Subcooled boiling of nano-particle suspensions on Pt wires*

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Abstract An experimental investigation is conducted to explore the subcooled boiling characteristics of nano-particle suspensions on Pt wires. Some phenomena are observed for the boiling of water-SiO_2 nano-particle suspensions on Pt wires. The experiments show that there exist not any evident differences for boiling of pure water and of nano-particle suspensions at high heat fluxes. However, bubble overlap phenomenon can be easily found for nano-particle suspensions at low heat fluxes, which probably results from the increase of the attracter force between bubbles and of the bubble mass.

Keywords: nano-particle suspension, boiling, subcooling, bubble behavior.

Fluids are often used as heat carriers in various heat exchange equipments, such as boiler, cooling systems and other associated applications. In these applications, low thermal conductivity of fluids has been becoming a bar for intensifying heat transfer. It is well known that normal solid materials, especially metals, have thermal conductivity orders of magnitude higher than that of usual liquids at a specified temperature. For example, thermal conductivity of copper is about 700 times higher than that of water and about 3000 times higher than that of engine oil. It is reasonable to believe that the effective thermal conductivities of solid-particle (especially metal-particle) suspensions are much higher than that of pure or traditional fluids. Numerous theoretical and experimental studies on the effective thermal conductivity of solid-particle suspensions have been conducted since Maxwell's theoretic work was published more than 100 years ago. All of the studies were about millimeter- or micrometer-sized particles. However, suspensions made from millimeter and micrometer particles display less applicable performance. Particularly, the stability of these suspensions was very poor, which greatly limited the application of suspensions.

The development of nano-phase materials makes the preparing of the stable suspensions possible. Choi et al.[1] proposed a new terminology of "nano-fluid" in 1995, which is actually the nano-particle suspension. Due to the significant improvement of stability, nano-particle suspensions become more applicable. Many investigations have been conducted on nano-particle suspensions, especially on the thermal conductivity of nano-particle suspensions[2~5]. Most investigations have shown that the addition of nano-particles can greatly increase the thermal conductivity of suspensions, and the thermal conductivity increases with the increasing of the nano-particle concentration. So far, the research on boiling of nano-particle suspensions is still very limited.

Das et al.[6] conducted an investigation on the boiling of water-Al_2O_3 nano-particle suspensions on horizontal tubes having diameter 20 mm with different surface roughness. The diameter of Al_2O_3 nano-particle was about 38 nm. It was found that the superheat needed for nano-particle suspension nucleation was higher than that for pure water. Surface roughness could also greatly affect the nucleation superheat of nano-particle suspensions, and the required superheat for a smooth surface was higher than that for a rough surface. When the volume concentration was higher than 0.1, the effect was well-regulated in their experimental conditions, and the superheat for high concentration nano-particle suspensions was higher than that for low concentration suspensions at a specified heat flux. The subsidence of nano-particles was considered as the main reason for the increasing of superheat.

Li et al.[7] investigated the boiling of CuO nano-particle (about 50 nm) suspensions on a horizontal heater plate. Four different working fluids were employed, including pure water, water with anionic sur-

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factant SDS (sodium dodecyl sulfate, $C_{12}H_{25}SO_4Na$) of 1% (kg/kg), nano-particle suspension with 0.05% (kg/kg) CuO and 1% (kg/kg) surfactant SDS, and nano-particle suspension with 0.2% (kg/kg) CuO and 1% (kg/kg) surfactant SDS. The CuO nano-particles, surfactant and pure water were put into and surged in a super-sonic water bath for about 10hr to prepare the working suspensions. The experimental results showed that the stability of suspension was not good and the subsidence of nano-particles seriously affected the number and distribution of active nucleate.

Wang et al.[8,9] conducted experimental investigations of liquid boiling on Pt wires and observed the colorful phenomena, such as jet flow and sweeping bubble on the wire, etc. This paper is going to extend Wang's work[8,9] and conduct an experimental investigation of subcooled pool boiling of nano-particle suspensions on Pt wires.

1 Experiments

1.1 Test system

The experimental set-up consisted of two major parts, test section and acquisition system, as shown in Fig. 1. The test section was a transparent glass vessel, 300 mm high and with a 200 mm × 200 mm rectangular cross-section. The Pt wire of 0.1 mm in diameter, installed on two copper poles, was heated by a DC power supply. The Agilent Model-6031A power supply system, which can provide maximum power of 1200 W and maximum current of 120 A, was employed as power source. Two copper poles were insulated to reduce the heat loss of the Pt wire along the copper poles. The temperature of the liquid was measured using the thermometer about 10 mm away from the Pt wire.

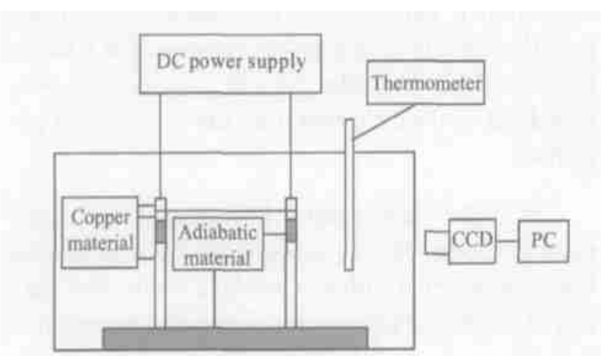

Fig. 1. The experimental system.

The video imaging system consisted of a CCD camera, a Matrox Pulsar high-speed video imaging card, zoom lens and tripod. In the experiment, a WAT-505EX CCD camera with zoom lens was used to capture images of bubble generating and growth, and then the captured video was sent to the high-speed video imaging card through the connection cable. A power PC platform with 1GB memory unit, which can capture 500 ~ 1000 video frames, was used for data and video processing. The temperature of the Pt wire could be determined by the change of its resistance. The pressure during the boiling was kept at the atmosphere pressure.

1.2 Experimental procedure

SiO_2 nano-particles were commercial products made from gas condensation. The average diameter of SiO_2 nano-particles used in this experiment was about 25 nm. Nano-particle suspensions were prepared by the two-step technology. The suspension surged in a super-sonic water bath for about 10hr to make working suspensions stable. To take the images, the concentration of water- SiO_2 nano-particle suspension was very low, at about 0.05% (kg/kg). Due to the poor light transparency, a powerful light was used during collecting images for nano-particle suspensions.

The Pt wire was kept in boiling for a long time to degas and make the surface very well treated before the experimental observation and measurement. It is found that the number of bubbles increased, while the size of bubbles decreased with the increasing of the applied heat flux. When the heat flux reached some critical values, the bubbles could not be clearly observed, which was called "high energy liquid jet"[9]. The typical phenomena of boiling process on the wire with the increasing of the applied heat flux are shown in Fig. 2.

2 Bubble behavior

The boiling process of nano-particle suspensions is almost the same as that of pure water. However, the boiling phenomena exhibit some differences at low heat flux, as shown in Figs. 3 ~ 6. Vapor bubbles form individually and keep their own configuration quite stable even when they interacted with each other. This is different from ordinary bubble dynamics in pure or mixture liquids. In addition, bubbles usually do not depart directly, and adjacent bubbles may overlap rather than coalesce, and then, several bubbles together or a bubble cluster departs from the wire after a while or a longer time. The bubble overlap and the bubble overlap dynamics are common phenomena for low heat fluxes during nano-particle suspension boiling process. In this paper, emphasis is focused on the discussion of these phenomena.

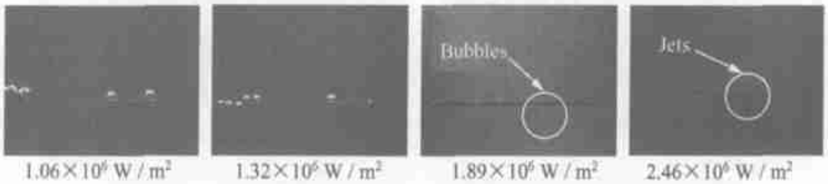

Fig. 2. Boiling process on a wire.

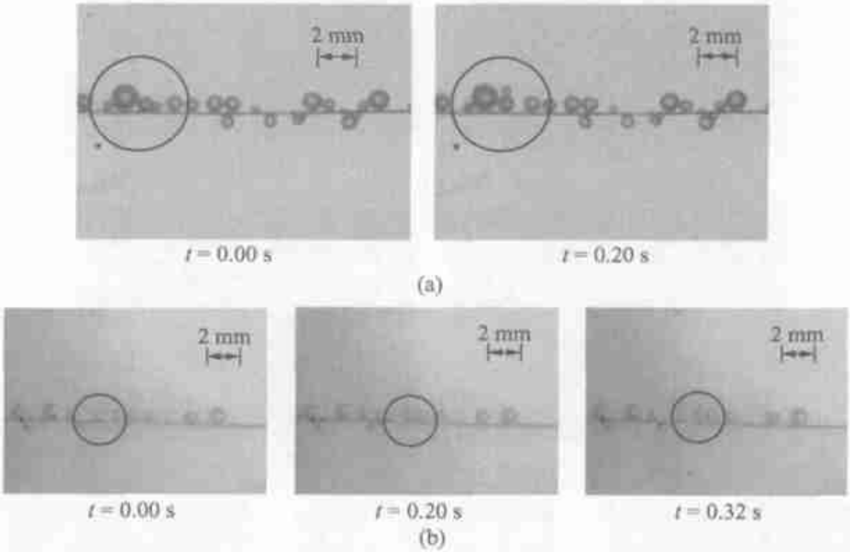

Fig. 3. Formation of bubble overlap/cluster.

2.1 Bubble overlap

The bubble overlap can be formed in two ways, as shown in Fig. 3(a) and (b). For the bubbles generating side by side, some bubbles move to and stay at the top of the other bubble(s), as shown in Fig. 3 (a); and for the bubbles generating at the same circumference of the wire, bubble(s) at the down surface move upwards, and finally overlap at the top of the bubble(s) at up surface, as shown in Fig. 3(b).

2.2 Departure of bubbles or bubble cluster

The overlapped bubbles or bubble cluster depart in two ways: bubble cluster or overlapped bubbles depart together, as shown in Fig. 4(a), (b), or the top bubble departs alone, as shown in Fig. 4(c), (d). These kinds of bubble departure are rarely observed in normal nucleation boiling of pure liquids.

2.3 Motion of bubble cluster

As the bubbles near to a bubble cluster depart from the wire, the bubble cluster is observed to move slowly together along the wire, as shown in Fig. 5.

3 Physical mechanism

3.1 Ideal particle distribution

To simplify the analysis, some assumptions are introduced as follows:

(1) Nano-particles have the physical properties of their macro material.

(2) The density variation of water and SiO_2 nano-particle with temperature is neglected.

(3) The shape of nano-particles is spherical, the named diameter is the same to be 25 nm and the particles are dispersed uniformly in the base-fluid.

The nano-particles dispersed in base fluid are idealized as shown in Fig. 6. The molecular number in a nano-particle n is

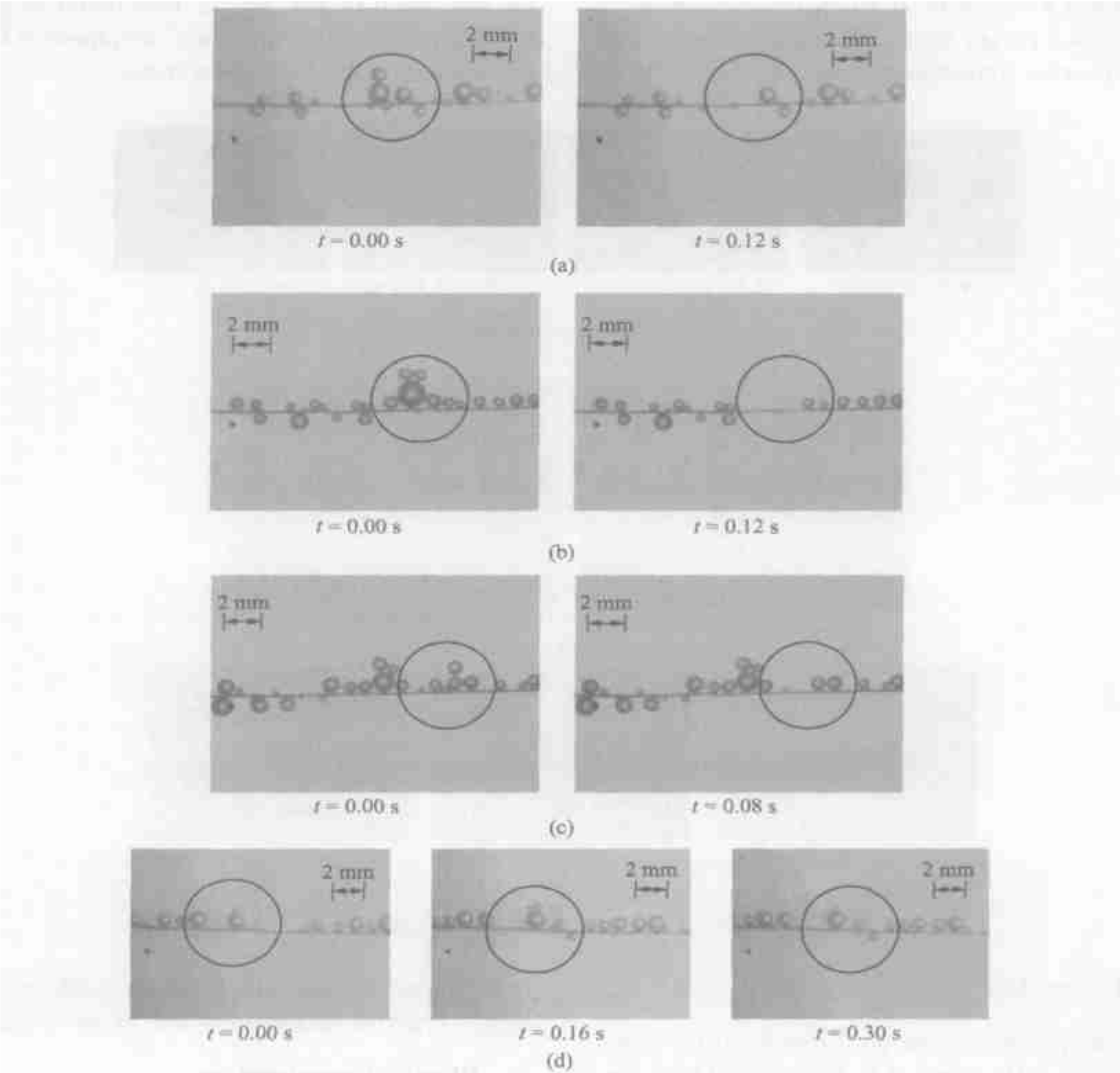

Fig. 4. Departure of bubble or bubble cluster.

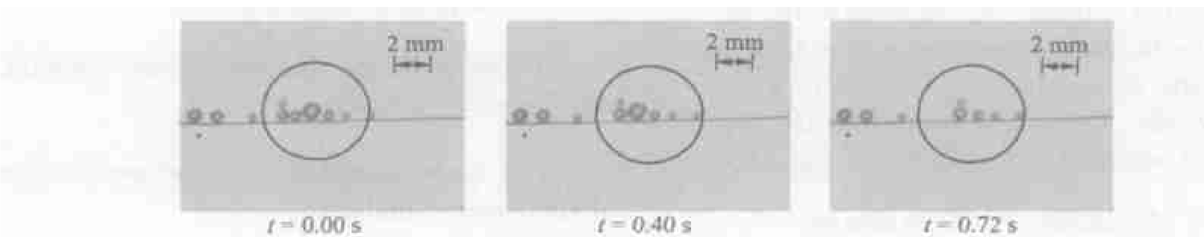

Fig. 5. Motion of bubble cluster.

$$n = \frac{\frac{\pi}{6} d_p^3 \rho_p \cdot N_A}{M}, \tag{1}$$

where d_p is the diameter of nano-particle, ρ_p is the density of nano-particle, N_A is Avogadro constant and M is molecular weight of SiO_2.

The number of nano-particles in unit volume can be expressed as:

$$\frac{cN_A}{n} = \left(\frac{1}{a} + 1\right)^3, \tag{2}$$

where a is the pitch distance between two nearby nano-particles' center, and c is the molar volume concentration of nano-particles.

This equation can be simplified if a is in the order of 10^{-3} to 10^{-6} m, or $a \ll 1$,

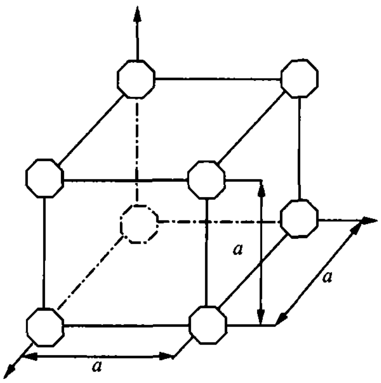

Fig. 6. Ideal distribution of nano-particles in base-fluids.

$$\frac{cN_A}{n} = \frac{1}{a^3}. \quad (3)$$

Hence, the distance between two particles can be expressed as:

$$a = d_p \sqrt[3]{\frac{\pi \rho_p}{6cM}}. \quad (4)$$

Table 1. Distance between neighboring SiO_2 nano-particles

Concentration (%, kg/kg)	Concentration (kg/m^3)	Concentration (kmol/m^3)	a (μm)
0.5	5	1/12	0.162
0.05	0.5	1/120	0.349

For the used suspensions in the present investigation, the calculated results are listed in Table 1. Apparently, the distance between two particles is very small even for very low concentration.

3.2 Analysis of the bubble behavior

As a bubble is forming, nano-particles that ever take up the space where bubbles come into being will be pushed aside and disappear in the vapor bubble. The nano-particles around the bubble will be attracted and distributed on the bubble interface, due to the interfacial tension of vapor and liquid, liquid and solid nano-particles, and vapor and solid nano-particles.

The nano-particles adsorbed on the surface of bubble will greatly affect the bubble moving on the wire and departing from the wire. These influences include the increase of bubble mass, the emergence of the attracting force between bubbles and the decrease of bubble motion velocity. The bubble shape is considered as a sphere and change of bubble shape is not considered for simplifying the discussion.

3.2.1 Increase of the bubble mass

For an ideal distribution, the number of nano-particles in a bubble volume is

$$n = \frac{\pi}{6}(d_b/a)^3 = \frac{\pi}{6}d_b^3 \Big/ \left(d_p^3 \cdot \frac{\pi \rho_p}{6cM} \right) = \frac{d_b^3 cM}{d_p^3 \rho_p}. \quad (5)$$

Total mass of the nano-particles in a bubble volume is

$$m_p = n\left(\frac{\pi}{6} d_p^3 \rho_p\right) = \frac{d_b^3 cM}{d_p^3 \rho_p} \times \frac{\pi d_p^3 \rho_p}{6} = \frac{\pi cM d_b^3}{6}. \quad (6)$$

The mass of vapor bubble is

$$m_b = \frac{\pi}{6} d_b^3 \rho_b. \quad (7)$$

The mass ratio of nano-particles to bubble in the same volume can be expressed as:

$$R = \frac{m_p}{m_b} = \frac{cM}{\rho_b}. \quad (8)$$

According to Eq. (8), if all nano-particles are attracted by the bubble surface, the mass of new bubble is 0.83 times larger than that of original bubble for the concentration of 0.05% (kg/kg). On the other hand, the volume of new bubble is almost the same as that of original bubble, while the mass almost doubles. This apparently decreases the bubble buoyancy and the bubble is not easy to depart.

3.2.2 Attracting force between bubbles

According to DLVO colloid theory[10], the attracting potential energy V_a between particles can be expressed as:

$$V_a = -\frac{A}{12}\left[\frac{1}{X^2+2X} + \frac{1}{X^2+2X+1} + 2\ln\frac{X^2+2X}{X^2+2X+1}\right], \quad (9)$$

where A is the Hamaker number, about 10^{-21} J for water, and $X = \frac{a-d_p}{d_p} = \sqrt[3]{\frac{\pi \rho_p}{6cM}} - 1$. The attracting force between particles can be accordingly derived:

$$F_a = -\frac{\mathrm{d}V_A}{\mathrm{d}h} = -\frac{\mathrm{d}V_A}{\mathrm{d}X} \cdot \frac{\mathrm{d}X}{\mathrm{d}h} = \frac{A}{6d \cdot X^2 \cdot (X+2)^2 \cdot (X+1)^3}. \quad (10)$$

The attracting force between nano-particles is a kind of short-distance force, which begins to take action when the distance between nano-particles is smaller than a critical value. The attaching force between bubbles is dependent on the number of nano-particles in the critical distance. The differences between bubbles affect the attracting force. As shown in Fig. 7, the larger the difference of bubble diameters is, the smaller the number of nano-particles exerting attracting force between the nearby bubbles is.

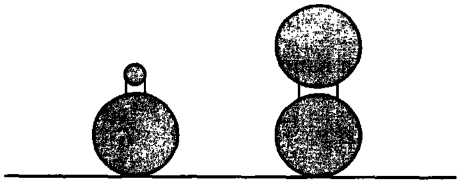

Fig. 7. Attracting action between neighboring bubbles.

The attracting force can play a role of a resistance force to prevent bubble from departing from the Pt wire. The direction of bubble motion can also change and the nano-particles distributed on the bubble surface can exert a resistance to bubbles coalescence.

3.2.3 Decrease of the bubble velocity

As nano-particles exist on the bubble surface and the attracting force exerts, the acceleration for a bubble moving on the wire in nano-particle suspension should be lower than that in pure water, which can alter the moving behavior of the bubble on the wire and the interaction between bubbles.

For example, owing to the smaller acceleration of a bubble and the attracting force among bubbles, the bubble can easily move along another bubble surface, as shown in Fig. 8, and a bubble may stay on the bubble surface forming bubble overlap, when their impact can balance the buoyancy and the bubble velocity decreases to zero.

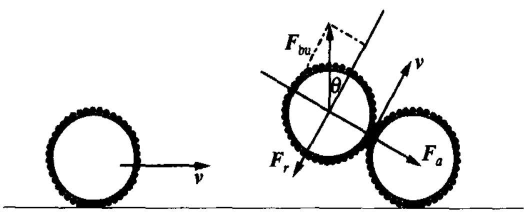

Fig. 8. Bubble motion.

In a word, the increase of bubble mass, which directly results in the decrease of the bubble motion velocity, and the appearance of the attracting force between bubbles are expected to be the important factors of overlapped bubble group or bubble cluster formation.

3.2.4 Bubble departure

For a pure liquid, it is known that buoyancy and interfacial tension affect bubble departure and the buoyancy, and inertial force and resistance force determine the bubble departure velocity. However, the bubble departure in nano-particle suspensions has some other influences as mentioned above. The overlapped bubble or bubble clusters stay on the wire for some time, and then, the overlapped bubbles depart together or the top bubble departs alone. These phenomena are caused by the special bubble interface, unique bubble dynamic behavior, the disturbance of the overlapped bubbles or bubble clusters around, and the attracting force between the bubbles.

For a bubble cluster or group consisting of bubbles having almost the same diameters, it will all depart if the attracting force between bubbles is stronger than the disturbing force as shown in Fig. 4 (a), while the top bubble departs alone if the disturbing force is stronger than the attracting force, as shown in Fig, 4(c).

As shown in Fig. 7, if larger diameter difference between bubbles exists, the number of nano-particles contacting between adjacent bubbles will decrease, which results in smaller attracting force with each other. Therefore, the top bubble will depart alone, as shown in Fig. 4(d). When increasing the nano-particles numbers involved in a bubble group or bubble cluster, the resulted attracting force between the top and bottom bubbles is very large. If the bubble diameter difference decreases to a certain value, bubbles in a bubble group or cluster will all depart, as shown in Fig. 4(b). Bubble groups or clusters can even move along the wire for strong attracting force between the two bubbles, as shown in Fig. 5.

4 Conclusions

(1) The experiment of nano-particle suspension shows different boiling phenomena from pure water at low heat flux, and bubble overlapping or clustering are common in nano-particle suspensions.

(2) The bubble overlapping or clustering probably results from attracting force between the nano-particles and the increasing bubble mass. The attracting force can cause the bubble to move along and finally stay on another bubble surface.

(3) Different attracting forces and disturbances can result in different modes of bubble departure. A bubble group or cluster departs together when the attracting force is larger than the outside disturbance, while the top bubble departs alone when the attract-

ing force is smaller than disturbance.

(4) The attracting force between bubbles plays an important role only at low heat flux.

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