Prediction of Bubble Behavior in Subcooled Pool Boiling Based on Microlayer Model*

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Bubble behaviors of subcooled nucleate pool boiling are investigated both experimentally and theoretically. The analytical study based on the dynamic microlayer model predicts that one cycle of an individual bubble experiences four stages, i.e., the initial growth with a semi-spherical shape, the final growth with a spherical segment geometry, the condensation process and the waiting time. Also, vapor bubbles on the Pt wire are experimentally observed by a high-speed camera at the speed of 10 000 frames/sec in the nucleate pool boiling of subcooled water. The predicted four stages of an individual bubble are clarified experimentally. Relatively good agreement is shown between the present predictions of the total periods of individual bubbles and experimental data.

Key Words: Bubble Dynamics, Subcooled Boiling, Microlayer Model, Boiling Heat Transfer

1. Introduction

Subcooled nucleate boiling heat transfer, as a very efficient mode of heat transfer, has been widely used in practice. Although extensive studies have been performed during the past several decades, a mechanistic model to predict the heat transfer without employing empirical constants has not been developed because the mechanism of heat transfer has not been clarified essentially.

It is well recognized that boiling bubble behaviors play the most important roles in quantifying nucleate boiling heat transfer. Some quasi-empirical formulations have been proposed to predict boiling bubble behaviors such as the lifetime, waiting period and bubble size in previous studies. However, modeling of bubble dynamics has been overly simplified even for saturated pool boiling, because details of heat transfer processes on/near the boiling surface (i.e., where and how heat on the heater surface transfers to the boiling

liquid) remain unclear.

Ibrahim and Judd⁽¹⁾ experimentally investigated the effect of subcooling on bubble growth and waiting time for relatively low water subcooling (<20 K) and wall heat flux in nucleate boiling. Then, Judd⁽²⁾ developed a theoretical prediction of waiting time based on the Mikic, Rohsenow and Griffith bubble growth model⁽³⁾. Judd concluded that the waiting time is the time required for the liquid replacing the previous bubble to acquire sufficient energy to sustain the growth of the subsequent bubble, and not the time required to establish the conditions required to enable the nucleus to commence growing into a bubble. However, from Ibrahim and Judd's experimental data, the calculated heat transfer coefficients (defined as $q/(T_w - T_{sat})$ or $q/(T_w - T_b)$) of nucleate boiling decrease with increasing liquid subcooling. Such a phenomenon is abnormal. Furthermore, both water subcooling and wall heat flux in their experiments are relatively low, in which water subcooling is less than 20 K and wall heat flux is lower than 3×10^5 W/m².

In the past few years, we have established a dynamic microlayer model⁽⁴⁾⁻⁽⁸⁾ that focuses on individual bubbles and can be used to explain pool boiling mechanism. This model can predict heat flux in the nucleate boiling region at high heat flux and in the transition boiling region including the minimum heat flux point. In this model, the evaporation and partial

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dryout of the liquid microlayer underneath the individual bubbles are considered to be important in nucleate boiling heat transfer, and critical heat flux has been derived as the maximum value of the possible heat flux. For transition boiling, in the low-superheat region, the heat flux is mainly contributed by the evaporation of the microlayer, and in the high-superheat region, the evaporations of both the microlayer and the macrolayer play important roles in heat transfer.

For subcooled boiling, the structures of the liquid layers (microlayer and macrolayer) are supposed to be the same as that of saturated pool boiling. In the low subcooling region, a coalescence bubble is formed as in saturated pool boiling. However, in the high subcooling region, many experiments show that the coalescence bubble is not substantially formed before burnout occurs. The heat transfer is mainly controlled by the behaviors of individual bubbles.

In the present study, we only pay attention to individual bubbles on the boiling surface. The objective of the present work is twofold:

- (1) to predict theoretically the bubble behaviors of subcooled boiling based on the dynamic microlayer model; and
- (2) to observe experimentally the behaviors of vapor bubbles on a Pt wire by a high-speed camera at the speed of 10 000 frames/sec in the nucleate pool boiling of subcooled water and to verify the theoretical predictions.

Nomenclature

A_b : microlayer area $=\pi/(d/2)^2$
 A_d : the largest cross-sectional area of individual bubble
 A_{ev} : evaporating area of liquid layers
 c : constant
 c_1 : change rate of surface temperature
 c_{pl} : specific heat of liquid
 D_d : departure diameter of individual bubble
 D : diameter of Pt wire
 d : diameter of individual bubble at the end of initial growth
 g : acceleration of gravity
 h_{fg} : latent heat of evaporation
 k_l : thermal conductivity of liquid
 m : group number of nucleation
 $\dot{m}$: condensation mass rate
 N : density of active sites per unit area
 Pr : Prandtl number
 q : wall heat flux
 q_c : heat flux in the macrolayer area
 q_{ev} : evaporation heat flux on microlayer
 R : radius of individual bubble

r : coordinate
 r_b : radius of curvature of a bubble as it grows out from a cavity
 r_c : position at which the superheat boundary layer reaches the liquid-vapor interface
 R_e : bubble radius at the end of final growth
 r_m : radius of cavity
 $r_{(t)}^d$: radius of dryout area
 S_1 : projection of the actual contact area S_2
 S_2 : contact area between vapor bubble and heater surface
 t : time
 t_g : period of initial growth
 T : temperature
 T_b : bulk temperature of liquid
 y : coordinate in the vertical direction
 y_b : height of a bubble growing out from a cavity
 α : thermal diffusivity of liquid
 β : configuration angle
 ΔT_{sat} : wall superheat
 δ_l : thickness of liquid thermal boundary layer
 δ_{ma} : thickness of macrolayer
 δ_{mi} : thickness of microlayer
 δ_{mi}^0 : initial thickness of microlayer
 θ : contact angle
 ν_l : kinematic viscosity of liquid
 ρ_l : density of liquid
 ρ_v : density of vapor
 σ : surface tension
 τ_b : lifetime of individual bubble
 τ_c : condensation time of individual bubble
 τ_d : total period of individual bubble $(=\tau_b + \tau_w)$
 τ_e : evaporation time microlayer
 τ_w : waiting time of individual bubble

Subscripts:

l : liquid
 s : solid
 v : vapor
 w : heater surface

2. Analyses

2.1 Dynamic microlayer model

As shown in Fig. 1, the growing process of individual bubbles can be divided into two periods, i.e., the initial growth period and the final growth period. During the initial growth period, the bubbles grow in a semi-spherical shape and a microlayer is formed underneath. The microlayer does not extend in the final growth period and the shape of bubble changes from semi-spherical to spherical segment geometry due to the continuous evaporation of the microlayer (Fig. 1). In the final growth period, a liquid layer thicker than the microlayer is formed under the bubble and among the adjacent individual bubbles, as

shown in Fig. 1. This layer is termed macrolayer in this paper.

The formation mechanism of the microlayer has been studied theoretically and experimentally by Cooper et al.^{(9),(10)}. Its initial thickness can be expressed by the following equation:

$$\delta_{mi}^0 = 0.8\sqrt{\nu t} = \sqrt{c\alpha \cdot t}, \quad 0 \leq t \leq t_g, \quad (1)$$

where $c = 0.64Pr$. Here, the effect of surface tension can be neglected because the duration of initial growth is usually very short⁽¹⁰⁾.

The heated surface can be divided into three regions, i.e., dryout area, microlayer area and macrolayer area. The evaporation occurs mainly at the microlayer area, whereas the evaporation of the macrolayer is small and can be neglected if wall superheat is not extremely high. The areas of the three parts change with time. The dryout region with zero initial area develops due to the evaporation of the microlayer during the period of the individual bubble. As a result, the microlayer area decreases with time. Here, it is supposed that no liquid is resupplied into the microlayer, because the very small interface curvature produces no driven force to resupply liquid into the markedly thin microlayer. After individual bubbles collapse or depart from the boiling surface, the old microlayer area is replaced by fresh liquid from the macrolayer and new microlayer is formed again while the next bubble grows. We define such a microlayer as the dynamic microlayer to distinguish the fixed microlayer (or meniscus) near the vapor-liquid-solid contact line which is used to explain the evaporation mechanism of vapor stem in boiling heat transfer recently by Lay and Dhir⁽¹¹⁾.

The local surface heat flux can be given as follows:

(a) The forming period (b) The evaporation period

(c) Microlayer dryout and macrolayer

Fig. 1 Dynamic microlayer

$$q(r, t) = \begin{cases} 0, & r \leq r_{(t)}^d \\ -\rho_l h_{fg} \frac{d\delta_{mi}}{dt}, & r_{(t)}^d < r \leq d/2 \\ -\rho_l h_{fg} \frac{d\delta_{ma}}{dt}, & d/2 < r \leq r_c \\ q_c, & r \geq r_c \end{cases} \quad (2)$$

where $r_{(t)}^d$ is the radius of dryout area. δ_{mi} and δ_{ma} are microlayer thickness and macrolayer thickness, respectively. The heat flux in the dryout area is sufficiently small to be neglected. The heat flux q_c in the macrolayer area is evaluated by the periodically transient heat conduction in a semi-infinite liquid layer⁽⁶⁾.

2.2 Growth and period of individual bubble

In the present study, we only investigate the behaviors of individual bubbles. It can be seen that one cycle of an individual bubble consists of two parts, one is its lifetime and the other is the waiting time of nucleus activity. The lifetime of the individual bubble consists of three durations, that is, the initial growth duration, the final growth duration and the condensation duration before the individual bubble collapses (Figs. 2(a), (b), (c)).

2.2.1 Initial growth duration of individual bubble ($0 \leq t \leq t_g$) During the initial growth of individual bubbles, semi-spherical bubbles grow from active nuclei and a microlayer is formed under the bubbles, as shown in Fig. 1. The initial thickness of the microlayer is given by Eq. (1). The growth equation of individual bubbles can be derived from the heat balance between the latent heat of evaporation of the liquid microlayer and the conduction heat through the microlayer.

$$\frac{2}{3} \pi R^3 \rho_v h_{fg} = 2\pi k_l \int_0^R \int_{\tau_g}^t \frac{\Delta T_{sat}}{\delta_{mi}} r dt dr, \quad 0 \leq t \leq t_g, \quad (3)$$

where τ_g is the time required for formation of the liquid microlayer at the position r (Eq. (8)).

$$0 \leq t \leq t_g \quad t_g \leq t \leq t_g + \tau_e \quad t_g + \tau_e \leq t \leq t_g + \tau_e + \tau_c$$

(a) (b) (c)

Waiting time τ_w Active nuclei

(d) (e)

Fig. 2 One cycle of an individual bubble

In the nucleate boiling region, when the wall superheat is low, the following approximation can be made:

$$\frac{2}{3}\pi R^3 \rho_v h_{fg} \approx 2\pi k_l \int_0^R \int_0^t \frac{\Delta T_{sat}}{\delta_{mi}^0} r dt dr, \quad 0 \leq t \leq t_g. \quad (4)$$

By utilizing Cooper's equation (1), the bubble radius is obtained as

$$R = r = \frac{2k_l \Delta T_{sat}}{\rho_v h_{fg} \sqrt{C\alpha}} t^{1/2}. \quad (5)$$

At the end of the initial growth of an individual bubble, i.e., at $t = t_g$, the bubble diameter d can be given by:

$$d = \frac{4k_l \Delta T_{sat}}{\rho_v h_{fg} \sqrt{C\alpha}} t_g^{1/2}, \quad (6)$$

or the initial growth duration of the individual bubble is given by

$$t_g = C\alpha [\rho_v h_{fg} d / (4k_l \Delta T_{sat})]^2. \quad (7)$$

From Eq. (5), we can obtain the time τ_g at which the front edge of the semi-spherical bubble with radius R reaches the radial position r ($=R$, where bubble radius is the same as coordinate position) as a function of r :

$$\tau_g = \left[\frac{\sqrt{C\alpha} \rho_v h_{fg} r}{2k_l \Delta T_{sat}} \right]^2, \quad r \leq d/2. \quad (8)$$

Therefore, the initial thickness of the microlayer at any position r ($r \leq d/2$) can be given by

$$\delta_{mi}^0 = \sqrt{C\alpha} \cdot \tau_g = \frac{C\alpha \rho_v h_{fg} r}{2k_l \Delta T_{sat}}. \quad (9)$$

2.2.2 Final growth duration due to evaporation of microlayer ($t_g \leq t \leq t_g + \tau_e$) During the final growth period, the microlayer does not expand and the shape of bubble changes from semi-spherical to spherical segment geometry due to the evaporation of the microlayer. In this duration, a liquid layer thicker than the microlayer is formed under the bubble outside the microlayer area (as shown in Fig. 1), which is termed macrolayer by the present authors. Meanwhile, vapor condensation occurs at the bubble interface. In this duration, the energy equation can be written as:

$$\frac{d}{dt} \left[\frac{4\pi}{3} \beta_1 R^3 \rho_v h_{fg} \right] = 2\pi \int q_{ev} r dr - 2(1 + \cos \beta) \pi R^2 \dot{m} h_{fg}, \quad (10)$$

Here, $\dot{m}$ is the condensation mass rate per unit area at the interface of bubbles. β is the configuration angle of bubble as shown in Fig. 1. β_1 is given by

$$\beta_1 = \frac{1}{2} + \frac{3}{4} \cos \beta - \frac{1}{4} \cos^3 \beta. \quad (11)$$

τ_e is defined as the evaporation time of the microlayer. It can be determined by the consumption equation of the liquid microlayer

$$-\rho_l h_{fg} \frac{d\delta_{mi}}{dt} = \frac{k_l \Delta T_{sat}}{\delta_{mi}}, \quad \delta_{mi}^0 = \sqrt{C\alpha} \cdot \tau_g, \quad (12)$$

and the condition,

$$\delta_{mi}(r=d/2)=0, \quad \text{at } t=t_g + \tau_e, \quad (13)$$

They give the following result,

$$\tau_e = \frac{C^2 \alpha h_{fg}^3 \rho_v^2 d^2}{32 C_p k_l^2 \Delta T_{sat}^3}. \quad (14)$$

Because τ_e is very short and the evaporation heat flux at the microlayer is very high, the effect of condensation heat is small compared to evaporation heat and can be disregarded in this duration. Therefore, by considering the total heat balance, Eq. (10) can be written as:

$$\frac{2\pi}{3} (d/2)^2 \delta_{mi}^0 \rho_v h_{fg} = \frac{4\pi}{3} \beta_1 R^3 \rho_v h_{fg}, \quad t_g \leq t \leq t_g + \tau_e. \quad (15)$$

The bubble radius R_e at the end of final growth is given by

$$R_e = [C\alpha \rho_l h_{fg} / (32 \beta_1 k_l \Delta T_{sat})]^{1/3} \cdot d. \quad (16)$$

2.2.3 Condensation duration τ_c ($t_g + \tau_e \leq t \leq t_g + \tau_e + \tau_c$) After the dryout of the microlayer, evaporation occurs mainly at the macrolayer surface. However, the evaporation heat flux is much smaller than that on the microlayer. On the other hand, heat transfer of vapor condensation at the interface of vapor bubble becomes dominant. The condensation process of the individual bubble is controlled by the following equation before the bubble collapses.

$$\frac{d}{dt} \left[\frac{4\pi}{3} \beta_1 R^3 \rho_v h_{fg} \right] = \int q_{ev} dA_{ma} - 2(1 + \cos \beta) \pi R^2 h_v \Delta T_{sub} \quad (17)$$

Initial condition: $R = R_e$, $t = t_g + \tau_e$ Bubble collapse condition: $r = 0$, $t = t_g + \tau_e + \tau_c$.

In Eq. (17), it has been considered that the heat transfer of vapor condensation is governed by heat convection of subcooled liquid, i.e., $\dot{m} h_{fg} = h_v \Delta T_{sub}$. The heat transfer coefficient of vapor condensation h_v obtained by Brucker and Sparrow⁽¹²⁾ is $h_v = 10^4$ W/m²K, which is independent of liquid subcooling. The evaporation heat transfer on the macrolayer can be given by the following equation, which has been obtained by the present authors in the study of transition boiling heat transfer^{(5),(6)}.

$$\begin{aligned} \int q_{ev} dA_{ma} &= \int \frac{k_l \Delta T_{sat}}{\delta_{ma}} dA_{ma} \\ &= 2\pi k_l \Delta T_{sat} \sqrt{R^2 - (d/2)^2} \left[1 + \frac{2C_p \Delta T_{sat}}{\pi h_{fg}} \right]^{-1/2} \\ &\times \ln \left[\sqrt{\frac{\pi h_{fg}}{2C_p \Delta T_{sat}}} \left(1 + \sqrt{1 + \frac{2C_p \Delta T_{sat}}{\pi h_{fg}}} \right) \right] \\ &- 2\pi k_l \Delta T_{sat} \left[1 + \frac{2C_p \Delta T_{sat}}{\pi h_{fg}} \right]^{-1} \sqrt{\pi \alpha t}. \end{aligned} \quad (18)$$

As the wall superheat is small, $\pi h_{fg} \gg 2C_p \Delta T_{sat}$, the above equation can be approximately given by

$$\int q_{ev} dA_{ma} \approx \pi k_l \Delta T_{sat} \sqrt{R^2 - (d/2)^2} \cdot \ln \frac{\pi h_{fg}}{2C_p \Delta T_{sat}}. \quad (19)$$

For usual nucleate boiling, the evaporation heat transfer on the macrolayer is within 5% of total heat

transfer and can be neglected⁽⁵⁾, then

$$\frac{d}{dt} \left[\frac{4\pi}{3} \beta_1 R^3 \rho_v h_{fg} \right] \cong -2(1 + \cos \beta) \pi R^2 h_v \Delta T_{sub}. \quad (20)$$

The condensation duration τ_c can be derived from Eq. (20),

$$\tau_c = \frac{2\beta_1 \rho_v h_{fg} R_e}{(1 + \cos \beta) h_v \Delta T_{sub}}. \quad (21)$$

Therefore, the lifetime of individual bubble τ_1 is $\tau_1 = t_g + \tau_e + \tau_c$. (22)

It is possible that the individual bubble departs from the heater surface before it collapses due to vapor dynamics. If the departure time is represented by τ_2 , the attached duration of bubble τ_b on the heater surface is determined by

$$\tau_b = \min [\tau_1, \tau_2]. \quad (23)$$

For higher subcooling, it can be considered that τ_b is mainly dominated by the collapsing process, that is, $\tau_1 \leq \tau_2$, so, $\tau_b = \tau_1$.

2.2.4 Waiting time τ_w Immediately after the bubble collapses, the subcooled bulk liquid is resupplied to the heated wall. The thermal boundary layer grows by transient heat conduction in the subcooled liquid. The temperature profile in the boundary layer should be determined by solving the conjugated heat transfer in both the liquid and the heater wall. In the present study, we consider two special cases, the uniform temperature wall and the uniform heat flux wall.

(1) Uniform heat flux wall

For a thin heated surface with a heated rate Q per unit area, the temperature distribution in the boundary layer is given by⁽¹³⁾

$$T_l - T_b = \frac{QaH}{k^2} \left[\frac{2\mu}{\sqrt{\pi}} e^{-y^2/4at} - \operatorname{erfc} \frac{y}{2\sqrt{at}} - \frac{ky}{aH} \operatorname{erfc} \frac{y}{2\sqrt{at}} + e^{\frac{ky}{aH} + \mu^2} \operatorname{erfc} \left(\frac{y}{2\sqrt{at}} + \mu \right) \right]. \quad (24)$$

Here, $\mu = (k/H)\sqrt{0/\alpha}$, $H = \rho_s c_{ps} \delta_s$. δ_s is the thickness of the heated surface.

In the present study, we consider such a case in which the heat capacity of the heater wall $\rho_s c_{ps} \delta_s$ is very small, so the wall temperature T_w and the wall heat flux q can be approximately given by

$$T_w - T_b = \frac{2Q\sqrt{at}}{\sqrt{\pi} k_l}, \quad q = Q. \quad (25)$$

As shown in the above equations, the heater wall can be considered as a uniform heat flux wall.

After the collapse of individual bubble, both the wall temperature and the liquid thermal boundary layer vary with time. If we linearly approach the temperature profile in the liquid thermal boundary layer, the equivalent thickness of the thermal boundary layer and its temperature profile are

$$\delta_l = 2\sqrt{\alpha t} / \sqrt{\pi} \quad (26)$$

$$T_l = T_w - (T_w - T_b)y/\delta_l. \quad (27)$$

As is well known, in the thermal boundary layer, the activity condition for a nucleus site (cavity) with radius r_m is given by

$$T_y = T_s + 2 \sin \theta \cdot \sigma T_s / (r_m h_{fg} \rho_v) \quad (28)$$

$$\text{at } y = y_b = r_b(1 + \cos \theta).$$

As shown in Fig. 3, the minimum waiting time can be yielded from Eqs. (27) and (28) as the temperature profile (Eq. (27)) becomes the tangent line of Eq. (28)⁽¹⁴⁾.

$$\begin{aligned} \tau_w &= \left[\frac{\pi(1 + \cos \theta) \rho_v h_{fg} r_m^2}{4 \sin^2 \theta \cdot \sigma T_s} \right]^2 \frac{(T_w - T_b)^2}{\pi \alpha}, \\ &= \left[\frac{\pi k_l}{2Q} \right]^2 \frac{(T_w - T_b)^2}{\pi \alpha}, \end{aligned} \quad (29)$$

where θ is the contact angle. The radius of the activity cavity r_m is

$$r_m = \left[\frac{2\sigma T_s k_l \sin^2 \theta}{(1 + \cos \theta) \rho_v h_{fg} Q} \right]^{1/2}. \quad (30)$$

Here, the instantaneous wall temperature T_w satisfies the following equation.

$$T_w - T_s = \left[\frac{8(1 + \cos \theta) \sigma T_s}{\rho_v h_{fg} \delta_l} \right]^{1/2} (T_w - T_b)^{1/2} \quad (31)$$

(2) Uniform temperature wall

For uniform temperature wall, the equivalent thickness of the thermal boundary layer is

$$\delta_l = \sqrt{\pi \alpha t}, \quad (32)$$

and the minimum waiting time is given by

$$\tau_w = \left[\frac{8(1 + \cos \theta) \sigma T_s}{\rho_v h_{fg}} \right]^2 \frac{(T_w - T_b)^2}{\pi \alpha (T_w - T_s)^4}. \quad (33)$$

The total period of individual bubble is the sum of all of the four durations.

$$\tau_d = \tau_b + \tau_w = t_g + \tau_e + \tau_c + \tau_w \quad (34)$$

Vapor nuclei

Uniform heat flux

Uniform wall temperature

Fig. 3 Activity condition of vapor nuclei

For a uniform wall heat flux surface, the total period of the individual bubble τ_d is

$$\tau_d = ca \left[\frac{\rho_v h_{fg} d}{4 k_i \Delta T_{sat}} \right]^2 + \frac{c^2 a h_{fg}^3 \rho_v^2 d^2}{32 c_{pl} k_i^2 \Delta T_s^3} + \left[\frac{\pi k_i}{2 \bar{q}_w} \right]^2 \frac{(T_w - T_b)^2}{\pi a} + \tau_c, \quad (35)$$

and for a uniform wall temperature surface, τ_d is

$$\tau_d = ca \left[\frac{\rho_v h_{fg} d}{4 k_i \Delta T_{sat}} \right]^2 + \frac{c^2 a h_{fg}^3 \rho_v^2 d^2}{32 c_{pl} k_i^2 \Delta T_s^3} + \left[\frac{8(1 + \cos \theta) \sigma T_s}{\rho_v h_{fg}} \right]^2 \frac{(T_w - T_b)^2}{\pi a (T_w - T_s)^4} + \tau_c. \quad (36)$$

For both uniform heat flux surface and uniform temperature surface, the waiting time τ_d increases approximately with the second power of liquid subcooling and dominates the total period of individual bubble compared to the other durations when the subcooling is high. However, for the uniform temperature surface, the waiting time is inversely proportional to the fourth power of wall superheat. A surface with good conductivity and large capacity might be approximately considered a uniform temperature surface.

3. Experiments

3.1 Apparatus

To verify the above analytical prediction of bubble behaviors, an experimental investigation is also performed in this study to observe vapor bubble behaviors by a high-speed camera in the nucleate pool boiling of subcooled water.

Figure 4 shows a relatively conventional experimental apparatus. The boiler vessel consists of a thick-walled container (300 mm × 300 mm × 200 mm) with two glass windows. The boiling surfaces are the side surfaces of Pt wires with diameters of 0.3 mm and 0.5 mm. The working liquid is water ranging from 20°C to 60°C in subcooling at atmospheric pressure.

The pool is thoroughly degassed prior to operation and is maintained at a given temperature by two auxiliary tank heaters. The wire surface heat flux is calculated from wire electric resistance and current. The mean wire temperature, as the surface temperature, is also obtained from the wire electric resistance. The behaviors of vapor bubbles are observed by a high-speed camera at the speed of 10 000 frames per second.

3.2 Observation of bubble behaviors

The photographs of bubble behaviors are shown in Figs. 5 and 6 at different values of wire diameter D , liquid subcooling ΔT_{sub} and mean heat flux q . Every time step per frame is 0.1 ms in all figures. The scales of each photograph are 0.5 mm in width and 2.0 mm in height.

As shown in the photographs, a semi-spherical

Fig. 4 Schematic diagram of experimental system

vapor bubble suddenly appears at an active nuclei site, then grows, condenses and collapses or departs from the heater surface, in that order. As predicted in the above analyses (Eq. (7)), the initial growth period of bubble is very short (i.e., $t_g < 3.0 \times 10^{-5}$ s when $\Delta T_{sat} \geq 10$ K); thus, its total process cannot be captured by our present high-speed camera. Other processes except the initial growth can be clearly observed and are similar to our theoretical predictions.

For the same diameter and liquid subcooling (e.g., Figs. 5 (a) and (b) or Figs. 6 (a) and (b)), the lifetime of individual bubble becomes shorter with the increase of wall heat flux. Actually, the wall superheat becomes higher with the increase of wall heat flux. From Eq. (9), the initial thickness of microlayer decreases with the increase of wall superheat. As a result, the initial growth duration τ_g (Eq. (7)), the evaporating duration τ_e (Eq. (14)) and the condensation duration τ_c (Eq. (21)), which compose the lifetime, become shorter.

From Figs. 5 (c) and (d) as well as Figs. 6 (a) - (d), it is shown that the waiting time and the total period of bubble decrease with the increase of wall heat flux. The total latent heat removed by vapor bubbles becomes smaller as the wall heat flux is increased.

By comparing Fig. 5 (a) with Fig. 5 (c), the waiting time becomes much longer with increasing liquid subcooling. Such a result is totally different from Ibrahim and Judd's result in which the waiting time decreases with increasing liquid subcooling when the subcooling is higher than about 6 K. For a high subcooling of 60 K, the bubble diameter becomes very small even at very high wall heat flux. Also, the waiting time is very long. The total latent heat removed by vapor bubbles becomes smaller as the

Fig. 5 Photographs of bubble behaviors ($D=0.3$ mm)

liquid subcooling is increased.

4. Results and Discussion

The experimental observation has clarified that one cycle of the individual bubble experiences four stages, i.e., the initial growth with a semi-spherical shape, the final growth with a spherical segment geometry, the condensation process and the waiting time.

The total period of the individual bubble τ_d predicted by Eq. (35) is valid for horizontal uniform-heat-flux plate surfaces. In the present experiments, the fine Pt wire with the diameter of 0.3 mm can be

approximately considered as a uniform-heat-flux surface because its heat capacity is very small.

To consider the curvature of the cylindrical surface of the Pt wire, some corrections should be made on the Eq. (35). As shown in Fig. 7, the planar area S_1 used in the analyses equals that of the projection of the actual contact area S_2 between vapor bubble and heater surface. Therefore, the corrected equation of total bubble period is given by

$$\tau_d = c\alpha \left[\frac{\rho_v h_{fg} d}{4k_l \Delta T_{sat}} \right]^2 + \frac{c^2 a h_{fg}^3 \rho_v^2 d^2}{32 c_p k_l^2 \Delta T_s^3} + \left[\frac{\pi k_l}{2 \bar{q}_w (S_2/S_1)} \right]^2 \frac{(T_w' - T_b)^2}{\pi \alpha} + \tau_c \quad (38)$$

(a) $\Delta T_{sub}=40\text{ K}$, $q=0.45\times 10^6\text{ W/m}^2$ (b) $\Delta T_{sub}=40\text{ K}$, $q=0.90\times 10^6\text{ W/m}^2$ (c) $\Delta T_{sub}=60\text{ K}$, $q=0.73\times 10^6\text{ W/m}^2$ (d) $\Delta T_{sub}=60\text{ K}$, $q=1.08\times 10^6\text{ W/m}^2$ Fig. 6 Photographs of bubble behaviors ($D=0.5\text{ mm}$) Fig. 7 Schematic diagram of S_1 and S_2

The predictions of total bubble periods are shown in Fig. 8. Also, the experimental results are plotted in the same figure for comparison. The experimental data are slightly lower than the analytical predictions. We consider the slight differences are caused by the fine Pt wires which are not the real uniform-heat-flux surfaces. However, relatively good agreement can be seen between the present predictions and experimental data.

From our observation, the waiting time and the total period of bubble decrease with the increase of

wall heat flux at the same liquid subcooling. It means that the higher frequency of bubble leads a higher wall heat flux. Therefore, heat transfer is mainly controlled by the behaviors of individual bubbles. Furthermore, as liquid subcooling is increased, the mean maximum diameter of bubble becomes smaller, the waiting time becomes longer and the total latent heat removed by vapor bubbles becomes smaller. Thus, the total heat flux is mainly contributed by the heat conduction outside the evaporating area as liquid subcooling becomes larger. In other words, the enhancement of heat transfer for subcooled boiling is mainly contributed by the augmented heat removal caused by the formation and collapse of individual bubbles.

5. Conclusions

The individual bubble behaviors in subcooled nucleate boiling are investigated both theoretically and experimentally in this study. The following conclusions are obtained:

(1) One cycle of the individual bubble experiences four stages, i.e., the initial growth with a semi-spherical shape, the final growth with a spherical segment geometry, the condensation process and the waiting time.

Fig. 8 Comparison of experimental data to analytical predictions

(2) Both lifetime and waiting time of bubble decrease with the increase of wall heat flux at the same liquid subcooling. The waiting time increases with increasing liquid subcooling.

(3) The latent heat removed by vapor bubbles becomes small in the total removed heat from the heater wall as the liquid subcooling is increased. The enhancement of heat transfer for subcooled boiling is mainly contributed by the augmented convection caused by the formation and collapse of individual bubbles.

(4) Relatively good agreement can be seen between the present predictions and experimental data.

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