Experimental Study on Behaviors of Two Successive Bubbles in Subcooled Flow Boiling at High Degrees of Subcooling

Yang CAO†, Zensaku KAWARA†, Takehiko YOKOMINE†, Tomoaki KUNUGI†

Abstract

Subcooled flow boiling is an effective heat transfer approach and used widely in industries. In this paper, an experimental study was conducted on the bubble behaviors in subcooled flow boiling in an upward annular flow at relatively high degrees of subcooling. The bubble images during its whole lifetime were captured with high spatial and temporal resolutions by using a high speed video camera and a Cassegrain telemicroscope. The degree of subcooling in this study was above 30 K. The phenomenon of two successive bubbles was observed and analyzed. This phenomenon was caused by the severe deformation of the first bubble departing from the wall, and the second bubble grows from the remaining vapor of the first bubble after its departure from the wall. Consequently, its dynamical behaviors were strongly influenced by the first bubble. Quantitative data were also obtained to analyze the bubble behavior, such as the maximum size of the second bubble was smaller than the first one, and both the growth and condensation rates of the second bubble were slower than the first bubble.

Key Words: Successive bubble behaviors, Subcooled flow boiling, Upward annular channel, High temporal and spatial resolutions

1 Introduction

Subcooled flow boiling is an effective way of heat exchange, it can obtain a high heat-exchange flux with a relatively low temperature difference, so it is widely used in heat exchange equipment of many industrial occasions, such as in nuclear power plants, advanced micro-electrical devices or microprocessors. The high heat transfer efficiency associated with subcooled flow boiling results from several complex processes working together, e.g., heat transfer by bulk turbulent flow, latent heat transportations by bubble cycles, turbulence enhancement induced by bubbles moving and agitation, etc.

Subcooled flow boiling is a very complicated physical process. First of all, the two-phase channel flow in subcooled flow boiling, which changes from single-phase liquid flow regime, through bubbly flow, slug flow, churn flow, annular flow and finally to single-phase vapor flow caused by the phase change (boiling) process occurring in the channel is very complicated. Second, the heat transfer characteristic among the solid wall, liquid and vapor is also very complicated and important. In order to obtain a better understanding on the hydrodynamic and heat transfer mechanisms related to the complex process of the subcooled flow boiling, many research works have been conducted, e.g. the studies on flow and heat transfer characteristic at different flow and boiling regimes. Because the size of bubble is in sub-millimeter scale and the temporal scale of its lifetime is usually milliseconds for subcooled flow boiling, many researches of experimental visualizations with high spatial and temporal resolutions have been conducted.

Rong S. et al. [1] conducted an experimental study on subcooled water flow boiling in a vertical annular channel. Their visualization results show that the bubble waiting period varies significantly with different nucleus cavities and different experimental conditions, the bubble departure frequency generally increases as an increase of the heat flux applied on the heating surface, and the departure frequency may reach a limit around 1,000 bubbles per second. The bubble lift-off diameters, bubble growth rate and velocity after lift-off were also analyzed.

Based on the same experimental system, Rong S. et al. [2] studied the bubble lift-off diameters from images of 91 test conditions. Their results indicated that the bubble lift-off diameter increases with increases of the inlet

Received: July, 26, 2015, Editor: Tomio Okawa
† Department of Nuclear Engineering, Kyoto University (615-8540, Nishikyo-ku, Kyoto, Japan)
© 2015 The Heat Transfer Society of Japan
temperature and heat flux, and with decreases of the inlet fluid velocity. Prodanovic et al. [3] carried out the experiments on subcooled boiling in an upward vertical annular test section, and the bubble behaviors from inception to collapse were captured by a high speed camera at the image capture frequency of 6,000-8,000 frames per second. The bubble growth rate and condensation rate, the variation of bubble lift-off time and the bubble size with various working conditions were investigated. They proposed new correlations and reported 3 different boiling regimes with different bubble behaviors and the heat transfer mechanism between ONB (Onset of Nucleate Boiling) and OSV (Onset of Significant Void): low heat flux region, isolated bubble region and region of significant bubble coalesce. They also found that the bubble size and its life time generally decrease with increasing the bulk liquid velocity, the degree of subcooling or the system pressure. A study on bubble growth and departure of FC-87 in both the vertical upward and downward flow boiling was carried out by Thorncroft et al. [4]. They concluded that the observed vapor bubble behaviors between upward flow and downward flow are significant different: in the upward flow configuration, bubbles departing the nucleation sites slide along the heater wall, and typically do not depart from the wall, however, in the downward flow configuration, bubbles depart directly from the nucleation sites or firstly slide and then depart, depending on the flow and thermal conditions. The bubble behaviors of R-134 in subcooled flow boiling in a narrow annular duct were investigated by Lie [5]. Their experimental results showed that bubbles are suppressed to become smaller and less dense by increasing mass flux and inlet subcooling. Increasing the heat flux significantly increased the bubble populations, coalesce and departure. Rong S. et al. [6] studied the bubble departure frequency based on their experimental data, the existing models and correlations were found not to be in good agreement with experimental data of bubble waiting time, growth time and departure frequency, they proposed a new correlation which agrees well with existing experimental data. Zhang [7] studied the bubble behaviors of FC-72 in subcooled flow boiling of a horizontal channel, they captured the sequence of bubble events leading to CHF. Okawa [8] studied the bubble rising characteristic after departure from the nucleating site in vertical upflow boiling and nearly saturated water was used as working fluid. They studied the bubble size, distance from the wall, and bubble rising velocity etc. They also considered the model development of interfacial force acting on a vapor bubble important for understanding the heat transfer mechanism in force convective boiling.

The studies on bubble dynamics reviewed above contained a wide range of content, and played an important role in understanding the thermal-dynamic mechanism and heat transfer characteristic of subcooled flow boiling. However, the visualization studies on bubble behaviors in subcooled flow boiling under a relatively high degree of subcooling was seldom, so in the present study, the bubble dynamical behaviors in subcooled flow boiling at a relatively high degrees of subcooling were investigated by capturing the bubble images with high spatial and temporal resolutions through using a high speed video camera and a Cassegrain tele-microscope.

2 Experimental System

An experimental system has been built for studying the bubble dynamical behaviors in subcooled flow boiling. The experimental system consists of a fluid circulating loop and a high speed video imaging system. They are described in detail as follow, respectively.

The fluid circulating loop consists of a storage tank, a pump, flow meters, a test section of annular channel, a condenser as shown in Fig.1. These parts are connected to the flow passages built by metallic annular channel, which are covered by blankets for thermal insulation. The purified water was chosen as the working fluid and stored in the storage tank. A cartridge heater was installed at the bottom of the tank, and it is controlled by an automatic PID controller (Hakko Co.). The capacity of the storage tank is about 180 liter which is large enough for storing water and keeping the water temperature stable during experiments running.

Once the experiments are started, the pre-heated water is circulated by the pump, firstly make the water cycling in the branch loop, then a valve is used to adjust the flow rate of the water flowing to the test section in the main loop. In the annular channel of the test section the working fluid is heated by the inner heating rod and boiling bubbles are generated at the heating wall. The whole process of bubble lifetime, including nucleation, growth, lift-off and condensation are observed and recorded by the high speed video imaging system. The test section is a 1,000 mm long vertical annular channel composed of a transparent tube made of acrylic resin with an inner diameter of 20 mm, and a co-axial cylindrical heater rod with an outer diameter of 8 mm, which consists of a heating part made of nickel in the
center and two non-heating part made of copper at two sides. The roughness of the heater surface was about 0.3 microns, and there is no special treatment for the heater surface.

![Acrylic Pipe](image)

Fig. 2 The configuration of high speed video imaging system (Lens: Cassegrain telemicroscope).

The cross section of the annular channel was shown in Fig. 2. The heating section of the heater is 400 mm long, starting from 550 mm above the inlet of the test section. The electric power to the heating rod is supplied by a DC rectifier with a maximum voltage of 20 V and a maximum electric current of 1,200 A, so a maximum electric power of 24 kW could be provided, corresponding to a maximum heat flux of 2.39 MW/m² on the heating surface of the heater rod. After flowing in the test section, the water and vapor mixture flows back to the storage tank through the condenser, where vapor is condensed to water. The flow meters are a turbine-type flow meter (Hoffer Flow Control Inc.). The temperature at the inlet and outlet of the test section channel are measured by 2 thermocouples, respectively.

The high speed video imaging system consists of a high speed video camera (Phantom V7.1 from Vision Research Inc.), a Cassegrain telemicroscope (Seika Corporation), and an illumination lamp. The highest recording speed of the video camera is 160,000 frames per second (fps), the maximum pixel of a photograph obtained by this camera is 800 × 600 pixels. The Cassegrain telemicroscope has a focal length in the range of 300 ~ 600 mm, corresponding to a spatial resolution of the photographic image in the range of about 4~9 microns per pixel. The configuration of high speed video imaging system, including the high speed video camera, the Cassegrain telemicroscope and the illumination lamp is shown in Fig. 2. An image box of a square cross section filled with water is installed outside the transparent tube of the annular channel to correct the image optical distortion caused by the light refraction. Illumination light is provided from the opposite side of the test section by the lamp.

Before running the experiments, the water in the storage tank is firstly heated to the temperature required by the degree of subcooling of the experimental plan. When the experiments are started, the water is circulated by the pump, and firstly flows into the branch loop and then the valve of the channel connecting to the test section is slowly opened, and the flow rate of the liquid flowing in the test section is controlled to the desired value. The temperatures at the inlet and outlet of the test section are measured. After the flow rate and temperature reached a stable condition, the DC rectifier turns on, and the heat flux applied on the heater rod is adjusted to provide the heat flux needed for the bubble nucleation and growth. Before capturing and recording the bubble images, it is essential to find a stable bubble nucleate site, where the repeatability of the observed bubble behaviors can be guaranteed, and the nucleate bubble can survive a wide range of experimental conditions, e.g. the different flowrates and the heat fluxes. During one experiment period, the observing position of the camera is fixed, and the experimental conditions, e.g. the heat flux and the mass flow rate, are specified to study the bubble behaviors at the same nucleation site although the conditions are different. Under every experimental condition, at least 20 bubble cycles at the same nucleate site were recorded in the video.

The experiments have been carried out under various conditions, the degree of subcooling at the inlet of the test section sets to the range from 30 K to 50 K; the liquid average flow velocity in the annular channel is ranging from 0.12m/s to 0.7m/s; the heat flux applied on the heater is adjusted to keep the boiling occurring in the isolated bubble regime. The position for observing the bubble behavior is very close to the beginning of the heating section of the heater rod, because in this region, the density of bubble nucleate sites is lower, and the interference from bubbles of other nucleate sites and the sliding bubbles are rare, so it is easier to get clear image of the bubble. The focus of the Cassegrain telemicroscope was adjusted to the position near the surface of the heater to get the side-view of the bubble behaviors as shown in Fig. 2. The camera and Cassegrain telemicroscope were supported by a tripod, so the height and position can be adjusted freely during the experiments to get a good image of the bubble.

In the present study, the image capture frequency of the camera was in the range of 8,000-14,000 fps, the exposure time was set to 2 μs. The video with 256×256 or 256×512 pixels in an image were used. The images obtained by the high speed video imaging system were analyzed in order to extract the quantitative data by an image processing program developed by using the MATLAB Simulink toolbox computer vision system.

### 3 Results and Discussion

In this paper, the phenomenon of two successive bubbles in subcooled flow boiling was reported and discussed. This phenomenon was very common in subcooled flow boiling of relatively high subcooling degrees and lower flowrates. In our experiments this phenomena was found to occur in subcooling degrees of 30 ~ 50 K and the range of liquid average velocity is about 0.07 ~ 0.3 m/s.

A series of the images of bubble behaviors showing this phenomenon were shown in Fig. 4. The
experimental conditions were as follows: the degree of subcooling at the inlet of test section was 29.6 K, the average heat flux applied on the heater surface was 156 kW/m² and the average flow velocity of liquid in the channel was 0.14 m/s. The observation position was about 20 mm above the beginning of the heating section. The temporal variation of bubble equivalent diameter was given in Fig. 5. The equivalent diameter is defined as the diameter of the assumed a circle which has the same area as the bubble. The equivalent diameter was obtained by the image processing program developed by the MATLAB.

For quantitative analyzing the characteristics of the two successive bubbles’ behavior, 46 groups of the two successive bubbles data at the subcooling degree of 30 K were chosen to extract the quantitative data. The maximum equivalent diameter, the growth and condensation times of the first and second bubble were obtained, and the growth rate and condensation rate of the first and second bubble were also calculated. Fig. 3 shows the distribution of the diameter of the first bubble obtained from 46 group data, the distribution of the bubble diameter is close to standard normal distribution, so the statistical data obtained from 46 group data are credible.

![Distribution of bubble diameter](image)

Fig. 3  Distribution of bubble diameter

As can be seen from Fig. 4 (a) ~ (f), after the bubble embryo nucleated on the heating wall, the bubble grew very rapidly and reached its maximum size in a short time (about 600 µs). This is also illustrated by the temporal variation of equivalent diameter of the bubble given in Fig. 5. The bubble at its maximum size became nearly the spherical shape as shown in Fig. 4 (d) because of the effect of surface tension.

From Fig. 4 (e) ~ (g), the condensation deformation of the bubble bottom was observed as follows: firstly a small concave deformation on the upstream side surface was formed, as marked by the arrow in Fig. 4 (f), then this deformation became larger and larger, and finally at the moment when the bubble was departing from the wall, the bottom of bubble became a very thin and long neck, like a thread connecting the bubble body to the wall, and the bubble size also became smaller during this process as quantitatively shown in Fig. 5. After this, the bubble neck broke apart and the bubble departed from the heating wall and condensed in the subcooled bulk flow rapidly, as shown in images (h) and (i) of Fig. 4.

This kind of condensation deformation of bubble was not a special case, in other words it was quite general. This phenomenon has been observed regarding many bubbles in the subcooled flow boiling at relatively high degree of subcooling in our experiments. The condensation deformation of bubble is attributed to the condensation occurred at the bubble bottom region. Because the degree of subcooling in our experiments was very high, at least 30 K, the bulk flow in the channel was highly subcooled. However, as for the nucleation bubbles on the heating wall, the wall should be highly superheated: this means the temperature difference between the wall and the bulk flow is very large, therefore the superheated boundary layer must be very thin, as illustrated in Fig. 6 (a). During the rapid bubble growth and deformation processes, the liquid surrounding the bubbles could be pushed or attracted by the bubbles movement. Some subcooled liquid can be entrained to the bubble bottom region during the bubble deforming process as indicated in Fig. 6 (a). These highly subcooled liquid caused the condensation at the bubble bottom, and making it very thin, finally like a thread connecting the bubble to the wall.

After the departure of the bubble, a small amount of vapor of the bubble neck was left on the wall, as shown in Fig. 4 (h). This small amount of vapor grew larger very quickly, and it reached the maximum size in a short time period, as shown in images (h) to (l) of Fig. 4, then it departed from the wall and extinguished in the subcooled liquid. This phenomenon of two successive bubbles was observed quite often in the subcooled flow boiling at relatively high degrees of subcooling.

From Fig. 5, it can be seen that the maximum diameter of the second bubble is a little smaller than the first one, this is because the second bubble grows immediately after the first bubble departed from the heating wall, and there was no enough time for the reconstruction of the thermal (superheated) boundary layer, so the growth of the second bubble consumes mainly the heat of the high temperature wake flow of the first bubble, as shown in Fig. 6 (b). So, the size of the second bubble is always smaller than the first one. This is confirmed by the average bubble diameter obtained from the 46 group data. The average maximum diameter of the first and second bubble was 0.75 mm and 0.62 mm respectively, and the standard deviations were 0.137 mm and 0.143 mm, respectively. The maximum diameters of the first and second bubbles were given in Fig. 7 (a). As can be seen, almost all the dots lie in the downside of the diagonal line. This means that in almost all the pairs of two successive bubbles, the maximum diameters of the first bubble are larger than the maximum diameter of the second one.
The growth rates of the first bubble and second bubble from the 46 groups of data were also acquired, as shown in Fig. 7 (b). The growth rate of a bubble is defined as the increment of the bubble diameter per unit time, the average growth rates of the first and second bubble were 1.10 m/s and 0.86 m/s, respectively, and the standard deviations were 0.081 m/s and 0.115 m/s, too. This confirmed that the growth rate of second bubble is slower than first one. In Fig. 7 (b), most of the dots, lie in the downside of the diagonal line. The reason why the growth rate of the second bubble is slower than the first bubble is because after the first bubble growth and departure the superheat of the heating wall near the nucleate site was decreased, and there is no enough time to recover the wall temperature, so as mentioned above, the growth of the second bubble consume mainly the heat released by the condensation of the first bubble, therefore its growth rate is slower than that of the first bubble.

The condensation rate of the bubble was defined as the decrement of bubble diameter per unit time, the average condensation rates of the first and second bubble calculated from the 46 groups of data were 0.85 m/s and 0.51 m/s, respectively, and the standard deviation were 0.12 m/s and 0.11 m/s. Therefore, the condensation rate of the second bubble is much slower than that of the first bubble, which can also be confirmed by the condensation rates of the first and second bubbles of 46 groups of data shown in Fig. 7 (c), as most of the dots lie in the downside of the diagonal line. The reason is because the second bubble exists in the wake flow region of the first bubble, and the temperature of the wake region is relatively high compared to the bulk flow region because the heat is released by the condensation of the first bubble. Eventually the condensation rate was not so fast than that of the first bubble.

For this kind of two successive bubbles, since the second bubble exists in the wake flow of the first bubble, as illustrated by the schematic of Fig. 6 (b), the first bubble has a great effect on the second bubble during its lifetime, including the nucleation, growth and departure. Strictly speaking, the second bubble was not a new nucleated bubble, but grew up from the remaining part of the first bubble after it departed from the heating wall. For generating the second bubble of the two successive bubbles phenomenon, the remaining part on the wall is essential, which is generated by breaking the long thin neck of first bubble. Almost all the bubbles with a long and thin neck were observed to be followed by the second successive bubble. However, as for bubbles without the severe deformation and the long thin neck, the second successive bubble was not observed. Though the phenomena of bubble severe deformation and two successive bubbles are quite common in subcooled flow boiling of high subcooling degrees, it is impossible to guarantee every bubble can deform severely and leave a remaining vapor on the heater wall after it departed even in the subcooled flow boiling of high subcooling degrees, because many factors in the subcooled flow boiling can affect the bubble behaviors, such as, the inevitable variation of thermal and velocity boundary layers and the turbulent bulk flow, and the influence from the bubbles in the neighborhood. Furthermore, the temperature of the heating wall underneath the nucleate site will fall down because the growth of the first bubble consume the heat, and there is no time to recover the wall temperature, so the remaining vapor has a possibility of condensation on the heating wall, this also limits the occurrence of the two successive bubbles.

The diameter variation of bubble nucleated at the same site within a period of 0.15 s was shown in Fig. 8. As can be seen, most of time, the first bubble was followed by the second bubble, as marked by the number from 1 to 12 in the figure. Sometimes, the single-bubble nucleation was observed as the peaks without the number mark in Fig. 8. From an investigation over 105 bubbles at the same nucleate site under the experimental conditions (the degree of subcooling 30K, the average liquid velocity 0.14m/s, and the heat fluxes 156, 170 and 186 kW/m²), the number of single bubble and two successive bubbles observed were 45 and 60, respectively, so the ratio was about 3:4.

The deformation of the second bubble at the bottom during the process of growth and departure from the wall was not so severe, as can be seen in Fig. 4 (l) (m), this is because the second bubble submerged in the high temperature wake region of the first bubble, therefore the condensation at the bubble bottom region caused by the cold liquid of the entrainment flow during its growth was not so strong as the first bubble did. There was no remaining vapor left on the heating wall after the second bubble departed from the wall. Moreover, the wall temperature was decreased by the growth of the two successive bubbles, and there is no enough time to recover the wall temperature, this also prevents the generation of the third or bubble, therefore the phenomenon of three or more successive bubbles was never found.
Fig. 4 Images of two successive bubbles
Degree of subcooling: 29.6K, Heat flux: 156kW/m², Average flow velocity: 0.14m/s.

Fig. 5 Time variation of equivalent diameter of two successive bubbles shown in Fig. 4.

Fig. 6 Schematic of bubble behaviors (a) deformation of first bubble (b) growth of second bubble
Fig. 7 Comparison of bubble parameters of 1st and 2nd bubbles

Fig. 8 Diameter variation of bubble at the same nucleate site
4 Conclusions

An experimental study on the bubble behaviors in subcooled flow boiling in the annular upward flow channel under relatively high degrees of subcooling was carried out. The degree of subcooling was in the range from 30 K to 50 K. The bubble images during its lifetime were captured with high spatial and temporal resolutions by using a high speed video camera and a Cassegrain telemicroscope. The phenomenon of two successive bubbles was observed. This phenomenon was caused by the severe deformation of the first bubble departing from the wall, the second bubble grows from the remaining vapor of the first bubble after it departed from the wall, and its dynamical behaviors were strongly influenced by the first bubble. The quantitative data regarding the bubble behaviors were also obtained statistically. It is found that the maximum size of the second bubble was smaller than the first one, and the growth rate and condensation rate of the second bubble were slower than the first bubble. It is considered that the deformation due to the condensation at the bubble bottom region and the high temperature wake of the first bubble departed from the wall played an important role in this phenomenon. The present study provides a good clarification and deep understanding on the bubble dynamical behaviors of subcooled flow boiling at high degrees of subcoolings. Moreover, the bubble behavior characteristic observed in the present study can be used as a benchmark for numerical studies on bubble dynamics in subcooled flow boiling at high subcooling degrees.

Reference