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Method for predicting boiling curves of saturated nucleate boiling

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Abstract

The present paper proposes a new correlation for nucleate boiling consisting of heat flux, superheat, density of nucleation sites, and a group of physical properties. The correlation is based on a model in which heat transfer occurs primarily by heat conduction through the conduction layers formed under primary bubbles. Nucleation site densities were calculated by combining the correlation with experimental data of $q - \Delta T_{\mathrm{sat}}$. This procedure yielded a semi-empirical correlation of the densities of nucleation sites that takes into account the effects of growth of neighboring bubbles and changes in wettability with pressure. Combining these two correlations results in a correlation that predicts boiling curves.

1. Introduction

Heat transfer characteristics in nucleate boiling are generally believed to be closely related to the nucleation site density of a heating surface. Mikic and Rohsenow [2] proposed a method for predicting boiling curves in which the concrete form of the general correlation

$$f(q, \Delta T_{\mathrm{sat}}, n, B_H) = 0 \tag{1}$$

was derived theoretically. A specific relation between n, ΔT_{sat}, physical properties, and surface characteristics was assumed, thereby establishing a method for predicting boiling curves. However, the correlation has not been verified using experimental data, and the predicted boiling curves are not always accurate.

Except at low heat fluxes, nucleate boiling forms large vapor masses on a heating surface by the coalescence of bubbles, and a liquid macrolayer is attached to the bottom of the vapor masses. The critical heat flux (CHF) is determined by the dryout of this macrolayer, as proposed by Haramura and Katto [3]. Sakashita and Kumada [4] carried out boiling experiments and confirmed that transition boiling is also strongly related to the dryout process of the liquid macrolayer. Experimental evidence showing that the liquid macrolayer is formed by the coalescence of bubbles has been presented in several studies, including [5–7]. This indicates that the number and size of primary bubbles are important when considering the mechanism of macrolayer formation at lower pressures. At higher pressures, Sakashita and Kumada [8] proposed a model of macrolayer formation that is based on the boiling mechanism deduced from bubble diameter and photographic records obtained by Séméria [9]. In their model, the macrolayer is formed by the coalescence of second-

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Nomenclature

A	constant for boiling curves
A_i	time averaged area of conduction layer formed under primary bubbles, m^2
a	thermal diffusivity, m^2/s
B_H	group of physical properties of liquid and vapor
C_p	specific heat, J/kg K
C_s	constant related to surface characteristics
C_l, C_{lshp}	constants related to surface characteristics and boiling liquid
D	diameter of circular heating surface or horizontal cylinder, m
D_b	bubble diameter at detachment, m
D_{bF}	D_b by Fritz, $=0.0208\ \theta\{\sigma/g(\rho_l-\rho_v)\}^{1/2}$, m
D_{bK}	D_b by Kocamustafaogullari and Ishii, $=0.0012\ (\Delta\rho/\rho_v)^{0.9}D_{bF}$. m
f	frequency of bubble detachment, s^{-1}
g	gravitational acceleration, m/s^2
H_{fg}	latent heat of evaporation, J/kg
m	exponent of the boiling curve
N_{Ja}	Jakob number, $=\rho_l C_{pl}\Delta T_{sat}/\rho_v H_{fg}$
N	density of candidates for nucleation sites (or density of cavities), m^{-2}
n	density of nucleation sites, m^{-2}
P	pressure, Pa
P_c	critical pressure, Pa
Pr	Prandtl number
q	heat flux, W/m^2
q_b	nucleate boiling heat flux defined by Mikic and Rohsenow, $=q-q_{nc}(1-n\pi D_b^2)$, W/m^2
q_{nc}	heat flux of natural convection, W/m^2
R	radius of primary bubbles, m
R_b	radius of primary bubbles at detachment, m
r^*	critical radius of cavity, m
s	constant related to surface characteristics
T_{sat}	saturation temperature, K
t	time, s
u_l	velocity of liquid, m/s
$\bar{u}_l$	mean liquid velocity defined by Zuber [1], $=(4/\pi)N_{Ja}^2 a_l n^{1/2}$, m/s
α	heat transfer coefficient, W/m^2 K
ΔT_{sat}	superheat, K
$\Delta\rho$	$\rho_l-\rho_v$, kg/m^3
δ_l	thickness of conduction layer averaged over heating surface, m
δ_{li}	thickness of conduction layer formed under primary bubble, m
θ	contact angle between bubble and heating surface, degrees
λ	thermal conductivity, W/m K
μ	viscosity, Pa s
ν	kinematic viscosity, m^2/s
ρ	density, kg/m^3
σ	surface tension, N/m
subscript	
l	liquid
v	vapor

ary bubbles formed by the coalescence of primary bubbles. The thickness of macrolayers at higher pressures is not related to the size of the primary bubbles, but rather to the coalesced, secondary bubbles. Also in this case, nucleate boiling by primary bubbles prevails primarily in the thicker macrolayer. In the coalesced bubble region at both lower and higher pressures, the size of the primary bubbles can be estimated from the relation $nD_b^2=1$, which is the condition under which primary bubbles fully cover a heating surface.

A correlation such as Eq. (1) relating q, ΔT_{sat}, and n is therefore important in the study of nucleate boiling. The present paper will discuss correlation Eq. (1), referred to as the ‘correlation of boiling heat transfer’, with respect to the nucleate boiling heat transfer region.

Previously reported correlations were evaluated and a new correlation is proposed for flat surfaces. As an application of the correlation proposed herein, calculation of nucleation site densities from measured $q-\Delta T_{sat}$ data that were obtained for various liquids, pressures, and heating surfaces was performed. The obtained results lead to a semi-empirical correlation consisting of n, ΔT_{sat}, the density of the candidates for nucleation sites N, and a group of physical properties. By combining the two correlations, a correlation that predicts boiling curves in nucleate boiling was derived.

2. Correlation of boiling heat transfer in nucleate boiling

The present paper investigates saturated nucleate boiling on flat plates in large pools in which the thermal conductivity and heat capacity of the heating surfaces are sufficiently large to disregard the effects of fluctuations and distribution of surface temperature on the boiling.

Table 1
Correlation of boiling heat transfer in nucleate boiling

Author	Correlation	
Tien [10]	$q = B_H \Delta T_{sat} n^{1/2}$	(c-1)
	$B_H = 61.3 Pr_l^{0.33} \lambda_l$	(c-2)
Hara [11]	$q = B_H \Delta T_{sat}^{3/2} n^{3/8}$	(c-3)
	$B_H = (C_1 C_2)^{3/4} (4\pi C_2/3)^{-1/2} (\rho_l C_{pl} \lambda_l)^{3/4} / (\rho_v H_{fg})^{1/2}$	(c-4)
	$C_1 = 5.5$, $C_2 = 0.056$ m/s	
Mikic and Rohsenow [2]	$q_b = q - (1 - n\pi D_b^2) q_{nc}$	(c-5)
	$q_b = B_H \Delta T_{sat} n$	(c-6)
	$B_H = 2(\pi \rho_l C_{pl} \lambda_l)^{1/2} f^{\ 1/2} D_b^2$	(c-7)
	$D_b = C_2 (\sigma / g\Delta\rho)^{1/2} (\rho_l C_{pl} T_{sat} / \rho_v H_{fg})^{4/5}$	(c-8)
	$C_2 = 1.5 \times 10^{-4}$ (water), 4.65×10^{-4} (other liquid)	
	$f \cdot D_b = 0.6 (\sigma g \Delta\rho / \rho_l^2)^{1/4}$	(c-9)
Kurihara and Meyers [12]	$q = B_H \Delta T_{sat} n^{1/3}$	(c-10)
	$B_H = 36 \lambda_l Pr_l^{0.33} (\rho_v / \mu_l)^{1/3}$	(c-11)
Kocamustafaogullari and Ishii [13]	$q = B_H \Delta T_{sat}^{3/2} n^{3/8}$	(c-12)
	$B_H = 14 \lambda_l (\rho_l C_{pl} / \rho_v H_{fg})^{1/2} Pr_l^{-0.39} \{0.012 (\Delta\rho/\rho_v)^{0.9} D_{bF}\}^{-1/4}$	(c-13)

2.1. Published correlations

Published correlations of q, ΔT_{sat}, n, and a group of physical properties are listed in Table 1. These correlations are obtained for nucleate boiling on horizontal upward facing flat plates in the isolated bubble region.

With the exception of the experiment by Barthau [14], Table 2 shows the specifications of various experiments where q, ΔT_{sat}, and n were measured for horizontal upward facing flat plates of copper. Barthau's experiments were conducted using R114 on a horizontal copper cylinder of 8 mm o.d. at pressures of 1.5, 1.91, and 2.47 bar and heat fluxes up to 7×10^4 W/m^2. Nucleation sites up to 5×10^7 sites/m^2 were successfully measured by observing the vertical flank of the cylinder. Among Barthau's data, those measured at the higher n region can be compared with the various correlations, because the effect of surface orientation on the heat transfer may be considered to be negligible, as pointed out by Nishikawa et al. [20]. The lower limit for n is, however, not clear from Barthau's data, and the data in the region $n > 10^4$ sites/m^2, in which the heat transfer is affected only slightly by natural convection, were compared with the correlations.

Fig. 1(a)–(e) shows data arranged by the published correlations. The contact angle θ included in D_{bK} in equation (c-13) by Kocamustafaogullari and Ishii [13] is assumed to be a constant 50°. Equation (c-12) by

Table 2
Experimental conditions of $q - \Delta T_{sat} - n$

Author	Surface	Boiling region	P (MPa)	Liquid	Symbol
Yamagata et al. [15]	D = 100 mm, copper	Isolated bubble	0.101	Water	●
Kurihara and Myers [12]	D = 20 mm, copper	Isolated bubble	0.101	Water	△
				Acetone	▼
				CCl_4	◆
				n-Hexane	◬
				CS_2	▲
Gaertner [16]	D = 2 in., copper	Isolated bubble	0.101	Water	□
Cornwell and Brown [17]	D = 83 mm, copper	Isolated bubble	0.101	Water	▽
Singh et al. [18]	D = 32 mm, copper	Isolated bubble	0.101	Water	◇
Nishikawa and Urakawa [19]	D = 100 mm, copper	Isolated bubble	0.101		◎
			0.068	Water	○
			0.041		▽
Iida and Kobayashi [7]	D = 20 mm, copper	Coalesced bubble	0.101	Water	■
Barthau [14]	D = 8 mm, copper	Isolated bubble	0.15		⬖
	Horizontal cylinder		0.19	R114	◑
			0.25		◭

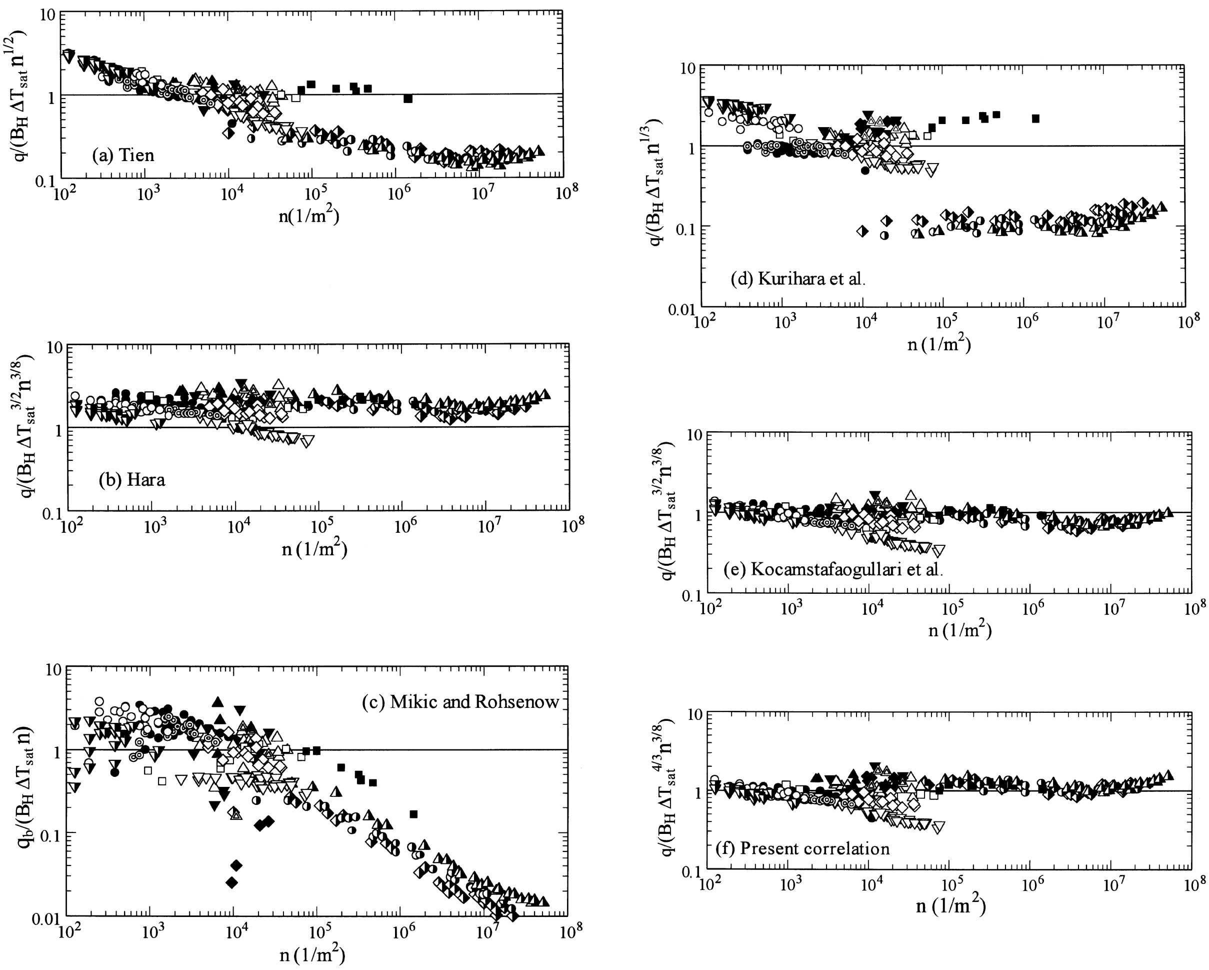

Fig. 1. Plots of published data of nucleate boiling heat transfer. Symbols are described in Table 2. Plot using the correlation by Tien [10] (a), Hara [11] (b), Mikic and Rohsenow [2] (c), Kurihara [12], (d), Kocamustafaogullari and Ishii [13] (e), and by the present authors.

Kocamustafaogullari and Ishii fits all the data except Cornwell and Brown's [17] from the isolated to coalesced bubble region. The original form of the Kocamustafaogullari and Ishii relation is

$$Nu_b = \text{Const} \cdot Re_b^a Pr_l^b \left(n \cdot D_{bK}^2\right)^c \tag{2}$$

where Nu_b is the Nusselt number defined as $Nu_b = q/(\Delta T_{sat} \lambda_l n^{1/2})$ and D_{bK} is the bubble diameter at detachment used by Kocamustafaogullari and Ishii. Re_b is the Reynolds number defined as $Re_b = \bar{u}_l/(\nu_l n^{1/2})$. The dominant mechanism of heat transfer in the model used to derive the correlation is therefore liquid flow by bubble growth in a superheated liquid layer. Kocamustafaogullari and Ishii, however, did not explain the physical meaning or role of the dimensionless quantity nD_{bK}^2 (the ratio of the bubble diameter at detachment to the average distance between two neighboring bubble centers) in the heat transfer.

2.2. Proposed correlation

In nucleate boiling, the density of primary bubbles increases with the heat flux. Primary bubbles fill the heating surface above 20–30% of CHF and coalesce to form coalesced bubbles that are much larger than the primary bubbles. The coalesced bubbles (or coalesced bubbles formed by further coalescence of the coalesced bubbles) have a liquid macrolayer attached at the bottom. Primary bubbles are created and detach or collapse with very high frequency in the macrolayer. When the effects of liquid agitation induced by bubble motion on the heat transfer is small, the heat transfer from the heating surface is mainly controlled by the heat conduction through the conduction layer that is formed under the primary bubbles. If the diameters of primary bubbles at coalescence and detachment or collapse are nearly equal, then $nD_b^2 = 1$ may be assumed.

Using the time, spatially averaged thickness as δ_{li} and the time averaged area of the conduction layer formed under the primary bubbles as A_i, and considering the relation $nD_b^2 = 1$, heat flux through these conduction layers can be expressed as

$$q = \sum_{i=1}^{n} A_i \lambda_l \Delta T_{sat}/\delta_{li} = \lambda_l \Delta T_{sat}/\delta_l. \tag{3}$$

δ_l in Eq. (3) is the thickness of the conduction layer averaged over the heating surface, and is given by

$$\delta_l = 1 \bigg/ \sum_{i=1}^{n} A_i/\delta_{li}. \tag{4}$$

The heat transfer from the heating surface is increased by liquid agitation that is caused by the repeated nucleation, growth, detachment and collapse of primary bubbles. There are four main forces governing the behavior of primary bubbles:

$$\rho_l u_l^2,\ gR_b(\rho_l - \rho_v),\ \sigma/R_b,\ \mu_l u_l/R_b \tag{5}$$

these are inertia, buoyancy, surface tension, and the viscous force per unit area at detachment or collapse, respectively. At higher heat fluxes, at which there is a macrolayer on the heating surface, the buoyancy is not large because the diameter of the primary bubbles is small enough so that any buoyancy acting on the bubbles may be neglected.

The effect of liquid agitation by bubble growth is related to the ratio of inertia to viscous forces. The Prandtl number of a liquid is also related to the effect of liquid agitation by bubble growth, and this effect can be expressed as a power function of the ratio of $\rho_l u_l^2$ to $\mu_l u_l/R_b$ and Pr_l as:

$$(u_l R_b/\nu_l)^a Pr_l^b. \tag{6}$$

The radius of a growing bubble may be expressed by

$$R = C \cdot N_{Ja}(\pi a_l t)^{1/2} \tag{7}$$

where C is a constant. On the other hand, Labuntsov et al. [21] proposed a relation for the bubble radius at higher pressures as:

$$R = (2\beta N_{Ja} a_l t)^{1/2} \tag{8}$$

where β is a constant. Eq. (8) agrees well with the experimental data for water presented by Labuntsov et al. from 0.1 to 10 MPa. In the present model, u_l in a relation (6) is assumed to be equal to the bubble growth rate (dR/dt) at detachment or collapse, and substituting Eq. (7) and Eq. (8) into Eq. (6) gives

$$(u_l R_b/\nu_l)^a Pr_l^b = \text{Const} \cdot N_{Ja}^{2a} Pr_l^{b-a} \tag{9}$$

$$(u_l R_b/\nu_l)^a Pr_l^b = \text{Const} \cdot N_{Ja}^{a} Pr_l^{b-a} \tag{10}$$

respectively. As both Eqs. (9) and (10) contain N_{Ja} and Pr_l, and the exponents of N_{Ja} and Pr_l are determined empirically, either may be used to derive the same form of the correlation for nucleate boiling heat transfer. Eq. (10) is used here because Eq. (8) may give a more accurate bubble growth rate at higher pressures. The average thickness of the conduction layers formed under the primary bubble is determined primarily by the size and bottom shape of the primary bubbles, which is related to the ratio of surface tension σ/R_b to viscous force $\mu_l u_l/R_b$ as

$$(\sigma/R_b)/(\mu_l u_l/R_b). \tag{11}$$

Therefore, it is assumed that δ_l in Eq. (3) is given by

$$\delta_l = CR_b\left[(\sigma/R_b)/(\mu_l u_l/R_b)\right]^c. \tag{12}$$

The total heat transfer from the heating surface may be expressed by substituting Eq. (12) into Eq. (3) and modifying the resulting equation with Eq. (10) to obtain:

$$q = C(\lambda_l \Delta T_{sat}/R_b) N_{Ja}^a Pr_l^{b-a} (\mu_l a_l N_{Ja}/\sigma R_b)^c. \tag{13}$$

Substituting the relation $nD_b^2 = 1$ into Eq. (13) and arranging yields

$$q = C\lambda_l(\mu_l a_l/\sigma)^c Pr_l^{b-a}\left(\rho_l C_{pl}/\rho_v H_{fg}\right)^{a+c} \Delta T^{\,1+a+c} n^{(1+c)/2}. \tag{14}$$

The exponents a, b, and c, and the constant C in Eq. (14) should be determined empirically from the experimental data in a coalesced bubble region. As shown in Table 2, however, the available data, with the exception of those presented by Iida and Kobayasi, are measured in the isolated bubble region. From the isolated to coalesced bubble regions, the $q - \Delta T_{sat}$ data are arranged in a single boiling curve of the form $q = A\Delta T_{sat}^m$ for most heating surfaces, except at heat fluxes higher than the DNB point. This suggests that the correlation relating q, ΔT_{sat} and n can also have the same form in both regions. The present paper, therefore, determined the exponents and the constant in Eq. (14) using the data from both isolated and coalesced bubble regions. Using the experimental data listed in Table 2, the correlation for nucleate boiling heat transfer is obtained as

$$q = B_H \Delta T_{sat}^{4/3} n^{3/8} \tag{15}$$

where

$$B_H = 0.5\lambda_l(\sigma/\mu_l a_l)^{1/4} Pr_l^{-1/12} \left(\rho_l C_{pl}/\rho_v H_{fg}\right)^{1/3}. \tag{16}$$

Fig. 1(e) and (f) show that equation (c-12) by Kocamustafaogullari and Ishii [13] and Eq. (15) by the present authors result in good arrangement of the experimental data. Equation (c-12) is, however, more complicated and includes a dimensionless quantity of uncertain physical meaning. The present paper therefore uses Eq. (15) as the correlation for nucleate boiling heat transfer.

2.3. Validity of Eq. (15) at higher pressures

Séméria [9] took photographs of nucleate boiling of water at high pressures and measured the diameters of bubbles. In this section, the validity of Eq. (15) at very high pressures is evaluated based on the measurements of primary bubble diameters conducted by Séméria.

The diameter of primary bubbles at detachment is only weakly related to the heat flux in an isolated bubble region. The diameter of the primary bubble in an isolated bubble region is only slightly different from that at a slightly lower heat flux at which primary bubbles cover the heating surface entirely. This allows the bubble diameter to be calculated from n and $nD_b^2 = 1$, which may then be compared with the diameters measured by Séméria. Fujita and Nishikawa [22] measured $q - \Delta T_{sat}$ for water up to 7.8 MPa ($P/P_c \sim 0.36$) and combining Eq. (15) with this data yields a calculated diameter of primary bubbles.

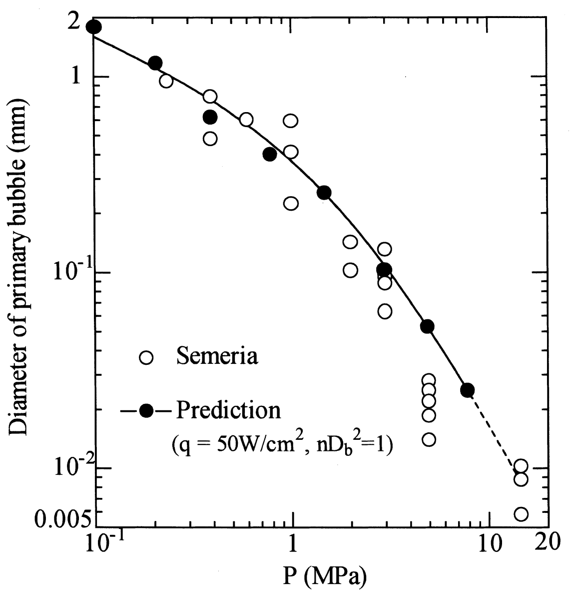

Fig. 2. Measured diameter of primary bubbles by Séméria [9] and predicted values.

In Séméria's experiment, primary bubbles do not coalesce below a heat flux of 15 W/cm^2, which is lower than the minimum heat flux, at which primary bubbles cover the heating surfaces. The assumption that primary bubbles cover the heating surface at a heat flux of 50 W/cm^2 results in the diameter shown in Fig. 2. The predictions and measured data by Séméria agree well, showing that Eq. (15) can be applied up to $P/P_c = 0.3$.

3. Correlation for density of nucleation sites

Prediction of boiling curves using Eq. (15) requires a correlation to be determined for density of nucleation sites. However, the nucleation mechanism has not been fully explained, and it is difficult to determine n theoretically. The data shown in Table 2 are not suitable for evaluating n, because heating surfaces having different characteristics were used in the different experiments. Therefore, n must be obtained indirectly by combining Eq. (15) with data of $q - \Delta T_{sat}$.

A candidate for a nucleation site is generally idealized as a conic cavity having a mouth of radius r^*. This cavity is activated when it satisfies the criterion

$$r^* \geq 2\sigma T_{sat}/\left(\rho_v H_{fg} \Delta T_{sat}\right). \tag{17}$$

The density of cavities (equal to the density of candidates for nucleation sites), N, having radii greater than r^* is approximately a power function of r^* and N may be expressed by

$$N(r^*) = C_s\left(1/r^*\right)^s \tag{18}$$

where C_s and s are constants that are determined by surface characteristics.

The density of cavities N generally differs from the density of nucleation sites n, because cavities that satisfy (17) are not always activated due to the behavior of neighboring bubbles and changes in wettability with pressure. Here the growth rate of bubbles and wettability are considered to be the main factors affecting nucleation of cavities in determining the relation between N and n.

If a bubble covers its neighboring cavities satisfying the criterion (17), the bubble inhibits nucleation at the neighboring cavities. Furthermore, if a dry spot at the bottom of a bubble covers flooded cavities, it may leave a residue of vapor in the cavities, causing nucleation of the flooded cavities when they come into contact with boiling liquid. These effects on the nucleation of cavities are closely related to the growth rate of bubbles and the density of cavities. By assuming that the effects of the growth rate of bubbles and the density of cavities are expressed by a power function of N_{Ja} and r^* respectively, these effects may be expressed as $N_{Ja}^{\alpha} \cdot r^{*\beta}$ and the function may be assumed to have the same form for different liquids and pressures.

Rapid growth of bubbles produces fluctuations in the temperature of the surrounding plate area, which causes fluctuations in the number of cavities satisfying (17). This effect is not considered in the present study, because the discussion herein is limited to metal plates having high thermal conductivity.

Wettability is also an important parameter with respect to the nucleation of cavities. The contact angle between the liquid and the solid surface is generally used as a measure of wettability. The contact angle between a liquid and the solid surface varies with the physical properties of the liquid and the solid surface, motion of boiling liquid, microstructure of cavities, and other factors. There are several theoretical studies on the effects of contact angle on the nucleation of an idealized cavity, but the effects on nucleation are not easily quantified for real surfaces. Changes in wettability result in changes in the nucleation criteria for cavities, and it is assumed that a function of r^*, $r^{*\gamma}$ can express the effect of wettability on the nucleation of cavities and that this function has the same form for different liquids and pressures. Here, the absolute effect of wettability can not be represented by a function of r^* only. Rather, the absolute effect of wettability is affected by the surface materials and conditions. The present method determines unknown constants via a boiling curve for a specific pressure and assumes that the absolute effect of a surface is included in the constant and that the absolute effect does not change with the pressure.

Based on the above considerations, n may be given

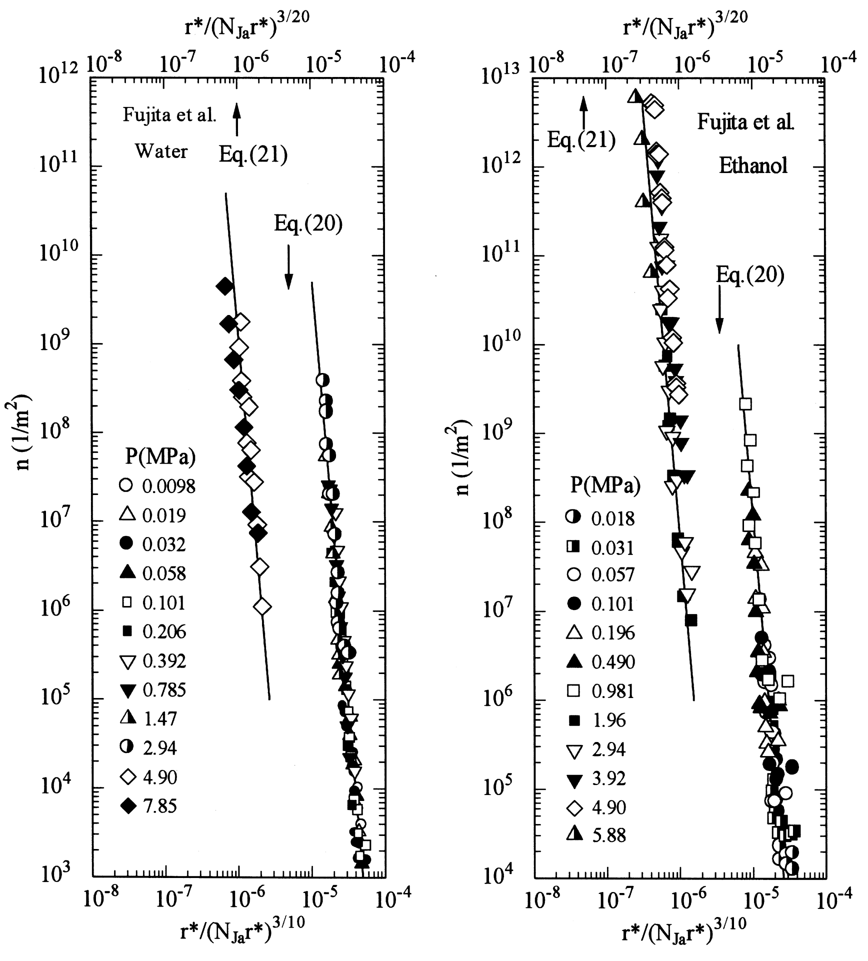

Fig. 3. Comparison of Eqs. (20) and (21) with n calculated from data for $q - \Delta T_{sat}$ by Fujita and Nishikawa [22].

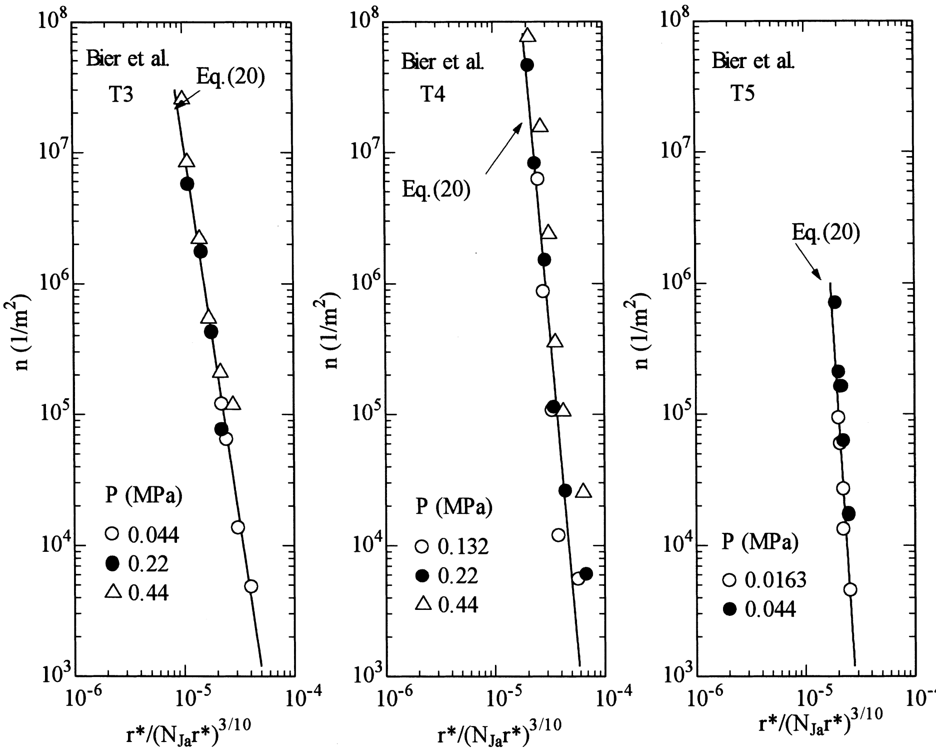

Fig. 4. Comparison of Eq. (20) using n calculated from data for $q - \Delta T_{\mathrm{sat}}$ by Bier et al. [23].

by

$$n = C_{\mathrm{ls}}\left\{N_{\mathrm{Ja}}^{\alpha} r^{*\beta+\gamma}\left(1/r^{*}\right)\right\}^{s} \tag{19}$$

where C_{ls} and s are determined by a boiling curve at a spesific pressure for a given liquid and heating surface. In order to evaluate the validity of Eq. (19) and to determine the unknown exponents α and $\beta+\gamma$, n was calculated by combining correlation (15) with experimental data of $q - \Delta T_{\mathrm{sat}}$ for horizontal upward facing flat surfaces. The data for ethanol and water presented by Fujita and Nishikawa [22] and for R11 presented by Bier et al. [23] with three heating surfaces of different roughnesses (T3,T4,T5) were used. The calculated values of n were found to correlate well with Eq. (19), with the exponents α and $\beta+\gamma = 3/10$ for $P/P_{\mathrm{c}} \leqq 0.2$ as

$$n = C_{\mathrm{ls}}\left\{N_{\mathrm{Ja}}^{3/10} r^{*3/10}\left(1/r^{*}\right)\right\}^{s} \quad P/P_{\mathrm{c}} \leq 0.2. \tag{20}$$

For $P/P_{\mathrm{c}} \geqq 0.2$, α and $\beta+\gamma$ had to be changed to 3/20 in order to correlate n well with Eq. (19). This may be attributed to differences in the nucleation and/or heat transfer mechanisms at $P/P_{\mathrm{c}} \leqq 0.2$ and $P/P_{\mathrm{c}} \geqq 0.2$. There is, however, little theoretical or experimental basis for a discussion of the causes. In the present paper, the following correlation is proposed for practical use:

$$n = C_{\mathrm{lshp}}\left\{N_{\mathrm{Ja}}^{3/20} r^{*3/20}\left(1/r^{*}\right)\right\}^{s} \quad P/P_{\mathrm{c}} \geq 0.2. \tag{21}$$

A comparison of the calculated n with Eqs. (20) and (21) is shown in Figs. 3 and 4. The solid lines in the

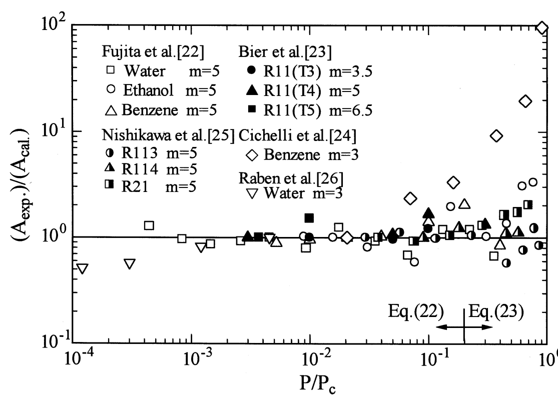

Fig. 5. Measured boiling curves and values predicted by Eqs. (22) and (23).

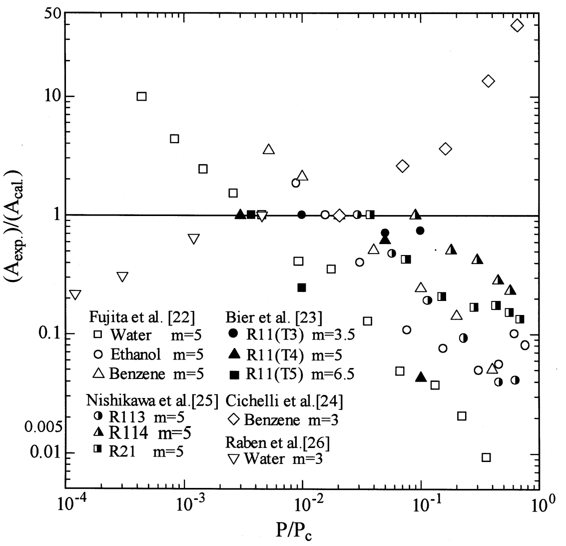

Fig. 6. Measured boiling curves and values predicted by the method of Mikic and Rohsenow [2].

figures are the theoretical results obtained using the equations. The C_{ls} and s in Eq. (20) were determined to fit the equation using the data presented by Fujita and Nishikawa [22] at atmospheric pressure, and using the data presented by Bier et al. [23] at the lowest pressure for each surface. The C_{lshp} in Eq. (21) was determined by equating Eqs. (20) and (21) at $P/P_c = 0.2$. Eqs. (20) and (21) correlate the data well over the whole range of pressures.

4. Prediction of boiling curves

Substituting Eqs. (20) and (21) into Eq. (15) gives

$$q = B_H C_{ls}^{3/8} \left[\frac{\rho_v H_{fg}}{2\sigma T_{sat}} \left\{ \frac{2\sigma T_{sat} \rho_l C_{pl}}{\left(\rho_v H_{fg}\right)^2} \right\}^{3/10} \right]^{m-4/3} \cdot \Delta T_{sat}^m$$

$$P/P_c \leq 0.2 \tag{22}$$

and

$$q = B_H C_{lshp}^{3/8} \left[\frac{\rho_v H_{fg}}{2\sigma T_{sat}} \left\{ \frac{2\sigma T_{sat} \rho_l C_{pl}}{\left(\rho_v H_{fg}\right)^2} \right\}^{3/20} \right]^{m-4/3} \cdot \Delta T_{sat}^m$$

$$P/P_c \geq 0.2. \tag{23}$$

Here, B_H is given by Eq. (16) and m $(=3s/8 + 4/3)$ is the exponent of the boiling curves expressed by $q = A\Delta T_{sat}^m$, and varies with surface characteristics. One boiling curve at a specific pressure is required in order to determine m and C_{ls} in Eq. (22) for a given boiling liquid and heating surface; C_{lshp} can be determined by equating Eqs. (22) and (23) at $P/P_c = 0.2$. As shown in Eqs. (22) and (23), m is one value for a given heating surface, and the boiling curves that can be predicted by the equations are of the form $q = A\Delta T_{sat}^m$ for any pressure.

Fig. 5 shows a comparison of boiling curves predicted by Eq. (22) for $P/P_c \leqq 0.2$ and Eq. (23) for $P/P_c \geqq 0.2$ using experimental results for horizontal upward facing flat surfaces. The values of m are the exponents of the boiling curves that are obtained by fitting the curves through the reported data points for $q - \Delta T_{sat}$. The constant C_{ls} was determined by the boiling curve of each boiling liquid at atmospheric pressure or at the lowest pressure reported, when that at atmospheric pressure was not reported. All results, with the exception of those reported by Cichelli and Bonilla [24], agree fairly well with the predictions.

As mentioned in the introduction, prediction of nucleate boiling curves by combining the correlation of boiling heat transfer with the correlation for n was first attempted by Mikic and Rohsenow [2], who proposed the correlation for n as

$$n = C_{ls}\left(1/r^*\right)^s \tag{24}$$

and combined this correlation with their correlation (c-6), shown in Table 1. Fig. 6 shows the results predicted by Mikic and Rohsenow. The data are scattered widely and the method is not very accurate.

Rather than expressing boiling curves in the form $q = A\Delta T_{sat}^m$, studies have often expressed boiling curves using the heat transfer coefficient α and heat flux q. The boiling curves shown in Fig. 5 were recalculated to account for this, and the results are in Fig. 7.

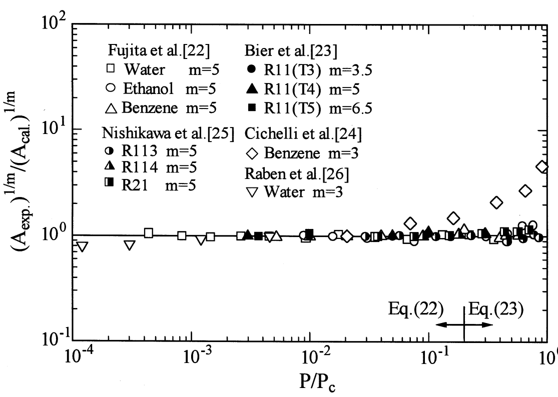

Fig. 7. Measured boiling curves and values predicted for $\alpha - q$ by Eqs. (22) and (23).

5. Conclusions

A new correlation expressing nucleate boiling heat transfer was derived for the coalesced bubble region. The correlation results in a good arrangement of the data of q, ΔT_{sat}, and n from the isolated to coalesced bubble region. In addition, a semi-empirical correlation for n was derived by assuming the effects of growth of neighboring bubbles and changes in wettability with pressure. The boiling curves that were predicted by combining the two correlations agree well with the data of various boiling conditions over a wide range of pressures. More data will enable the proposed correlation and method to be refined further.

References

[1] N. Zuber, The region of isolated bubbles and the similarity with natural convection, Int. J. Heat and Mass Transfer 6 (1963) 53–78.
[2] B.B. Mikic, W.M. Rohsenow, A new correlation of pool-boiling data including the effect of heating surface characteristics, ASME J. Heat transfer 91 (1969) 245–250.
[3] Y. Haramura, Y. Katto, A new hydrodynamic model of critical heat flux, applicable widely to pool and forced convection boiling on submerged bodies in saturated liquids, Int. J. Heat Mass Transfer 26 (1983) 389–399.
[4] H. Sakashita, T. Kumada, Macrolayer formation and mechanisms of nucleate boiling, critical heat flux, and transition boiling, Heat Transfer — Japanese Research 27 (1998) 155–168.
[5] D.B. Kirby, J.W. Westwater, Bubble and vapor behavior on a heated horizontal plate during pool boiling near burnout, Chemical Engineering Progress Symposium Series 61 (1965) 238–248.
[6] K. Torikai, T. Yamazaki, The contact area of boiling bubbles on the heating surface, Transaction of JSME 31-223 (1965) 440–446 (Japanese).
[7] Y. Iida, K. Kobayashi, An experimental investigation on the mechanism of pool boiling phenomena by a probe method, in: Proceedings of 4th International Heat Transfer Conference 5, Versailles, 1970, pp. 1–11.
[8] H. Sakashita, T. Kumada, A new model for CHF in pool boiling at higher pressure, JSME Int.J. 36-3 (1993) 422–428.
[9] R. Séméria, La Cinematographie Ultra-rapide et l'ebullition a haute pression, La Houille Blanche No. 6, 1963, pp. 679–687.
[10] C.L. Tien, A hydrodynamic model for nucleate pool boiling, Int. J. Heat and Mass Transfer 5 (1962) 533–540.
[11] A. Hara, The mechanism of nucleate boiling heat transfer, Int. J. Heat and Mass Transfer 6 (1963) 959–969.
[12] H. Kurihara, J.E. Myers, The effects of superheat and surface roughness on boiling coefficients, AIChE J. 6 (1960) 83–91.
[13] G. Kocamustafaogullari, M. Ishii, Interfacial area and nucleation site density in boiling system, Int. J. Heat and Mass Transfer 26 (1983) 1377–1387.
[14] G. Barthau, Active nucleation site density and pool boiling heat transfer — an experimental study, Int. J. Heat and Mass Transfer 35 (1992) 271–278.
[15] K. Yamagata, K.F. Hirano, K. Nishikawa, H. Matsuoka, Nucleate boiling on horizontal heating surface, 2nd report, Transactions of JSME 18–67 (1952) 53–56 (Japanese).
[16] R.F. Gaertner, Photographic study of nucleate pool boiling on a horizontal surface, ASME J. Heat Transfer 17 (1965) 17–29.
[17] K. Cornwell, R.D. Brown, Boiling surface topography, in: Proceedings of 6th International Heat Transfer Conference 1, Toronto, 1978, pp. 157–161.
[18] A. Singh, B.B. Mikic, W.M. Rohsenow, Relative behavior of water and organics in boiling, in: Proceedings of 6th International Heat Transfer Conference 1, Toronto, 1978, pp. 163–168.
[19] K. Nishikawa, K. Urakawa, An experimental study of nucleate boiling under reduced pressure, Transactions of JSME 23 (1957) 935–939 (Japanese).
[20] K. Nishikawa, Y. Fujita, S. Uchida, H. Ohta, Effect of heating surface orientation on nucleate boiling heat transfer, in: Proceedings of ASME–JSME Thermal Engr. Joint Conf., Honolulu, 1, 1983, pp. 129–136.
[21] D.A. Labuntsov, B.A. Kol'chugin, V.S. Golovin, É.A. Zakharova, L.N. Vladimirova, Study of the growth of bubbles during boiling of saturated water within a wide range of pressures by means of high-speed moving pictures UCS 536.423 1, 1964, pp. 404–409.
[22] Y. Fujita, K. Nishikawa, On the pressure factor in nucleate boiling heat transfer, Memoirs of the Faculty of Engineering, Kyushu University 36 (1977) 303–341.
[23] K. Bier, D. Gorenflo, M. Salem, Y. Tanes, Pool boiling heat transfer and size of active nucleation centers for horizontal pates with different surface roughness, in: Proceedings of 6th International Heat Transfer Conference 1, Toronto, 1978, pp. 151–156.
[24] M.T. Cichelli, C.F. Bonilla, Heat transfer to liquid boiling under pressure, Transactions of AIChE 41 (1945) 755–787.
[25] K. Nishikawa, Y. Fujita, H. Ohta, S. Hidaka, Effect of the surface roughness on the nucleate boiling heat transfer over the wide range of pressure, in: Proceedings of 7th International Heat Transfer Conference 4, Munich, 1982, pp. 61–66.
[26] I.A. Raben, R.T. Beaubouef, G.E. Commerford, A study of heat transfer in nucleate pool boiling of water at low pressure, Chemical Engineering Progress Symposium Series 61 (1965) 249–257.