Int. J. Heat Mass Transfer. Vol. 20, pp. 233–245. Pergamon Press 1977. Printed in Great Britain

CORRELATION OF NUCLEATE BOILING HEAT TRANSFER BASED ON BUBBLE POPULATION DENSITY

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(Received 28 April 1976)

Abstract A general correlating equation of heat transfer in nucleate boiling is derived, based on the assumption that the main driving force for convection in nucleate boiling is the stirring action of the generated bubbles and by means of analogy between pool boiling and free convection. In the theoretical analysis, the degree of superheating is represented not only by the heat flux but also by the bubble population density. Furthermore, the nucleation factor and the pressure factor are introduced into the final correlating equations. Good coincidence has been attained between these equations and the available experimental data in nucleate boiling of various liquids at various pressures.

NOMENCLATURE

a, constant in equation (20);
A, area of heating surface;
b, constant in equation (21);
B, constant in equation (8);
c_p, specific heat of liquid;
C, constant in equation (48);
C_b, constant defined by equation (6);
C_k, constant defined by equation (19);
C_q, constant in equation (13);
C_t, constant defined by equation (5);
C_{sf}, surface factor in equation (66);
d_o, diameter of a bubble just leaving the heating surface (diameter of a sphere with the same volume);
d_u, diameter of a bubble just arriving at the free liquid surface (diameter of sphere with the same volume);
f, frequency of bubble formation;
f_p, pressure factor defined by equation (74);
f_ζ, nucleation factor defined by equation (50);
g, acceleration due to gravity;
Gr, Grashof number;
H_e, effective stirring length of bubbles;
k, exponent defined by equation (10);
K, constant in equation (7);
K^*, constant defined by equation (11);
K_B, $d_o^2\chi$;
L, latent heat of evaporation;
m, exponent in equation (7);
M, constant in equation (14);
n, constant in equation (48);
N, number of bubble formation sites;
N/A, bubble population density;
Nu, Nusselt number, $\alpha R/\lambda_L$;
p, pressure;
p_c, critical pressure;
p_s, atmospheric pressure;
P, constant defined by equation (25);
Pr, Prandtl number;
q, heat flux of heating surface;
R, representative length of heating surface (radius of heating surface in case of horizontal circular plate);
s, exponent in equation (8);
T, temperature of liquid;
T_w, temperature of heating surface;
T_∞, temperature of bulk liquid;
T^*, constant in equation (26);
u, constant defined by equation (16);
U_m, average rising velocity of a bubble;
V_o, volume of a bubble just leaving the heating surface;
x, exponent in equation (13);
X, nondimensional variable defined by equation (46);
y, exponent in equation (13), or normal distance from heating surface;
Y, nondimensional variable defined by equation (28);
z, exponent defined by equation (17).

Greek symbols

α, heat-transfer coefficient;
α_c, calculated heat-transfer coefficient by equations (67) or (68);
α_M, measured heat-transfer coefficient;
α_s, heat-transfer coefficient for the fresh and smooth heating surface with $f_\zeta = 1$;
β, coefficient of thermal expansion;
δ, thickness of thermal boundary layer;
ΔT, temperature difference between heating surface and liquid, $T_w - T_\infty$;
ΔT_s, temperature difference between fresh and smooth heating surface and liquid;
λ_L, thermal conductivity of liquid;
μ_L, viscosity of liquid;
ν_L, kinematic viscosity of liquid;
ρ_L, density of liquid;

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ρ_v, density of vapor;
σ, surface tension of liquid;
Φ, constant defined by equation (29);
χ, product of the diameter of a bubble just leaving the heating surface and the frequency of bubble formation, $d_o f$.

1. INTRODUCTION

THE ADVENT of high power density system gave a great impetus to research in boiling heat transfer. Although great efforts to clarify the boiling phenomena have been made, and many equations have been proposed for correlating experimental data of nucleate boiling heat transfer, the results have not been entirely satisfactory. This is due to the complexity and the irreproducibility of boiling phenomena. Because the high heat-flux densities in nucleate boiling are attributed to bubbles which induce locally a strong agitation of the liquid near the heating surface, most of the correlations have been formulated on the basis of the bubble-agitation model.

On the assumption that the driving force for convective currents in nucleate boiling is mainly the liquid stirring action of generated bubbles, one of the authors [1] derived earlier a correlating equation for heat transfer in nucleate boiling based on the similarity between boiling and free convection. From the recognition that the difference in nucleation characteristics of heating surface must appear phenomenally as the difference in number of nucleation sites in that case, it was pointed out that the boiling heat flux q should be expressed by two parameters: the temperature difference ΔT between surface and liquid; and the number of nucleation sites N. Then an empirical relation between ΔT, N and q was established. Because available data up to that time were of low heat flux, however, the correlating equation obtained was intended mainly for the case where the flow in the boundary layer is laminar.

Recently data for higher heat fluxes have been obtained; so a general equation of heat transfer for the whole region of heat flux in nucleate boiling can be derived, applicable to both laminar and turbulent flow. In this derivation, it is necessary to use many empirical relations of the individual elementary processes of nucleate boiling. These relations have been mostly obtained at atmospheric pressure. Therefore, the pressure factor will be introduced into the correlating equations as the pressure-correction term.

It is well known that the heat-transfer coefficient in nucleate boiling depends strongly on the condition of the heating surface; this fact makes it very difficult to correlate heat transfer in nucleate boiling. One of the authors [1] had proposed earlier the "foamability" factor, in order to express the surface characteristics in relation to the proposed correlation. However, the foamability was defined mainly by reference to data in the lower-heat-flux region. So a new definition of the nucleation factor will be given in this paper so that it may be applied consistently for the whole region of nucleate boiling.

This paper aims to derive the general correlating equation of heat transfer to be applicable for the whole region of nucleate boiling.

2. ANALOGY BETWEEN NUCLEATE BOILING AND FREE CONVECTION

Consider the case of pool nucleate boiling of a saturated liquid. In nucleate boiling, there are two kinds of driving forces conceivable as the cause of convection current. They are the buoyancy force due to the change of density of liquid itself as in problems of pure free convection, and the liquid stirring force of rising bubbles. The latter is caused by the apparent change in density of fluid due to the rising bubbles contained in it; its effect is confined to the range of the effective stirring length of bubbles above the heating surface [1]. These two driving forces, W_t and W_b, are expressed in the units of static head as follows.

$$W_t = \int_0^{\delta} \beta(T - T_s)\,\mathrm{d}y \qquad (1)$$

$$W_b = \int_0^{H_e} \frac{N}{A} \cdot f \cdot \frac{V(y)}{U(y)} F(y)\,\mathrm{d}y \qquad (2)$$

where: δ is the thickness of thermal boundary layer; β is the coefficient of thermal expansion of liquid; f is the frequency of bubble formation; y is the normal distance from heating surface; T and T_s are the local and the bulk temperature respectively; N/A is the bubble population density; $V(y)$ is the volume of a rising bubble at a point y; $U(y)$ is the rising velocity of a bubble at a point y; H_e is the effective stirring length of bubbles, that is the distance from the heating surface to the point where the liquid stirring effect of bubbles disappears; and $F(y)$ is a function representing the difference in intensity of the liquid stirring effect due to the position of rising bubbles, and whose limiting values should be as follows: $F(0) = 1$ and $F(H_e) = 0$.

Since these two convective driving forces act simultaneously in nucleate boiling, the total driving force for convective current is obtained as their sum. The total driving force W and its nondimensional quantity, i.e. Grashof number Gr can be expressed as foilows:

$$W = C_t \beta(T_w - T_s)\delta + C_b \pi \frac{N}{A} \cdot d_o^2 \cdot \frac{\chi}{U_m} \cdot H_e \qquad (3)$$

$$\begin{aligned} Gr &= (gR^3/v_L^2 C_t \delta)W \\ &= \frac{R^3 g\beta(T_w - T_s)}{v_L^2} + \frac{C_b \pi}{C_t}\left(\frac{N}{A} d_0^2\right)\frac{\chi}{U_m} \cdot \frac{H_e}{\delta} \cdot \frac{gR^3}{v_L^2} \end{aligned} \qquad (4)$$

where

$$C_t \equiv \int_0^1 \frac{T - T_s}{T_w - T_s}\,\mathrm{d}\eta, \quad \eta \equiv y/\delta \qquad (5)$$

$$C_b \equiv \frac{1}{6}\int_0^{H_e} \frac{V(y)}{V_o} \cdot \frac{U_m}{U(y)} \cdot F(y)\frac{\mathrm{d}y}{H_e} \qquad (6)$$

and, d_o and V_o are the diameter and the volume of a bubble just leaving the heating surface respectively; g is the acceleration due to gravity; R and T_w are the representative length and the temperature of the heating surface respectively; U_m is the average rising velocity of a bubble; and ν_L is the kinematic viscosity of liquid. The most important factor affecting heat transfer in nucleate boiling is the stirring action of bubbles; for it has already been proved that W_t can be neglected in comparison with W_b [2]. Therefore the first term on the RHS of equation (4) will be neglected hereafter.

As it is difficult to obtain directly the correlating equation of heat transfer in nucleate boiling, it is conceivable that with the rule of heat transfer in free convection indicated by the following equation (7), an equation which uses the Grashof number in equation (4) instead of the Grashof number in equation (7), is applicable to heat transfer in nucleate boiling.

$$Nu = K(Gr \cdot Pr)^m. \tag{7}$$

3. DERIVATION OF GENERAL CORRELATING EQUATION OF HEAT TRANSFER

3.1. *Formulation of elementary processes*

In order to apply equation (9) to heat transfer in the nucleate boiling of liquids with different physical properties, it is necessary to know experimentally the values of H_e, d_0, χ and U_m, which are properties of the liquid, besides N/A.

(1) If the heat flux from surface is assumed to be ultimately carried away to the vapor space by bubbles, the following relation holds.

$$\frac{N}{A} = \frac{6}{\pi} \cdot \frac{1}{L\rho_v} \cdot \frac{q}{d_0^3 f}\left(\frac{d_0}{d_u}\right)^3 \tag{12}$$

where d_u is the diameter of a bubble just arriving at the free liquid surface; L is the latent heat of evaporation; and ρ_v is the density of vapor.

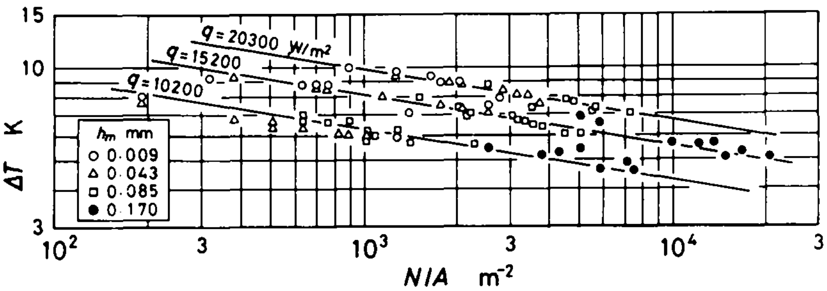

FIG. 1. Relation among heat flux q, bubble population density N/A, and temperature difference ΔT between heating surface and liquid.

On the other hand, as it has been shown experimentally that there exists the relation of $\alpha^s\delta$ = const. between heat-transfer coefficient α, and thickness of thermal boundary layer δ, in nucleate boiling [3–6], the following nondimensional equation holds

$$Nu^s \frac{\delta}{R} = B, \quad Nu \equiv \frac{\alpha R}{\lambda_L} \tag{8}$$

where s and B are constants, whose values are different according to whether the flow in the boundary layer is laminar or turbulent; and λ_L is the thermal conductivity of liquid.

From equations (7), (4) and (8), the following equation is obtained.

$$Nu = K^*\left(Pr \cdot \frac{N}{A} d_o^2 \cdot \frac{gH_e}{\nu_L^2} \cdot R^2 \cdot \frac{\chi}{U_m}\right)^k \tag{9}$$

where

$$k \equiv \frac{m}{1-sm}; \tag{10}$$

$$K^* \equiv K^{1/(1-sm)}\left(\frac{C_b \pi}{C_t B}\right)^k. \tag{11}$$

and Pr is the Prandtl number of liquid. Equation (9) is the fundamental equation of nucleate boiling heat transfer including the bubble population density.

(2) It has been experimentally confirmed that the heat flux q is not a single-valued function of the temperature difference ΔT but that it depends on the number of nucleation sites N [3, 7]. Therefore, the expression for heat flux q in term of ΔT and N is considered. In order to generalize this relation to the whole region of nucleate boiling, it is reasonable to take the bubble population density N/A, irrespective of the size of heating surface, rather than to use the number of nucleation sites N itself. The two-parameter expression for heat flux may therefore be written as follows.

$$\Delta T = C_q\left(\frac{N}{A}\right)^x q^y \tag{13}$$

where C_q is a constant, which is different according to the kind of liquid. Numerical values of x, y and C_q are different also, depending on the flow condition in the boundary layer, whether it is laminar or turbulent. An example of the author's experimental results [8] on the level of lower heat flux on the roughened horizontal surfaces with artificial grooves is shown in Fig. 1 after the expression by equation (13). In Fig. 1, h_m represents the average depth of groove as the measure of roughness. The data which are scattered due to roughness in plotting of q vs ΔT have seemingly disappeared in Fig. 1.

(3) From equations (9), (12) and (13), the following equations are derived.

$$\left(\frac{d_u}{d_o}\right)^3 = M\left(\frac{N}{A}\right)^z R^u \tag{14}$$

$$\frac{N}{A} = \left(\frac{6}{\pi L\rho_v}\cdot\frac{qR^u}{Md_o^3 f}\right)^{1/(1+z)} \tag{15}$$

where

$$u \equiv \frac{3k-1}{1-y}; \tag{16}$$

$$z \equiv \frac{k+x+y-1}{1-y}; \tag{17}$$

$$M \equiv (C_q C_K)^{1/(1-y)}\left(\frac{6}{\pi L\rho_v}\right)(d_o^3 f)^{(k+y-1)/(1-y)}; \tag{18}$$

$$C_K \equiv \lambda_L K^*\left(Pr\cdot\frac{q}{U_m \nu_L^2}\cdot\frac{H_e}{R}\right)^k \tag{19}$$

and C_K is a constant which depends on the kind of liquid; and M is considered as a constant independent of physical properties of liquid [1].

(4) In the field of heat transfer in nucleate boiling, d_o and U_m may be given experimentally by the following equations.

$$d_o = a\left[\frac{\sigma}{g(\rho_L-\rho_v)}\right]^{1/2} \tag{20}$$

$$U_m = b\left[\frac{\sigma g(\rho_L-\rho_v)}{\rho_L^2}\right]^{1/4} \tag{21}$$

where σ and ρ_L are the surface tension and the density of liquid respectively. Numerical values of constants a and b are given empirically as $a = 1.04$ by Fritz [9] and as $b = 1.18$ by Peebles Garber [10].

(5) If distilled water, boiling on a fresh and smooth surface at atmospheric pressure, is taken up as the standard, and if its relevant values are distinguished by addition of suffix "s", then the bubbles for arbitrary liquid are considered to require ψ times as much energy as those of distilled water at their departure from heating surface. Hence

$$\psi = \left(\frac{d_o}{d_{os}}\right)^3\left(\frac{\rho_v}{\rho_{vs}}\right)\left(\frac{L}{L_s}\right). \tag{22}$$

On the other hand, if the frequency of bubble formation varies with the following relation according to Jakob's study [11],

$$f = f_s/\psi \tag{23}$$

then the product of the departure diameter of a bubble and the frequency of bubble formation, χ, may be expressed as follows.

$$\chi \equiv d_o f = P/d_o^2\rho_v L; \tag{24}$$

$$P \equiv \chi_s d_{os}^2 \rho_{vs} L_s. \tag{25}$$

χ_s is constant and has the absolute value of 0.111 m/s according to the author's study [3].

(6) The effective stirring length of bubbles H_e seems to bear a value peculiar to each liquid, which is experimentally related to bubble Reynolds number $U_m d_o/\nu_L$, as expressed by the following equation.

$$\frac{H_e}{R} = T^*(U_m d_o/\nu_L) \tag{26}$$

where T^* is a proportionality constant. The result of $T^* = 1100$ has been obtained from the author's experiment made on certain kinds of liquid [12].

By substitution of the relation of equations (15), (20), (21), (24) and (26) into equation (9), the general correlating equation of heat transfer in nucleate boiling is finally derived as follows:

$$Y = K^*\Phi\tilde{X}^{k/(1+z)} \tag{27}$$

where

$$Y \equiv \alpha R/\lambda_L; \tag{28}$$

$$\Phi \equiv \left[\frac{6^{1/(1+z)}}{\pi^{1/(1+z)}}\frac{T^*}{ab^2}\right]^k; \tag{29}$$

$$\tilde{X} \equiv \left[\frac{P^{z/(1+z)}}{M^{1/(1+z)}}\frac{c_p\rho_L^2 g}{\lambda_L\sigma L\rho_v}\right]^{1/(1+z)} qR^{(u-3)/(1+z)} \tag{30}$$

and c_p is the isobaric specific heat of liquid.

3.2. *Evaluation of various constants*

There now follows the estimation of various constants and exponents in the correlating equation (27).

(1) If it is assumed the temperature in the boundary layer may be expressed by the following equation

$$\frac{T-T_s}{T_w-T_s} = (1-\eta)^2 \tag{31}$$

then

$$C_t = \int_0^1 (1-\eta)^2\,\mathrm{d}\eta = \tfrac{1}{3}. \tag{32}$$

(2) As it is difficult to evaluate accurately the value of C_b, the results estimated from the photographic records of Jakob [13] are employed; these run as follows.

$$\frac{V(y)}{V_o} = 1+2\left(\frac{y}{H_e}\right)^2 \tag{33}$$

$$\frac{U(y)}{U_m} = \tfrac{2}{3}\left(1+\frac{y}{H_e}\right). \tag{34}$$

Furthermore, the following relation has been obtained from author's experiments on air injection over the heating surface in free convection, where the position of the injection nozzle was variable [14].

$$F(y) = 1 - y/H_e. \tag{35}$$

By using these relations, C_b can be evaluated as follows.

$$C_b = \tfrac{1}{6}\int_0^{H_e}\frac{V(y)}{V_o}\cdot\frac{U_m}{U(y)}F(y)\frac{\mathrm{d}y}{H_e} = 0.123. \tag{36}$$

(3) With respect to the relation (13) between q, ΔT and N/A, the following result obtained by Nishikawa [3] is applicable when the flow in the boundary layer is laminar.

$$x = -\tfrac{1}{6},\quad y = \tfrac{2}{3},$$
$$C_q = 0.0412[K(\mathrm{m^2/W})^{2/3}(1/\mathrm{m^2})^{1/6}]. \tag{37}$$

For turbulent flow in the boundary layer, it is reasonable to use the result given by Zuber [7].

$$x = -\tfrac{1}{5}, \quad y = \tfrac{3}{5},$$
$$C_q = 0.0987[K(\mathrm{m}^2/\mathrm{W})^{3/5}(1/\mathrm{m}^2)^{1.5}]. \tag{38}$$

Although the values x and y are common to any kinds of liquid, the value of C_q is relevant to the distilled water at atmospheric pressure. To evaluate M, these values are substituted into equation (18).

(4) With respect to the relation, as expressed by equation (8), between heat-transfer coefficient α and thickness of thermal boundary layer δ, the following values of exponent and constant are obtained on the basis of the experimental results shown in Fig. 2.

laminar flow region: $s = 1,\ B = 3.22$ (39)

turbulent flow region: $s = 1/2,\ B = 0.292.$ (40)

The data of α and δ for three kinds of liquid obtained by Lippert–Dougall [5] are shown in Fig. 2. Lippert–Dougall adopted the thickness of the equivalent conduction layer as δ. The data for water obtained earlier by one of the authors [3] are also plotted in Fig. 2.

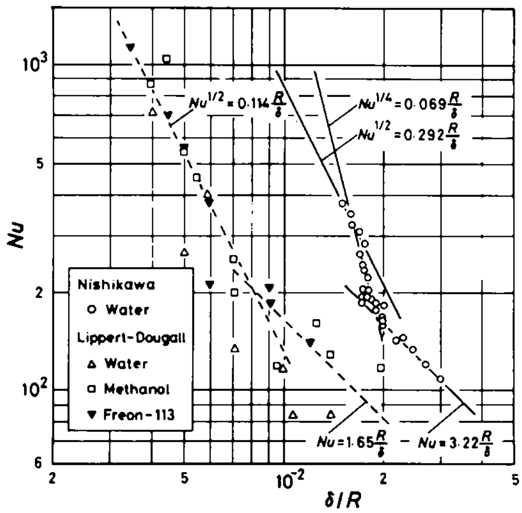

FIG. 2. Relation between heat-transfer coefficient α, and thickness of thermal boundary layer δ in nucleate boiling.

The authors adopted the conventional thickness of the thermal boundary layer as δ. Since the definition of δ is different between them, the results by Lippert–Dougall are used only to verify the appropriateness of the relation by equation (8). In this paper, the evaluation of exponent s and constant B is carried out by using the thickness of thermal boundary layer adopted by the authors.

The constants and exponents evaluated with use of the above relations are summarized in Table 1, where the suffix "l" or "t" is used to distinguish quantities which differ between the regions of the laminar and turbulent flows. The correlating equation of heat transfer becomes as follows.

laminar flow region:

$$Y = 4.62\tilde{X}^{2/3};$$
$$\tilde{X} \equiv \left(\frac{1}{M_l^2 P}\cdot\frac{c_p\rho_L^2 g}{\lambda_L \sigma L \rho_v}\right)^{1/2} qR^{3/2} \tag{41}$$

Table 1. Values of constants and exponents

	Laminar	Turbulent
K	0.56	0.13
m	$\frac{1}{4}$	$\frac{1}{3}$
s	1	$\frac{1}{2}$
B	3.22	0.292
$k = \dfrac{m}{1-sm}$	$\frac{1}{3}$	$\frac{2}{5}$
x	$-\frac{1}{6}$	$-\frac{1}{5}$
y	$\frac{2}{3}$	$\frac{3}{5}$
$u = \dfrac{3k-1}{1-y}$	0	$\frac{1}{2}$
$z = \dfrac{k+x+y-1}{1-y}$	$-\frac{1}{2}$	$-\frac{1}{2}$
$n = \dfrac{1+z}{1+z-k}$	3	5
K^*	0.328	0.105
Φ	14.08	23.89
M	$805\,\mathrm{m}^{-1}\,(\equiv M_l)$	$10504\,\mathrm{m}^{-3/2}\,(\equiv M_t)$
P	1.00 W	1.00 W

turbulent flow region:

$$Y = 3.58\tilde{X}^{4/5};$$
$$\tilde{X} \equiv \left(\frac{1}{M_t^2 P}\cdot\frac{c_p\rho_L^2 g}{\lambda_L \sigma L \rho_v}\right)^{1/2} qR. \tag{42}$$

3.3. *Expression of heat transfer in unified form*

When one of the authors derived earlier the correlating equation [1], the following experimental values were used invariably, putting no distinction between two regions of the laminar and turbulent flows.

$$P = 1.976W, \quad M = 900\,\mathrm{m}^{-1}. \tag{43}$$

The experimental value of $d_{os} = 0.00363$ m obtained by one of the authors [3] was taken in the evaluation of P. Since this value loses consistency with equation (20), here the value calculated from equation (20) is used for the evaluation of P in Table 1. As M_l and M_t in equations (41) and (42) are different in the numerical value and in the dimension between the laminar and turbulent flow regions, they are calculated from equation (18) separately for both of the laminar and turbulent flow regions.

Before comparing either the correlating equation (41) or (42) with experimental results, it is necessary to make sure which region the data points fall in, laminar or turbulent region, because the content of $\tilde{X}$ is different between two regions. As this discrimination is difficult in practice, however, it is convenient to use commonly the numerical values given by equation (43) as P and M, regardless of the regions of the laminar and turbulent flows. Then the correlating equation of heat transfer in nucleate boiling may be put in the unified form of expression as follows:

laminar flow region: $Y = 6.24X^{2/3}$; (44)

turbulent flow region: $Y = 0.66R^{-2/5}X^{4/5}$ (45)

where

$$X = \left[\frac{1}{M^2 P} \cdot \frac{c_p \rho_L^2 g}{\lambda_L \sigma L \rho_v} \right]^{1/2} q R^{3/2} \tag{46}$$

and the transition point from the laminar to the turbulent flow region is given as follows.

$$Y_t = 4.71 \times 10^5 R^2; \quad (R \text{ in m}). \tag{47}$$

Since the units of M_l and M_t are respectively m^{-1} and $m^{-3/2}$ while unit of M in equation (43) is m^{-1}, the numerical constant in equation (45) becomes dimensional as it has been given the unit of $m^{2/5}$ by using X instead of $\tilde{X}$.

4. EFFECT OF SURFACE CONDITION ON HEAT TRANSFER

4.1. *Definition of nucleation factor*

Since the correlating equations (44) and (45) are derived for the combination of a fresh and smooth surface and a pure liquid, it is necessary to take account of the nucleation ability of the surface when the correlating equations are applied to heat transfer from the heating surfaces with different surface characteristics. The difference in the nucleation ability of the surface comes out as a difference in the bubble population density, and it causes a change in the proportionality constant C of the boiling characteristic curve.

$$q = C \Delta T^n \tag{48}$$

where the exponent n becomes as follows from the comparison of two equations (27) and (48)

$$n = \frac{1+z}{1+z-k}. \tag{49}$$

Hence the nucleation factor f_ζ may be defined by the following equation.

$$\alpha = C_o (f_\zeta \Delta T)^{n-1} \tag{50}$$

$$q = C_o f_\zeta^{n-1} \Delta T^n \tag{51}$$

where C_o is a proportionality constant for $f_\zeta = 1$ (that is, for the fresh and smooth surface), which varies according to the kind of liquid. Therefore f_ζ is a function of the nucleation ability of surface alone. From equation (50)

$$\alpha = C_o^{1/n}(f_\zeta q)^{(n-1)/n} = C_o^{1/n}(f_\zeta q)^{k/(1+z)}. \tag{52}$$

Consequently

$$f_\zeta = (\alpha/\alpha_s)^{n/(n-1)} = (\Delta T_s/\Delta T)^{n/(n-1)} \tag{53}$$

where suffix "s" refers to the values for the heating surface with $f_\zeta = 1$.

The correlating equation of heat transfer in nucleate boiling, in which the nucleation characteristic of heating surface is taken into account, may be obtained by using $f_\zeta X$ instead of X in equations (44) and (45), as given below:

laminar flow region:

$$Y = 6.24(f_\zeta X)^{2/3}; \quad Y \leqslant Y_t \tag{54}$$

turbulent flow region:

$$Y = 0.66 R^{-2/5}(f_\zeta X)^{4/5}; \quad Y \geqslant Y_t. \tag{55}$$

A few examples of comparison between the earlier experimental data at atmospheric pressure and the calculated results by equations (44) and (45), are shown in Fig. 3(a) as q vs ΔT [15–17]. Solid curves express equations (44) and (45). Since earlier experiments were not necessarily carried out under the condition of the fresh and smooth surface, broken curves express equations (54) and (55), where the nucleation factor for each experiment is accounted for. The slope of the boiling characteristic curve has been considered as constant in the whole range of heat flux and a fixed exponent n in the expression of $q - C\Delta T^n$ has been used usually. As clearly seen from Fig. 3(a), however, it seems more reasonable to divide the whole region of nucleate boiling into two regions of the laminar and turbulent flows, and to adopt the different values of exponent n for each region ($n = 3$ for the laminar flow region and $n = 5$ for the turbulent flow region).

The available experimental results [12, 15–22] up to the higher heat flux region at atmospheric pressure are plotted in Fig. 3(b) by taking Y as the ordinate and $f_\zeta X$ as the abscissa. The values of nucleation factor estimated for each experiment are shown in Table 2. It is seen from Fig. 3(b) that the experimental points lie close to the curves given by the correlating equation (54) or (55).

4.2. *Physical meaning of nucleation factor*

From equation (13), the following equation is obtained.

$$\alpha = C_q^{-1/x}(N/A)^{-y/x} q^{1/x}. \tag{56}$$

By eliminating q from equations (52) and (56) and by using the relation of equations (17) and (49), the following equation may be obtained.

$$\alpha = C_q^{k/x} C_o^{(x-k)/x} f_\zeta^{k(1-1/x)} (N/A)^k. \tag{57}$$

On the other hand, equation (9) may be written as follows by expressing collectively such variables as are constant for the specified liquid by C_k.

$$\alpha = C_K (N/A)^k K_B^k R^{3k-1} \tag{58}$$

where

$$K_B = d_a^2 \chi. \tag{59}$$

From relations (16), (17), (49), (52) and (56), the relation between f_ζ and K_B is obtained.

$$f_\zeta = C_K^{x/k(1-y)} C_o^{(k-z-1)/k} C_q^{1/(y-1)} K_B^{x/(1-y)} R^{xu/k}. \tag{60}$$

Well, heat-transfer coefficient α in the nucleate boiling depends on bubble population density N/A, and α increases with the increase of N/A. Two ways to increase N/A for the specified liquid are considered.

(i) Increase of heat flux
(ii) Increase of nucleation ability.

In the case of (i), heat flux will be raised keeping the surface condition constant, that is f_ζ = constant. By putting f_ζ = constant in equation (57),

$$\alpha \propto \left(\frac{N}{A}\right)^k. \tag{61}$$

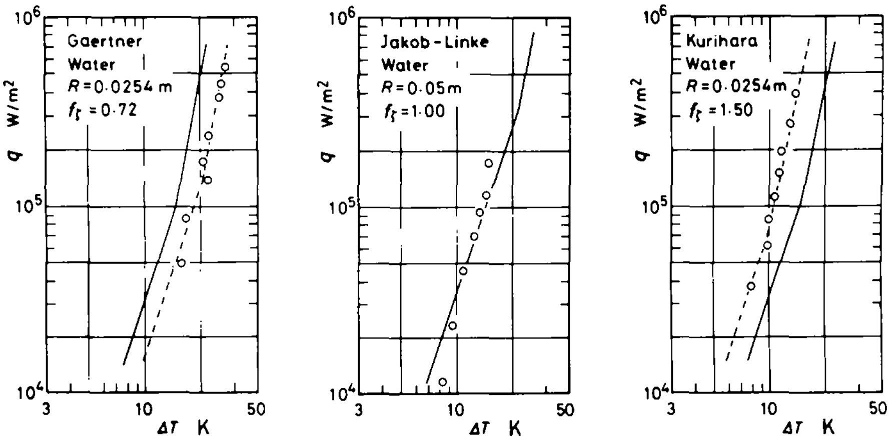

FIG. 3(a). Examples of comparison with experimental results.

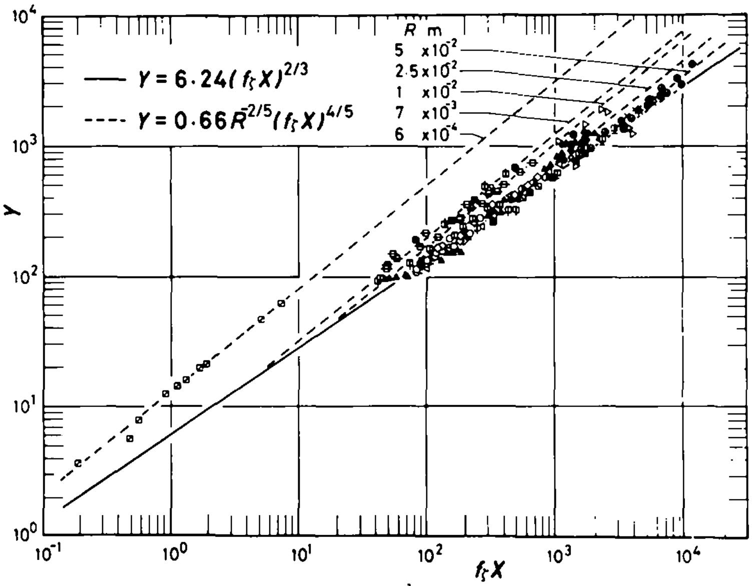

FIG. 3(b). Correlation of experimental results at atmospheric pressure by Y vs $f_\zeta X$.

Table 2. Data in Fig. 3(b) and values of nucleation factor f_ζ (HW, HT and HP are horizontal wire, tube and plate respectively; Dia. and Rad. are in m)

Key	Observer	Liquid	Heating surface	Representative length of heating surface	f_ζ
⧄	Addoms	Water	HW	Dia. = 6.096×10^{-4}	0.59
⊡	Borishanskii *et al.*	Water	HT	Dia. = 6.94×10^{-3}	1.00
⊞		Ethanol	HT	Dia. = 6.94×10^{-3}	1.86
⊠		Ethanol	HT	Dia. = 4.99×10^{-3}	1.32
⊕	Cichelli–Bonilla	Water	HP	Rad. = 4.763×10^{-2}	1.56
×		Benzene	HP	Rad. = 4.763×10^{-2}	1.30
⊗		*n*-Heptane	HP	Rad. = 4.763×10^{-2}	1.40
⧅	Cryder–Finalborgo	Water	HT	Dia. = 3.81×10^{-2}	3.38
⊞		Methanol	HT	Dia. = 3.81×10^{-2}	3.95
⊞		Carbon tetrachloride	HT	Dia. = 3.81×10^{-2}	3.82
▷	Gaertner	Water	HP	Rad. = 2.54×10^{-2}	1.00
◁		Water	HP	Rad. = 2.54×10^{-2}	0.72
▲		Water	HP	Rad. = 2.54×10^{-2}	0.70
◑	Jakob–Linke	Water	HP	Rad. = 5.0×10^{-2}	1.00
●	Kurihara	Water	HP	Rad. = 2.54×10^{-2}	1.50
○	Nishikawa	Water	HP	Rad. = 7.0×10^{-2}	0.83
○		Water	HP	Rad. = 5.0×10^{-2}	0.89
◇		Ethanol	HP	Rad. = 5.0×10^{-2}	1.27
⊞	Raben *et al.*	Water	HP	Rad. = 1.886×10^{-2}	1.70

In the case of (ii), the nucleation factor f_ζ will be increased under the constant heat flux. Hence, from equation (56)

$$\alpha \propto \left(\frac{N}{A}\right)^{x}. \tag{62}$$

Namely, in the cases of (i) and (ii), there will be noticed difference in the increase rate of α when N/A has increased. As known from equation (60), there is a close relation between f_ζ and K_B. In the case of (i), f_ζ is constant and K_B remains unchanged even if q is increased. On the other hand, in the case of (ii), f_ζ increases with the increase of N/A and at the same time K_B decreases, because the exponent $x/(1-y)$ of equation (60) is negative as seen from Table 1. Thereby the stirring effect of liquid becomes smaller and α does not increase as much as in the case of (i).

The relations mentioned above are traced in Fig. 4 by using the experimental results obtained earlier by the author in the lower heat flux region [8]. From equations (58) and (60),

$$\alpha\left(\frac{N}{A}\right)^{-k} d_o^{-2k} R^{1-3k} = C_K \chi^k \tag{63}$$

$$f_\zeta d_o^{2x/(y-1)} = C_K^{xk(1-y)} C_o^{x(k-z-1)k} C_q^{1/(y-1)} \chi^{x/(1-y)} R^{xu/k}. \tag{64}$$

Since $k = 1/3$, $x = -1/6$, $y = 2/3$ and $u = 0$ for the laminar flow region, equations (63) and (64) become as follows.

$$\alpha\left(\frac{N}{A}\right)^{-1/3} d_o^{-2/3} = C_K \chi^{1/3}$$

$$f_\zeta d_o = C_K^{-3/2} C_o^{-1/6} C_q^{-3} \chi^{-1/2}.$$

As χ is considered to be constant, the LHS of the above equations ought to be constant. The validity of these relations is verified from Fig. 4.

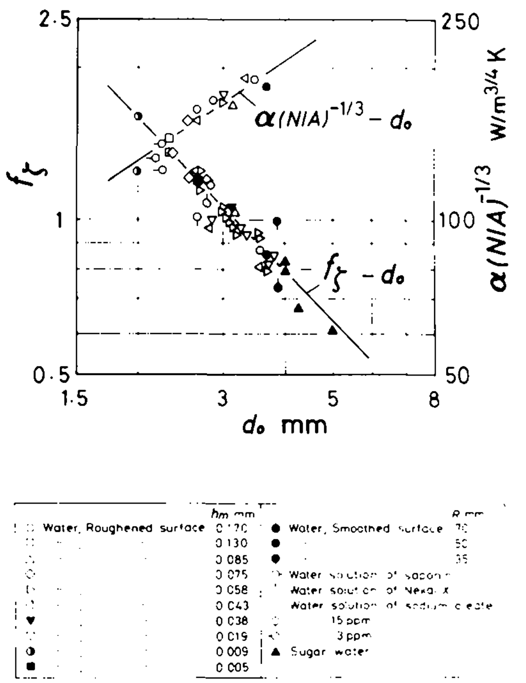

FIG. 4. Relation between nucleation factor f_ζ, and diameter of a bubble departing from heating surface d_o.

Physical meaning of nucleation factor will be explained as follows. From equation (56),

$$\chi = \frac{1}{C_q}\left(\frac{N}{A}\right)^{x} q^{1-y}.$$

Hence

$$\chi_s = \frac{1}{C_q}\left(\frac{N}{A}\right)_s^{x} q^{1-y}.$$

From equation (53)

$$f_\zeta = \left[(N/A)/(N/A)_s\right]^{-xn/(n-1)} \tag{65}$$

laminar flow region: $x = -\frac{1}{6}$, $n = 3$ $\therefore -\frac{xn}{n-1} = \frac{1}{4}$

turbulent flow region: $x = -\frac{1}{5}$, $n = 5$ $\therefore -\frac{xn}{n-1} = \frac{1}{4}$.

Consequently, the nucleation factor is expressed by the fourth root of the ratio of bubble population density on a surface in question to that on the fresh and smooth surface, irrespective of the laminar or turbulent flow region.

4.3. *Comparison of surface factor and nucleation factor*

The surface factor C_{sf} proposed by Rohsenow [23] is well known as the factor describing the condition of heating surface in nucleate boiling. Hence various investigations about it [23, 25] have been done based on many experimental results. C_{sf} is defined by the following equation.

$$\frac{c_p \Delta T}{L} = C_{sf}\left\{\frac{q}{\mu_L L}\left[\frac{\sigma}{g(\rho_L - \rho_V)}\right]^{1/2}\right\}^s Pr^r \tag{66}$$

Although the exponent s has the constant value of 0.33, the exponent r varies between 0.8 and 2.0 and it is usually taken as 1.7. Figure 5 shows the relation between C_{sf} and f_ζ evaluated for various combinations of the boiling liquid and the heating surface by many investigators [3, 12, 13, 15–22, 26–36]. There exists a close relation between C_{sf} and f_ζ, and both of them are considered to be good enough for representing the nucleation ability of heating surface for the specified liquid. But the results obtained from the data judged to be measured on the comparatively fresh and smooth surface are picked up and shown in Fig. 6, so as to clarify the difference in both factors under the same surface condition. As a whole, f_ζ changes from 0.8 to 2.3, corresponding to the change of C_{sf} from 0.0018 to 0.023 and data points show the tendency to fall on the different curves according to the kind of liquid. These facts seem to imply that f_ζ may be more reasonable as the nucleation factor specifying the condition of heating surface in nucleate boiling. Nucleation factor f_ζ is just like as emissivity in radiation heat transfer and it will be important in future to find out the unified rule on f_ζ after accumulation of more data for various surface conditions.

5. EFFECT OF PRESSURE ON HEAT TRANSFER

5.1. *Definition and evaluation of pressure factor*

As seen in Fig. 3(b), the experimental data of nucleate boiling heat transfer for various kinds of liquids at atmospheric pressure have been correlated well by

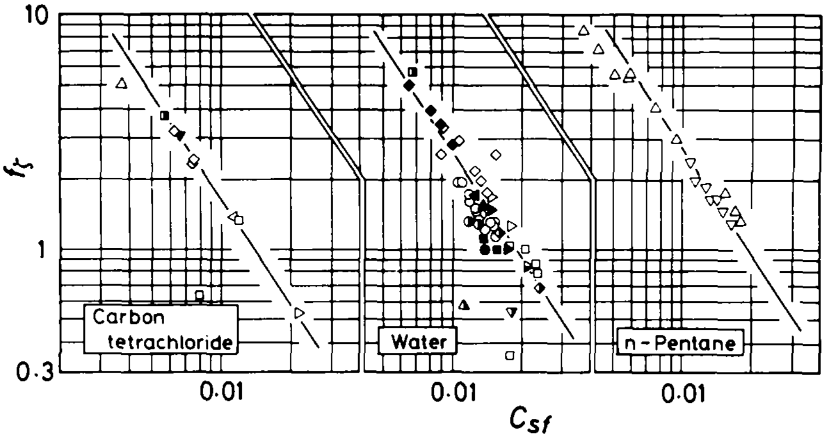

FIG. 5. Relation between surface factor C_{sf}, and nucleation factor f_ζ for various conditions of heating surface.

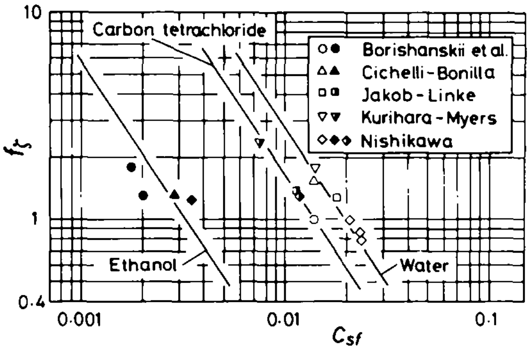

FIG. 6. Relation between C_{sf} and f_ζ for nearly same con-condition of heating surface.

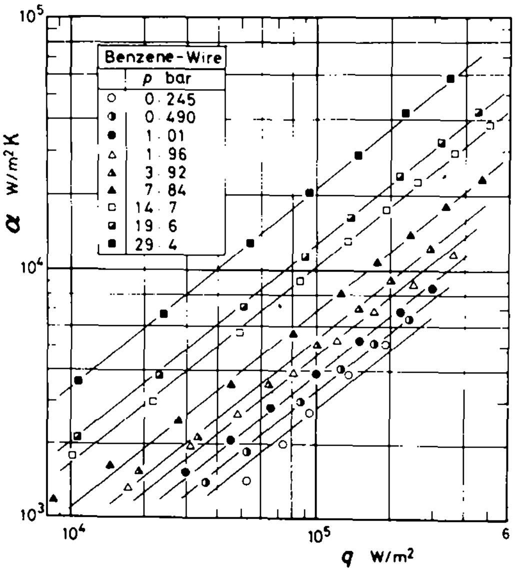

FIG. 7(a). Heat-transfer coefficient α in nucleate boiling vs heat flux q.

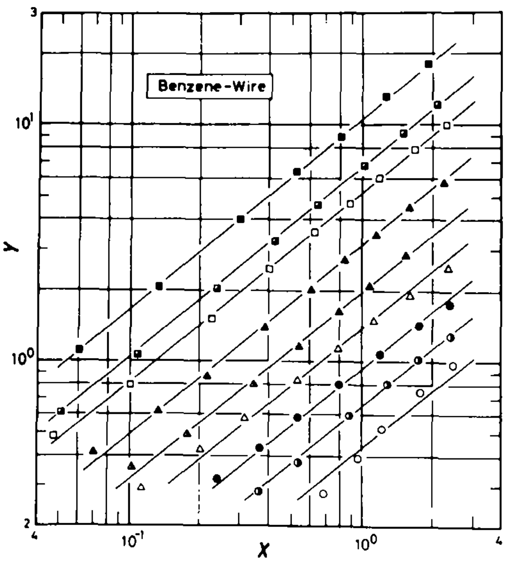

FIG. 7(b). Correlation of heat-transfer data at various pressures shown in Fig. 7(a).

means of the correlating equation (54) or (55). However, when these formulas are applied to correlate the data at various pressures, i.e. above or below the atmospheric pressure, the experimental points slip up in parallel with the straight lines of the formula of equation (54) or (55) making the pressure a parameter, as seen in Fig. 7(b), where Y is plotted against X for the data presented in Fig. 7(a). Such discrepancy in the experimental data may be mainly caused by using the empirical relations on the individual elementary processes of nucleate boiling obtained under the atmospheric condition. The validity of those relations was not verified over the wide range of pressure because of the scarcity of data. On this account, for example, the factor concerning the rate of growth of bubble M, which had been treated as a constant, may actually become a function of pressure. Therefore, it is reasonable to introduce the pressure factor f_p as the pressure correction term of the correlating equations and to insert $f_p X$ in place of X. Finally, the correlating equations for heat transfer in nucleate boiling are expressed as follows.

$$Y = 6.24(f_\zeta f_p X)^{2/3}; \quad Y \leqslant Y_t \tag{67}$$

$$Y = 0.66R^{-2/5}(f_\zeta f_p X)^{4/5}; \quad Y \geqslant Y_t. \tag{68}$$

Evaluation of the pressure factor will require a task to measure the effect of pressure on heat transfer in nucleate boiling over the wide range of pressure apart from the effect of heating surface condition. For this purpose it is important to keep the surface condition constant during a series of experimental pressures. Taking special care of this point, the authors measured the heat-transfer coefficient in nucleate boiling of certain liquids on certain heating surfaces over the wide range of pressure. One of the results is given in Fig. 7(a) as a plot of heat-transfer coefficient α vs heat flux q. Most data in this experiment fall in the relatively high heat flux region where the correlating equation (68) is to be applied, and they satisfy the relation of $\alpha \propto q^{4/5}$ at each pressure. The nucleation factor f_c is considered to be constant irrespective of pressure, because the same surface condition was kept in each run throughout this experiment. Expressing collectively the independent terms on pressure for the specified liquid by C^*, equation (68) becomes as follows.

$$Y = C^*(f_p X)^{4/5}. \tag{69}$$

Putting pressure factors at the pressure in question p and at the chosen reference pressure p_o, as f_p and f_{p_o} respectively, and expressing two values of Y at these pressures, corresponding to X_o which is the arbitrarily fixed value of X, as Yo,p and Yo,p_o respectively, then the following equations are obtained from equation (69).

$$Yo,p = C^*(f_p X_o)^{4/5} \tag{70}$$

$$Yo,p_o = C^*(f_{p_o} X_o)^{4/5}. \tag{71}$$

By eliminating C^* and X_o from the above equations,

$$\frac{Yo,p}{Yo,p_o} = \left(\frac{f_p}{f_{p_o}}\right)^{4/5}. \tag{72}$$

From a plot of Y vs X for the data from the runs of experiment for each combination of the liquid and the heating surface as illustrated in Fig. 7(b), Yo,p is easily determined at each pressure. A plot of $Yo,p/Yo,p_o$ vs the reduced pressure p/p_c, which is evaluated in this way from the data by the present authors as well as those by other authors [20–22, 37, 38], is given in Fig. 8, where p_c denotes the critical pressure and where p_o is selected as $p_c/100$ for the sake of convenience. It is evident from the foregoing figure that the data points lie on a single curve, irrespective of the kind of liquid over the entire range of pressure, only excluding the discrepancy near the critical pressure in the data by Borishanskii *et al.* [20]. If the change of $Yo,p/Yo,p_o$ with p/p_c is represented by the curve shown in the figure, the following expression with $\bar{C}$ as a numerical constant is obtained under consideration of the relation (72).

$$\frac{f_p}{f_{p_o}} = \bar{C}\left(\frac{p}{p_c}\right)^{0.7}\left[1+3\left(\frac{p}{p_c}\right)^3\right]. \tag{73}$$

By eliminating f_{p_o} and $\bar{C}$ on condition that the pressure factor at atmospheric pressure p_s is unity, i.e. $f_{p_s} = 1$, the generalized expression of pressure factor at the pressure in question becomes ultimately as follows.

$$f_p = \left(\frac{p}{p_s}\right)^{0.7}\frac{1+3(p/p_c)^3}{1+3(p_s/p_c)^3}. \tag{74}$$

For the liquids whose critical pressures exceed about 10 bar, equation (74) is approximated by

$$f_p = \left(\frac{p}{p_s}\right)^{0.7}\left[1+3\left(\frac{p}{p_c}\right)^3\right]. \tag{75}$$

Furthermore, at the pressure lower than $p_c/10$ for these liquids, equation (75) is simplified as

$$f_p = \left(\frac{p}{p_s}\right)^{0.7} \tag{76}$$

5.2. *Correlation of heat transfer*

The formulas for heat transfer in nucleate boiling are finally expressed by equations (67), (68) and (74) in which the nucleation factor f_c and the pressure factor f_p are included respectively so that the effect of heating surface condition and the effect of pressure

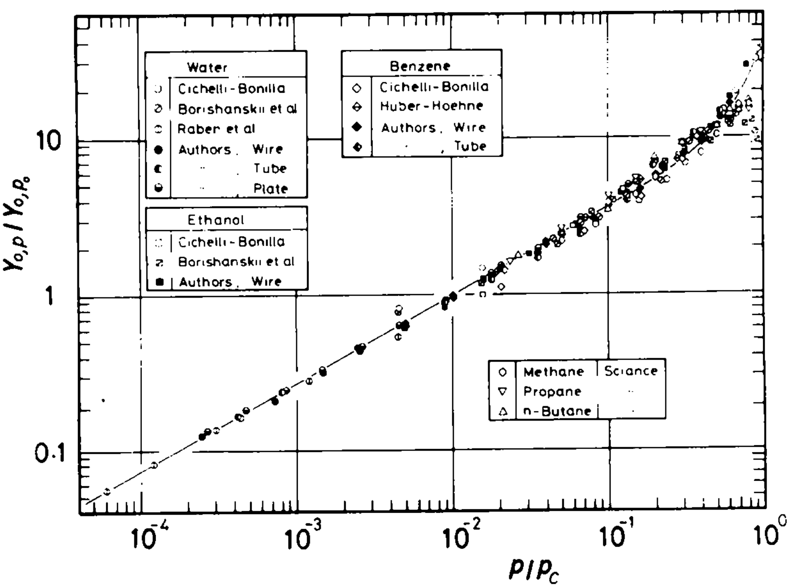

FIG. 8. Relation between $Yo,p/Yo,p_o$ and p/p_c.

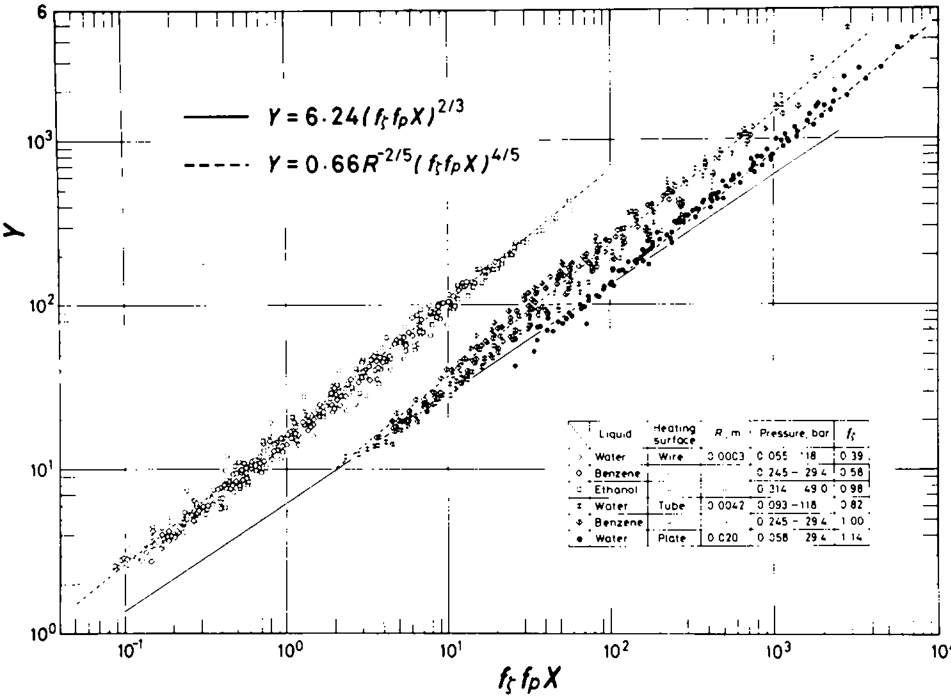

FIG. 9. Correlation of heat transfer in nucleate boiling; present authors' measurements.

may be accounted for. The result of comparison made between these formulas and the experimental data is shown in Fig. 9 and Fig. 10. The experimental results by the present authors are compared in Fig. 9, plotted in the $Y - f_\zeta f_p X$ coordinates. The values of nucleation factor are given in this figure. The results by other investigators [21, 22, 37] are compared in Fig. 10, plotted in the $\alpha_M - \alpha_c$ coordinates, where α_M denotes the measured heat-transfer coefficient and α_c the calculated coefficient from the formula (67) or (68). Though the nucleation factor is assumed to be constant for each run of experiments in calculating α_c, this assumption seems to be reasonable from Fig. 10. All the data points by the present authors and by other authors are correlated well by the formulas (67), (68) and (74) within $\pm 30\%$ accuracy. Such an agreement confirms the validity of the proposed correlating equations for heat transfer in nucleate boiling.

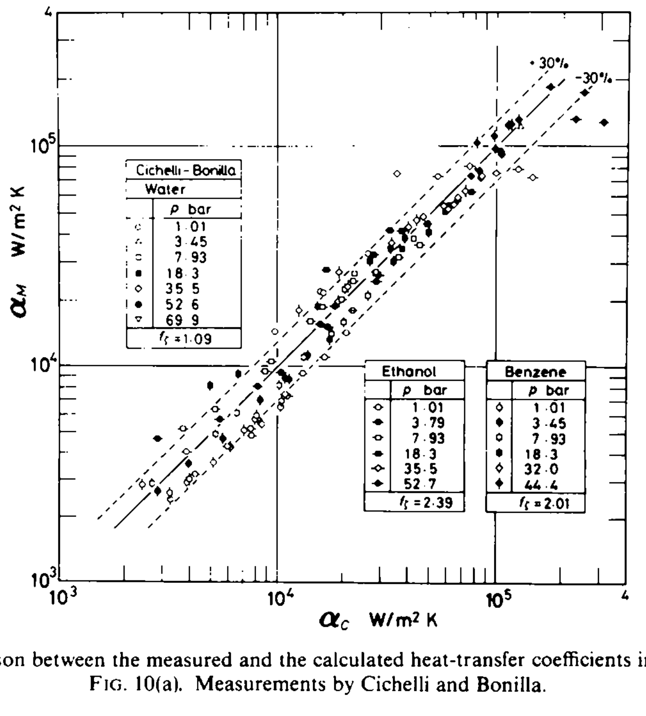

FIG. 10. Comparison between the measured and the calculated heat-transfer coefficients in nucleate boiling.
FIG. 10(a). Measurements by Cichelli and Bonilla.

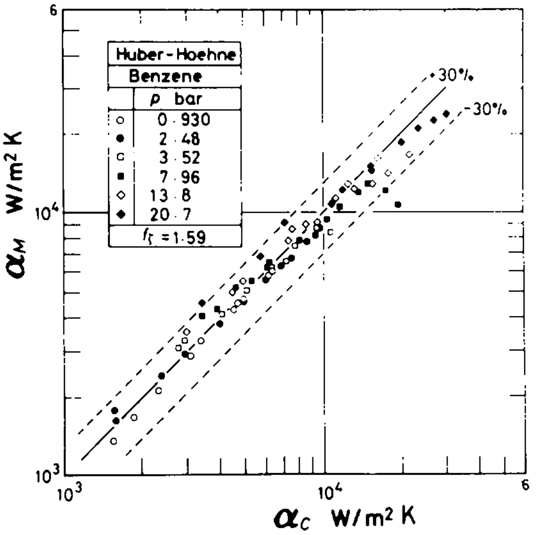

FIG. 10(b). Measurements by Huber and Hoehne.

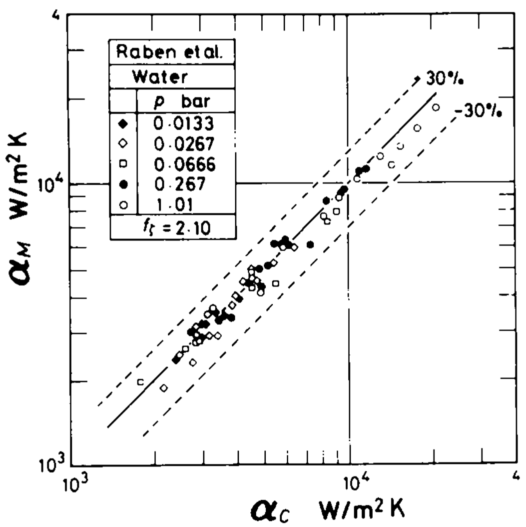

FIG. 10(c). Measurements by Raben *et al.*

6. CONCLUSIONS

The general correlating equation of heat transfer in nucleate boiling is derived on the basis of the similarity between free convection and nucleate boiling and it has been confirmed that the relation between heat flux and heat-transfer coefficient is different with respect to the flow condition in the boundary layer.

In relation to the correlating equation derived here, a new nucleation factor has been introduced in order to describe the condition of heating surface. This nucleation factor can be used consistently through the whole region of heat flux in nucleate boiling.

In addition to the nucleation factor, the pressure factor is introduced in the correlating equation as the pressure correction term. Final correlating equations are as follows.

$$Y = 6.24(f_t f_p X)^{2/3}; \quad Y \leqslant Y_t$$

$$Y = 0.66R^{-2/5}(f_t f_p X)^{4/5}; \quad Y \geqslant Y_t$$

$$Y = \frac{\alpha R}{\lambda_L}; \quad X = \left[\frac{1}{M^2 P} \cdot \frac{c_p \rho_L^2 g}{\lambda_L \sigma L \rho_v}\right]^{1/2} q R^{3/2}$$

$$P = 1.976\,\mathrm{W}; \quad M = 900\,\mathrm{m}^{-1}$$

$$f_p = \left(\frac{p}{p_s}\right)^{0.7} \frac{1 + 3(p/p_c)^3}{1 + 3(p_s/p_c)^3}$$

$$Y_t = 4.71 \times 10^5 R^2; (R \text{ in } m).$$

The validity of these formulas has been confirmed by using the experimental results for a number of liquids.

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EQUATION DE L'EBULLITION NUCLEEE ET TRANSFERT THERMIQUE TENANT COMPTE DU FACTEUR DE NUCLEATION

Résumé En tenant compte du fait que le facteur principal dans l'ébullition nucléée est l'agitation du liquide par les bulles générées, on établit l'équation générale du transfert thermique à partir d'une analogie entre l'ébullition en réservoir et la convection libre. On fait l'analyse théorique du mécanisme élémentaire particulier au phénomène d'ébullition et on utilise une expression à deux paramètres dans laquelle le degré de surchauffe est représenté non seulement par le flux thermique mais aussi par la densité de population des bulles. De plus, le facteur de nucléation et le facteur de pression sont introduits dans les équations finales et on obtient une bonne coincidence entre ces équations et les données expérimentales relatives à l'ébullition nucléée de nombreux liquides.

EINE KORRELATIONSGLEICHUNG FÜR DEN WÄRMEÜBERGANG BEIM BLASENSIEDEN UNTER BERÜCKSICHTIGUNG DES KEIMBILDUNGSFAKTORS

Zusammenfassung– Unter dem Gesichtspunkt, daß die wesentliche treibende Kraft für die Konvektion beim Blasensieden die durch die entstehenden Dampfblasen bewirkte Rührwirkung in der Flüssigkeit ist, wurde eine allgemeine Korrelationsgleichung für den Wärmeübergang beim Blasensieden auf der Grundlage der Analogie zwischen dem Behältersieden und der freien Konvektion abgeleitet. Die Ableitung erfolgte mit Hilfe einer theoretischen Untersuchung des grundlegenden Mechanismus des Siedevorganges; dabei wurde ein zweiparametriger Ausdruck verwendet, in welchem der Grad der Überhitzung nicht allein vom Wärmestrom, sondern auch von der Keimstellendichte abhängig dargestellt wird. Desweiteren wurde der Keimbildungsfaktor und der Druckfaktor in die endgültigen Gleichungen eingeführt. Die mit diesen Gleichungen ermittelten Werte stimmen gut mit den vorhandenen experimentellen Werten für das Blasensieden verschiedener Flüssigkeiten bei verschiedenen Drücken überein.

КОРРЕЛЯЦИОННОЕ УРАВНЕНИЕ ДЛЯ ТЕПЛООБМЕНА ПРИ ПУЗЫРЬКОВОМ КИПЕНИИ, УЧИТЫВАЮЩЕЕ ФАКТОР ОБРАЗОВАНИЯ ЦЕНТРОВ ПУЗЫРЬКОВ

Аннотация — Исходя из предположения, что основной причиной конвективного движения при пузырьковом кипении является смешение генерируемых пузырьков и на основе аналогии между кипением в большом объеме и свободной конвекцией, получено обобщенное уравнение теплообмена при пузырьковом кипении. Уравнение получено в результате теоретического анализа элементарного процесса, описывающего кипение. В этом случае используется выражение для двух параметров, в котором степень перегрева определяется не только тепловым потоком, но также и плотностью распределения пузырьков. Кроме того, результирующие обобщенные уравнения учитывают образование центров пузырьков и давление. Получено хорошее соответствие между данными уравнениями и имеющимися экспериментальными данными по пузырьковому кипению разных жидкостей при различных давлениях.