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Bubble leaping and slipping during subcooled boiling on thin wires

J.F. Lu [a], X.F. Peng [a,b,*]

[a] Laboratory of Phase-Change and Interfacial Transport Phenomena, Tsinghua University, Beijing 10084, China
[b] Department of Thermal Engineering, Tsinghua University, Beijing 100084, China

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Abstract

An experimental investigation was conducted to observe periodic bubble leaping and slipping during subcooled boiling of water on horizontal wires, and associated analyses were made to describe and understand these phenomena. In experiments, bubbles were observed leaping, slipping and leaping during slipping on the wires. The bubble leaping and slipping had four main stages in one period, leaping away, slipping, returning and growing up on the wires. During leaping, a bubble had a significant volume variation. It grew up on the wire, while it reduced its volume after it departed from the wire. The experimental and theoretical evidences indicated that the interfacial thermocapillary force played an important role during the bubble leaping, and the bubble volume variation was other important factor for the leaping oscillation. The experimental results also indicated that the heat transport performance were enhanced by the periodic bubble volume variation and associated bubble leaping and slipping phenomena.

Keywords: Bubble; Leaping; Slipping; Thermocapillary force; Wire

1. Introduction

Boiling might be one of the most challenge and puzzling phenomena for its complexity and diversity, and the physical nature is still far from being truly understood [1,2]. In recent 20 years, because of the increasingly urgent needs for new and high technological applications, especially for the development of micro-electro-mechanical systems (MEMS), micro energy systems, electronic cooling, thermal management in various compact devices/systems, the investigation of boiling phenomena faced with many new challenges and researchers paid more attention to understand bubble dynamical behavior [3]. In these applications, bubble expansion and other dynamic characteristics were considered as very important factors controlling dynamic process and associated performance.

A bubble moving along a heating surface was widely investigated in open available literature. In some boiling experiments, such as forced flow boiling, boiling on a vertical wall [4], a downward wall [5], and on different orientated surfaces [6], bubbles might sweep along wall surfaces caused by fluid flow or forces like gravity/buoyancy. Qiu and Dhir [7] experimentally investigated the bubble sliding dynamical behavior, and the associated flow pattern and heat transfer over an inclined downward facing surface, and pointed out that the heat transfer could be significantly enhanced by the motion of the bubbles sliding along the heater surface during boiling. Wang et al. [8] observed sweeping bubbles moved along horizontal heating wires without forced liquid flow. Cornwell [9] noted that the sliding bubbles on the tube could enhance the heat transfer performance. Takahashi et al. [10] investigated the microfluidic oscillation by using a vapor bubble on a thin film heater, and considered the effect of thermocapillary force in this single bubble oscillation phenomenon. Qiu and Dhir [7] found that bubbles changed its shape during sliding and bubbles hopped along the heater surface at inclinations close to the vertical direction. Wang et al. [11] observed very small bubbles reattaching on or returning to the wire. Marek and Straub [12] indicated that the Marangoni force would push the bubble towards the wire in a temperature gradient region.

Various mechanisms, especially thermocapillary effects were previously proposed to explain these bubble dynamic phe-

* Corresponding author. Tel. (fax): (+8610)6278 9751.
E-mail address: pxf-dte@mail.tsinghua.edu.cn (X.F. Peng).

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Nomenclature

a	acceleration	$\mathrm{m\,s^{-2}}$
B	temperature coefficient of surface tension	$\mathrm{J\,m^{-2}\,K^{-1}}$
D	temperature gradient	$\mathrm{K\,m^{-1}}$
f	force	N
h	latent heat	$\mathrm{J\,kg^{-1}}$
l	distance	m
R	radius	m
t	time	s
T	temperature	K
V	volume	$\mathrm{m^3}$

Greek symbols

ρ	density	$\mathrm{kg\,m^{-3}}$
θ	angle	rad
σ	interfacial tension	$\mathrm{J\,m^{-2}}$

Subscripts

0	initial or reference state
b	buoyancy
c	critical
l	liquid
t	thermocapillary
v	vapor

nomena in the available investigations. The Marangoni effect induced by surface tension gradients was noted to be very strong in some special cases, such as in microgravity environments or microscale systems [10,13,14]. In this paper an investigation is conducted to understand the periodic leaping and slipping phenomenon of bubbles during subcooled boiling on horizontal thin wires, and associated mechanisms and heat transfer performance are also discussed.

2. Experiments and observations

2.1. Test facility

The experimental facility employed in this investigation is schematically illustrated in Fig. 1, mainly including three parts, the test module, power supplier, and data and photo image acquisition system. The test module was constructed in a vessel made of stainless steel having size of 250 × 250 × 400 $\mathrm{mm^3}$. There were two glass windows machined on two opposite sides. A platinum wire heater was horizontally installed in the vessel, and the ends of the wire were connected to two electrodes having diameter of 5 mm. The wires used in this investigation were 80–100 mm long and diameter of 100 µm. A preheater and cooler were employed for keeping the bulk liquid temperature approximately invariable. The pressure in the vessel was kept at atmospheric pressure.

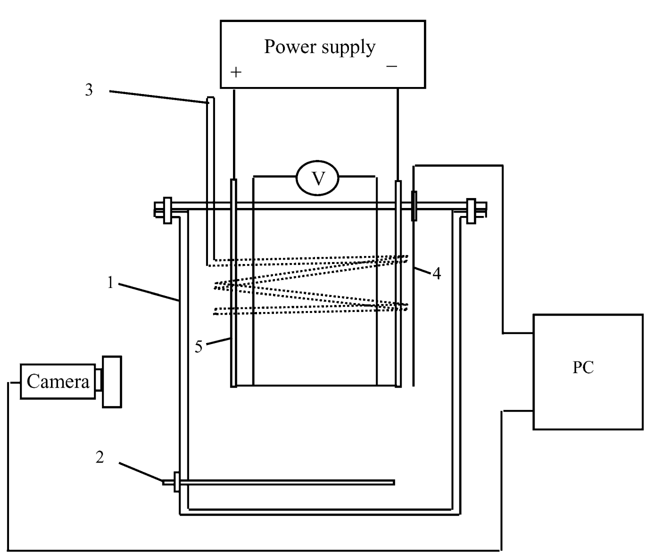

Fig. 1. Schematics of testing system. (1) testing vessel, (2) preheater, (3) cooler, (4) thermocouple, (5) electrode.

The power was supplied using a HP Agilent Model-6031A supplier, which can provide a maximum voltage of 20 V and maximum power of 1000 W. Direct current was applied to the wire and a uniform heat flux was generated to heat the liquid. To reduce the boundary effect of the electrodes, the voltage of the investigated section was directly measured on the effective test section using a voltage meter, as shown Fig. 1. The working liquid employed in the experiments was pure water.

The acquisition system included photo image and data acquisition system. The photographic system consisted of a high-speed CCD camera (the Motionscope PCI, Redlake imaging), a high-resolution image acquisition card, and zoom lenses. The present experiments used recording rates of 1000 fps, the resolution 320 × 280 pixels. In this investigation, the image field is about 2 × 1.75 $\mathrm{mm^2}$–5 × 4.4 $\mathrm{mm^2}$, and the size of one pixel is about 6–15 µm. The images were transported to a computer and stored for further analysis.

The current and voltage applied to the wire were measured to determine the heat flux, and the average wire temperature was estimated from the wire resistance simultaneously measured by the calibrated correlation. The bulk liquid temperature was measured using the thermocouples placed in the bulk liquid as shown in Fig. 1, and the uncertainty was 0.2 K. The resistance of the wire was pre-calibrated as an approximately linear function of temperature, so the temperature change of the wire could be obtained from the measurement of the wire resistance. The error analysis shows that the overall uncertainty of the wire temperature measurement was ±2 K, while the uncertainty of the heat flux was less than 2%. It is worth to note that local temperature is of critical importance for recognizing the bubble dynamic characteristics. However, it was not measured due to the difficulty.

2.2. Bubble leaping

In most experiments, bubbles and their motions kept on the wire. Some investigators mentioned that the bubbles could hop along the heater surfaces at inclinations close to the vertical direction [7] or returned to the wire [11], but so far, these phenomena still have not been considered as important and basic ones in boiling systems. In present experiments, bubbles were observed leaping on the wire and changing their volume during slipping or leaping at a regular position or during leaping very periodically, and these could be considered as common and basic phenomena in boiling systems. Bubble leaping mostly occurs at low heat flux ranging 6–10 × 10^5 W m^{-2} and bulk liquid temperature 35–45 °C without degassed. If the liquid temperature is below 35 °C, the liquid should be preheated or boiled to degas or reduce the concentration of non-condensable air to a suitable level.

Bubble leaping at a regular location was observed at lower heat generation conditions. The radius of a leaping bubble at a regular position was normally much smaller than the wire diameter, and it would depart from the wire or slip in the liquid close to the wire. Fig. 2 presents a periodic leaping of a bubble at a regular location at the bulk water temperature 30 °C and heat flux of 6.6 × 10^5 W m^{-2}. At 0.008 s, the bubble was just on the wire, and then it grew up and was ready to depart in the next 0.002 s. At 0.012 s, the bubble jumped away from the wire about 0.12 mm. At 0.014 s, the bubble returned to the wire and finished a leaping period. Again, the bubble departed form the wire into the liquid at 0.018 s, and it returned to the wire at 0.020 s. After 0.020 s, the bubble began to keep on the wire, and then it slipped away from the initial place.

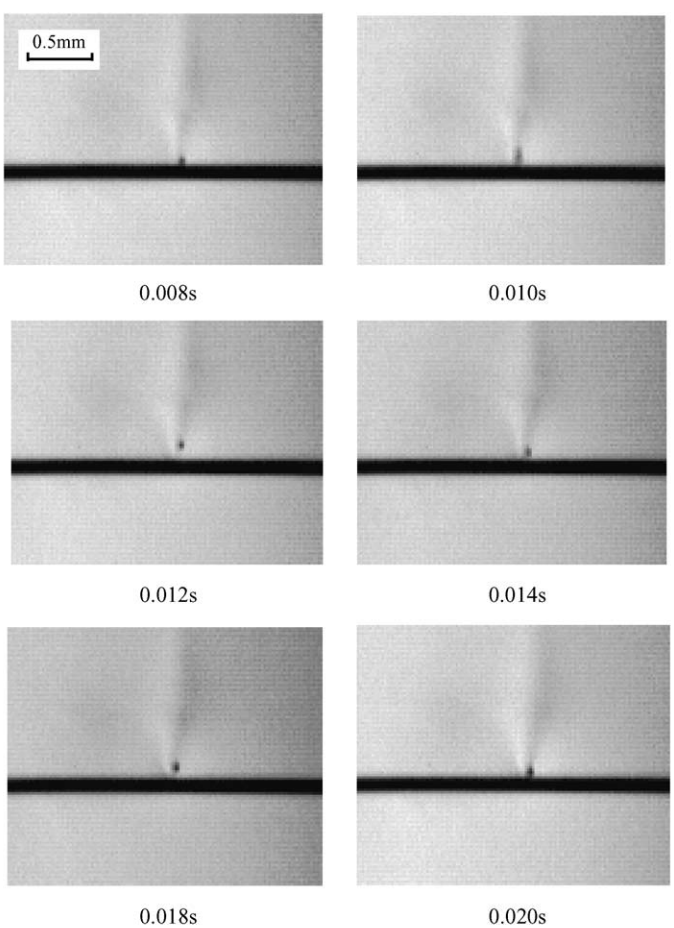

Fig. 2. Bubble periodically leaping at a regular position. ($T_{liq} = 30$ °C, $P = 1.01 \times 10^5$ Pa, $q'' = 6.6 \times 10^5$ W m^{-2}, $T_w = 101$ °C.)

2.3. Bubble leaping with slipping

The bubble leaping with slipping, for convenience or bubble leaping and slipping usually occurred at bulk liquid temperature 35–45 °C and heat flux 7–10 × 10^5 W m^{-2}, and it was more stable and regular than that of bubble periodic leaping at a special place. A series of photographs is illustrated in Fig. 3 to show the details of the bubble leaping and slipping on the heating wire, which were obtained from the boiling of water at heat flux 8.8 × 10^5 W m^{-2} and bulk temperature 41 °C. At initial time $t = 0$ s, a bubble with radius of 0.15 mm was on the middle of the wire. At 0.001 s, the bubble jumped off the wire and its size became smaller. In the next 0.001 s, the bubble just

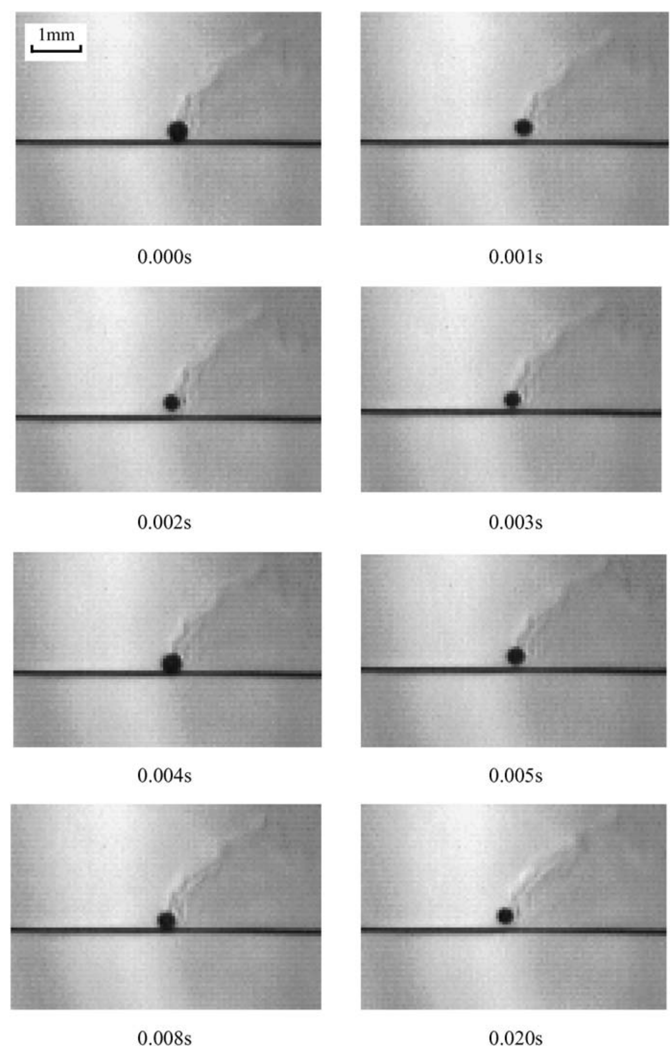

Fig. 3. Small bubble leaping and slipping. ($T_{liq} = 41$ °C, $P = 1.01 \times 10^5$ Pa, $q'' = 8.8 \times 10^5$ W m^{-2}, $T_w = 103$ °C.)

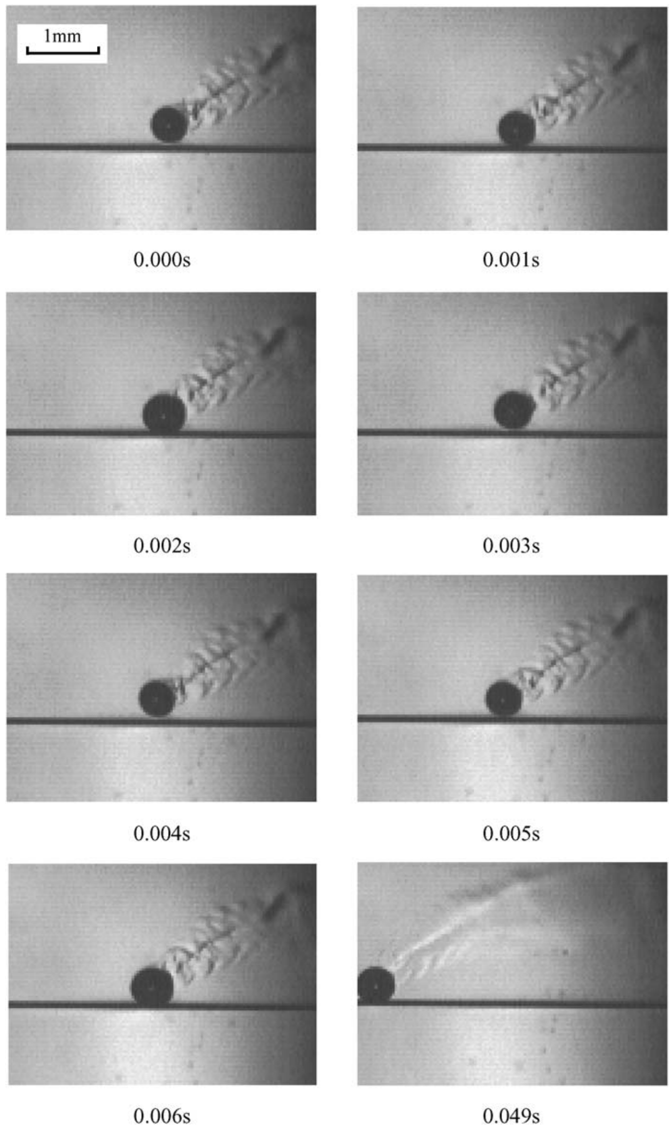

Fig. 4. Large bubble leaping and slipping. ($T_{liq} = 41\,°C$, $P = 1.01 \times 10^5$ Pa, $q'' = 9.2 \times 10^5\ W\,m^{-2}$, $T_w = 106\,°C$.)

slipped in the water over the wire for a distance of 0.037 mm. At 0.003 s, the bubble reattached the wire and then slipped on the wire much slowly. At 0.004 s, the bubble finished its leaping period, and it grew up on the wire just to the size at the initial time. After $t = 0.004$ s, the bubble began the second leaping and slipping period, jumping off from the wire, then slipping and reattaching back to the wire, and growing up to the original at 0.008 s. This bubble leaping and slipping could continue a long time until it met with another bubble or strong perturbation. Relatively, the bubble slipped on the wire very much slowly with less significant distance during a period for almost all cases. As a result, the slipping on the wire would not be considered for a very much short time period in this investigation.

Another series of photographs is illustrated in Fig. 4 to show the details of a large bubble leaping and slipping on a heating wire, which was obtained from the boiling of water at heat flux $9.2 \times 10^5\ W\,m^{-2}$ and bulk temperature 41 °C. At the initial time $t = 0$ s, the bubble with radius of 0.23 mm was just near

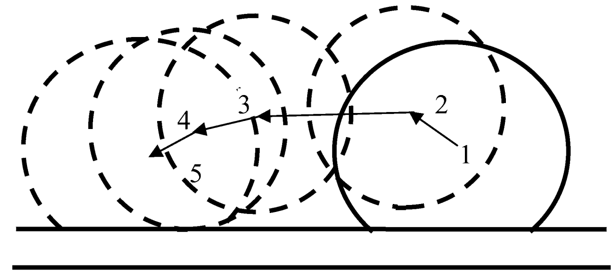

Fig. 5. Stages of bubble leaping and slipping.

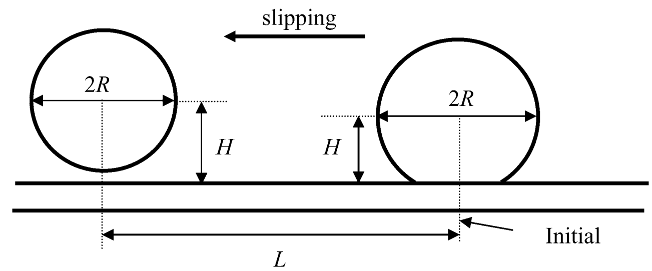

Fig. 6. Analytical model for bubble leaping and slipping.

the wire. At 0.001 s, the bubble returned to and reattached on the wire. From 0.001 to 0.003 s, the bubble grew up quickly on the wire, and from 0.003 to 0.004 s it became a little bit smaller and was ready for next jumping. After the bubble finished its first leaping period, it jumped away from the wire same as the initial height at 0.004 s and slipped. The slipped distance was actually longer than that in Fig. 3 for a small bubble, which will be discussed later. After 0.004 s, the bubble began the second period, and the leaping and slipping continued for a long time. For these two processes in Figs. 3 and 4, the basic characteristics of these leaping and slipping processes are similar, and slipping velocity for small bubble is lower than that of large bubble.

Generally, the bubble leaping and slipping had four main stages in one period, as illustrated in Fig. 5, jumping from 1 to 2, slipping from 2 to 3, returning from 3 to 4 and growing from 4 to 5, and every stage was nearly 0.001 s in Figs. 2 and 3. A simple leaping process at a regular or special position is similar to the process described in Fig. 5, while it had no horizontal displacement.

3. Bubble dynamic behavior

For investigating the bubble leaping and slipping presented in Figs. 2–4, an analytical model is proposed to describe the dynamical process, as shown in Fig. 6, and meanwhile some geometrical parameters are specified, including bubble radius R, bubble center height H (the distance from the bubble center to wire surface), slipping distance L. According to the experimental results, a bubble away from the wire is usually an idea sphere as $R < H$, while it is a spherical crown on the wire as $R > H$.

For the bubble periodic leaping process at a regular place, $L = 0$. Corresponding to the experimental observation in Fig. 2, the variation of the bubble radius and height is illustrated in Fig. 7. Obviously, the bubble radius increased as it approached

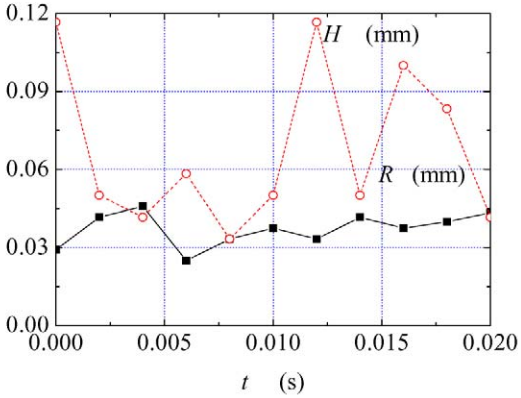

Fig. 7. Variation of the height and bubble radius.

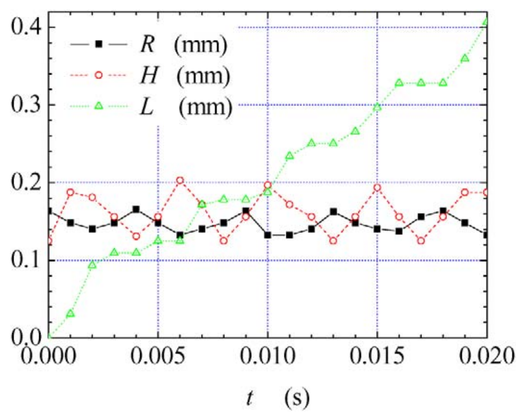

Fig. 8. Parameter change corresponding to Fig. 3.

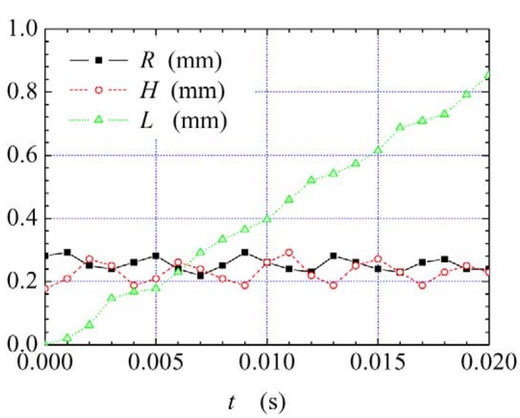

Fig. 9. Parameter change corresponding to Fig. 4.

the wire, while the radius decreased as it jumped off. For the whole bubble leaping process, its period was 0.004–0.006 s, the leaping amplitude was 0.03–0.08 mm, and the leaping oscillation continued for about 0.020 s. Usually, the bubble leaping amplitude and radius would not keep very stable.

Fig. 8 presents the dynamic parameters for the bubble leaping and slipping corresponding to the experiment shown in Fig. 3. The bubble had the radius ranging from 0.13 to 0.17 mm and slipped along the wire with an average speed of 20 mm s^{-1}. The bubble height varied in the range of 0.13–0.21 mm. Fig. 9 presents the change of the parameters for the bubble leaping

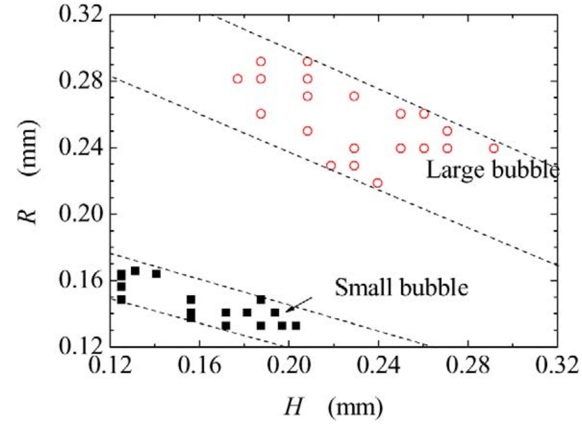

Fig. 10. Change of bubble radius with the center height.

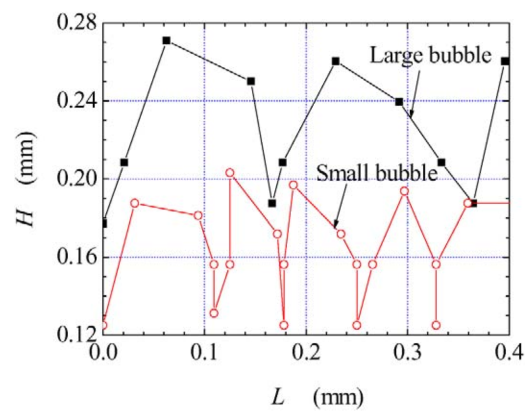

Fig. 11. Variation of bubble center height with slipping distance.

and slipping in Fig. 4. The bubble radius changed in the range of 0.23–0.29 mm and slipped along the wire with an average speed of 40 mm s^{-1}. And the bubble center height varied in the region of 0.18–0.30 mm. Very clearly, the bubble leaping and slipping in these two cases was very stable.

From Figs. 8 and 9, as the bubble approached to the wire, its radius increased, while the radius decreased as it jumped off. The relationship of the center height and bubble radius is illustrated in Fig. 10. Obviously, they were directly proportional to each other. When the bubble jumped off, it was surrounded with subcooled liquid and became smaller due to the cooling of the subcooled liquid, sometime maybe condensation even occurring at the bubble interface, and it would grow up to a large size for the heating and evaporation happening at the bubble interface on the wire.

Fig. 11 shows the bubble center height changes with the slipping distance. Obviously, the bubble away from the wire had significant slippage, while it had little displacement along the wire when it attached on the wire. Additionally, the average speed due to the slipping distance in a 0.001 s period is illustrated in Fig. 12. The average slipping speed of the large and small bubble away from the wire was about 60 mm s^{-1} and 45 mm s^{-1}, respectively. On another hand, the speed could approximate to zero as the bubble attached on the wire. Comparing these two bubble leaping and slipping processes, the spatial period of the large bubble was about two times that of

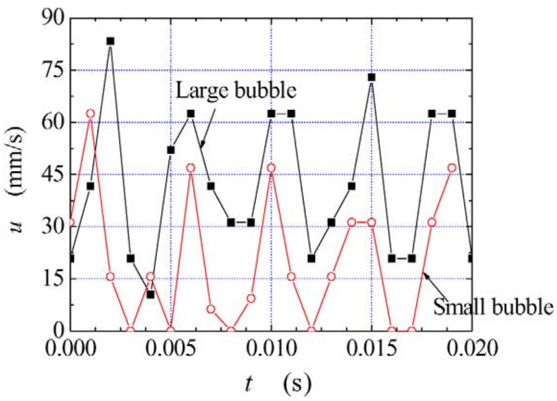

Fig. 12. Average speed of bubble slipping in 0.001 s.

the small bubble, and the average speed of the large bubble was also larger. For the whole slipping process, the bubble slipping away from the wire slips much faster than that on the wire, and there might be resistance acting on bubbles as they attached on the wire.

4. Dynamic mechanisms and heat transfer performance

4.1. Mechanisms of bubble leaping and slipping

The bubble leaping and slipping includes two different dynamic processes, bubble leaping and bubble slipping. Bubble slipping plays an important role in subcooled boiling on a heating wire, and its mechanisms were investigated in some available articles [8]. Comparing with a normal simple slipping with the coupled phenomenon of bubble leaping and slipping, the speed of bubble leaping and slipping would not keep constant, but it usually periodically varied with the companied leaping.

Available investigations [17,18] qualitatively discussed the possible reasons of bubble slipping and collision mechanics, and considered the thermocapillary effect as a dominant driving force. Because the temperature of the liquid before the siding bubble is higher than that behind the bubble, the thermocapillary force induced by bubble motion itself would act as a drive force, which can balance the liquid viscous force. As the leaping bubble reattaches to the wire, it impacts on the wire and changes its shape, and that causes a great resistance to decrease the slipping speed compared with the resistance imposed only by the liquid. Relatively, the slipping in the liquid was much significant than that on the wire, and the slipping on the wire was much slowly in the experiments. As a conclusion, the leaping characteristics govern the slipping behavior.

A periodic leaping process experiences departing and returning two sub-stages. When the bubble attaches on the wire, it would grow up to an enough large size and depart from the wire due to the heating of the wire. As the bubble is away from the wire, it will be cooled by the subcooled liquid surrounded to decrease its volume and reattach to the wire.

The departing or returning process also has two sub-processes, or accelerating and decelerating. For the departing process, the bubble first leaves away from the wire, then accelerates to the maximum velocity, finally it decelerates to zero at the highest place. In the accelerating process, the escaping force is larger than the attraction force, while the attraction force should be larger than the escaping force in the decelerating process. As the bubble reaches the maximum velocity, the escaping force just balances the attraction force. Here the location at maximum velocity or zero acceleration is termed as equilibrium position. On the other hand, the basic dynamical characteristics of the returning process are similar to those of departing process.

To investigate the bubble leaping process, we will qualitatively consider the forces applying on the bubble during the leaping process to investigate the bubble dynamical characteristics. Additionally, we assume the bubble as an idea sphere and mainly consider the formation of oscillation or leaping in vertical direction.

During bubble leaping process, the bubble accelerates and decelerates very quickly. Expectedly, the inertia effect will play an important role in the bubble motion. For a bubble submerged in a bulk liquid, the inertia quality is $M = \rho_l 2\pi R^3/3$ [15]. A bubble near a wall usually has larger inertia quality than that in bulk liquid [16]. In present investigation, the bubbles with various radiuses are on or near a thin wire, and then their inertia quality would be influenced by the relative radius and position of the bubble to the wire. Generally, bubble inertia quality can be expressed as

$$M = \psi \rho_l 4\pi R^3/3 \tag{1}$$

where ψ is defined as a non-dimensional inertia coefficient here. For a bubble submerged in bulk liquid, $\psi = 1/2$. For a variation bubble above the thin wire in the present investigation, inertia is mainly determined by the vertical velocity of the bubble, the distance to the wall, the growth rate of the bubble and the radii of the wire and bubble, and $\psi > 1/2$ from available investigations [16].

Apparently, there exists a returning force acting on the bubble during the leaping process, and the thermocapillary force can make the bubble re-attach the wire as mentioned in available investigations [11]. For subcooled boiling on a wire, non-condensable gas could also play an important role in the interfacial thermocapillary force and this bubble leaping process. If the concentration of non-condensable gas is very small, the thermocapillary force as a returning force is probably not strong enough to pull the bubble back to the wire [13]. If the concentration of non-condensable gas is too high, the bubble with much non-condensable gas will be difficult to have significant volume variation at a short time, and the leaping cannot continue. As a conclusion, the concentration level of non-condensable gas should be moderate for bubble leaping process as noted in the present experiments.

For boiling on a wire, the temperature near the wire T_n is higher than that away from the wire T_a, or $T_n > T_a$ as shown in Fig. 13, and the average interfacial temperature gradient along the vertical direction is assumed to be D_y. According to Appendix A, the thermocapillary force imposed on a bubble having radius R can be expressed as [1]

$$f_t = D_y B 8\pi R^2/3 \tag{2}$$

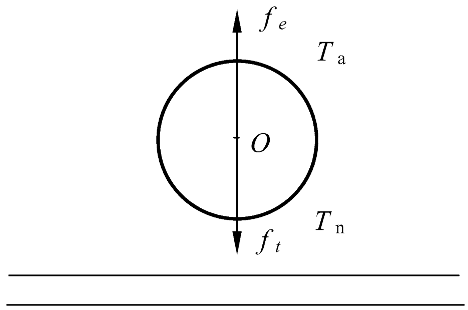

Fig. 13. Forces acting on a bubble.

where $B = \mathrm{d}\sigma/\mathrm{d}T$ means temperature coefficient of the surface tension.

The corresponding gravity and buoyancy imposed on the bubble are derived as, respectively,

$$f_g = -\rho_g g 4\pi R^3/3 \tag{3a}$$

$$f_b = \rho_l g 4\pi R^3/3 \tag{3b}$$

From Eq. (3), their resultant force as escaping force is

$$f_e = (\rho_l g - \rho_g g) 4\pi R^3/3 \tag{4}$$

Correspondingly, the bubble dynamical equation away form the wire can be expressed as

$$Ma = (\rho_l g - \rho_g g) 4\pi R^3/3 - D_y B 8\pi R^2/3 \tag{5}$$

Obviously, the basic bubble dynamical characteristics are dependent upon the relation of escaping force f_e and returning force f_i. For the bubble leaping process in Fig. 3, $R = 0.15$ mm, $\rho_l - \rho_g = 957\ \mathrm{kg\,m^{-3}}$, $g = 9.8\ \mathrm{m\,s^{-2}}$, we have $f_e = 1.33 \times 10^{-4}$ N. The average temperature gradient is estimated as $D_y \approx \Delta T/\delta h$ along the bubble interface, where ΔT means the temperature difference between the top and bottom of bubble, δh characteristic length. Assuming $\Delta T \approx 1\,^\circ\mathrm{C}$, $\delta h \approx 2R = 0.3 \times 10^{-3}$ mm, $D_y \approx -3.33 \times 10^3\ \mathrm{K\,m^{-1}}$, and $B = 1.7 \times 10^{-4}\ \mathrm{N\,m^{-1}\,K^{-1}}$, $f_t = -1.06 \times 10^{-4}$ N. As a conclusion, the escaping force and returning force can be in the same order. When the bubble moves through the equilibrium position, the acceleration velocity will change its sign, and is dependent upon the relation of the escaping force and returning force.

Re-arranging Eq. (5) yields non-dimension acceleration as

$$\bar{a} = \overline{R}^3 - \overline{R}^2 \tag{6}$$

where $\overline{R} = \frac{R}{R_c}$, $R_c = \frac{2D_y B}{\rho_l g - \rho_g g}$, $\bar{a} = \frac{1}{MR_c^3}\frac{a}{\rho_l g - \rho_g g}$. Eq. (6) is illustrated in Fig. 14.

Now we discuss the departing process. If $R > R_c$ in Eq. (5)–(6) or Fig. 14, the escaping force f_e is larger than the returning force f_t, and this will cause an accelerating process away from the wire as observed in the present experiments. For $R_1 < R_c$ in Eq. (5)–(6) or Fig. 14, the escaping force f_e decreases and is smaller than the returning force f_t, and the bubble will experience a decelerating process. Similar to the departing process, the bubble returning also experiences the accelerating and decelerating process. As bubble departing and returning continues, the bubble will exhibit a periodic leaping phenomenon. If an estimation model is applied to the case in Fig. 3,

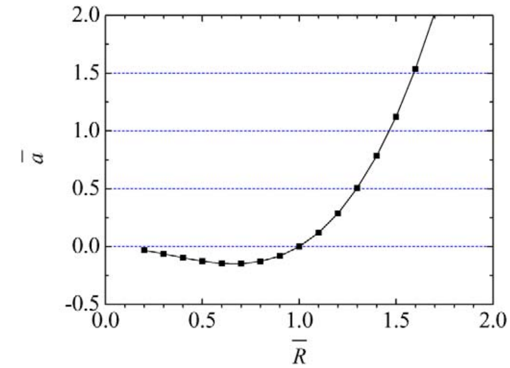

Fig. 14. Bubble dynamic characteristics.

$D_y \approx -3.33 \times 10^3\ \mathrm{K\,m^{-1}}$, the critical radius from Eq. (6) is $R_c = 0.12$ mm, and this shows a good agreement with the experimental results.

Generally, the interfacial thermocapillary force acting as the returning force plays an important role during the bubble leaping, and the bubble volume variation is another important factor for the leaping oscillation.

4.2. Heat transfer performance

The heat transfer performance is expected to be greatly influenced by the bubble leaping and slipping. Certainly, it is mainly dependent upon the associated convection and phase change. Since the temperature near the wire is higher than that away from the wire, the convection is caused by both buoyancy and interfacial thermocapillary flow. The bubble slipping also plays an important role, inducing significant perturbation on the liquid flow around the bubble and wire, like the wake in Figs. 3 and 4. If the slipping exists on the wire, it would totally alter the evaporation and contact situation of fluid with the wire. These effects all greatly enhance the heat transfer. Available investigations in literature considered the heat transfer characteristics of convection, bubble evaporation and bubble slipping [7,8], while special heat transfer performance of bubble leaping with volume variation should be further investigated.

For general cases, the periodic volume variation of a single bubble has little effect for heat transport. During bubble leaping and slipping, the heat transport with periodic volume variation should be more important. For a leaping and slipping process, the volume varies periodically including four stages, and here assume the volume variation during one stage (0.001 s) is ΔV. For this boiling system, the bubble volume variation is mainly caused by liquid evaporation and condensation, and latent heat or heat transport caused by the volume variation can be described as $h\rho_g\Delta V$.

The heat transport with periodic volume variation during 0.001 s in Fig. 3 is illustrated as Fig. 15. During 0.020 s, the heat absorbed from the wire for the volume increment is about 227.74 μJ, and then average heat transfer power P is 11.387 mW. To estimate this local heat flux imposed on the wire, the radius of influence domain is considered to be the average bubble radius of 0.26 mm. Under these conditions, the contribution of local heat flux by periodic volume variation is

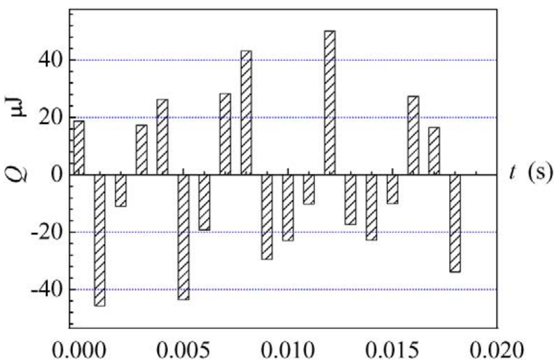

Fig. 15. Heat transport for periodic volume variation (large bubble).

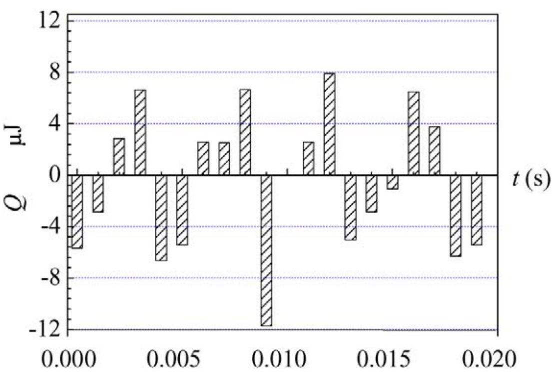

Fig. 16. Heat quantity with periodic volume variation (small bubble).

about $P/\pi R^2 = 1.68 \times 10^5\ \text{W}\,\text{m}^{-2}$, and that is about 18.3% of the wire heat flux.

The heat transport with periodic volume variation during 0.001 s in Fig. 4 is illustrated in Fig. 16. During 0.020 s, the heat absorbed from the wire for the volume increment is about 41.91 μJ, and heat transfer power P is 2.09 mW. Similar to above analysis the radius of influence domain is assumed as the average bubble radius of 0.14 mm, the contribution of local heat flux by periodic volume variation is about $P/\pi R^2 = 1.06 \times 10^5\ \text{W}\,\text{m}^{-2}$, which is about 12.1% of the wire heat flux.

As a conclusion, the heat transport with periodic volume variation can significantly enhance the local heat transfer, but is still much less than the wire heat flux. The main reason is that the evaporation near the wire is mostly balanced by the condensation on the bubble top. So the heat flux with volume variation is just one part of heat transport through phase change.

Bubble leaping and/or slipping has two special mechanisms to enhance the heat transport. The heat transport enhancement for slipping process is described in some literatures [7,8]. In this article, the leaping process or periodic bubble volume variation is considered. When the bubble stands on the wire, the bubble grows quickly by absorbing heat from the wire. As the bubble jumps away from the wire, the bubble is surrounded by cold water, and it shrinks quickly by releasing heat that is absorbed from the wire. Generally, the leaping process is an effective cycle for heat transport from high temperature region to the cold temperature region by the phase change of the bubble variation.

5. Conclusions

Both experimental observation and theoretical analyses were conducted to understand bubble leaping and slipping during subcooled boiling on thin wires. The bubble can continue leaping during the slipping or at a regular place. The bubble leaping and slipping mainly had four stages in one period, leaping away, slipping in the liquid, returning and growing on wire. The slippage characteristics were described with bubble radius, bubble center height and slipping distance. Because of the high liquid subcooling, the bubble had significant volume variation during leaping. It grew up on the wire due to the heating of the wire, while it reduced its volume as it departed away from the wire and was cooled down by the surrounding subcooled liquid. These effects are revealed to induce the variation of the forces acting on the bubble, and then resulted in the bubble leaping phenomenon. The bubble volume variation and interfacial thermocapillary force were the most important factors playing key roles in the bubble leaping and slipping processes. The experimental results also indicate that heat transport performance were greatly enhanced by the periodic bubble volume variation and associated bubble leaking and slipping phenomena.

Appendix A. Thermocapillary force on a bubble

Consider a bubble having linear temperature profile of $T(x) = T_0 + Dx$ along its interface, as shown in Fig. 17, where T_0 being a reference temperature, and D temperature gradient. Apparently, the reverse force of the momentum transfer due to the Marangoni flow would push the bubble to move toward high temperature region, and the thermocapillary force is expressed as

$$f_t = -\int_0^{\pi} \frac{\partial\sigma(T_i)}{\partial T_i} \cdot \frac{\mathrm{d}T_i}{R\,\mathrm{d}\theta} 2\pi R\sin\theta \cdot \sin\theta \cdot R\,\mathrm{d}\theta \qquad \text{(A.1)}$$

The temperature gradient would be

$$\frac{\mathrm{d}T_i}{R\,\mathrm{d}\theta} = \frac{\mathrm{d}T_i}{\mathrm{d}x} \cdot \frac{\mathrm{d}x}{R\,\mathrm{d}\theta} = \frac{\mathrm{d}T_i}{\mathrm{d}x} \cdot \sin\theta \qquad \text{(A.2)}$$

The interfacial tension changing with temperature is [1]

$$\sigma(T_i) = \sigma(T_0) - B(T_i - T_0) \qquad \text{(A.3)}$$

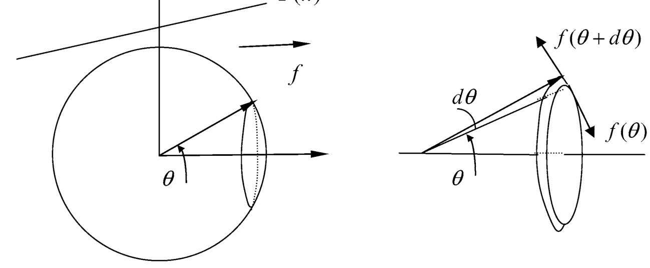

Fig. 17. Thermocapillary force on a bubble.

where $\sigma(T_0)$ is the interfacial tension at temperature T_0, B a positive constant. Substituting Eqs. (A.2)–(A.3) into Eq. (A.1) and integrating yields

$$f_t = \frac{8}{3}\pi DBR^2 \tag{A.4}$$

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