac{q_{c0}}{GH_{fg}} = 0.25\frac{1}{l/d_{he}} \tag{2}$$

$$\text{(b)}\quad \frac{q_{c0}}{GH_{fg}} = C\left(\frac{\sigma\rho_l}{G^2 l}\right)^{0.043}\frac{1}{l/d_{he}} \tag{3}$$

$$\text{(c)}\quad \frac{q_{c0}}{GH_{fg}} = 0.15\left(\frac{\rho_v}{\rho_l}\right)^{0.133}\left(\frac{\sigma\rho_l}{G^2 l}\right)^{1/3} \times \frac{1}{1+0.0077\,l/d_{he}} \tag{4}$$

$$\text{(d)}\quad \frac{q_{c0}}{GH_{fg}} = 0.26\left(\frac{\rho_v}{\rho_l}\right)^{0.133}\left(\frac{\sigma\rho_l}{G^2 l}\right)^{0.433} \times \frac{(l/d_{he})^{0.171}}{1+0.0077\,l/d_{he}} \tag{5}$$

on the condition of $\rho_v/\rho_l = 0.048$ for equations (4) and (5). In Fig. 3, it is noticed that there are few data in the regimes represented by the lines (a) and (b). It is almost impossible to derive correlation equations from such few data; and equations (2) and (3) tentatively used above are nothing but the correlation equations obtained for the CHF in tubes [5]. Nevertheless, it may be noted that the line (b) in Fig. 3 agrees fairly well with the existing data if the constant C on the RHS of equation (3) is assumed to be 0.25 for small l/d_{he} and 0.34 for large l/d_{he} in the same manner as in the case of tubes [5].

Next, it is clearly noticed in Fig. 3 that most of the existing data appear in the regime represented by the line (c), and equation (4) giving the line (c) is the one determined so as to fit in with these data. However, there are a few singular data points in Fig. 3, on which the following remarks will be given. Three data points denoted by × for $l/d_{he} = 25$ in Fig. 3 are those of R-113 obtained by Tong, Efferding and Bishop [15]. The trend of Freon data appearing slightly lower than water data has already been observed for tubes [5] and annuli [9], but it must be noted here that since the experiment of Tong, Efferding and Bishop was made in a channel heated by condensing steam, there might be a possibility of deviating from the uniform heat flux condition. Meanwhile, three data points denoted by a solid triangle for $l/d_{he} = 110$ and 125 in Fig. 3 are the special ones of Gambill and Bundy [13] which has been mentioned in Section 2.1. According to the result of Fig. 6 in the preceding study [3], for example, there is a trend that q_{c0} for downflow is lower than that for upflow, but the data shown by solid triangles in Fig. 3 seem to be too low, and the cause may be ascribed to the error induced by the indirect determination of q_{c0} (see Section 2.4). On the other hand, two data points denoted by the solid circle for $l/d_{he} = 200$ in Fig. 3 belong to the total of 43 data of DeBortoli *et al.* [11] listed in Table 1. However, the two data alone show abnormalities not only in Fig. 3 but also in Fig. 4 for the effect of inlet subcooling enthalpy on CHF (see Section 2.4).

Finally, it is noted in Fig. 3 that there are scarcely any data in the regime represented by the line (d).

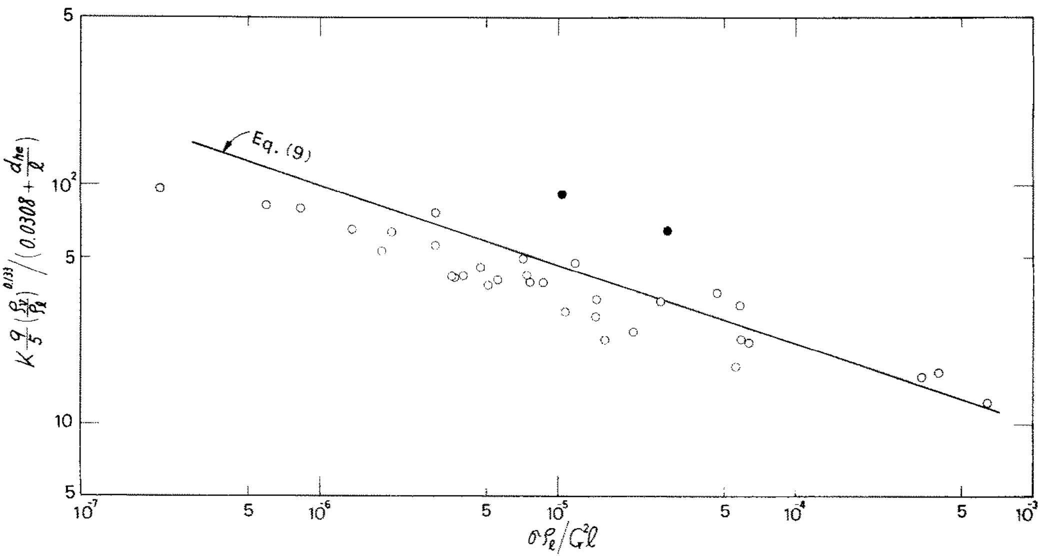

FIG. 4. Comparison between prediction of equation (9) and experimental data for K.

Equation (5), which gives the line (d), is no more than a tentative equation determined by modifying the correlation equation for annuli [8, 9] so as to fit a few data in Fig. 3 for $l/d_{he} = 55$ and 125.

2.3. *Remarks on characteristic regimes of CHF*

In my studies on CHF in tubes [6, 7], CHF has been classified into four characteristic regimes called L, H, N and HP, where L-regime is the one corresponding to low mass velocities, N-regime to very high mass velocities, H-regime is the intermediate one between L- and N-regime, and HP-regime is the regime that replaces N-regime when the system pressure is very high.

For rectangular channels, the boundary between L- and H-regime can be determined by the intersecting point of the lines (b) and (c) in Fig. 3. However, the equation to predict the boundary between H- and N-regime cannot be obtained because of lack of the existing data for N-regime which is characterized by the non-linear relationship between q_c and ΔH_i.

In the case of $l/d_{he} = 500$ in Fig. 3, a special trend is noted for a few data of Troy [12] near the left end to deviate upward from the line (c). For these data, ρ_v/ρ_l is rather high as 0.136, and l/d_{he} is very high as 500, so that the deviation from the line (c) may be regarded as resulting from the generation of HP-regime. If the criterion obtained for the onset of HP-regime in tubes [6] is tentatively applied to this case, it shows that the above-mentioned data certainly satisfy the conditions of entering into HP-regime.

2.4. *Generalized correlation of* K

The experimental data collected in Section 2.1 exhibit a linear relationship between q_c and ΔH_i such as shown in Fig. 2, for which the following equation can be written

$$q_c = q_{c0}\left(1 + K\frac{\Delta H_i}{H_{fg}}\right) \tag{6}$$

where K is the dimensionless parameter for the effect of inlet subcooling enthalpy ΔH_i, and is obtainable from the experimental data. Meanwhile, according to a preceding paper [4], if it is assumed that the concept of boiling length holds for the inlet subcooling condition of $(G\Delta H_i/q_c)/(4l/d) \ll 1$, then K can be derived theoretically from equations (2)–(4), respectively as follows:

from equation (2)

$$K = 1 \tag{7}$$

from equation (3)

$$K = \frac{1.043}{4C(\sigma\rho_l/G^2 l)^{0.043}} \tag{8}$$

from equation (4),

$$K = \frac{5}{9}\frac{0.0308 + d_{he}/l}{(\rho_v/\rho_l)^{0.133}(\sigma\rho_l/G^2 l)^{1/3}}. \tag{9}$$

As has been pointed out in Section 2.2, the greater part of the existing data is in the regime represented by the line (c) in Fig. 3 or equation (4). Therefore, the experimental K can be compared with the prediction of equation (9) to give the result of Fig. 4. Two data points denoted by solid circles in Fig. 4 correspond to the singular data points of the same symbol in Fig. 3. The rest of the data points have a similar trend to that of equation (9) for the variation with $\sigma\rho_l/G^2 l$, but statistically speaking, their magnitudes are about 20% below the prediction of equation (9) for unknown reasons.

It is noted here that the data of q_{c0} denoted by solid triangles in Fig. 3 are those determined by equation (6) for experimental conditions of q_c, ΔH_i and H_{fg}, assuming K to be 80% of the value predicted by equation (9).

Table 2. Summary of the data of q_{c0} for very small l/d_{he}

Source	Fluid	Type	l(cm)	s(cm)	b(cm)	w/b	l/d_{he}	$(\rho_v/\rho_l)\times 10^2$	$\sigma\rho_l/G^2l$	No. of data	δ(mm)
[18]	Water	B	30.0	2.20	1.70	0.882	6.02	0.0624	8.37×10^{-3}–9.31×10^{-2}	5	∞*
[19, 20]	Water	B	12.7	1.27	0.652	0.896	4.47	0.0624	1.11×10^{-5}–2.79×10^{-4}	4	0.178
[19, 20]	Water	B	12.7	1.27	0.952	0.613	3.07	0.0624	1.11×10^{-5}–2.79×10^{-4}	2	0.178
[21]	Water	B	1.00	0.600	1.80	0.833	0.694	0.0624	1.01×10^{-4}–1.23×10^{-3}	10	∞*
[21]	Water	B	1.50	1.00	1.80	0.833	0.625	0.0624	1.33×10^{-4}–8.24×10^{-4}	9	∞*
[21]	Water	B	1.00	1.00	1.80	0.833	0.417	0.0624	2.38×10^{-4}–4.73×10^{-3}	10	∞*

* Very thick heated plate.

3. CHF FOR VERY SMALL l/d_{he}

In a preceding study [9] on CHF in annuli with inside heating, I showed that when l/d_{he} decreased to the magnitude of about 1 to 5, the experimental data of q_{c0} deviated from the generalized correlation in the form of Fig. 3. Then, Katto and Kurata [10] made an experimental study on CHF of forced convection boiling of water and R-113 on uniformly heated plane surface submerged in a parallel flow to derive the following generalized correlation equation

$$\frac{q_{c0}}{GH_{fg}} = 0.186\left(\frac{\rho_v}{\rho_l}\right)^{0.559}\left(\frac{\sigma\rho_l}{G^2l}\right)^{0.264} \tag{10}$$

and showed that equation (10) also agrees with the existing data of q_{c0} for acetone, toluene, monoisopropylbiphenyl and water flowing through internally heated annuli of very small l/d_{he}.

A similar situation is expected for the CHF in rectangular channels too, and Table 2 lists the data sources collected for q_{c0} in the case of very small l/d_{he}. All the studies listed in Table 2 are made with the channels of type B in Fig. 1, and the study of Isshiki *et al.* [18] for horizontal flow with bottom heating, Yücel and Kakaç [19] on the second line in Table 2 for horizontal flow with either bottom or top heating, Yücel and Kakaç on the third line in Table 2 for vertical upflow, and Goto for horizontal flow with top heating (the experiment of Yücel and Kakaç has been confirmed [20] to be made under conditions of l = 127 mm and w = 5.84 mm).

In Fig. 5, the data of q_{c0} mentioned above are compared with two lines (c) and (d) based on correlation equations (4) and (5) for rectangular channels, and with a line based on correlation equation (10) for plane surfaces in a parallel flow. All the data of q_{c0} are those obtained for water at atmospheric pressure (see Table 2), so that ρ_v/ρ_l is taken as 0.000624 for three equations (4), (5) and (10) represented in Fig. 5.

It is noted in Fig. 5 that for l/d_{he} = 6.0, the experimental data (of Isshiki *et al.* [18]) still appear near the line (c). The data for l/d_{he} = 3.0 and 4.5 in Fig. 5 are those of Yücel and Kakaç [19] showing that q_{c0} differs slightly from each other for vertical upflow, horizontal flow with bottom heating or top heating, and Yücel and Kakaç ascribed the difference to the effect of gravity. However, now apart from this problem, it may be noticed that the experimental data for l/d_{he} = 3.0 and 4.5 are much nearer the line of equation (10) than the lines (c) and (d). As is seen in Table 2, these data are those of the experiment made with a very thin heated plate (δ = 0.178 mm), so that there is a possibility of giving somewhat lower values of q_{c0} than usual. However, the experimental data of Goto [21] for l/d_{he} = 0.5 in Fig. 5 are those obtained with a very thick heated plate. To sum up, therefore, it may be concluded that q_{c0} in rectangular channels of very small l/d_{he} takes the value near the prediction of equation (10).

Finally, the result of Fig. 5 suggests a possibility that when l/d_{he} becomes very small, q_{c0} may be affected by

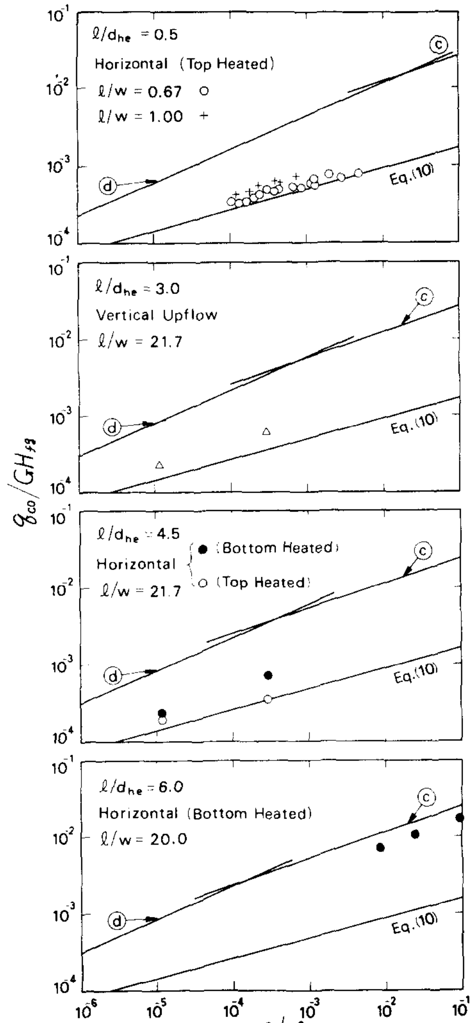

FIG. 5. Generalized graphic representation of q_{c0} data of water at atmospheric pressure ($\rho_v/\rho_l = 0.000624$) in the case of very small l/d_{he}.

length to width ratio of heated plate l/w. However, further studies are needed on the complicated effects of l/d_{he} and l/w on CHF in this special regime.

4. CONCLUSIONS

(1) For forced convection boiling in uniformly heated rectangular channels, existing data of CHF are analyzed to give the generalized correlation of Fig. 3 for the basic critical heat flux q_{c0} and that of Fig. 4 for the inlet subcooling parameter K. In addition, q_{c0} for very small l/d_{he} is investigated to give the result of Fig. 5.

(2) The existing data of CHF in rectangular channels are very limited in number, experimental condition, and kind of test fluid (see Tables 1 and 2). Further experimental studies are needed to accomplish the generalized correlation of CHF of course. However, the present study has suggested that CHF in rectangular channels is similar in character to CHF in tubes for which general frameworks are comparatively well known [5, 6]. Viewed at this angle, even the results obtained in this paper may be rather useful for estimating CHF in rectangular channels under various conditions as long as high accuracies are not required.

(3) For L-regime of CHF in annuli with inside heating, the author [8, 9] tentatively assumed a single value $C = 0.25$ on the RHS of equation (3) because of lack of the existing data of annuli in this regime. However, the result of Fig. 3 for rectangular channels seems to cooperate with the result for tubes [5] to suggest that the value of C may change between 0.25 and 0.34 for annuli too according to the magnitude of l/d_{he}.

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CONFIGURATIONS GENERALES DU CHF EN EBULLITION AVEC CONVECTION FORCEE DANS DES CANAUX RECTANGULAIRES UNIFORMEMENT CHAUFFES

Résumé — Pour le flux critique (CHF) en ébullition avec convection forcée dans des canaux rectangulaires alimentés en liquide sous-refroidi, des données expérimentales sont analysées pour obtenir une formule générale sur les mêmes principes que dans les précédentes études de l'auteur pour les tubes et les espaces annulaires. De plus, des expériences faites dans des conditions spéciales de faible l/d_{he} où l est la longueur chauffé du canal et d_{he} le diamètre équivalent chauffé, sont étudiées pour confirmer que, dans ces conditions, le CHF est presque égal au CHF d'ébullition en convection forcée sur des surfaces planes chaudes et un écoulement parallèle.

ALLGEMEINE CHARAKTERISTIK DER KRITISCHEN WÄRMESTROMDICHTE BEIM STRÖMUNGSSIEDEN IN GLEICHMÄSSIG BEHEIZTEN, RECHTECKIGEN KANÄLEN

Zusammenfassung—Zur Ermittlung der kritischen Wärmestromdichte beim Strömungssieden von unterkühlter Flüssigkeit in gleichmaßig beheizten, rechteckigen Kanälen werden vorhandene Versuchsdaten mit dem Ziel ausgewertet, eine allgemeine Korrelation der Daten zu ermitteln. Dabei wird dasselbe Prinzip wie in den früheren Arbeiten des Autors über die kritische Wärmestromdichte beim Strömungssieden in Rohren und Ringspalten angewandt. Darüber hinaus werden Versuche unter den besonderen Bedingungen eines sehr kleinen Verhältnisses L/d_{he} durchgeführt, wobei L die beheizte Länge des Kanals und d_{he} der beheizte äquivalente Durchmesser ist. Bei diesen Untersuchungen zeigt sich, daß die kritische Wärmestromdichte unter derartigen Bedingungen nahezu gleich groß ist wie beim Strömungssieden an beheizten, ebenen Oberflächen in einer Parallelströmung.

ОБЩИЕ ХАРАКТЕРИСТИКИ КРИТИЧЕСКОГО ТЕПЛОВОГО ПОТОКА ПРИ КИПЕНИИ В УСЛОВИЯХ ВЫНУЖДЕННОЙ КОНВЕКЦИИ В РАВНОМЕРНО НАГРЕВАЕМЫХ ПРЯМОУГОЛЬНЫХ КАНАЛАХ

Аннотация — Проведен анализ экспериментальных данных по критическому тепловому потоку (КТП) при кипении в условиях вынужденной конвекции в равномерно нагреваемых прямоугольных каналах, в которые поступает недогретая жидкость. Анализ выполнен с целью получения обобщенного соотношения по тому же принципу, что и в ранее проведенных автором исследованиях КТП при кипении в условиях вынужденной конвекции в трубах и кольцевых каналах. Кроме того, проведены эксперименты при малых значениях l/d_{he} (где l — длина нагреваемого участка канала, а d_{he} — эквивалентный диаметр нагрева) для проверки предположения о том, что КТП в рассматриваемых условиях примерно равен КТП при кипении с вынужденной конвекцией на плоских поверхностях нагрева в параллельном потоке.