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An improved version of the generalized correlation of critical heat flux for the forced convective boiling in uniformly heated vertical tubes

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Abstract—One of the present authors proposed previously a generalized correlation of the critical heat flux (CHF) of forced convective boiling in uniformly heated tubes. However, through various studies made subsequently on the related problems, it has been revealed that there are a few questionable points in the foregoing correlation to be solved or to be revised. In the present study, therefore, careful experiments have been attempted with an identical test tube covering all the main characteristic regimes of CHF. The systematic data thus obtained are then used together with the other recent findings to solve the pending problems mentioned above. As a result, an improved version of the generalized correlation is successfully developed, being accompanied with a very clear-cut structure as compared with the previous correlation.

1. INTRODUCTION

A GENERALIZED correlation of the critical heat flux (CHF) of forced convective boiling in uniformly heated tubes was presented previously by one of the present authors [1], where the CHF q_c at an inlet subcooling enthalpy ΔH_i and a latent heat of evaporation H_{fg} was written as

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

and the basic CHF q_{co} as well as the inlet subcooling parameter K thus defined was correlated as follows.

First, as for q_{co}, the following four equations are given so as to be employed depending on given conditions

$$\frac{q_{co}}{GH_{fg}} = C\left(\frac{\sigma\rho_l}{G^2 l}\right)^{0.043}\frac{1}{l/d} \tag{2}$$

$$\frac{q_{co}}{GH_{fg}} = 0.10\left(\frac{\rho_v}{\rho_l}\right)^{0.133}\left(\frac{\sigma\rho_l}{G^2 l}\right)^{1/3}\frac{1}{1+0.0031\,l/d} \tag{3}$$

$$\frac{q_{co}}{GH_{fg}} = 0.098\left(\frac{\rho_v}{\rho_l}\right)^{0.133}\left(\frac{\sigma\rho_l}{G^2 l}\right)^{0.433}\frac{(l/d)^{0.27}}{1+0.0031\,l/d} \tag{4}$$

$$\frac{q_{co}}{GH_{fg}} = 0.0384\left(\frac{\rho_v}{\rho_l}\right)^{0.60}\left(\frac{\sigma\rho_l}{G^2 l}\right)^{0.173} \times \frac{1}{1+0.280(\sigma\rho_l/G^2 l)^{0.233}(l/d)} \tag{5}$$

where G is the mass velocity through the tube, σ the surface tension, ρ_l the liquid density, l the length of heated tube, d the internal diameter of the tube, and ρ_v the vapor density. The value of the dimensionless parameter C on the RHS of equation (2) has been determined empirically through subsequent studies [2–4] as follows

$$C = 0.25 \quad \text{for} \quad l/d < 50,$$

$$C = 0.25 + 0.0009\{(l/d) - 50\} \quad \text{for} \quad l/d = 50\text{–}150,$$

and

$$C = 0.34 \quad \text{for} \quad l/d > 150.$$

Equation (5) is the correlation that has been revised in the study of ref. [4].

Next, as for K, the boiling length concept is used to derive the correlation equations of K from the foregoing equations, equations (2)–(5), for q_{co} [5], giving the following equations corresponding to equations (2)–(5), respectively

$$K = \frac{1.043}{4C(\sigma\rho_l/G^2 l)^{0.043}} \tag{6}$$

$$K = \frac{5}{6}\cdot\frac{0.0124 + d/l}{(\rho_v/\rho_l)^{0.133}(\sigma\rho_l/G^2 l)^{1/3}} \tag{7}$$

$$K = 0.416\frac{(0.0221 + d/l)(d/l)^{0.27}}{(\rho_v/\rho_l)^{0.133}(\sigma\rho_l/G^2 l)^{0.433}} \tag{8}$$

$$K = 1.12\frac{1.52(\sigma\rho_l/G^2 l)^{0.233} + d/l}{(\rho_v/\rho_l)^{0.60}(\sigma\rho_l/G^2 l)^{0.173}}. \tag{9}$$

A fairly good correspondence between the foregoing generalized correlation and the experimental data was found through the above-mentioned studies [1–5], but later studies have disclosed that there are problems such as those mentioned below.

(1) The value of q_{co} is predicted by equations (2)–(5) in the manner to be continuous in magnitude at each boundary between the adjoining two equations, when the value of K predicted by equations (6)–(9) becomes discontinuous at the above-mentioned boundary. In order to escape from this dilemma, a tentative method

NOMENCLATURE

C dimensionless parameter, equation (2)
d internal diameter of tube [m]
G mass velocity through tube [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 (1)
l heated length of tube [m]
p absolute pressure [MPa]
q_c critical heat flux [W m^{-2}]
q_{co} basic critical heat flux, equation (1) [W m^{-2}].

Greek symbols
ρ_l liquid density [kg m^{-3}]
ρ_v vapor density [kg m^{-3}]
σ surface tension [N m^{-1}]
χ_{ex} exit quality at critical heat flux condition

was attempted in ref. [6] of taking an average of the two different values of K near the boundary. However, there is no physical justification for this means.

(2) Equation (5) is the correlation of the q_{co} data obtained under the condition that the system pressure is extremely high (in other words, the vapor-to-liquid density ratio ρ_v/ρ_l is near unity), and at the same time, the mass velocity G is very high. However, when equation (5) was derived in ref. [4], there were no systematic data of the CHF obtained at very high density ratios except for those of water obtained for $l/d > 100$ and liquid helium obtained for $l/d < 51$, and that the liquid helium data for $l/d < 51$ did not agree with equation (5), but agreed with equation (4). Hence a very sophisticated criterion for the application of equation (5) was tentatively derived by taking into account not only the effect of ρ_v/ρ_l but also that of l/d so as to match the exceptional nature observed under the test conditions of liquid helium. However, facing the need to ascertain the applicability of equation (5) to fluids other than water as well as the general validity of the above-mentioned tentative criterion, the following three experiments were carried out successively: the first [7] with R-12 for $d = 3$ and 5 mm, $l/d = 200$ and 333, $\rho_v/\rho_l = 0.109$–0.306, $G = 1100$–8800 kg m^{-2} s^{-1}; the second [8] with R-12 for $d = 5$ mm, $l/d = 50$, $\rho_v/\rho_l = 0.109$–0.306, $G = 700$–7000 kg m^{-2} s^{-1}; and the third [9] with liquid helium for $d = 1$ mm, $l/d =$ 25–200, $\rho_v/\rho_l = 0.409$, $G = 10.5$–108 kg m^{-2} s^{-1}. In consequence, it has been revealed that equation (5) is applicable to R-12 and liquid helium as well, whereas the foregoing criterion for the application of equation (5) must be discarded.

(3) In parallel with the foregoing experiments of R-12 [7, 8], Nishikawa *et al.* [10] also carried out experiments of CHF with R-22 for $d = 13$ mm, $l/d = 154$, $\rho_v/\rho_l = 0.187$–0.517, $G = 200$–1300 kg m^{-2} s^{-1}, and with R-115 for $l/d = 154$, $\rho_v/\rho_l = 0.184$–0.394, $G = 400$–1300 kg m^{-2} s^{-1}. They analyzed their data thus obtained using the boiling length concept to make an approximate estimation of q_{co} for various values of l/d between 10 and 154, resulting in the presentation of the following correlation equations of q_{co}

$$\frac{q_{co}}{GH_{fg}} = 0.60\left(\frac{\rho_v}{\rho_l}\right)^{0.19}\left(\frac{\sigma\rho_l}{G^2 l}\right)^{0.16}\frac{1}{(l/d)^{0.84}} \quad (10)$$

$$\frac{q_{co}}{GH_{fg}} = 0.63\left(\frac{\rho_v}{\rho_l}\right)^{0.88}\left(\frac{\sigma\rho_l}{G^2 l}\right)^{0.50}\frac{(l/d)^{0.50}}{1+0.011\, l/d} \quad (11)$$

$$\frac{q_{co}}{GH_{fg}} = 9.8\times10^{-4}\frac{1}{1+0.0032(\rho_v/\rho_l)^{-0.72} l/d}. \quad (12)$$

When the Nishikawa equations, equations (10)–(12), are compared with the present authors' equations, equations (2)–(5), it is noticeable that equation (10) has an intermediate character between equations (2) and (3), while equations (11) and (12) correspond to equations (4) and (5), respectively. However, all the Nishikawa equations are based on the experimental data of R-22 and R-115 obtained at very high pressures, whereas the present authors' first two, equations (2) and (3), are originally the correlations of the data of various fluids obtained at low and intermediate pressures though intended for use under very high pressures as well. Thus the validity of equations (2) and (3) needs to be examined with the experimental data obtained at very high pressures.

Problems (1)–(3) mentioned so far strongly suggest the need to solve these problems and to make improvements on the authors' generalized correlation of CHF based on equations (2)–(9). Hence the present study has been attempted in the following way. First, coherent data are obtained with an identical tube covering all the operating regimes of equations (2)–(5). The data thus obtained are then used to solve the foregoing problems, and finally the authors' generalized correlation of CHF in tubes is revised.

2. EXPERIMENTAL APPARATUS AND RESULTS

2.1. *Experimental apparatus*

Figure 1 shows schematically the experimental apparatus used in this study, which is a new apparatus with a larger capacity than that in previous studies [7, 8] though of the same principle. Part of the test liquid flowing out of circulating pumps, passes through two parallel flow meters, an electric preheater and a precooler successively to enter the test section with a prescribed mass velocity and subcooling, and the two-phase flow from the test section is introduced to a pressurizer equipped with a spray condenser as well as a

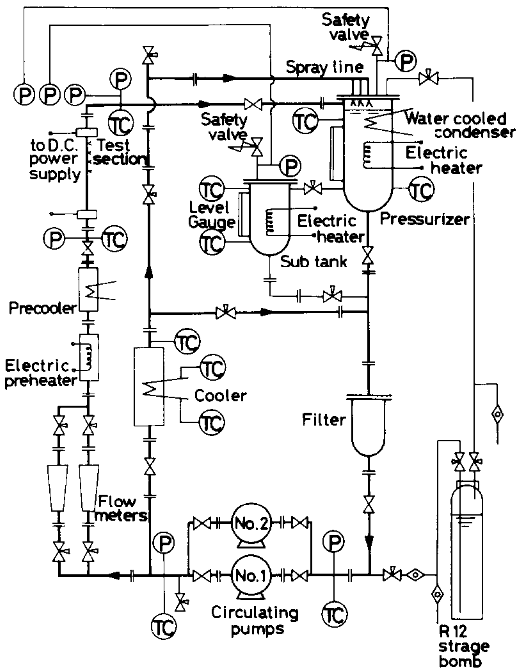

FIG. 1. Experimental apparatus (P, pressure gauge; TC, thermocouple).

water-cooled condenser. The system pressure is kept at a prescribed value by adjusting the temperature of the saturated liquid stored in the pressurizer with the aid of an electric heater.

The test section is a stainless steel tube of 10 mm I.D. and 12 mm O.D. heated by the direct passage of a DC current. The temperature excursion of CHF is detected by a chromel–alumel thermocouple spot-welded to the outer wall of the test tube at a location about 10 mm upstream of the exit end of the test section, when a circuit breaker of DC current is operated automatically. For the sake of caution, eleven other thermocouples are additionally mounted along the test tube length at nearly equal intervals to detect the anomalous upstream CHF if it occurs.

2.2. *Experimental data*

Using R-12 as a test fluid, experiments have been performed under the following conditions without the onset of upstream CHF.

- Tube diameter: $d = 0.010$ m.
- Heated length: $l = 1.00$ m.
- Pressure: $p = 1.96$–3.44 MPa (corresponding density ratio $\rho_v/\rho_l = 0.109$–0.306).
- Mass velocity: $G = 120$–2100 kg m^{-2} s^{-1}.
- Inlet subcooling enthalpy: $\Delta H_i = 0.4$–39.9 kJ kg^{-1}.

All the raw data of CHF thus obtained are plotted in Figs. 2 and 3.

3. ANALYSIS OF EXPERIMENTAL DATA

3.1. *Regularities observed in raw data*

Experimental data in Figs. 2 and 3 appear to exhibit the following systematic characteristics.

First, the data points in Figs. 2 and 3 represent a linear relationship between q_c and ΔH_i for a fixed value of G. As for this regularity, it must be added that the quality χ_{ex} at the tube exit end is calculated to be positive for all the data points shown in Figs. 2 and 3 without exception.

Second, it is noticeable on the LHS of Fig. 2 for $p = 1.96$ MPa that the group of data points for $G \geq 906$ kg m^{-2} s^{-1} has a characteristic of converging on a single value of q_c at $\Delta H_i = 0$. Then, as is seen in Fig. 3, this group of data points tends to the lower part of the diagram with increasing pressure, causing a new group of data points to appear behind it such as the

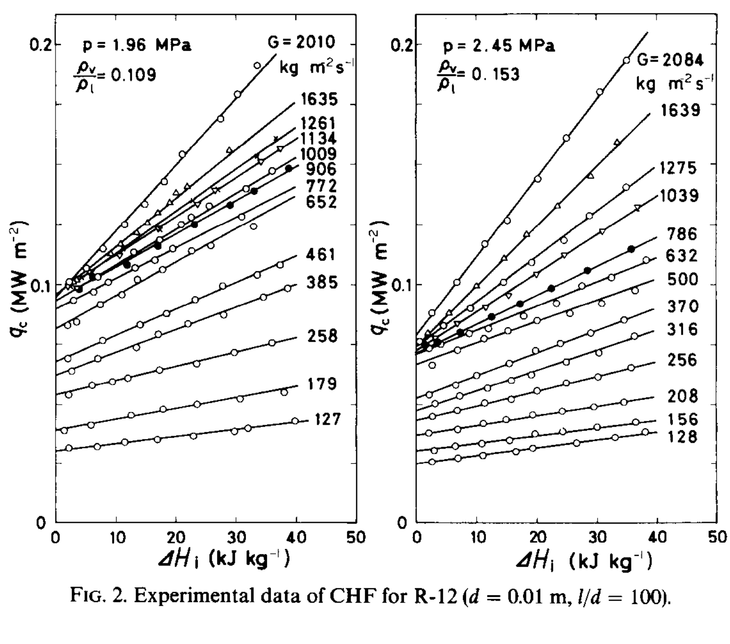

FIG. 2. Experimental data of CHF for R-12 ($d = 0.01$ m, $l/d = 100$).

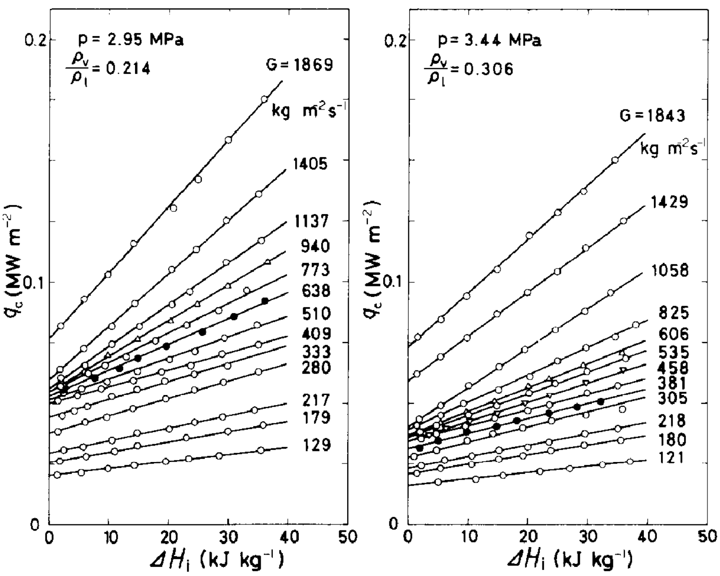

FIG. 3. Experimental data of CHF for R-12 ($d = 0.01$ m, $l/d = 100$).

group for $G \geqslant 1405$ kg m^{-2} s^{-1} at 2.95 MPa and the group for $G \geqslant 1058$ kg m^{-2} s^{-1} at 3.44 MPa. This new group is characterized by the nature that the gradient of the linear $q_c/\Delta H_i$ relationship is kept rather constant independent of the change of G.

3.2. *Experimental data of* q_{co}

Owing to the first regularity (linear $q_c/\Delta H_i$ relationship) mentioned in the last section, the respective values of q_{co} and K on the RHS of equation (1) can be evaluated for each set of data with a fixed G in Figs. 2 and 3.

First, Figs. 4 and 5 represent all the experimental data of q_{co} thus obtained, and Fig. 6 shows a comparison of equations (3) and (4) with the same data points as those plotted in the bottom diagram of Fig. 5. When ρ_v/ρ_l is comparatively low as in the top diagram of Fig. 4, the data points of q_{co} agree well with the prediction of equations (2)–(4). However, Fig. 6 shows that when ρ_v/ρ_l is sufficiently high, the data points of q_{co} agree well with the predictions of equations (2) and (5), but disagree with the prediction of either equation (3) or equation (4) in the intermediate region. A simple analysis has been attempted to show that the data in the foregoing intermediate region can be correlated well by the following equation, that is a modified form of equation (4)

$$\frac{q_{co}}{GH_{fg}} = 0.234\left(\frac{\rho_v}{\rho_l}\right)^{0.513}\left(\frac{\sigma\rho_l}{G^2 l}\right)^{0.433}\frac{(l/d)^{0.27}}{1+0.0031\,l/d}. \tag{13}$$

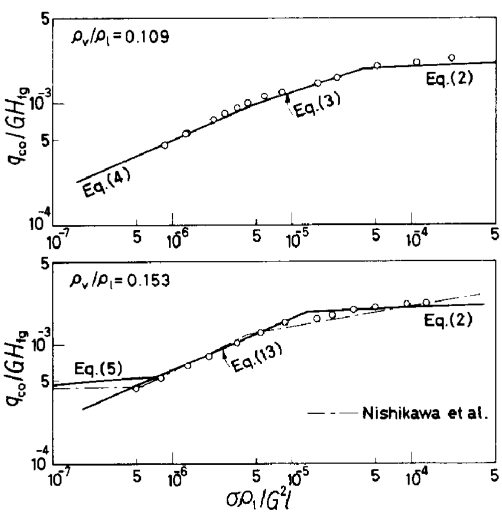

FIG. 4. Comparison between the experimental and the predicted q_{co} for R-12 ($d = 0.01$ m, $l/d = 100$): —·—, prediction of equations (10)–(12).

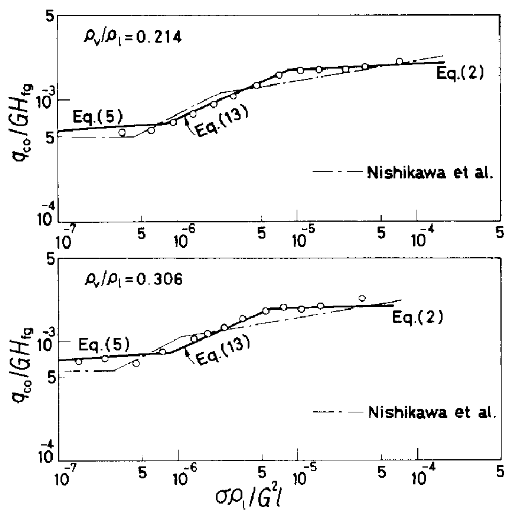

FIG. 5. Comparison between the experimental and the predicted q_{co} for R-12 ($d = 0.01$ m, $l/d = 100$): —·—, prediction of equations (10)–(12).

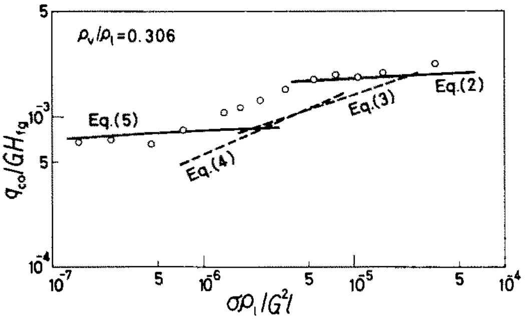

FIG. 6. Comparison between the experimental and the predicted q_{co} for R-12 (d = 0.01 m, l/d = 100).

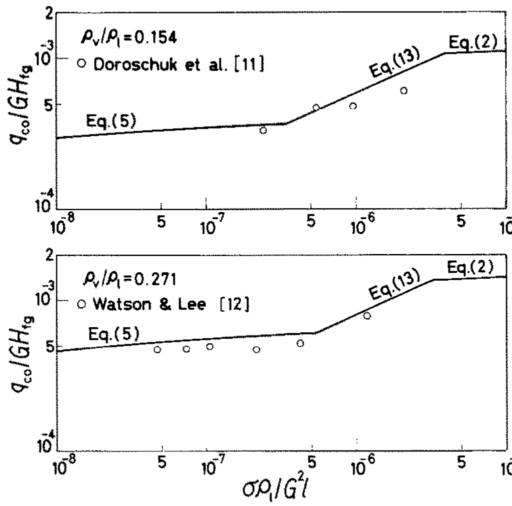

FIG. 8. Comparison between the experimental and the predicted q_{co} for water (top diagram, d = 0.008 m, l/d = 187.5; bottom diagram, d = 0.0387 m, l/d = 145).

In fact, it will be noted in Figs. 4 and 5 that the data points of q_{co} for $\rho_v/\rho_l = 0.153$, 0.214 and 0.306 agree well with the predictions of equations (2), (13) and (5).

However, there is a problem on the generality of equation (13), because the q_{co} data shown in Figs. 4 and 5 are the data obtained with a tube of l/d = 100 which is incapable of verifying the function of l/d included in equation (13). Of course, it is noted that when the pressure falls to the state of $\rho_v/\rho_l = 0.101$, equation (13) agrees with equation (4) for the prediction of q_{co}, and the latter equation with the same function of l/d as that of equation (13) has already been verified for various values of l/d [3]. But this is insufficient to prove the validity of equation (13) at high pressures.

Now, consider the Nishikawa equations, equations (10)–(12), derived from the approximate data of q_{co} obtained for various values of l/d, which are represented by chain lines in Figs. 4 and 5. A rough agreement of trend is noted between the prediction of the Nishikawa equations and that of equations (2), (13) and (5), suggesting that equation (11) corresponds to equation (13). Thus, if the ratio is taken between the respective functions of l/d in these two equations as

$$B = \left\{\frac{(l/d)^{0.50}}{1+0.011\,l/d}\right\} \Big/ \left\{\frac{(l/d)^{0.27}}{1+0.0031\,l/d}\right\} \qquad (14)$$

then the value of B appears to be nearly constant over the conventional range of l/d as is seen in Fig. 7. This fact might be regarded as indirect evidence of the function of l/d included in equation (13).

Next, the experimental data of water at high ρ_v/ρ_l ratios obtained by Doroschuk *et al.* [11] and Watson and Lee [12], respectively, are compared with the prediction of equation (13) in Fig. 8. The data points, though limited in number, appear to be close to the foregoing prediction, suggesting the applicability of equation (13) to water as well. Incidentally, the results of Fig. 8 serve as direct evidence of the function of l/d in equation (13) because the data in Fig. 8 have been obtained for l/d = 187.5 and 145.

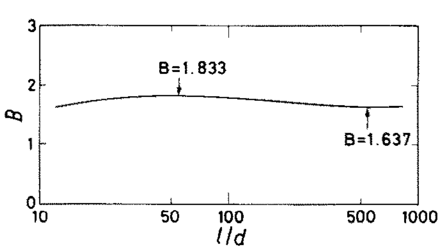

FIG. 7. Variation of B vs l/d.

3.3. *Experimental data of K*

Experimental values of K obtained from raw data in Figs. 2 and 3 are plotted in Fig. 9, though the case of $\rho_v/\rho_l = 0.153$ has been omitted to save space.

When the magnitude of ρ_v/ρ_l is comparatively low as in the top diagram of Fig. 9, the following empirical facts can be noticed. First, the data points of K are close to the prediction of equation (6) in the range of high

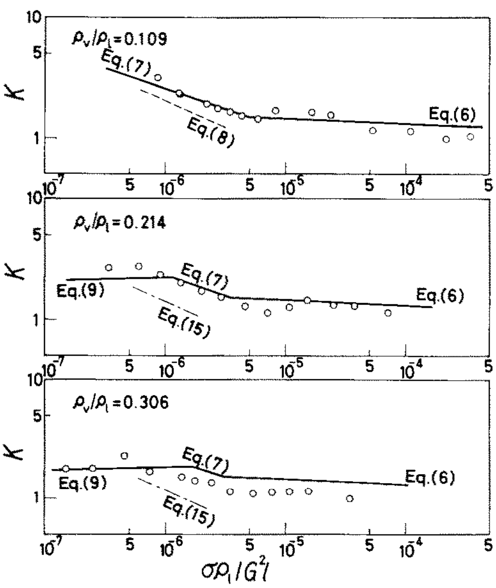

FIG. 9. Comparison between the experimental and predicted K for R-12 (d = 0.01 m, l/d = 100).

$\sigma\rho_l/G^2l$, while they are close to that of equation (7) in the range of low $\sigma\rho_l/G^2l$. Second, the border between the two characteristic regimes of K mentioned above does not correspond to the border between the operating range of equation (2) and that of equation (3) shown in the top diagram of Fig. 4. Third, a broken line illustrated in the top diagram of Fig. 9 represents the prediction of K by equation (8), being inferior to the prediction of equation (7) for the agreement with the data points. This situation is in fact the same as those which have already been found in the previous two studies [7, 8].

Next, for sufficiently high ρ_v/ρ_l ratios as in the middle and bottom diagrams of Fig. 9, the data points of K are close to the prediction of equation (6) in the region of high $\sigma\rho_l/G^2l$, while are close to that of equation (9) in the region of low $\sigma\rho_l/G^2l$, being separated by a short intermediate region where the data points are close to the prediction of equation (7). The extent of this intermediate region tends to reduce rapidly with increasing pressure as is seen in Fig. 9, suggesting that the prediction of K by equation (7) becomes less important with increasing pressure.

Finally, if the predictive equation of K is derived from equation (13) in the same manner as that of the derivation of equations (6)–(9) from equations (2) to (5), it yields

$$K = 0.174\frac{(0.0221+d/l)(d/l)^{0.27}}{(\rho_v/\rho_l)^{0.513}(\sigma\rho_l/G^2l)^{0.433}}. \quad (15)$$

However, the K value predicted by equation (15) deviates considerably from the data points as is noted from the chain line represented in the middle and bottom diagrams of Fig. 9.

4. IMPROVEMENTS OF GENERALIZED CORRELATION OF CHF

Based on the findings mentioned in Sections 1 and 3, the authors' generalized correlation of CHF will be revised as follows.

4.1. *Division of CHF regime by ρ_v/ρ_l*

As has been mentioned in Section 1, the criterion proposed tentatively in the previous study [4] for the application of equation (5) was not approved in subsequent studies [7–9]. And the same situation as above is also observed in the present study. Namely, the foregoing criterion predicts that the special type of CHF related to equation (5) should not occur under the experimental conditions of the present study (that is, $l/d = 100$ and $\rho_v/\rho_l = 0.109$–0.306), but actually this prediction is unrealized as has been seen in Fig. 6. In addition, the present study has revealed that the special character of CHF at very high pressures does not connect only with equation (5) but connects also with equation (13), accordingly the foregoing criterion for the application of equation (5) becomes more meaningless.

Thus a new criterion for discriminating the high pressure regime from others must be devised. The experimental information of CHF obtained at high ρ_v/ρ_l ratios for R-12 [7, 8], for liquid helium [9], for R-22 and R-115 [10], for water [4], and for R-12 in the present study are then examined synthetically yielding a new criterion that the lower bound of the high pressure regime exists in the vicinity of $\rho_v/\rho_l = 0.15$ irrespective of l/d if a transitional intermediate region is neglected for the sake of simplicity. Accordingly the prediction of q_{co} and K on the RHS of equation (1) will be made by distinguishing the regime of $\rho_v/\rho_l < 0.15$ from that of $\rho_v/\rho_l > 0.15$ as in the following sections.

4.2. *CHF in the regime of $\rho_v/\rho_l < 0.15$*

In this regime, q_{co} on the RHS of equation (1) is predicted by equations (2)–(4) through the following steps. Namely, if the values of q_{co} calculated by the above three equations under given conditions of ρ_v/ρ_l, $\sigma\rho_l/G^2l$ and l/d are designated as $q_{co}(2)$, $q_{co}(3)$ and $q_{co}(4)$ respectively, then q_{co} is determined as

$$\begin{cases} \text{when } q_{co}(2) < q_{co}(3),\ q_{co} = q_{co}(2) \\ \text{when } q_{co}(2) > q_{co}(3) \\ \qquad \begin{cases} \text{if } q_{co}(3) < q_{co}(4),\ q_{co} = q_{co}(3) \\ \text{if } q_{co}(3) > q_{co}(4),\ q_{co} = q_{co}(4). \end{cases} \end{cases}$$

Next, designate the values of K calculated by equations (6) and (7) under the given conditions of ρ_v/ρ_l, $\sigma\rho_l/G^2l$ and l/d as $K(6)$ and $K(7)$, respectively, and K on the RHS of equation (1) is determined as

$$\begin{cases} \text{when } K(6) > K(7),\ K = K(6) \\ \text{when } K(6) < K(7),\ K = K(7). \end{cases}$$

4.3. *CHF in the regime of $\rho_v/\rho_l > 0.15$*

In this regime, the values of q_{co} calculated by equations (2), (13) and (5) under given conditions of ρ_v/ρ_l, $\sigma\rho_l/G^2l$ and l/d are designated as $q_{co}(2)$, $q_{co}(13)$ and $q_{co}(5)$, respectively, and q_{co} on the RHS of equation (1) is determined as

$$\begin{cases} \text{when } q_{co}(2) < q_{co}(13),\ q_{co} = q_{co}(2) \\ \text{when } q_{co}(2) > q_{co}(13) \\ \qquad \begin{cases} \text{if } q_{co}(13) > q_{co}(5),\ q_{co} = q_{co}(13) \\ \text{if } q_{co}(13) < q_{co}(5),\ q_{co} = q_{co}(5). \end{cases} \end{cases}$$

Next, K on the RHS of equation (1) is determined as follows by designating the K values of equations (6), (7) and (9) as $K(6)$, $K(7)$ and $K(9)$, respectively

$$\begin{cases} \text{when } K(6) > K(7),\ K = K(6) \\ \text{when } K(6) < K(7) \\ \qquad \begin{cases} \text{if } K(7) < K(9),\ K = K(7) \\ \text{if } K(7) < K(7),\ K = K(9). \end{cases} \end{cases}$$

4.4. *Supplementary remarks on the present correlation*

(1) Although it is neglected in the present correlation as has been mentioned in Section 4.1, there is an intermediate regime in the vicinity of $\rho_v/\rho_l = 0.15$ (say,

$\rho_v/\rho_l = 0.13$–0.17) where q_{co} and K exhibit transitional characteristics between the two regimes of $\rho_v/\rho_l \lessgtr 0.15$.

(2) In the authors' previous correlation [1–9], four characteristic regimes designated L, H, N and HP were classified. However, in the present correlation where q_{co} and K are correlated in the way mentioned in Sections 4.2 and 4.3, the foregoing classification is not only useless but also rather injurious, hence the characteristic regimes mentioned above have been discarded. However, only the following condition to discriminate the H regime from the N regime in the previous correlation

$$\frac{\sigma\rho_l}{G^2 l} = \left(\frac{0.77}{l/d}\right)^{2.70} \tag{16}$$

where l_b is the boiling length, must be preserved in the regime of $\rho_v/\rho_l < 0.15$, because it has a physical meaning of discriminating annular flow CHF from froth flow CHF [13]. Whether a similar condition exists or not in the high pressure regime of $\rho_v/\rho_l > 0.15$ has not yet been clarified.

(3) The exit quality χ_{ex} corresponding to a CHF q_c in a uniformly heated tube is calculated by the following equation via heat balance

$$\chi_{ex} = \frac{4q_c}{GH_{fg}} \cdot \frac{l}{d} - \frac{\Delta H_i}{H_{fg}}. \tag{17}$$

It is well known that when ΔH_i is positive and G is very high for the case of tubes with comparatively small l/d ratios, χ_{ex} can become negative. In such a case, if χ_{ex} is remarkably smaller than zero, a question may arise on the reliability of the prediction of q_c, because the present correlation has been made using the basic CHF q_{co}, that is, the CHF condition with $\Delta H_i = 0$, for which the exit quality χ_{ex} is always positive.

(4) According to the empirical fact revealed in the previous studies [14, 15], the q_{co} value predicted by equations (3) and (4) is unapplicable to the region of $l/d > 600$, where no reliable generalized correlation of CHF can be made due to the lack of sufficient data obtained under subcooled inlet conditions. However, if restricted to water, Levy's analytical prediction method based on the annular flow model [16] seems to be able to find the outline of the CHF characteristics for such long tubes.

(5) The heat-flux/exit-quality type correlation that can be derived from the authors' previous correlation has been illustrated in ref. [17] being compared with the U.S.S.R. standard data of the CHF of water [18]. A similar correlation derived from the present correlation gives a result differing somewhat from the above-mentioned one, but the difference is not so noticeable.

5. CONCLUSIONS

In this study, experiments have been performed using an identical test tube to cover the whole characteristic regimes of the CHF of forced convective boiling in uniformly heated vertical tubes. The experimental data of systematic nature thus obtained are used together with the other recent findings to solve the pending problems related to the generalized correlation of CHF published previously by one of the authors, resulting in an improved version of the generalized correlation of CHF, which has a very clear-cut, and hence a very convenient, structure as compared with the previous correlation.

The studies of refs. [7, 8] have shown that when the mass velocity G is excessively high (say, $G > 3000$ kg m^{-2} s^{-1}) under very high pressures, an anomalous phenomenon of the upstream CHF occurs in the region of comparatively low inlet subcoolings. It must be noted that this anomalous regime of very high G and pressure is out of the scope of the present study.

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UNE VERSION AMELIOREE DE LA FORMULE GENERALE DU FLUX THERMIQUE CRITIQUE POUR L'EBULLITION CONVECTIVE DANS LES TUBES VERTICAUX UNIFORMEMENT CHAUFFES

Résumé—L'un des auteurs a déjà proposé une formule générale pour le flux thermique critique (CHF) dans l'ébullition convective dans les tubes uniformément chauffés. Néanmoins à travers différentes études faites sur des problèmes reliés, il s'est révélé que certains points d'interrogation nécessitaient une révision. Dans cette étude, des expériences sont soigneusement faites avec un tube d'essai identique pour tous les régimes caractéristiques du CHF. Les données ainsi obtenues sont utilisées avec les autres pour résoudre les points mentionnés. Il en résulte une version améliorée de la formule générale, accompagnée d'une structure clairement distinguée en comparaison avec la formule précédente.

EINE VERBESSERTE VERSION DER ALLGEMEINEN BEZIEHUNG FÜR DIE MAXIMALE HEIZFLÄCHENBELASTUNG BEI ERZWUNGENER KONVEKTIVER VERDAMPFUNG IN GLEICHFÖRMIG BEHEIZTEN SENKRECHTEN ROHREN

Zusammenfassung—Einer der Verfasser hat vor einiger Zeit eine allgemeine Beziehung für die maximale Heizflächenbelastung bei erzwungener konvektiver Verdampfung in gleichförmig beheizten Rohren angegeben. Jedoch traten später durch verschiedene Untersuchungen an verwandten Problemen einige offene Fragen in der oben erwähnten Beziehung auf, die gelöst oder revidiert werden mußten. Deshalb wurden in der vorliegenden Untersuchung sorgfältige Experimente an einem identischen Testrohr in allen wesentlichen charakteristischen Bereichen der maximalen Heizflächenbelastung unternommen. Die so systematisch ermittelten Daten wurden zusammen mit anderen neueren Ergebnissen benutzt, die oben erwähnten Fragen zu lösen. Schließlich wurde erfolgreich eine verbesserte Version für die allgemeine Beziehung entwickelt, die im Vergleich zur früheren Beziehung eine sehr klar aufgebaute Form hat.

УСОВЕРШЕНСТВОВАННЫЙ ВАРИАНТ ОБОБЩЕННОГО СООТНОШЕНИЯ ДЛЯ КРИТИЧЕСКОГО ТЕПЛОВОГО ПОТОКА В СЛУЧАЕ КИПЕНИЯ С ВЫНУЖДЕННОЙ КОНВЕКЦИЕЙ В РАВНОМЕРНО НАГРЕВАЕМЫХ ВЕРТИКАЛЬНЫХ ТРУБАХ

Аннотация—Одним из авторов статьи ранее была предложена обобщенная зависимость для критического теплового потока в случае кипения с вынужденной конвекцией в равномерно нагреваемых трубах. Однако, в результате выполненных затем многочисленных исследований близких по типу задач выяснилось, что при использовании этой зависимости или попытке ее усовершенствования возникает ряд спорных вопросов. В связи с этим были выполнены эксперименты с такой же трубой, в которых исследовались все основные характерные режимы КТП. Полученные таким образом систематизированные данные вместе с другими полученными в последнее время результатами были использованы затем для решения упомянутых выше задач. В результате предложен усовершенствованный вариант обобщенного соотношения, более точно отвечающего имеющимся данным, чем ранее предложенная зависимость.