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EXPERIMENTAL STUDY ON BUBBLE SLIDING AND LIFT-OFF BEHAVIOR IN A NARROW RECTANGULAR CHANNEL

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Abstract

Visual investigation on bubble sliding and lift-off behavior in a narrow rectangular channel was carried out. In upflow boiling for vertical and inclined downward facing heating surface, the bubbles always slid along the heating surface, and the bubble lift-off phenomenon was not observed with low heat flux in the isolated bubble region. The sliding velocity is less than that of local bulk liquid velocity at the initial moment. However, it will exceed the local liquid velocity with increasing time. In vertical downflow boiling and inclined upward facing upflow boiling, the bubble tends to lift off from the surface. Based on the experimental results, the bubble sliding and lift-off mechanism are explained by the analysis of forces.

Introduction

Boiling heat transfer in a narrow rectangular channel is frequently encountered in various industrial applications, such as plate-type fuel elements, compact evaporators and heat exchangers. In recent years, there are a lot of investigations focusing on boiling heat transfer in narrow channels in published literatures [1-5], and these researches implies that boiling heat transfer process and hydrodynamics in a narrow channel are distinctly different from that in an ordinary sized channel. However, only a few of the available microscope knowledge can be applied to the microscale phenomena of boiling, and the boiling heat transfer mechanism in a narrow channel is not fully understood and further research is necessary.

It is important to study the bubble dynamics in order to understand the boiling heat transfer mechanism based on visualized technology. Lee et al. (2004) [6]studied bubble dynamics in a single trapezoid microchannel with a hydraulic diameter of 41.3μm. The results showed that the bubble departure diameter was controlled by surface tension and drag force induced by bulk flow, and the bubble departure diameter could be predicted by a modified Levy equation. Pan et al. (2006) [7] studied the bubble behavior under different heating conditions in narrow rectangular channels. They reported the wall superheat with two-side heating was lower than that with one-side heating when heat flux was the same. With the same subcooling condition, the required heat flux of onset of nucleate boiling in one-side heating channel was higher than that in two-side channel. Lie and Lin (2005 and 2006) [8-9] studied bubble characteristics of refrigerant R-134a in a horizontal narrow annular channel with 1.0 and 2.0 mm, and found that flow boiling heat transfer coefficient increased with decreasing the gap size in subcooled and saturated flow boiling, and many bubbles generated from the cavities tend to merge together to form big bubbles at a high heat flux. It was also found that the bubble departure frequency increased with decreasing channel size, which was mainly due to the rising shear stress of the liquid flow.

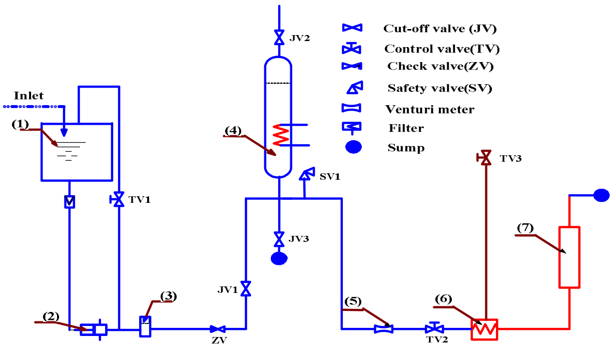
The study in published literature, as discussed above, shows that previous researches are mainly focused on bubble growth and detachment at nucleation site. However, it is known that the boiling heat transfer is significantly influenced by the motion of vapor bubbles after departure from nucleation sites. After a bubble departs from the nucleation site, it tends to slide along the heating surface, which is referred to as the typical sliding bubble phenomenon. Xu et al. (2007) [10]visually studied bubble characteristics in vertical narrow rectangular channel from the wide side of a narrow rectangular channel. The results showed that the bubbles departing from the nucleation sites always slid along the heating surface, and the bubble lift-off phenomenon was not observed with low heat flux. However, this phenomenon of bubble sliding was only observed from the wide side of the rectangular channel, and the phenomenon between the bubble base and the heating surface was not observed due to the limit of the design in experimental section and visual study technology. Therefore, further investigations are still necessary from the view of the wide side and the gap side of the narrow rectangular channel in order to better understand the mechanism of sliding bubble motion.

In this paper, bubble sliding and lift-off behavior in a narrow rectangular channel under atmospheric pressure is visual investigated from the wide side view and gap side view of the narrow rectangular channel with a high speed digital camera, and the bubble sliding and lift-off mechanism are analyzed in this paper.

1 Experimental facilities and measuring system

1.1 Experimental facilities

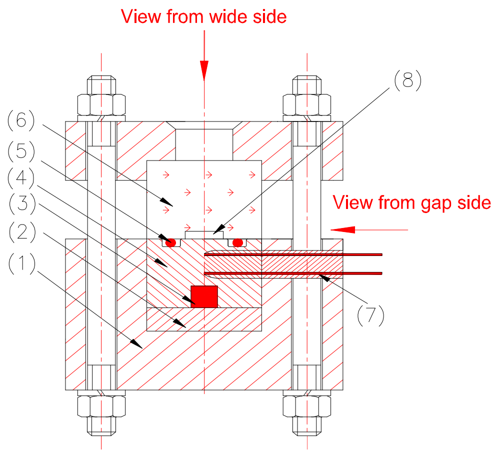
A schematic diagram of the experimental loop used in this work is shown in Fig. 1.The working fluid is deionized water in this study. Firstly, the working fluid in the tank 1 is pumped into the tank 2 which is equipped at a high location, and the pump will be shut down when the tank 2 is full. The subcooled water in the tank 2 is heated, and the non-condensable gas is removed by heating the water up to saturated temperature before carrying out experiments. The location of the test section is lower than that of the tank 2, so the work fluid in the tank 2 will flow to the test section due to the gravity. The work fluid flowing out the test section is directly dumped to the sump. The flow rate flowing into the test section is controlled by adjusting valve TV 2, and the inlet temperature of the test section is controlled by a preheater just before the test section, as shown in Fig. 1.



(1) Tank 1 (2) Pump (3) Buffer (4) Tank 2 (5) Venturimeter (6) Preheater (7) Test section

Fig. 1 Schematic diagram of the experimental loop

The test section mainly consists of a polyethylene block, a copper block, a heating plate, an optical quartz glass, and so on, as is shown in Fig. 2. The cross section of the narrow rectangular channel is 2×8 mm^2, which is fabricated in the optical quartz glass. Both the wide side and the gap side of the rectangular channel are polished to improve the transparency of the optical quartz glass. The working fluid in the channel is heated by D.C. current supplied to the heating blocks when the generated heat is transferred to the working fluid through the backside copper plate. 24 T-type thermocouples are equipped in the copper block, and the exact heat transferred to the working fluid can be evaluated based on the temperature difference obtained by 24 T-type thermocouples, as shown in Fig. 2.



(1) Polyethylene block (2) Stainless steel (3) Heater plate (4) Copper block (5) O-ring seal (6) Optical quartz glass (7) Thermocouple (8) Narrow rectangular channel

Fig. 2 Cross section of test section

All the T-type thermocouples are calibrated and the uncertainty is less than ±0.5 °C. The uncertainty of the power supplied to the heating block is less then ±0.9%. The flow rate is measured by a venturimeter with an uncertainty less then ±0.8% of full scale. The pressure is measured by a pressure transmitter with an uncertainty less than ±0.5KPa, and the heat loss of the test section is less than 7% of the total of the heating power in current study.

2.2 Visual investigation technique from wide side and gap side of the narrow rectangular channel

Successive bubble images are captured from the wide side and gap side of the narrow rectangular channel by a high speed digital camera. A Micro-NIKKOR lens (200 mm 1:1) is used in this study. The mounting of the high speed digital camera is shown in Fig. 3 schematically. During capturing the bubble behavior, the single bubble growth, departure and sliding are firstly obtained from the wide side of the narrow rectangular channels using the high speed digital camera, and the location of nucleation site on the heating surface is recorded at the same time. Secondly, the high speed digital camera is moved to the gap side of the rectangular channel to capture the bubble growth and departure focusing on the same nucleation site from the gap side of the narrow rectangular channel. Based on this technique, the growths of different single bubbles nucleating at the same nucleation site can be captured from the wide side and gap side.

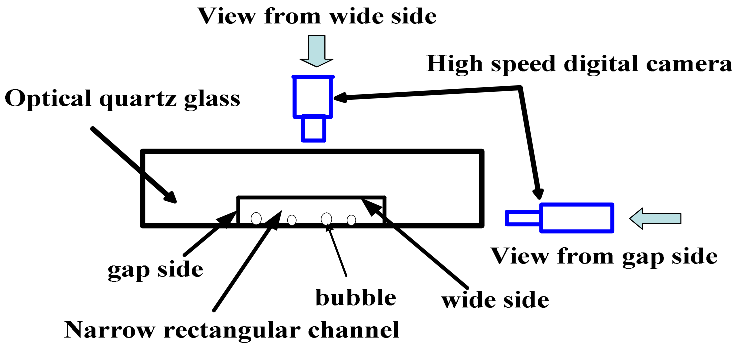


Fig. 3 Schematic diagram of the bubble capturing from wide side and gap side of the channel

2.3 Bubble data processing

In order to obtain the real dimension of the bubble, units and scale is defined. A scaleplate is captured firstly, and then, with the same focus, capture the sliding bubble by moving guide rail along the flow direction. The Phantom camera control software is used to obtain the real dimension of the image based on a conversion factor defined by the image of scaleplate. The images with a spatial resolution of 576×576 pixels are recorded at 3800 frame per second, and the resolution of each image corresponds to a 7.2 mm×7.2 mm in real dimension.

The sliding bubble velocity is calculated according to the successive images viewing by Phantom control software, and the sliding bubble velocity can be given by:

$$V_{bubble}\Big|_{t_2} = \frac{\mathrm{L}\big|_{t_2} - \mathrm{L}\big|_{t_1}}{t_2 - t_1} \tag{5}$$

where L is the sliding distance along flowing direction; t_1 is the initial time when the bubble just enters the observing field captured by the camera; t_2 is the time when the bubble moves to a certain position, and the interval between t_1 and t_2 is about 2 ms.

In order to analyze the forces acting on a sliding bubble, the sliding bubble velocity and the local liquid velocity on the streamline through the mass center of the bubble are required. It is supposed that the local liquid velocity can be estimated by universal single-phase turbulent flow profile. So the dimensionless velocity of different region is expressed as:

$$\begin{aligned} &u^+=y^+ && y^+\leqslant 5 \\ &u^+=5\ln y^+-3.05 && 5<y^+<30 \\ &u^+=2.5\ln y^+ +5.5 && y^+\geqslant 30 \end{aligned} \tag{6}$$

$$u^+ = \frac{u}{u^*} = \frac{u}{\sqrt{\tau_w / \rho_l}} \tag{7}$$

$$y^+ = \frac{yu^*}{\nu} = \frac{y\sqrt{\tau_w / \rho_l}}{\nu} \tag{8}$$

$$u^* = \sqrt{\tau_w / \rho_l} \tag{9}$$

The wall shear stress is defined as:

$$\tau_w = \frac{1}{2} C_f \rho_l U^2 \tag{10}$$

where U is the bulk liquid velocity; C_f is the friction coefficients which is calculated by the following expression.

$$C_f = \lambda/4 \tag{11}$$

where λ is the friction factor. For a smooth surface, the friction factor is expressed as:

$$\lambda = 64/Re \qquad Re<2000$$
$$\lambda = 0.3164/Re^{0.25} \qquad 2000<Re<100000 \tag{12}$$
$$\mathrm{Re} = UD_h/v \tag{13}$$

where D_h *is* the hydraulic equivalent diameter.

3 Results and discussions

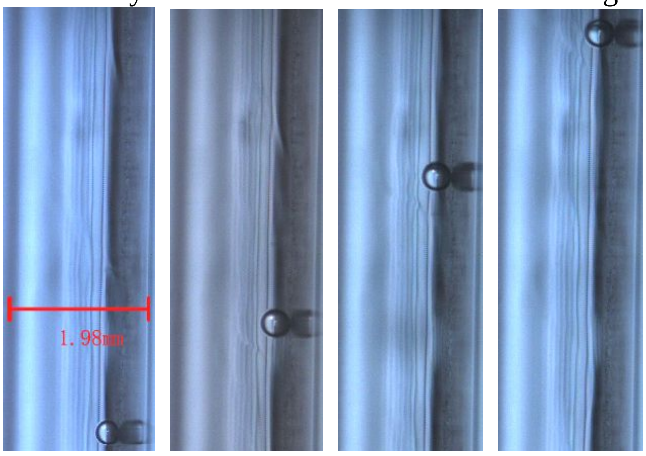
3.1 Sliding bubble behavior in vertical upflow boiling

The behavior of typical sliding bubble departing from nucleation site is observed from the wide side and gap side of the narrow rectangular channel, respectively. Consecutive images of a single sliding bubble motion obtained from the gap side with low heat flux referred as isolated bubble region are shown in Fig. 4. The bubbles always slide along the heating surface after departing from the nucleation sites, and the phenomenon of bubble lift-off from the heating surface is not observed. It should be noted that the behaviors of different bubbles from the same nucleation site, including bubble nucleation, growth and departure, are very steady. According to the observation, there is a small contact diameter between the sliding bubble base and heating surface, which indicates that the sliding bubble still attaches to the heating surface. The shape of the sliding bubble is elongated in the direction normal to the heating surface, and it is not confined by the walls of the narrow channel as the gap is 2 mm. During the bubble sliding, the upstream and downstream contact angles are almost equal, and the sliding bubble diameter changes a little when the bubble slides along the heating surface.

Focusing on the same nucleation site as mentioned above, the high speed digital camera is moved to the wide side of the narrow rectangular channel to capture the bubble growth and departure. Fig.5 shows the consecutive images of typical sliding bubble motion obtained from the wide side of the narrow rectangular channel. The bubbles slide along the heating surface after departing from the nucleation sites, and the sliding bubbles appear to be spherical, which are similar to the results obtained from the gap side of the narrow rectangular channel. A coordinate is drawn in Fig. 5 to distinguish the lateral motion of sliding bubbles, and it is found that the sliding bubbles only oscillate little laterally on the heating surface. So the lateral motion of sliding bubble is neglected in this study.

Fig.6 shows the images of sliding bubbles obtained from the same observation window with different heat flux. When the wall superheat exceeds the incipient boiling temperature, the bubbles will nucleate at the active nucleation sites and grow continuously until they depart from the nucleation sites The bubbles always slide along the heating surface after departing from the nucleation sites, and the phenomenon of bubble lift-off dose not occur in the present study. The shape of small sliding bubble is almost spherical, but the sliding bubble is elongated with increasing bubble diameter, and it appears as an inverted pear. The bubble inclines with a very small inclination angle when the bubble just departs from the nucleation site; the inclination angle approaches to 0 when the bubble slides along the heating surface steadily. It should be noted that the bubble coalescence among sliding bubbles are one of the main mode for bubble becoming a larger bubble in subcooled flow boiling, and the coalesced bubbles do not lift-off from the heating surface, and this shows that the coalescence between the sliding bubbles is little with low heat flux in the isolated bubble region. It is known that the turbulent effect between the bubbles and bulk flow becomes strong with increasing number of bubbles, which results in bubble lift-off from the heating surface with high heat flux. However, the heat flux in current experiment is limited by the indirect heating plate, thus the bubble characteristics after departing from the nucleation site with high heat flux is not discussed in this paper.

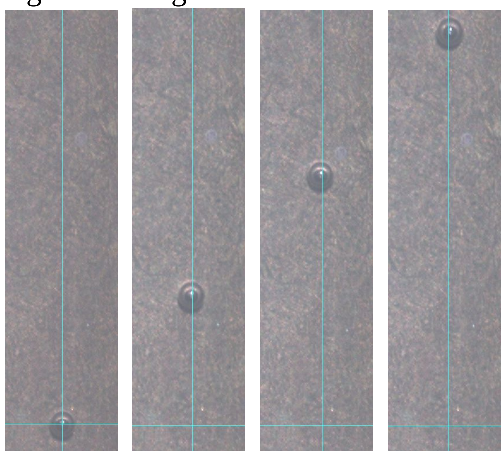
Fig. 7 shows the sliding bubble velocity with time, and the sliding bubble velocity increases with time. A sharp increase in sliding bubble velocity is obvious at the initial moment, but the trend of increase decreases gradually as time increases; the sliding bubble velocity reaches to a constant one, ultimately. It is also found that the sliding bubble velocity increases with increasing bubble diameter; the sliding bubble velocity is almost the same if the bubble size is approximately equal, which suggests the importance of buoyancy. The sliding bubble velocity at initial moment is less than that of local liquid velocity on the streamline through the mass center of the bubble. However, the sliding bubble velocity will exceed the local liquid velocity and even the bulk liquid velocity with time going. In the previous work of the authors (Xu et al. 2010), the forces acting on a sliding bubble in an ordinary sized channel were analyzed, and the results showed that the quasi-stead drag force and added-mass force due to bubble expansion would promote the bubble to slide along the surface at the initial moment. If the sliding bubble velocity is less than that of the local liquid velocity, the component of the shear lift force in the direction normal to the heating surface will promote the bubble to lift-off from the heating surface. However, if the sliding bubble velocity is higher than that of the local liquid velocity, the component of the shear lift force in the direction normal to the heating surface will push the bubble against the heating surface. Obviously, the direction of the shear lift force is varying during the bubble sliding, and the shear lift force will become a resistance which pushes the bubble against the heating surface but not promote the bubble to lift-off. Maybe this is the reason for bubble sliding along the heating surface.



0ms 16ms 31.6ms 47.6ms

T_{in}=79.5 ℃, q=31.1 kw/m^2,G=140 kg/(m^2.s)

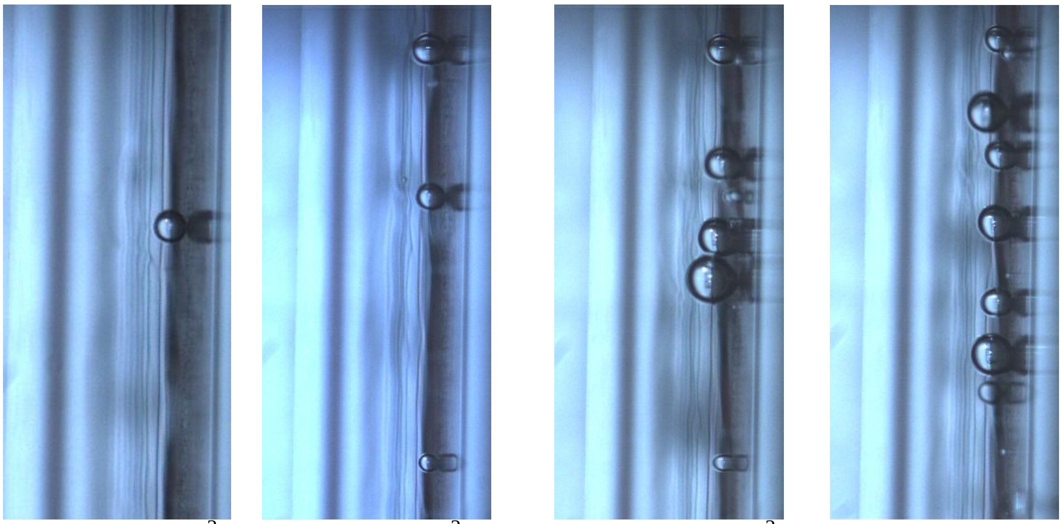
Fig. 4 The Single bubble sliding from the side view



0ms 16ms 31.6ms 47.6ms

T_{in}=79.5℃, q=31.1kw/m^2,G=140kg/(m^2.s)

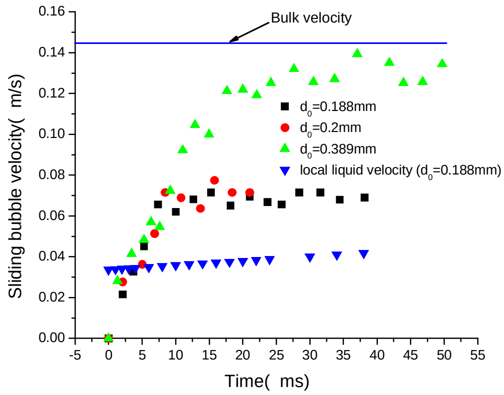
Fig. 5 Single sliding bubble from the wide side view



(a) $q=32kW/m^2$ (b) $q=40kW/m^2$ (c) $q=50kW/m^2$ (d) $q=55.4kW/m^2$

T_{in}≈78.5℃, G≈139.6 $kg/(m^2 \cdot s)$

Fig. 6 Typical sliding bubble with increasing heat flux

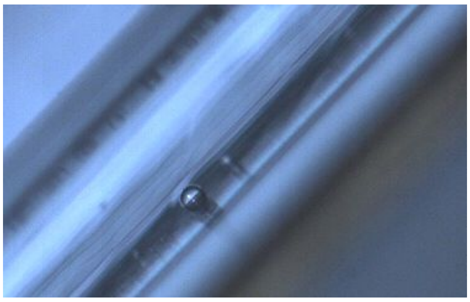
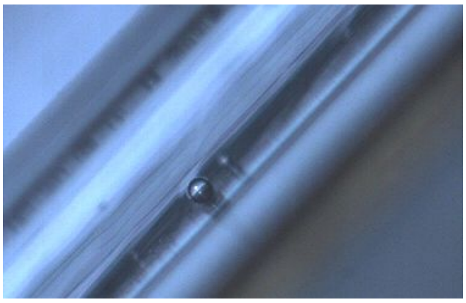


T_{in}=79.5℃, $q=31.1kw/m^2$, $G=140kg/(m^2.s)$, ΔT_w =3.3K

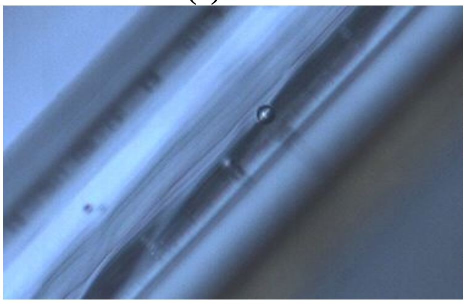
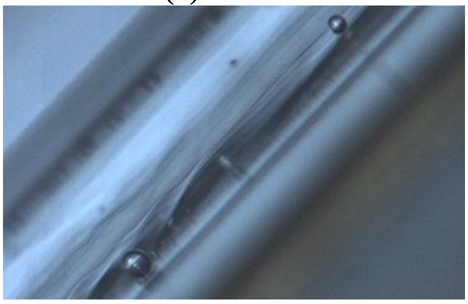
Fig. 7 Sliding bubble velocity with time

3.1 Sliding bubble behavior in inclined 45° upward facing upflow boiling

In inclined 45° upward facing upflow boiling, the phenomenon of bubble lift-off is observed from the gap side of the narrow rectangular channel at the same observation window, which is shown in Fig.8. After a bubble slides some distance, it tends to lift off from the surface, which is mainly due to the component of buoyancy is to promote bubble lift-off in inclined 45° upward facing heating surface. The bubble velocity will increase when the bubble lifts off from the heating surface, and the condensation phenomenon of lift-off bubble will occur when the bulk flow is subcooling, which results in the change of bubble shape.

(a) 0ms (b) 16.8ms

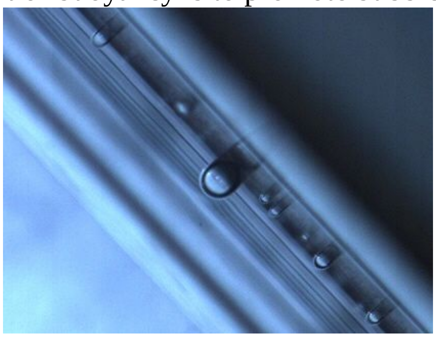
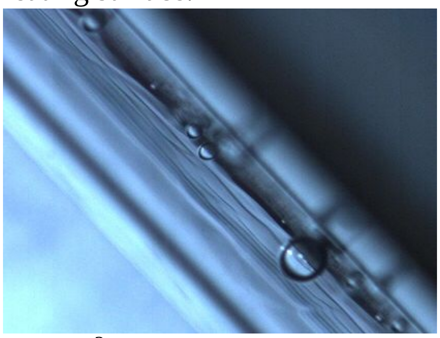
(c) 31ms (d) 43.7ms

T_{in}=64℃, G=138.7kg/(m^2.s), q=65.2kW/m^2

Fig.8 Single bubble motion in inclined 45° upward facing upflow boiling

3.2 Sliding bubble behavior in inclined 45° downward facing upflow boiling

Fig.9 shows the images of sliding bubbles obtained from the same observation window with different heat flux. The bubbles always slide along the heating surface after departing from the nucleation sites, and the phenomenon of bubble lift-off dose not occur, which is mainly due to the component of buoyancy is to promote bubble close to the heating surface.

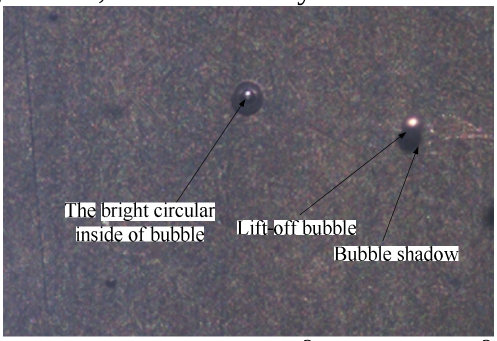



(a)T_{in}=79.5 ℃ ,q=29.7kW/m^2,G=195.3kg/(m^2.s) (b)T_{in}=78.7 ℃,q=39.1kW/m^2,G=194.1kg/(m^2.s)

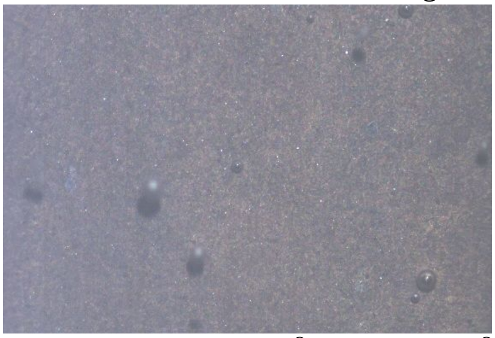
Fig.9 Bubble motion in inclined 45° downward facing upflow boiling

3.3 Sliding bubble behavior in vertical downflow boiling

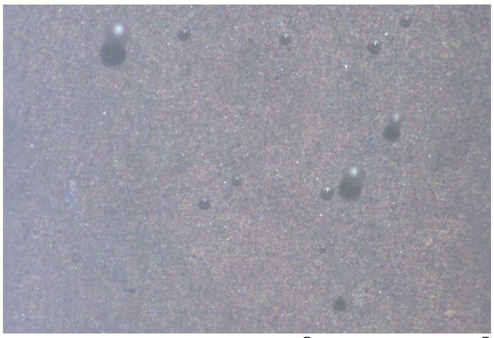
Fig.10 shows the images of sliding bubbles obtained from the same observation window with different heat flux. After a bubble departs from the nucleation site, it tends to lift off from the surface. The phenomenon of bubble lift-off is more obvious with increasing heat flux. The condensation phenomenon of lift-off bubble will occur when the bulk flow is subcooling, which results in the change of bubble shape, and so the bubble size is small. Because the opposite direction of the buoyancy and drag forces acting on the bubble in downflow boiling, so the bubble velocity is slow. If the fluid is to be a reference object, the local fluid velocity is always higher than that of the bubble velocity, and so the shear lift force is the driving force to promote bubble lift-off from the heating surface, which is mainly the reason for bubble lift-off in vertical downflow boiling.



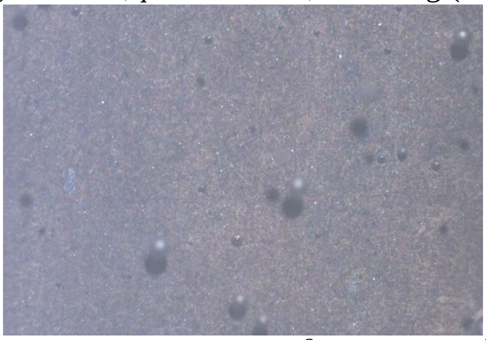
(a)T_{in}=85.9℃,q=33.5kW/m^2,G=309kg/(m^2.s)



(b)T_{in}=84℃,q=44.6kW/m^2,G=309 kg/(m^2.s)



(c)T_{in}=82.9℃,q=54.1kW/m^2,G=309kg/(m^2.s)



(d)T_{in}=82.3℃,q=63.6kW/m^2,G=309kg/(m^2.s)

Fig.10 Bubble motion in vertical downflow boiling

3.4 Discussion of the mechanism of bubble sliding and lift-off motion

In vertical upflow boiling, the quasi-stead drag force and added-mass force at the x-direction (parallel to the surface) due to bubble expansion will promote the bubble to slide along the surface at the initial moment. As the time increases, the sliding bubble velocity exceeds the local liquid velocity and even bulk liquid velocity, respectively, and therefore the quasi-stead drag force and added-mass force due to bubble expansion will become the resistances to prevent the bubble from sliding along the surface. The buoyancy is the only driving force to promote the bubble to slide along the surface. Since the sliding bubble velocity is higher than that of the local liquid of the center of mass of the sliding bubble when the bubble just lifts off the surface, and therefore the shear lift force at the y-direction(normal to the surface) will push the bubble against the wall. Meanwhile, the surface tension force is also resistances to prevent the bubble lift-off.

In vertical downflow boiling, because the opposite direction of the buoyancy and drag forces acting on the bubble, so the local fluid velocity is always higher than that of the bubble, hence the shear lift force is the driving force to promote bubble lift-off from the heating surface. During the progress of bubble motion, bubble will lift off from the heating surface when the shear lift force is just larger than the surface tension force.

In inclined 45° upward facing upflow boiling, the forces at the y-direction are the buoyancy at the y-direction, shear lift force and surface tension force. If the local fluid velocity is larger than that of the bubble velocity, the shear lift force is the driving force to promote bubble lift-off. When the composition of the shear lift force and the buoyancy at the y-direction is just larger than the surface tension force, the bubble will lift off from the heating surface. If the local fluid velocity is less than that of the bubble velocity, the shear lift force is the resistance to prevent bubble lift-off, and the buoyancy is the only driving force to promote the bubble lift-off. When the buoyancy at the y-direction is just larger than the composition of the shear lift force and the surface tension force, the bubble will lift off from the heating surface.

In inclined 45° downward facing upflow boiling, the forces at the y-direction are the buoyancy at the y-direction, shear lift force and surface tension force. The buoyancy at the y-direction and the surface tension force are the resistances to prevent bubble lift-off. As the time increases, the sliding bubble velocity exceeds the local liquid velocity and even bulk liquid velocity, and therefore the shear lift force will becomes the resistances to prevent the bubble lift-off.

4 Conclusions

The sliding bubble appears spherical according to the observation from the wide side of the narrow rectangular channel, but the sliding bubble is elongated in the direction normal to the heating surface according to the observation from the gap side of the narrow rectangular channel. In upflow boiling for vertical and inclined downward facing heating surface, the bubbles always slide along the heating surface after departing from nucleation sites, and the phenomenon of bubble lift-off from the heating surface with low heat flux in isolated bubble region does not occur. In vertical downflow boiling and inclined upward facing upflow boiling, the bubble tends to lift off from the surface. The sliding and lift-off mechanism of the bubble can be explained by the analysis of forces at the x-direction and y-direction. The buoyancy, quasi-stead drag force and added-mass force play an important role to promote the bubble to slide along the surface. The y-direction are the buoyancy at the y-direction, shear lift force and surface tension force. The sliding bubble velocity is less than that of local liquid velocity on the streamline through the mass center of the bubble at the initial moment. However, it will exceed the local liquid velocity with increasing time. Hence, the direction of the shear lift force is varying during the bubble sliding, and the shear lift force will become a resistance which pushes the bubble against the heating surface but not promote the bubble to lift-off.

Acknowledgements

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Reference

[1] Cheng, P., Wang, G.D., Quan, X.J.,“Recent work on boiling and condensation in microchannels”, Journal of heat transfer,Vol.131,No.4, 2009,pp.1-15.
[2] Peng,X.F.,Hu,H.Y.,Wang,B.X.,“Boiling nucleation during liquid flow in microchannels”, Int.J.Heat Mass Transfer,Vol.41,No.1,1998,pp.101-106.
[3] Piasecka, M.,Hozejowska,S.,Poniewski, M.E.,“Experimental evaluation of flow boiling incipience of subcooled fluid in a narrow channel”,International Journal of Heat and Fluid Flow,Vol.25,2004,pp.159–172.
[4] Satish, G. Kandikar.,“Fundamental issues related to flow boiling in minichannels and microchannels”, Experimental Thermal and Fluid Science,Vol.26,2002,pp.389-407.
[5] Tran, T.N., Wambsganss, M.W.,France, D.M.,“Small circular-and rectangular-channel boiling with two refrigerants”,International Journal of Multiphase Flow, Vol.22,No.3, 1996,pp.485–498.

[6] Lee, P.C., Tseng, F.G., Pan, Ch.,“Bubble dynamics in microchannels. Part I:single microchannel”, International Journal of Heat and Mass Transfer,Vol.47,2004,pp.5575–5589.

[7] Pan, L.M., Jen, T.Ch., He, Ch.,“Heat Transfer and Bubble Movement of Two-Side and One-Side Heating subcooled Flow Boiling in Vertical Narrow Channels”,Journal of Heat Transfer,Vol. 128,2006,pp.838-842.

[8] Lie, Y.M., Lin, T.F.,“ Saturated flow boiling heat transfer and associated bubble characteristics of R-134a in a narrow annular duct”,International Journal of Heat and Mass Transfer,Vol.48 2005,pp.5602–5615.

[9] Lie, Y.M., Lin, T.F.,“Subcooled flow boiling heat transfer and associated bubble characteristics of R-134a in a narrow annular duct”,International Journal of Heat and Mass Transfer, Vol. 49,2006,pp.2077–2089.

[10] Xu, J.J., Chen, B.D., Wang, X.J., “Prediction of Sliding Bubble Velocity and Mechanism of Sliding Bubble Motion along the Surface”, Journal of Enhanced Heat Transfer, Vol. 17, No. 2, 2010, pp. 111-124.