

**STUDY ON BUBBLE BEHAVIORS IN SUBCOOLED
FLOW BOILING**

YANG CAO

2016

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FLOW BOILING**

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Abstract

The present dissertation aims at improving the current understanding of the behavior characteristic of bubbles in subcooled flow boiling, which is very essential for clarifying the heat transfer features of forced convection subcooled boiling. The bubble behavior under wide ranges of experimental conditions: subcooling degrees from 5 K to 50 K, mean velocity of bulk liquid flow from 0.14 m/s to 0.8 m/s, were observed and recorded with high spatial and temporal resolutions by using the high speed video image system.

The bubble behaviors at different experimental system were found to be quite different. At a medium subcooling degree, the deformation at upstream side bottom of the bubble during its growing and departure period was observed and it was attributed to the condensation induced by the thermo-capillary flow of Marangoni effect, which is caused by the presence of the temperature gradient in the vertical direction normal to the heating wall. Numerical simulation of the bubble growth and departure behaviors in subcooled flow boiling was also carried out to support the proposed explanation of bubble deformation mechanism. At high subcooling degrees, deformation caused by condensation was found in both sides of the bubble bottom, and very thin and long bubble neck was formed when the bubble was lifting off from the heating wall. The phenomenon of two successive bubbles was also observed and discussed, the behavior of the second bubble was strongly affected by the first bubble. At high subcooling degrees and high flowrates, the elongation of bubble was obvious and it was hit by the subcooled bulk flow in the middle of the upstream side surface and concave deformation by condensation there was observed, after collapse in the subcooled liquid, two or more non condensed air spots instead one were found, because the bubble was

intersected in the middle. At low subcooling degrees, the bubble shape was very close to a sphere, only very weak deforming phenomena was observed, bubble behaviors at different flow rates are quite similar, only bubble size and lifetime were affected by the flow rate.

The wave propagation phenomenon on the bubble surface during the condensation process was also observed under various experimental conditions. The wave was generated by the recoil force when the bubble suddenly broke apart away from the heating wall. The enlarged area of the bubble surface and the rapid vibration and deformation caused by the wave propagation during condensation process can enhance the heat transfer performance between the bubble and the bulk subcooled liquid. Therefore it is reasonable that bubble condensation rate was enhanced by the wave propagation on the bubble surface.

Behaviors of multiple bubbles were also investigated. It was found that new bubbles were easier to nucleate at the separation flow region in upstream or downstream side of a large grown-up bubble. Since the nucleation sites of the new bubbles are very close to the pre-existing bubbles, so there is a high probability that bubbles would coalesce before they depart from the heating wall and after coalescence a long plug-shaped vapor clot is formed near the heating wall, this may be considered as one of the precursor phenomena of the Departure from Nucleate Boiling (DNB) which indicates the start of transition from nucleate boiling to film boiling.

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$$\Delta T_{\text{sub}}: 19.0 \text{ K}, v_m: 0.55 \text{ m/s}, q: 310 \text{ kW/m}^2$$

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Chapter 1

Introduction

1.1 Motivations

Subcooled flow boiling is a very efficient heat transfer approach and can achieve a high heat transfer flux with a lower temperature difference, so its broad applications in a lot of occasions were found, e.g., industrial heat-exchange system, air conditioning and refrigeration system, nuclear reactor cores, high energy density electrical devices, micro-electronic component or micro-processors. The high heat transfer performance associated with the subcooled flow boiling is ascribed to several complex physical processes working together, e.g. heat transportation by subcooled liquid flow, latent heat consumed by boiling bubbles, heat transfer enhancement by bubbles movement and agitations.

Flow boiling in the channel is a very complicated thermal and hydrodynamic process. The conjugate heat transfer among the solid wall, liquid and vapor was very complicated, and the flow pattern in the channel can change from single-phase liquid flow, through bubbly flow, slug flow, churn flow, annular flow and finally to single-phase vapor flow because of the boiling occurring in the channel. In order to obtain a better understanding of the thermal and hydrodynamic mechanism related to subcooled flow boiling, extensive research works have been conducted, e.g. the distribution of void fraction, heat transfer characteristic at various boiling regimes, the critical heat flux (CHF).

The bubble behaviors are crucial for analyzing and understanding the mechanism of flow boiling, therefore many researchers focused on investigating the characteristics of bubble behaviors and most of the studies in this field have been

carried out by experimental visualizations. The rapid development of the high speed video camera and microscopic visualization technique in recent decades made it possible to observe the bubble behavior with high spatial and temporal resolutions.

1.2 Subcooled flow boiling

Boiling is a phase change process in which vapor bubbles are formed either on a heated surface or in a superheated liquid layer adjacent to the heated surface. It differs from evaporation which occurs at pre-determined vapor/gas-liquid interfaces, boiling also involves creation of these interfaces at discrete sites on the heated surface. [1.1]

Pool boiling occurs on a heated surface submerged in a large volume of stagnant liquid, this liquid might be at its boiling point, in which case the term *saturated pool boiling* is used or below its boiling point, in which case the term *subcooled pool boiling* is used [1.2]. In pool boiling exists no flow except for natural convection, whereas if the liquid flowing over the heater surface is imposed by external means, this is called forced convection boiling or flow boiling. Forced convection or flow boiling includes external flow boiling and internal flow boiling. In external flow boiling, liquid flow occurs over unconfined heated surfaces, whereas internal flow boiling refers to flow inside channels or tubes.[1.1] The researches on boiling under conditions of natural (pool boiling) or forced convection (flow boiling) have always been important and extensive studies have been reported in the literature. The design of boilers, water-cooled nuclear reactors, refrigeration and air-conditioning equipment, heat pump, petrochemical plant reboiler and condenser, many items of chemical and power plant need the knowledge of the fluid dynamic and heat transfer processes occurring during the pool and flow boiling. [1.2], Nucleate boiling is also very efficient mode of heat transfer. It has been found in a wide range of applications in both traditional industries such as various energy conversion system, heat exchange system, chemical thermal process and in highly specialized fields such as cooling of high-energy-density electronic components, micro-fabricated fluidic system, the thermal control of aerospace station, bioengineering reactors. [1.3]

1.2.1 Pool boiling

The research results on pool boiling were often represented by a graph plot of surface heat flux against surface temperature of the heater wall. As an increase of the temperature or the heat flux of the heater wall, the pool boiling can exhibit several different heat transfer and boiling modes: natural convection, nucleate boiling regime after ONB (Onset of Nucleate Boiling), transition boiling and film boiling. In the nature convection region, the liquid is below the saturation temperature, the heat transfer mainly depends on single phase convection.

When a certain value of the wall superheat is achieved, vapor bubbles appear on the heater surface, the bubbles nucleate in the cavities or scratches on the heater wall that contain pre-existing gas/vapor nuclei. This is the onset of nucleate boiling, the beginning of the nucleate boiling region. In the nucleate boiling region the heater surface temperature rise very slowly for a large increase of the heat flux applied on the heater wall, the heat transfer mechanism has been debated considerably during the past decades, many theoretical models and semi-empirical correlations have been proposed. Hsu and Graham [1.4] concluded that the principal heat transfer mechanisms responsible for the increase in heat transfer could be attributed to bubble agitation, thermal boundary layer stripping, and evaporation. The actual boiling process is a combination of these mechanisms which are not mutually exclusive of one another. [1.2].

The Critical Heat Flux (CHF) refers to the peak in the boiling curve, and it is the border of the nucleate boiling and the transition boiling. The CHF also stands for the upper limit of heat flux and the termination of efficient cooling for the heater surface in nucleate boiling region. Some experimental and theoretical studies have been conducted to clarify the mechanism of onset of the critical heat flux. The occurrence of the CHF in pool boiling case is because the liquid which can reach the heater wall for cooling is not sufficient as a result of the increase of the vapor amount.

The transition boiling occurs if the temperature is increased continuously after

the CHF has reached, and the heat transfer flux will decreased sharply. Because the formation of large amounts of vapor forces the liquid away from the heater wall, so the liquid just contacts the heat surface periodically and as the heater wall temperature goes up, a vapor film or blanket is finally formed. During this boiling regime, the heat flux and temperature undergo large variations with time, because of the periodical cooling of the liquid. The transition boiling was relatively little studied.

As increase of the temperature continuous, the heater surface will be blanketed by the vapor film completely, which is the major resistance of the heat transfer. Because only the vapor-solid heat transfer dominates so the analysis is relatively tractable, many semi-mechanistic and mechanistic studies have been conducted. In the analysis, many simplifications for matching of interfacial conditions are made, so empirical constants are needed to match the predictions with the experimental data. Since the temperature of the heater surface is normally very high in film boiling, the radiation as a heat transfer way should also be considered.

1.2.2 Flow boiling

Forced convection or flow boiling includes external flow boiling and internal flow boiling. However, here only the researches on internal flow boiling was introduced, Internal flow here refers to the two-phase flow of liquid and its vapor flow inside of tubes, annuli etc. Usually the subcooled liquid enters the flowing passage and boiling takes place only at the superheated heater wall, this is the local subcooled boiling. As a result of the addition of heat along the axis of the channel, the enthalpy of the liquid increases as it flows through the channel. At some place of the channel, the liquid reaches the saturation point. Beyond this point the process is called bulk boiling. At low quality (below 5-8%) and in the subcooled region, the flow is bubbly. At higher qualities the flow becomes annular with a thin liquid layer on the wall and a vapor core, which may or may not contain significant amounts of liquid droplets in the center. In the annular flow regime there may or may not be nucleate boiling. If the liquid film on the wall is thin enough, heat is transferred by conduction through the liquid and

vaporization occurs at the liquid-vapor interface. Under these conditions the wall temperature is below that required for nucleation or activation of the cavities. At higher heat fluxes nucleation will take place under these thin liquid layers at the wall. At some point down the channel the heated wall may become dry. Beyond this point, the wall temperature usually rises significantly for a particular heat flux. This is the critical condition. The cause of the dry-out may be intensive nucleation if in the nucleation regime, or tearing off of the liquid film by high velocity of the vapor, which increases progressively down the channel. [1.5]

The flow boiling in a channel is a much more complicated process than a pool boiling. The boiling features, flow pattern and heat transfer characteristic are very closely related and mutual affected with one another. The flow pattern existing in a flow boiling of a channel can changed from single phase liquid flow, bubbly flow, slug flow, churn flow, annular flow, mist flow and single phase vapor flow because the boiling process changed the proportion of the liquid and the vapor. The flow and boiling characteristic depend also on the local wall temperature/heat flux and the vapor quality. The heat transfer characteristic is determined by the boiling and flow characteristic. The discussion of flow boiling is usually divided into the low quality and subcooled regions (bubbly flow) and the high quality regions (annular flow).

In the regime of bubbly flow, discrete vapor bubbles exist in the continuous phase (liquid). With an increase in the wall temperature/heat flux and the quality, small bubbles will getting larger and merge to form large long bubbles separated by liquid filaments. These large long bubbles can occupy almost the entire wall of the tube. As the wall temperature/heat flux and the quality increases further, the large long bubbles merge to form vapor film covering the wall of the channel, giving rise to annular flow. In annular flow, liquid is confined to the thin region adjacent to the wall, whereas vapor occupies the core of the tube. At a higher vapor flow rate, liquid droplets are entrained in the vapor phase, which is now continuous.

The CHF in flow boiling is also an important research subject, it is very important for design and safe operation of the heat exchanger equipment such as in an

nuclear power plant. When the critical heat flux occurs, the surface temperature of the channel wall will rise abruptly to a very high value, and the tube can even broke if the temperature exceeds the melting temperature of the heater material. For the flow boiling in channels, a distinction must be made between critical heat flux at low flowrates and high flowrates. At low flowrates, the thin liquid film on the channel wall can completely dry out and result in a sudden rise of the wall temperature because of the loss of liquid cooling and deteriorate of the heat transfer. Under high flow conditions, the critical heat flux occurs because of the local dry out of the channel surface resulting from the local extremely high wall temperature, even though plenty of liquid may still exists in the central region of the channel, the channel wall is covered by a vapor layer, this is very similar to the film boiling in the pool boiling case.

Some empirical correlations for dry out and critical heat flux have been reported considering various fluids, flowrates, size of channel, local quality, and system pressure. The mechanistic models for critical heat flux in flow boiling were also proposed, where empirical constants were incorporated to match the predictions of the models with the experimental data in the literature. The mechanisms have also been given. Some thought the CHF was caused by the failure of the bulk flow to remove the large amounts of vapor generated at the wall. Comprehensive reviews of correlations and models for critical heat flux have been given by Katto [1.6] and Celata et al.[1.7]

1.2.3 Research review on subcooled flow boiling

In order to activate a nucleation site, the temperature of the surface has to satisfy the superheated conditions, at least exceed the saturation temperature of the liquid at the local pressure. However, the temperature of the bulk liquid could remain below the saturation temperature, the process is known as subcooled boiling. In engineering application of forced convection or flow boiling, there is a large probability that the temperature of the liquid is below the boiling point at the current pressure, when it enters the channel. So if the local surface temperature of the heating wall is high enough, the boiling can take place, this is called the subcooled flow boiling.

As mentioned above, the liquid is subcooled when it is entering the inlet of the channel. At some location downstream of the channel wall, when the wall temperature is high enough to satisfying the bubble nucleation conditions, bubble nucleation occurs. This location is referred to as Onset of Nucleate Boiling (ONB). Just downstream of ONB, the bubbles are so small that they remain attached to the heater surface without sliding or departing. Farther downstream, as the temperature of the bulk liquid increases, the bubbles grow larger and begin to sliding away from their nucleate sites. These bubbles normally first slide along the heater wall, then lift off from the wall, and finally collapsed in the bulk liquid by condensation. The location where the bubbles start to lift off from the heated wall is called the Onset of Significant Voids (OSV). In the region between ONB and OSV, the void fraction is quite small, but after the OSV it increases rapidly.

The subcooled flow boiling in a channel can be classified into several regimes along the axial direction of the channel: single phase convection region, partial subcooled boiling and fully developed subcooled boiling. The fully developed subcooled boiling does not exist immediately where the surface exceeds the saturation temperature. A region of partial boiling exists before fully developed subcooled boiling. In this partial subcooled boiling region, comparatively few nucleation sites are active and are able to nucleate bubbles, so single phase convection heat transfer between patches of bubbles still plays an important role in the overall heat transfer of this partial boiling region. As the wall temperature increases, the number of active nucleate sites also increases, more bubbles can nucleate on the heater wall, so most of the heat exchange would be conducted by the nucleate boiling bubbles and the proportion of the single phase convection heat transfer would decrease.

As the wall temperature continues to increase, the whole surface of the heater wall would be covered by bubble nucleate sites, the boiling moves to the fully developed boiling regime and the proportion of single phase convection reduces to zero. In the fully developed boiling region, velocity and subcooling degree, both of which have a strong influence on single phase heat transfer, have little or no effect on the

surface temperature as observed experimentally. It has generally been assumed that the boiling curve of the fully developed boiling region in subcooled flow boiling coincides with the extrapolation of the boiling curve in pool boiling cases. This suggestion would appear reasonable, at least for low velocities. Bergles and Rohsenow [1.8] carried out experiments for the purpose of directly comparing data obtained from pool boiling and flow boiling. Data for both boiling processes were taken from the surface of the same quality. It is found that boiling curve of the flow boiling cannot be considered as an extrapolation of the boiling curve of pool boiling. However, the form of the equations developed for the correlation of pool boiling data is also suitable for the representation of fully developed subcooled flow boiling data.

1.2.3.1 Heat transfer mechanism of subcooled flow boiling

The heat transfer mechanisms of subcooled nucleate boiling have been the subject of much debate. It was found by Gunther and Krieth [1.9, 1.10] and Clark and Rohsenow [1.11] that the rate of visible vapor evolution only accounts for a very small fraction (about 1-2 %) of the total heat flow in subcooled flow boiling. Transportation of latent heat within the bubble by simultaneous evaporation at the base and condensation at the roof of the bubble was also shown [1.9] to be very small if the bubble is assumed to be surrounded by a stagnant liquid layer. However, Bankoff and Mikesell [1.12] argued that if turbulent and convective heat transport dominates the heat exchange of the condensing bubble surfaces, the latent heat transport might be significant. Jiji and Clark [1.13] carried out an experimental measurement of the bubble boundary layer thickness and the temperature profiles in the subcooled flow boiling of water in a rectangular channel, the pressures ranges between 14 and 70 bar. They reported that the bubble boundary layer increased with increasing the distance from the start of the boiling due to the increases of bubble size. Correlations in both dimensional and dimensionless forms were proposed to predict the boundary layer thickness. It was also found that the mean temperature at the interface between the single phase core and the bubble boundary layer is always well below the saturation temperature and approaches

the inlet liquid temperature when the heat flux is increased. Brown found [1.14] that because of the existence of the temperature gradient in the boundary layer near the heater wall, the vapor bubble is subjected to a surface tension gradient, which tends to move the interfacial liquid film to produce a net flow around the bubble from the hot to the cold region, this is known as thermo-capillarity flow, caused by the Marangoni effect. A considerable fraction of the heat transfer flux can be transferred by this thermo-capillarity flow around the bubble. Moreover, it can also explain some other phenomena observed by other researchers, e.g. the temperature fluctuations in the bubble boundary layer and the mean temperature in the boundary layer is lower than saturation [1.13] (Jiji and Clark 1964). The phenomena that the temperature at the interface between the single-phase core and the bubble boundary layer decrease with increasing the heat flux can be attributed to the increased circulation caused by thermos-capillarity flow. In recent studies Vandervort et al. [1.15] (1992) have identified all possible heat transfer mechanisms for subcooled boiling:

- (1) Convection heat transfer by single phase liquid.
- (2) Direct transport from wall to vapor at the point of bubble attachment.
- (3) Microlayer vaporization of liquid to vapor at the base of the bubble.
- (4) Internal micro-convection of vapor across the bubble.
- (5) Vapor condensation at the bubble tip and convection to the liquid.
- (6) Enhanced turbulent mixing of the liquid by bubble agitation.
- (7) Vapor-liquid exchange.
- (8) Thermo-capillarity or Marangoni-induced micro-convection.

The most dominant heat transfer processes in highly subcooled boiling are believed to be mechanisms (3) and (8).

1.2.3.2 Heat transfer modes and correlations

Subcooled flow boiling is characterized by the presence of thermodynamic non-equilibrium between the liquid and vapor phases. This increases the complexity of the process and makes the analysis of the process very challenging. During the last

several decades, numerous models have been developed to predict the heat transfer rate during subcooled flow boiling. These models can be classified into three categories: (1) empirical correlations for wall heat flux, (2) empirical correlations for partitioning of the wall heat flux, and (3) mechanistic models for wall heat flux and partitioning. Generally the empirical correlations for wall heat flux are just correlated from the experimental data and do not include any modeling of the heat transfer mechanisms involved in the subcooled flow boiling, so these correlations are limited to the prediction of total wall heat flux at some particular flow conditions and cannot provide any information regarding the partitioning of wall heat flux, which is quite important in a number of applications, such as nuclear reactors, knowledge of only the overall heat transfer rate from the wall is insufficient. Since the reactivity and two-phase thermal hydraulics is directly related to the void fraction in the reactor, which in turn depends on how the wall heat flux is partitioned between the liquid and vapor phases. [1.16]

Partial nucleate boiling is the transition region between single-phase forced convection and fully developed nucleate boiling. Some correlations have been developed to predict the heat transfer in the partial nucleate boiling regimes. Bowring [1.17] used a superposition method to determine the partial nucleate boiling heat flux, the total heat flux is the sum of the heat flux transferred by single phase convection and the surface heat flux transferred by bubble nucleation in a fully developed pool boiling. The similar empirical correlations have also been proposed by Rohsenow[1.18], Kutateladze[1.19], Bjorge et al. [1.20] . Liu and Winterton [1.21] developed a model to predict the heat flux in subcooled flow boiling. The total heat flux was expressed as a combination of the single-phase convection heat transfer and the pool boiling heat transfer. However, the single-phase convection heat transfer is assumed to be enhanced by the liquid velocity of the two-phase flow while the pool boiling heat transfer part is suppressed due to a lower effective wall superheat in flow boiling compared to that in pool boiling. So a single-phase heat transfer enhancement factor and the pool boiling heat transfer suppression factor were included in the correlations.

Some mechanistic models have also been developed by considering the heat

transfer mechanism of different boiling regimes. Del Valle and Kenning [1.22] developed a mechanistic model for subcooled partial nucleate boiling, by considering the bubble dynamics at the heated wall. In the model, it was assumed that once the boiling begins, the heated wall could be divided into four regions, namely, the maximum bubble projected area, the surrounding area of influence, the overlapping areas of influence, and the non-boiling area, and different heat transfer mechanisms were considered in each region. Kurul and Podowski [1.23] also developed a mechanistic model, the wall heat flux was divided into three heat flux components; single-phase convection heat flux, transient conduction heat flux, and heat transfer by evaporation. Recently, a new mechanistic model to the partitioning of the wall heat flux was proposed by Basu et al. [1.24,1.25]. The fundamental idea of this model is that all the energy from the wall is transferred to the liquid layer adjacent to the heated wall. Thereafter, a fraction of the energy from this superheated liquid layer is transferred to the vapor bubbles by evaporation while the remaining heat transfers into the bulk liquid. As in previous models, the heating surface of the heater wall was divided into two regions depending on the different heat transfer mechanism, namely, the region between ONB and OSV and the region downstream of OSV. Other mechanistic models for predicting the heat flux in subcooled flow boiling have also been provided by Tu and Yeoh[1.26], Kumar et al. [1.27], and Wintterle et al.[1.28].

1.3 Bubble dynamics

The previous section reviewed the research work on heat transfer characteristic of subcooled flow boiling, however, the high heat transfer performance of subcooled flow boiling was close related to the behaviors of boiling bubbles. The investigations on bubble dynamics include the processes of bubble growth, departure and condensation, bubble release frequency, the reformation of the thermal layer (waiting period), are very important research subjects because its important role in understanding the heat transfer mechanism of pool boiling and flow boiling. With respect to the bubble growth on a heated surface, there exists two points of view in the literature. Some investigators have

proposed that the growth of a vapor bubble depends on the evaporation all around the bubble interface. The heat needed for the vapor evaporation is supplied from the superheated liquid layer that surrounds the bubble after its nucleation. Some bubble growth models are proposed based on this point of view, e.g. Plesset and Zwick (1954) [1.29] , Mikic et al (1970) [1.30] . However, some researchers insisted that most of the vapor bubble evaporation occurs at the bottom of the bubble in the microlayer between the vapor-liquid interface and the heater surface. Snyder and Edwards [1.31] were the first to propose this mechanism for evaporation. Cooper and Lloyd [1.32] confirmed the existence of a microlayer underneath the bubbles formed on glass or ceramic surfaces, and also deduced the thickness of the microlayer from the observed response of thermocouple on the heater. However, Plesset and Prosperetti [1.33] concluded that in subcooled boiling, evaporation at the microlayer accounts for only 20% of the total heat flux. After several decades of research, there is still not an effective and consistent model for bubble growth on a heated surface of pool boiling that can appropriately include the microlayer contribution and temporal varying thermal and flow boundary layers around the bubble.

Most of the bubbles, in both pool boiling and flow boiling, will depart from the heater wall. The size and shape of bubble when it departs from the wall is dictated by the way in which they are formed [1.2]. The forces that act on the bubble include the inertia of the liquid and vapor, hydrodynamic drag on the bubble, the buoyancy, and the surface tension. The hydrodynamic drag on the bubble and the buoyancy attempts to detach the bubble from the wall and the surface tension and the initial forces of the liquid acts to prevent it from departing. The bubble departure diameter correlated by balancing the buoyancy with the surface tension force acting on a static bubble by Fritz [1.34]. At high system pressures, significant deviations of the bubble diameter was reported compared with experimental data, however, the correlation provided a correct length scale for the boiling process. Several other expressions have been reported for bubble departure diameter, obtained either empirically or analytically by involving various forces acting on a bubble. However, these expressions are not always consistent

with each other. Cole and Rohsenow [1.35] correlated bubble diameter at departure with fluid properties but found it to be independent of wall superheat. Gorenflow et al [1.36] proposed an expression for bubble departure diameter that the bubble diameter increases weakly with wall superheat. Generally, surface tension tends to pull the bubble against the wall and prohibits the bubble from departing from the wall. However, Cooper et al. [1.37] found that in some cases the surface tension can assist the bubble departure by making the bubble spherical in an experimental study on the bubble growth and departure in a stagnant uniformly superheated liquid under both normal and reduced gravity conditions. Buyevich and Webber [1.38] have also given the same conclusion.

For a certain nucleate site, the bubble departs from the wall at a specific mean frequency, however, it varies from site to site. The bubble departure frequency is the inverse of the sum of the bubble growth time and waiting time. The waiting time refers to the periods between the departure of a bubble and the initiation of growth of the next bubble, it is the time necessary for reconstructing the thermal layer for the nucleation of a new bubble. Predictions of bubble release frequency based on waiting and growth periods do not match well with the experimental data because many simplifications are made in obtaining waiting time and growth time. Some researchers (Jakob 1958[1.39], Zuber 1963 [1.40]) also found that the product of the bubble departure frequency and the diameter was a constant.

1.3.1 Review on experimental studies of bubble behaviors

The bubble behaviors are crucial for analyzing and understanding the mechanism of subcooled flow boiling, therefore many researchers focused on investigating the characteristics of bubble behaviors and most of the studies in this field have been carried out by experimental visualizations. The rapid development of the high speed video camera and microscopic visualization technique in recent decades made it possible to observe the bubble behavior with high spatial and temporal resolutions, which are necessary, because for subcooled flow boiling, the bubble size is in millimeter scale and its lifetime is usually less than a millisecond.

Gunther [1.41] carried out an excellent photographic study in attempt to establish the heat transfer mechanisms in subcooled flow boiling. The test section was a transparent channel with rectangular cross section. The working fluid was water at atmospheric pressure with velocities between 1.5 and 12 m/s. The study showed that at higher subcooling degrees (~ 50 °C) the vapor bubbles grow and collapse while still attaching and sliding downstream on the heater surface with a velocity approximately 80 % of the bulk flow velocity.

The bubble growth and collapse process was photographed at a rate of 20,000 frames per second. It was found that Bubble size, lifetime, population, and coverage decrease as the subcooling degree is increased. However, at high subcooling degrees, very large populations of small bubbles were observed. All four parameters of bubble decrease as the velocity is increased at the constant heat flux and subcooling degree. Bubble size and lifetime decrease moderately while bubble population and coverage increase sharply as the heat flux is increased at constant velocity and subcooling.

Experiments are conducted to investigate how the channel size affects the subcooled flow boiling heat transfer and associated bubble characteristics of refrigerant R-134a in a horizontal narrow annular duct by Lie [1.42]. The gap of the duct is fixed at 1.0 and 2.0 mm in this study. From the measured boiling curves, the temperature undershoot at ONB is found to be relatively significant for the subcooled flow boiling of R-134a in the duct. The boiling heat transfer coefficient increases with a reduction in the gap size, but decreases with an increase of the inlet liquid subcooling degree. Raising the imposed heat flux can cause a substantial increase in the subcooled boiling heat transfer coefficient. However, the effects of the refrigerant mass flux and saturated temperature on the boiling heat transfer coefficient are small in the narrow duct. Visualization of the subcooled flow boiling processes reveals that the bubbles are suppressed to become smaller and less dense by raising the refrigerant mass flux and inlet subcooling. Moreover, raising the imposed heat flux significantly increases the bubble population, coalescence and departure frequency. The increase in the bubble departure frequency by reducing the duct size is due to the rising wall shear stress of the

liquid flow. At a high imposed heat flux many bubbles generated from the cavities on the heating surface tend to merge together to form big bubbles. Correlation for the present subcooled flow boiling heat transfer data of R-134a in the narrow annular duct is proposed. Additionally, the present data for some quantitative bubble characteristics such as the mean bubble departure diameter and frequency and the active nucleation site density are also correlated.

In a study of Prodanovic et al. [1.43], they attempted to relate the boiling heat transfer process and the transition from partial to fully developed boiling with bubble behavior in the subcooled flow boiling of water in a vertical heated annulus. Within the partial nucleate boiling region, bubbles barely change in size and shape while sliding a long distance on the heater surface. Such bubble behavior indicates an important contribution from the micro-layer evaporation to the overall heat transfer. With increasing heat flux, or reducing flowrate at constant heat flux, bubble growth rates increase significantly. Bubbles grow while sliding, then detach from the heater, and subsequently collapse in the bulk fluid within a distance of $1 \sim 2$ bubble diameters parallel to the heater surface. This shows bubble agitation becomes a leading heat transfer mode. There is a sharp transition between these two observed bubble behaviors that can be taken as the symbol of transition from partial to fully developed boiling.

An investigation of forced convective subcooled nucleate boiling was carried out by E. L. Bibeau and M. Salcudean[1.44] using high speed photography. Experiments were performed using a vertical circular annulus at atmospheric pressure, for mean flow velocities of $0.08 \sim 1.2$ m/s and subcooling degrees of $10 \sim 60$ K. They found that bubbles detach from the nucleation site and start to slide immediately after the nucleation, then it detach from the heating wall as they are ejected into the flow. Bubbles become elongated in the vertical direction to the wall as they slide on the wall, and are shaped like an inverted pear with the stem touching the wall just prior to lifting off from the wall. The bubble diameter when it was lifting off is smaller than the maximum diameter, since the condensation already started when the bubble was sliding on the wall.

Thornicroft et al. [1.45] carried out a visual study on behaviors of vapor bubble growth and departure in a vertical upward and downward forced convective boiling. A vertical flow boiling facility was constructed with a transparent electrically heated test section in which the ebullition process could be observed. High speed digital images of flow boiling phenomena were obtained which were used to measure bubble growth, departure diameters, and lift diameters. Experiments were conducted for flow of FC76 over a commercially finished nichrome heating surface with mass flux of 190 ~ 666 kg/(m²s) and heat flux of 1.3 ~ 14.6 kW/m². The liquid flow was slightly subcooled ($\Delta T_{\text{sub}} = 1.0 \sim 5.0$ K). They concluded according their observations that vapor bubble behaviors in upward flow and downward flow were significantly different. In the upward flow, bubbles slide along the heater wall, and typically do not lift off from the heating wall. However, in the downward flow configuration, bubbles either lift off directly from the wall, or firstly slide and then lift off, depending on the flow and thermal conditions. The process of vapor bubble sliding on the heating wall appears to be responsible for the enhanced energy transfer from the heating surface as evidenced by the larger heat transfer coefficients for up-flow than for down-flow under otherwise identical operating conditions. Statistical data of bubble parameters, e.g. bubble growth rate, departure diameter, lift-off diameter and waiting time, were also investigated at various experimental conditions. Bubble growth increases with Jacob number under otherwise identical conditions in up-flow or down-flow. Conversely, bubble growth generally decreases with increasing mass flux. Bubble departure diameter also increases with Jacob number and decreases with increasing mass flux in both up-flow and down-flow. Lift-off diameters in down-flow were observed to decrease with increasing mass flux and show a possible increase with increasing Jacob number. Waiting times were observed to decrease with increasing heat flux, waiting time and departure diameter are observed to be directly related.

Prodanovic et al. [1.46] carried out experimental studies on subcooled flow boiling of water in an upward annular channel at pressure from 1.05 bar to 3 bar, bulk liquid velocity ranging from 0.08 m/s to 0.8 m/s, subcooling degrees from 10 K to 30 K.

The bubble behavior during its lifetime from inception to collapse was captured by a high speed camera at frequencies of 6,000 ~ 8,000 fps. Bubble growth rate and condensation rate, variation of bubble lifetime and size with flow rate, subcooling degree, heat flux and pressure were examined. The bubble size and lifetime generally decrease with increasing the heat flux, bulk liquid velocity, subcooling degree and pressure, which was in accordance with most previous experimental studies. New correlations for the maximum diameter, detachment diameter, and bubble lifetime have been proposed. They also reported three different boiling regions with different bubble behaviors and heat transfer mechanism between ONB (Onset of Nucleate Boiling) and OSV (Onset of Significant Void): low heat flux region, isolated bubble region, region of significant bubble coalesce. The effects of heat flux and flow rate are greater at lower heat transfer rates.

Maurus et al. [1.47] carried out optical experiments on subcooled flow boiling of water in a test section of horizontal rectangular channel heated from one side by a copper strip. A high speed camera and a low-speed high-resolution camera were used for observing the bubbles from two different directions. The high speed camera recorded the behaviors of bubble growth, detachment and collapse while the low speed camera from the perpendicular view delivered additional data like number of bubbles, bubble size and density distribution, average spacing of bubbles and local vapor content. The measurement techniques and the development of the image processing and analyzing algorithms for a statistical evaluation of the high speed films were also given. Results of the bubble characteristics and the vapor distribution obtained with the combined camera system are presented for various heat fluxes in the range of 0.2 ~ 1.1 MW/m² and different liquid mass fluxes (250 ~ 2000 kgm⁻²s⁻¹) at a constant subcooling rate of 20 K. They found that the bubble size distribution shows a high share of small bubbles. For small bubble sizes, the distribution function depends only weakly on the heat flux and the liquid mass flux. However, the effects are more pronounced for bigger bubble sizes. The local void fraction, the bubble distribution and phase distribution profile depend on the heat flux and bulk flow velocity. The bubble size distribution

shows a high share of small bubbles. Finally, a model is presented to predict the local void fraction as a function of the height above the heated surface assuming a spherical form of the bubbles.

In their later research [1.48] based on the same experimental system and techniques, it was found that mass flux dominates bubbles temporal behaviors, an increase of liquid mass flux reveals a strong decrease of bubble lifetime and waiting time, while the variation of heat flux has a much weak impact. The probability of bubble detachment varies for selected experimental parameters between 20 % and 65 % and depends on the mass and heat flux, for higher mass flow rate a lower fraction of bubble can detach from the heating wall. The temperature in thermal boundary layer and the turbulent intensity dominate the bubble behavior, because both parameters govern the heat transfer in the liquid near the interface. A remarkable novelty was the presentation of the results as distribution functions, this is of physical importance because the applied spatial and temporal averaging leads to a loss of information and an unjustified deterministic view of the boiling process, which exhibits in reality a wide spread of bubble sizes and characteristic times.

Subcooled flow boiling of water was investigated in a vertical annular channel by Situ et al. [1.49]. A high speed video camera was applied to record the dynamics of the subcooled boiling process. The visualization results showed that the bubble departure frequency generally increases as the heat flux increases, for some cases the departure frequency may reach a limit around 1000 bubbles/s. Bubble coalesce may occur at the nucleation site when the frequency is higher than 500 bubbles/s. The bubble departure frequency, lift-off diameters, and dynamics after lifting-off were also analyzed and discussed. They also proposed that bubble growth and condensation were determined by the distance between the bubble and heated wall. In another study of Situ et al. [1.50], the experiments were performed at atmosphere, and inlet temperature ranged from 80.0 °C to 98.5 °C, the inlet velocity ranged from 0.487 m/s to 0.939 m/s, and heat flux changed in 60.7 ~ 206 kW/m². The bubble lift-off diameter was investigated from images of 91 test conditions and their results indicated that bubble

lift-off diameter increased with increasing the inlet temperature and heat flux and decreasing inlet fluid velocity. A force balance analysis of a growing bubble was also performed to predict the bubble lift-off size, the dimensionless form of bubble lift-off diameter was formulated to be a function of Jacob number and Prandtl number and the proposed model agreed well with the experimental data. Bubble departure frequency was also investigated from the video of a total of 58 test conditions [1.51], the non-dimensional analysis was conducted from the present data as well as available data from literature, existing models and correlations were compared with experimental data of bubble waiting time, growth time and departure frequency, the correlations developed for pool boiling cannot work well with forced convective subcooled boiling, while the model proposed for subcooled boiling flow cannot predict bubble departure frequency in wide experimental ranges. Dimensionless bubble departure frequency is correlated with non-dimensional nucleate boiling heat flux, the new correlations agree well with existing experimental data at lower wall superheat.

Bubble dynamics in water subcooled flow boiling was investigated by Ahmadi et. al.[1.52] in a rectangular vertical channel through visualization using a high speed camera. Main experimental parameters were pressure, mass flux and subcooling degree. They found no bubbles stayed at the nucleate sites, though the experiments were carried out at low void fraction conditions close to onset of nucleate boiling. Two types of bubbles were observed, the sliding bubbles and the lift-off bubbles, the boundary of these two types of bubbles can be determined in the term of Jacob number. The unsteady growth force, the time variation of bubble shape and the condensation at the sidewall of bubble are the possible mechanism to cause the bubble lift off. The size and behaviors of bubbles depend significantly on pressure: at atmosphere most of the bubbles lifted off from the wall, and under elevated pressure bubbles slid long distance on the wall.

Visual study was performed by Okawa [1.53] for vapor bubbles in subcooled flow boiling in a vertical heated tube to measure the void fraction and 4 fundamental bubble parameters: nucleation site density, bubble release frequency, bubble lifetime

and bubble size. The void fraction was expressed as the function of the 4 parameters, since the release frequency, lifetime and size were strong function of lift-off diameter, so the bubble lift-off diameter was the most influential parameter, and could be regarded as the key parameter in determining the void fraction. Visualization was performed for the vapor bubbles in water subcooled flow boiling in a vertical heated tube to measure simultaneously the void fraction and the four fundamental bubble parameters: nucleation site density, bubble release frequency, bubble lifetime and bubble size. Using the mass flowrate and liquid subcooling as the experimental parameters, the changes of void fraction and bubble parameters with the wall heat flux were measured. The results of image analysis showed that the vapor void fraction could be approximated by the function of nucleation site density and bubble lift-off diameter; the bubble lift-off diameter was more influential than the nucleation site density. It was hence concluded that the bubble lift-off diameter could be regarded as the key parameter to determine the vapor void fraction under the present experimental conditions. The strong relation of bubble lift-off diameter to superheated liquid layer thickness was indicated for the future model development studies of bubble lift-off diameter.

The research works reviewed above studied the bubble behaviors in subcooled flow boiling of various boiling regimes. Correlations and models were also proposed to predict the basic bubble parameters: bubble frequency, bubble size, growth rate, waiting time and so on. The effect of experimental conditions, e.g. flow rate, subcooling degree, heat flux and hydrodynamic pressure on the parameters and bubble behaviors were also investigated.

1.3.2 Review on numerical studies of bubble behaviors

In recently decades, as the rapid development of the computing power and technology, the numerical simulation studies on flow boiling heating transfer and bubble behaviors were also carried out.

A complete numerical simulation of a growing and departing bubble on a horizontal surface has been performed by [1.54]. The equations governing conservation

of mass, momentum and energy were solved in the vapor and liquid phases by using a finite difference scheme. A level set method which can handle breaking and merging of the interface automatically was used for capturing the interface between vapor and liquid, the influence of phase change at the liquid-vapor interphase was also included. The computational domain was divided into micro and macro regions. The micro region contains the thin film that forms underneath the bubble and the macro region consists of the bubble and the nearby liquid region. The governing equation of microlayer thickness was derived based on the radial location of the vapor-liquid interface which was obtained from the macro region and the lubrication theory. The computation zone was assumed to be axisymmetric and flow was in laminar regime, and fluids properties were constant in each phase. It was found that bubble growth predicted by numerical computation agreed well with experimental data. From the numerical simulation, the location where the vapor-liquid interface contacts the wall is observed to expand and then retract as the bubble grows and departs. The effect of static contact angle and wall superheat on bubble dynamics has been quantified, the departing bubble becomes larger with the increase in contact angle and wall superheat. The local wall heat flux is seen to vary cyclically during the bubble growth. The contribution of microlayer to the total heat flux is found to be about 20 %.

A mesh-free numerical method (MPS-MAFL), which means combining the particle method (MPS) with a grid-less method (MAFL) for arbitrary-Lagrangian-Eulerian calculation, is presented for the analysis of gas liquid two-phase flows by Yoon et al. [1.55]. The bubble growth and departure process in nucleate pool boiling was directly calculated using the present method. The predicted bubble growth rate agreed well with the experimental data. Numerical results are provided for the bubble growth rate, departure radius, and the heat transfer rate, which show a good agreement with experimental observations. The energy equation is coupled with the equation of motion for the calculation of nucleate pool boiling. The superheated liquid microlayer beneath the bubble is not modeled in the present calculation although there are certain evidences of its existence in nucleate boiling. It is

obvious that the bubble growth rate is much influenced by the microlayer evaporation. In the present study, a superheated liquid layer is placed over the vapor bubble at the beginning of bubble formation, which may have a similar effect as the microlayer. In their study, the calculations were limited to the nucleate boiling at relatively low wall superheat. Additional physical models for non-equilibrium vapor phase are required for the application to a wide range of two-phase boiling problems.

The complex transport and coupled interface dynamics of nucleate boiling have been simulated in three-dimensions using the Level Contour Reconstruction Method by Shin et al. [1.56]. The work is aimed at predicting nucleate boiling heat flux values more accurately on a real heating surface by including the effect of nucleation site density in the numerical model. This has been achieved by changing the surface area for a single nucleate bubble corresponding to the wall temperature. The models for microlayer evaporation and contact line dynamics which are essential to the heat transfer mechanism were not included. The three-dimensional simulations demonstrated more accurate agreement with the Nusselt number correlations in the literature than the two-dimensional simulations. The results for Nusselt number lie close to existing experimental correlations. It was found that complete three-dimensional simulation, including the effect of neighboring bubbles, is very important for predicting the proper relationship between heat flux and the wall superheat in a realistic surface. Detailed structure of the velocity and temperature distributions during nucleate boiling has also been obtained. Numerical simulations can complement the experimental investigations by providing information that is hard to measure by experiment, more work needs to be done in comparing numerical and experimental results over broader ranges of operating conditions,

Kunugi et. al [1.57] conducted the three-dimensional pool and forced convective subcooled flow boiling by the direct numerical simulation based on the MARS (Multi-interface Advection and Reconstruction Solver) [1.58]. The slope of the multiphase interface was taken into consideration when calculating the fluid flux transported through the cell faces to modify this drawback that the interface can only be

represented by vertical or horizontal lines in donor-acceptor procedure of VOF method. The bubble growth and condensation model was a phase-change model based on the temperature-recovery method [1.59], which was an improved enthalpy method. In another study [1.60], they modified the boiling and condensation model by introducing the following models based on the quasi-thermal equilibrium hypothesis; (1) an improved phase change model which consisted of the enthalpy method for the water vapor system, (2) a relaxation time derived by considering unsteady heat conduction. Numerical simulation on the subcooled boiling phenomena was carried out, the heat transfer characteristics of the subcooled pool boiling and its mechanism were also clarified. The numerical results of both bubble growth and condensation processes obtained by the developed boiling and condensation model were in good agreement with the experimental data of subcooled pool boiling.

Simulation of bubble behaviors in flows boiling are among the most difficult challenges, because it is highly dependent on the simultaneous coupling of unsteady mass, momentum and energy transport with the interfacial physics of surface tension, latent heat, interphase mass transfer, discontinuous material properties and complicated liquid vapor interface dynamics.

1.4 Content of the dissertation

1.4.1 Limitation of previous studies

In order to improve the cooling performance of the cooling system and the operation safety in the nuclear power plant, the study on clarification of the subcooled flow boiling phenomena and the development or modification on the constitutive models of heat transfer prediction are very important. Over the past decades, a great amount of research on bubble behaviors in subcooled flow boiling has been carried out to understand the fundamental phenomena and heat transfer mechanism for providing the practical knowledge for the design requirements in various industrial and engineering fields. However, there are still some limitations in the study of this field, e.g. most studies on bubble behaviors were conducted only at narrow range of conditions,

which is not sufficient in understanding and investigating the bubble behavior completely, since bubble behaviors at different experimental conditions can be very different. The spatial and temporal resolutions of visualization techniques applied in the previous studies were not high enough, since the size of bubble in subcooled flow boiling is in millimeter scale and bubble lifetime is in millisecond scale. Most of the studies observed and investigated many bubbles at a time, investigations on detailed behaviors of individual bubble during its whole lifetime was lack. They focused on studying the bubble dynamical parameters for establishing the models or correlations, bubble was assumed as a spherical shape, ignoring the bubble shape change during the growth, departure and condensation, which is important for studying the heat transfer mechanism and modelling.

1.4.2 Content and layout of the dissertation

The aim of the present study is to clarify the bubble behaviors at various working conditions to improve the understanding on hydrodynamic and heat transfer mechanism of subcooled flow boiling and provide database for modelling and correlations. The visualization of bubble behaviors were achieved by using high spatial and temporal resolutions camera and lens.

The dissertation is composed of 6 chapters and organized as follows: Chapter 1 mainly introduces the motivations, review of previous studies on heat transfer and bubble dynamics of subcooled flow boiling, and the aim of this study. Chapter 2 gives the introduction of flow boiling experimental system and numerical procedures for bubble dynamics simulation. Chapter 3 discusses the behaviors of single bubble in subcooled flow boiling at different subcooling degrees and flowrates. Typical bubble behaviors were introduced and discussed at low, medium and high subcooling degrees and at each of the subcooling degree, bubble behaviors were also compared and investigated at low and high flow rate. The interesting two-successive bubbles phenomena, which is common at high subcooling degree and high flowrate, was discussed in Chapter 4. Chapter 5 discusses the interacting and coalescence phenomena

of multiple bubbles. Finally, the summary of this dissertation and the recommendation of the future work will be given in Chapter 6.

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Chapter 2

Experimental System and Numerical Method

2.1 Introduction

The bubble behaviors characteristic in subcooled flow boiling were investigated by experimental visualizations. Video images of bubble behaviors in an upward annular channel were obtained by using the high speed video camera and Cassegrain micro-telescope with high spatial and temporal resolutions. The numerical study on the bubble behaviors was also carried out for comparing with the experimental data. In this chapter, the experimental system of subcooled flow boiling and the numerical algorithm were introduced, respectively.

2.2 Experimental system

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

For circulating and boiling sub-system, the schematic of the basic experimental apparatus was shown in Fig. 1. It consists of a storage tank, a pump, flow meters, a pre-heater, a test section of annular channel, and a condenser. These parts are connected by flowing passages of metal pipes, which are covered by blankets for thermal insulation. The purified water was chosen as the working fluid and stored in the storage tank, where it can be heated to a specific temperature by the cartridge heater installed at the bottom, the cartridge heater 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 sufficient amount of working fluid and keeping the water temperature stable

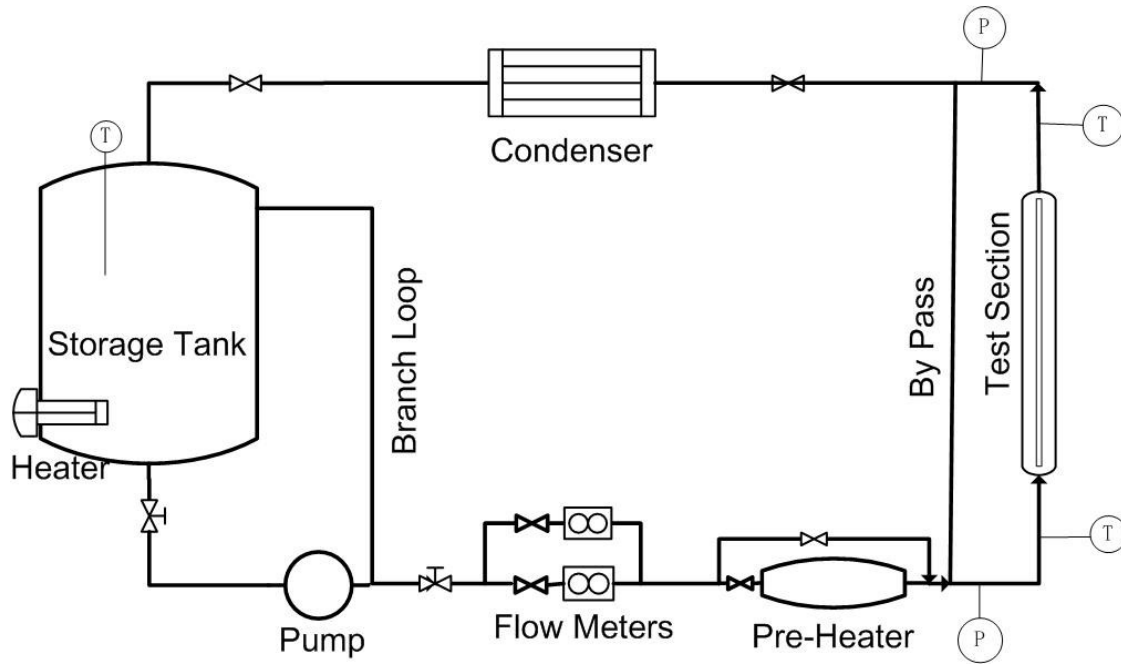
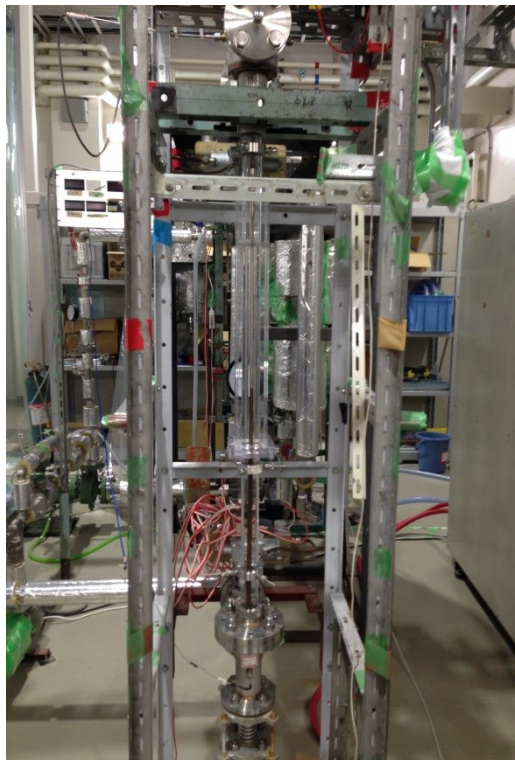


Fig. 2.1 Schematic of the circulating and boiling system

during the experiments. If the experiments under very low subcooling case were carried out, which means the liquid temperature at the inlet of test section needs to be quite high and approaching the saturation temperature, so the pre-heater would be turned on for heating the water to the required high temperature before entering the test section. The test section is a 1,000 mm long vertical annular channel consisting of a transparent round tube made of acrylic resin with an inside diameter of 20 mm and a co-axial cylindrical heater rod with an outer diameter of 8 mm. The heating part of the heater rod was 400 mm long and 0.5 mm thick hollow pipe made of nickel, starting at the position 500 mm above the inlet of the test section. The other parts were cylinder shaped rod made of copper and these non-heating parts cannot provide enough heat for boiling because of the low electricity resistance of copper. The water is heated by the heater rod when it passes the test section and boiling bubbles are generated on the heater wall. The electrical power to the heater rod is supplied by a DC rectifier with a maximum voltage of 20 V and a maximum electrical current of 1,200 A, so a maximum electrical power of 24 kW could be provided, corresponding to a maximum heating flux of 2.39 MW/m^2



(a)



(b)

Fig. 2.2 Photos of the experimental system

on the surface of the heater rod, the measurement error of the voltage and electrical current was about $\pm 1\%$ and $\pm 0.5\%$, respectively. The mixture of water and its vapor generated in the test section flows back to the storage tank after passing through a condenser, where the vapor is condensed to water. The flow meters are turbine-type flow meter from Hoffer Flow Control Inc, the measurement accuracy was about $\pm 0.5\%$. The temperature at the inlet and outlet of the test section channel are measured by 2 thermocouples, respectively, the error of the temperature measurement is within ± 0.5 K.

The high speed video imaging system consists of a high speed video camera (Phantom V7.1 from Vision Research Inc.), a Cassergrain microscopic lens (Seika Corporation), and an illuminating lamp. The highest speed of the video camera is 160,000 frames per second (fps), the maximum resolution of a photograph obtained by this camera is 800×600 pixels. The Cassegrain lens has a focal length in the range of 300 ~ 600 mm, corresponding to a spatial resolution in the range of 4 ~ 9 microns per pixel. An image box with square cross section was installed outside the annular channel of the test section and filled with water to correct the image optical distortion caused by light refraction. The high speed video camera and the Illuminating lamp were placed at two opposite sides of the test section, respectively. The arrangement of high speed video imaging system and the cross sectional view of the test section was shown in Fig. 2.

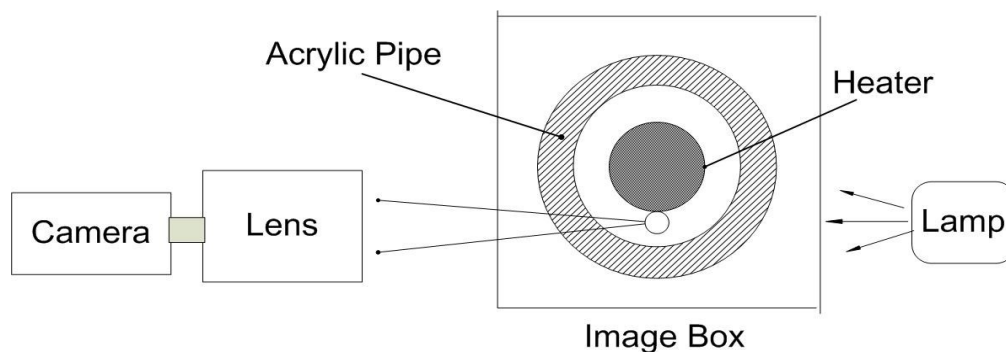


Fig. 2.3 Configuration of high speed imaging system

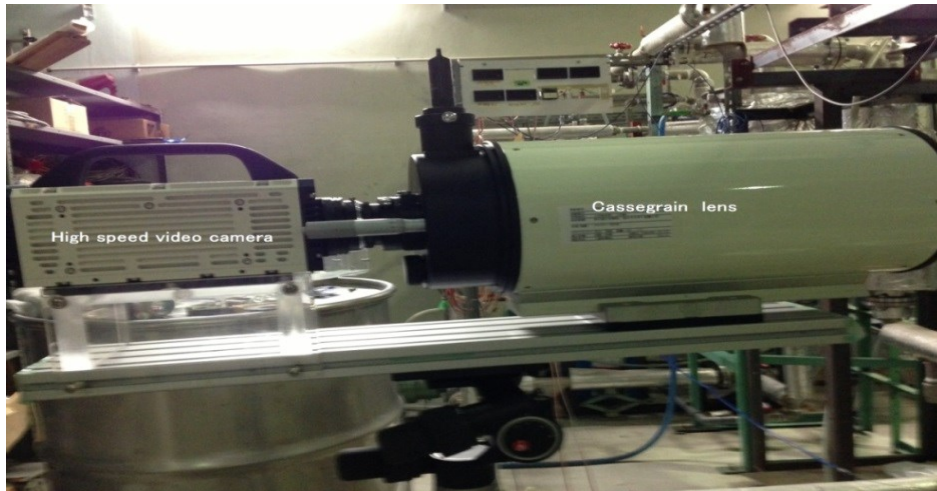


Fig. 2.4 Photo of the high speed video system

Before running the experiments, the water in the storage tank needs to be heated to the temperature required by the subcooling degree of the experiments plan. When the experiments are started, cycle the water, firstly in the branch loop, and then adjust the flowrate of water flowing in the test section and the temperature at the inlet and outlet of the test section. When the stable condition is attained, an appropriate heat flux is applied on the heater surface and provides the heat needed for the nucleation and growth of the boiling bubble. Before capturing and recording by using the high speed video camera, a stable nucleate site on the heater wall must be found, bubble nucleating at this site should be able to survive a wide range of working conditions, e.g. various flow rates and heat fluxes. During one run of the experiments, the observing position is fixed, and the working conditions, e.g. the heat flux and mass flow rate, are changed to study the bubble behavior at the same nucleation site but different experimental conditions. The bubble behavior during its whole lifetime, including nucleation, growth, departure and condensation was observed and recorded by the high speed imaging system. Under every working condition, at least 20 cycles of the bubble at the same nucleate site were recorded to guarantee the reproducibility of the bubble behavior.

The focus of the Cassegrain lens was adjusted to the bubble nucleating position on the heater surface to get the side view of the bubble behaviors, as shown in Fig. 2. The camera and Cassegrain lens were supported by a tripod, so the height and position

can be adjusted freely to get a good view of the bubble. The bubble observing position was chosen to be very close to the beginning of the heating section of the heater rod, because in this region, the bubble nucleating density was low, the interference from bubbles in the neighborhood or the sliding bubbles was less, it was easier to get clear images of the bubbles.

An image processing program was developed by using the MATLAB Simulink toolbox computer vision system to extract the quantitative data from the images obtained by the high speed image system.

2.3 Numerical method of MARS

The numerical simulation of the bubble behaviors in subcooled flow boiling was also conducted to compare with the experimental results. The numerical method was developed by Kunugi[2.1] and Ose[2.2,2.3,2.4]. MARS is a numerical method of interface capturing based on VOF method.

2.3.1 Governing equations

As for n fluids including the gas and liquid, the spatial distribution of fluids can be defined as:

$$\sum F_i = 1.0 \quad (2.1)$$

Here, F_i is the volume fraction of the fluid i .

The basic governing equations used in the MARS method are the continuity equation for multi-phase flows, momentum equation based on a one-field model and the energy equation, they are shown as follows:

$$\frac{\partial F_i}{\partial t} + (\mathbf{u} \cdot \nabla) F_i = 0 \quad (2.2)$$

$$\frac{\partial \mathbf{u}}{\partial t} + \nabla \cdot (\mathbf{u}\mathbf{u}) = \mathbf{G} - \frac{1}{\langle \rho \rangle} (\nabla P + \nabla \cdot \boldsymbol{\tau} - F_v) \quad (2.3)$$

$$\frac{\partial}{\partial t} \langle \rho C_v \rangle_M T + \nabla \cdot (\langle \rho C_v \rangle_M T \mathbf{u}) = \nabla \cdot (\langle \lambda \rangle_M \nabla T) - P(\nabla \cdot \mathbf{u}) + Q \quad (2.4)$$

Here, $\mathbf{G}$ is the gravity, P is pressure, ρ is density, Q is the term of heat source and

τ tau is the viscous stress tensor and can be calculated as:

$$\tau = -\langle \mu \rangle \left[(\nabla u) + (\nabla u)^T \right] \quad (2.5)$$

Because only one set of the governing equations were used to simulate the multi-phase flow, the properties used in the equations are average of the liquid and vapor properties weighted by the fraction of each phase, like:

$$\langle \phi \rangle = \sum (F_i \phi_i) \quad (2.6)$$

The two-step projection method [2.5] is applied to solve the momentum equation. First, the pressure term in momentum equations (2.3) is eliminated, and the middle velocity $\tilde{u}$ was obtained by solve the equation (2.7)

$$\frac{\partial u}{\partial t} + \nabla \cdot (uu) = G - \frac{1}{\langle \rho \rangle} (\nabla \cdot \tau - F_v) \quad (2.7)$$

Then the passion equation (2.8) which was derived from the continuity equation was solved to get the pressure.

$$\nabla \cdot \left[\left(\frac{\Delta t}{\langle \rho \rangle} \right) \cdot \nabla \delta P \right] = \nabla \cdot u \quad (2.8)$$

Then the velocity of the next time step was obtained by

$$u^{n+1} = u - \left(\frac{\Delta t}{\langle \rho \rangle} \right) \nabla \delta P \quad (2.9)$$

2.3.2 The interface capture method of the MARS

The well-known interface capture method used widely in multiphase flow simulation is the VOF (Volume of Fluid) method invented by Hirt, C. W. and Nichols [2.6]. At first, the donor-acceptor procedure was used to calculate the volume of fluid being advected through one face of the cell in one time increment, the conservation of the fluid volume can be guaranteed. However, in donor-acceptor procedure the interface of different fluids can only be represented by vertical or horizontal lines, so the sloping interface will be reconstructed as lines of stair-step it cannot reconstruct the real

interface with sufficient accuracy. In order to modify this drawback, the slope of the interface was taken into consideration when calculating the fluid flux transported through the cell faces, a new method named Multi-interface Advection and Reconstruction Solver (MARS) was proposed by Kunugi [2.1].

In the MARS method, the fluid volume flux transported in δt can be expressed as:

$$\delta F = \int_{x-u\delta t}^x S(x)dx \quad (2.10)$$

Here, $S(x)$ is the area function of fluid fraction, and it can be approximated by the linear function $C(x)$ as follows:

$$C(x) = \bar{f} + \frac{1}{2}, \bar{f} = \frac{\partial F}{\partial x} \Big|_{x_0} = \frac{n_y/\Delta y}{n_x/\Delta x} \Big|_{x_0} \quad (2.11)$$

$$S(x) \approx C(x) = \bar{f}(x_0 + x) + \frac{1}{2}, (x \leq 1) \quad (2.12)$$

Here, $S(x)$ and $C(x)$ were functions based on a local coordinate system, x-axis was set to be in the perpendicular direction to the cell face, y-axis means the local area fluid fraction, x_0 means the distance between the current interface cell and the assumed cell whose volume fraction of fluid equals 0.5. So the crucial of the method is how to calculate the x_0

When the normalized cell moves toward the right along the x-axis and the upper right corner of the cell is coincident with $y=1$ in case of $0 < \bar{f} < 1$, the center of the cell was x_1 . When the left corner of the cell is coincident with $y = 1$, the center of the cell was x_2 . If the cell moves toward the left, and when the lower left corner of the cell is coincident with $y = 0$, the center of the cell refers to $-x_1$. When the lower right corner of the cell is coincident with $y = 0$, the center of the cell refers to $-x_2$. Therefore, the possible transport fluid fraction $F(x)$ in the normalized cell in case of $0 < \bar{f} < 1$ can be calculated by the following equations:

$$F(x) = \begin{cases} 0.0, & \text{for } x \leq -x_2 \\ 1/2 \bar{f} [x - (-x_2)]^2 & \text{for } -x_2 < x \leq -x_1 \\ \bar{f}(x) + 1/2 & \text{for } -x_1 < x \leq x_1 \\ 1 - 1/2 \bar{f}'(x_2 - x)^2 & \text{for } x_1 < x \leq x_2 \\ 1.0 & \text{for } x_2 < x \end{cases} \quad (2.13)$$

The equations in both cases of $-1 < \bar{f} < 0$ and $1 < |\bar{f}|$ can be obtained by the same manner. Finally, in order to obtain the x_o , we can derive the following relations from the following Equations:

$$sign = sign(\bar{f}), x_1 = \frac{1}{2} \left| sign \times \frac{1}{\bar{f}} - 1 \right|, x_2 = \frac{1}{2} \left(sign \times \frac{1}{\bar{f}} + 1 \right) \quad (2.14)$$

$$\bar{F} = \min \left(1, sign \times \bar{f} \right), \bar{x}_0 = sign \times \left(F_{given} - \frac{1}{2} \right) \cdot \frac{1}{\bar{F}} \quad (2.15)$$

$$x_0 = \begin{cases} x_2 - \sqrt{-\frac{2}{\bar{f}} \left(F_{given} - \frac{1}{2} (1 + sign) \right)} & \text{for } x_1 < \bar{x}_0 \\ \bar{x}_0 & \text{for } -x_1 \leq \bar{x}_0 \leq x_1 \\ -x_2 + \sqrt{\frac{2}{\bar{f}} \left(F_{given} - \frac{1}{2} (1 - sign) \right)} & \text{for } \bar{x}_0 < -x_1 \end{cases} \quad (2.16)$$

Here, in case of $\bar{f} = 0$, $S(x) = F_{given}$ and the donor and in case of $\bar{f} = \pm\infty$ the donor and acceptor procedure was applied.

After the $S(x) \approx C(x)$ was determined, the volume of fluid transported through the left and right faces of the cell can be calculated from:

$$\delta F = \frac{1}{2} [C(x_i + 1/2 - \delta x) + C(x_i + 1/2)] \times u \Delta h \quad (2.17)$$

$$\delta x = u \Delta h / \Delta x \quad (2.18)$$

2.3.3 Boiling and condensation Model

The critical radius r_e of the embryo corresponding to TSH can be calculated by Eq. (5) based on thermodynamics.

$$r_e = \frac{2\sigma}{P_{sat}(T_l) \exp\{v_l [P_l - P_{sat}(T_l)] / RT_l\} - P_l} \quad (2.19)$$

The bubble growth and condensation model consists of the phase-change model

based on the temperature-recovery method [2.7], which was an improved enthalpy method. The bubble growth and condensation model is applied only to the interface cells. The phase-change fraction Δg is expressed as:

$$\Delta g = \frac{\rho_l C_{pl} \Delta T}{\rho_g h_{lv}} \quad (2.20)$$

Equation (9) means that the ratio of sensible heat to latent heat, it is similar to the expression of Jacob number, Ja. By considering the finite thickness of bubble interface and the feature of the quasi-thermal equilibrium hypothesis, a relaxation time was introduced by the VOF limiter. The phase changed model of Eqn. (9) was applied only to the cells which has the volume fraction between 0.15 and 0.85.

Moreover, the bubble growth and condensation model includes the expansion and contraction model to consider the external work done by the volume expansion of bubble. This work takes place only at the interface of bubble. The variation of volume due to both volume expansion and contraction of a bubble with the change of pressure is modeled as follows:

$$\Delta F = \frac{\delta v}{v} = -\frac{\delta \rho_g}{\rho_g^n} = -\frac{\delta P}{\gamma(P^n + \delta P)} \quad (2.21)$$

2.3.4 Surface tension and contact angle models

For surface tension, the CSF (Continuum Surface Force) model [2.8] was used, the curvature of the interface between the liquid and vapor was calculated as:

$$\kappa = -(\nabla \cdot \hat{n}) = \frac{1}{|n|} \left[\left(\frac{n}{|n|} \cdot \nabla \right) |n| - (\nabla \cdot n) \right] \quad (2.22)$$

The surface tension of the liquid-vapor interface which is a surface force is converted to a volume force by the CSF model, as follows:

$$F_v(x) = \left[\sigma \kappa(x) + (\tau_2(x)_{ii} - \tau_1(x)_{ii}) \right] n(x) \rho(x) / \bar{\rho} \quad (2.23)$$

Where, $\bar{\rho} = (\rho_1 + \rho_2)/2$, n is the normal vector of the liquid-vapor interface, pointing from liquid to vapor.

The normal vector at the cells where the liquid-vapor interface meets the solid wall was calculated as:

$$\hat{n} = \hat{n}_w \cos \theta_{eq} + \hat{t}_w \sin \theta_{eq} \quad (2.24)$$

Here, the $\hat{n}_w$ and $\hat{t}_w$ is the unit normal vector and unit tangent vector of the solid wall, respectively, and θ is the equilibrium contact angle. By this model, the contact angle which represents the wettability of the liquid to the wall was included in the calculation of the normal vector of the liquid-vapor interface cells adjacent to the wall, and finally it will affect the surface tension at the contact line.

2.3.5 Flow chart of the computation

The flow chart of the sequential steps of the computation process was shown in Fig. 2.5.

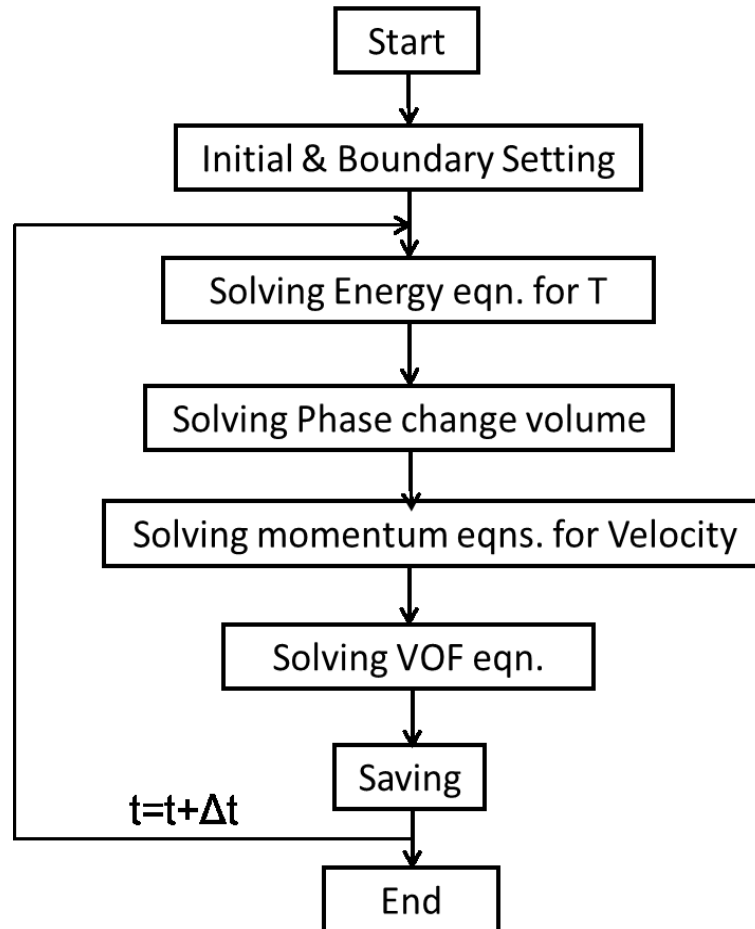


Fig. 2.5 Flow chart of the computation

References

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Chapter 3

Behaviors of Single Bubble in Subcooled Flow Boiling

3.1 Introduction

Visualization experiments on dynamic behaviors of individual bubble in subcooled flow boiling were carried out under wide ranges of subcooling degrees, bulk liquid flow rates and heat fluxes, e.g. subcooling degrees ΔT_{sub} from 5 K to 50 K, the mean velocity of bulk flow v_m ranges from 0.1 m/s to 0.8 m/s, and the heat flux applied on the heating wall q ranges 92 ~ 490 kW/m². It was found that the bubble shape and behavior were quite different as the variation of the experimental conditions. In this chapter, the characteristics of bubble behaviors in subcooled flow boiling are compared and discussed under various subcooling degrees and flow rates. Typical bubbles from various subcooling degrees (low, medium, high) and flow rate (low, high) were selected for comparison and discussion. Some basic parameter of the bubble was also investigated in a statistical way and conclusions in accordance with the previous research works were obtained. The deformation phenomena on the upstream side bottom of the bubble observed in subcooled flow boiling was explained by the Marangoni effect, and numerical simulation was also conducted to verify and provide the direct evidence for the explanation of the bubble deformation mechanism. The computing method was also proposed for calculating the volume of bubble reduced by the upstream-side deformation.

3.2 Behaviors of bubbles at various subcooling degrees and flowrates

In this section, typical bubbles from various subcooling degrees (low, medium, high) and flow rate (low, high) were selected for comparison and discussion. Characteristic of bubble behaviors at different subcooling degrees and flow rates were first discussed in a qualitative way and then some important parameter about the bubble dynamics were also analyzed in a quantitatively way. The qualitative discussions on bubble behaviors in this section are given in the order of subcooling degrees: medium subcooling degree, high subcooling degree and low subcooling degree. For each of the subcooling degrees, the bubble behaviors at both low and high flow rates are discussed, respectively.

3.2.1 Bubble behaviors at medium subcooling degrees

In this part, the bubble behavior at medium subcooling degrees ($10\text{ K} < \Delta T_{\text{sub}} < 30\text{ K}$) were discussed. At low flow rate (mean velocity less than 0.3 m/s), the bubble deformation on the upstream side bottom was observed and explained by Marangoni effect. At high flow rate the bubble behavior is a combination of deformation on the upstream side bottom and the rolling and sliding on the wall caused by the flow shearing effect.

3.2.1.1 At low flow rates

The bubble behavior at medium subcooling degrees and low flow rates are characterized by the deformation on the upstream-side bottom of the bubble. Sequential images of the selected typical bubble were shown in Fig. 3.1 from nucleation on the heating wall to the extinction in the subcooled bulk flow, these images were extracted from the video files obtained by the high speed video image system. The bubble nucleating position was about 30 mm downstream from the beginning of the heating section of the heater rod. The average heat flux q applied to the surface of the heater wall was 135 kW/m^2 , and the subcooling degree ΔT_{sub} was about 21.5 K based on the temperature of the bulk liquid entering the inlet of the test section. The mean liquid velocity in the annular flowing channel of the test section v_m was 0.14 m/s. The elapse time from the appearance of the bubble embryo on the heating wall was marked in each

image of Fig. 3.1, the length scale was also given in Fig. 3.1 (a).

As shown in Fig. 3.1 (a) ~ (h), after a short period of rapid growth, the bubble reached its maximum size and a semi-spherical shape bubble was observed. During this period, the bubble shape and growth was quite normal, similar to the bubble growth behavior in subcooled pool boiling case. From the images (i) ~ (o) in Fig. 3.1, the bubble size varied not so much, however, the shape of the bubble changed significantly. As indicated by the red arrow in Fig. 3.1 (l), a small concave deformation of the bubble was generated at the upstream-side bottom region, and this deformation became much severer and larger as shown in the following images of Fig. 3.1, finally when the bubble was about to lift off from the heating wall, as shown in Fig. 3.1 (o), the upstream side part of the bubble deformed to a particular shape, which is significantly different with the downstream side of the same bubble, the bubble shape at the departure time was like an eggplant. The deformation phenomena in the upstream side of the bubble during the bubble growth and departure regime was not an occasional phenomenon, actually this phenomenon was observed in almost all the bubbles of subcooled flow boiling under a suitable subcooling degree.

The deformation phenomenon on the upstream-side bubble surface described above could be explained by the condensation being occurred in this region caused by the low temperature liquid which flows from the subcooled bulk flow region. In subcooled flow boiling, the heating wall and the region close to the heating wall are superheated, therefore the vapor bubble can be nucleated and grow larger, but the bulk flow region far away from the heating wall is subcooled, which means the gradient of temperature in vertical direction to the heating wall was quite large, so there exists the thermal-capillary flow caused by Marangoni effect along the bubble surface from bubble bottom to the top. Some secondary flow or vortex could also be formed in the front bottom region of the bubble. The liquid of relatively lower temperature from bulk liquid flow might be “suck” into the upstream side bottom region of the bubble, and then result in condensation of the bubble.

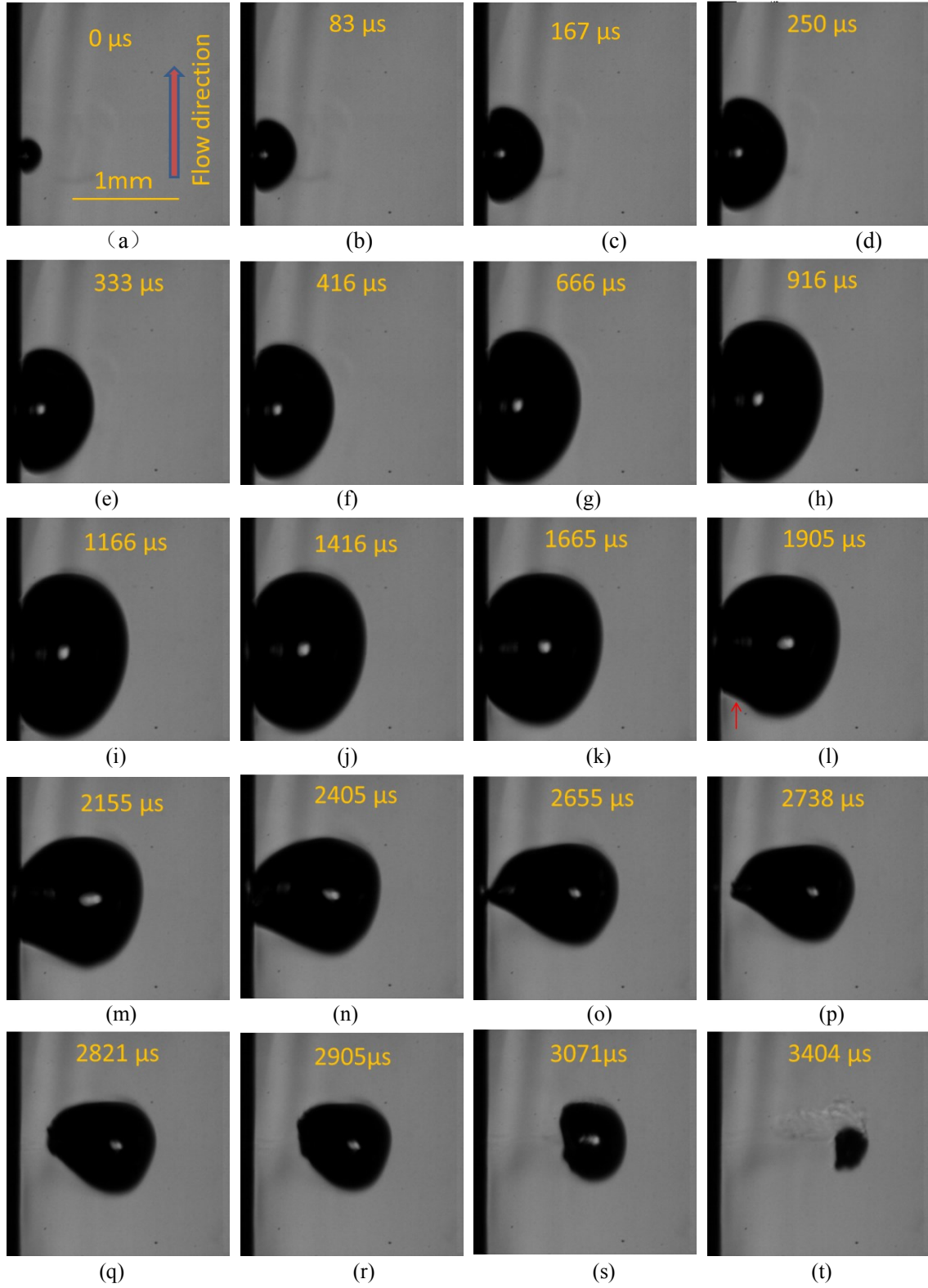


Fig. 3.1 Sequential images of bubble behavior,

ΔT_{sub} : 21.5 K, v_m : 0.14 m/s, q : 135kW/m²

At first the condensation might be very weak, but since the specific volume of the vapor is much larger than the liquid water, so the space of vapor after condensation needs to be filled by the liquid water from the bulk flow, and the supply of liquid water is quite sufficient from the incoming bulk flow, so the condensation would continue and make the upstream side surface of the bubble deforming from a convex shape to a concave one, as shown in Fig. 3.1 (l) ~ (o). As for the downstream side of the bubble, because the subcooled bulk flow was flowing away from the bubble, so the low temperature liquid from the bulk liquid flow may be difficult to reach the downstream side of the bubble, therefore, there is almost no condensation occurring at the downstream side of the bubble. The asymmetry shape of the bubble formed by the upstream side deformation working together with the surface tension will generate a recoil force, which has a positive effect on the bubble departure from the wall. The bubble deformation caused by condensation was also found by Ahamdi [3.1], they observed reduction of bubble volume prior to lift-off occurs not at the bubble top, but mainly at side surface of the bubble, especially the upstream side surface, and the condensation at side surface of the bubble was considered as one of the possible mechanism to cause bubble lift off. The explanation of bubble deformation by the thermal-capillary flow was first proposed, and will be given in more detail in Sec. 3.3, and the numerical simulation results were also carried out to provide the evidence of the explanation.

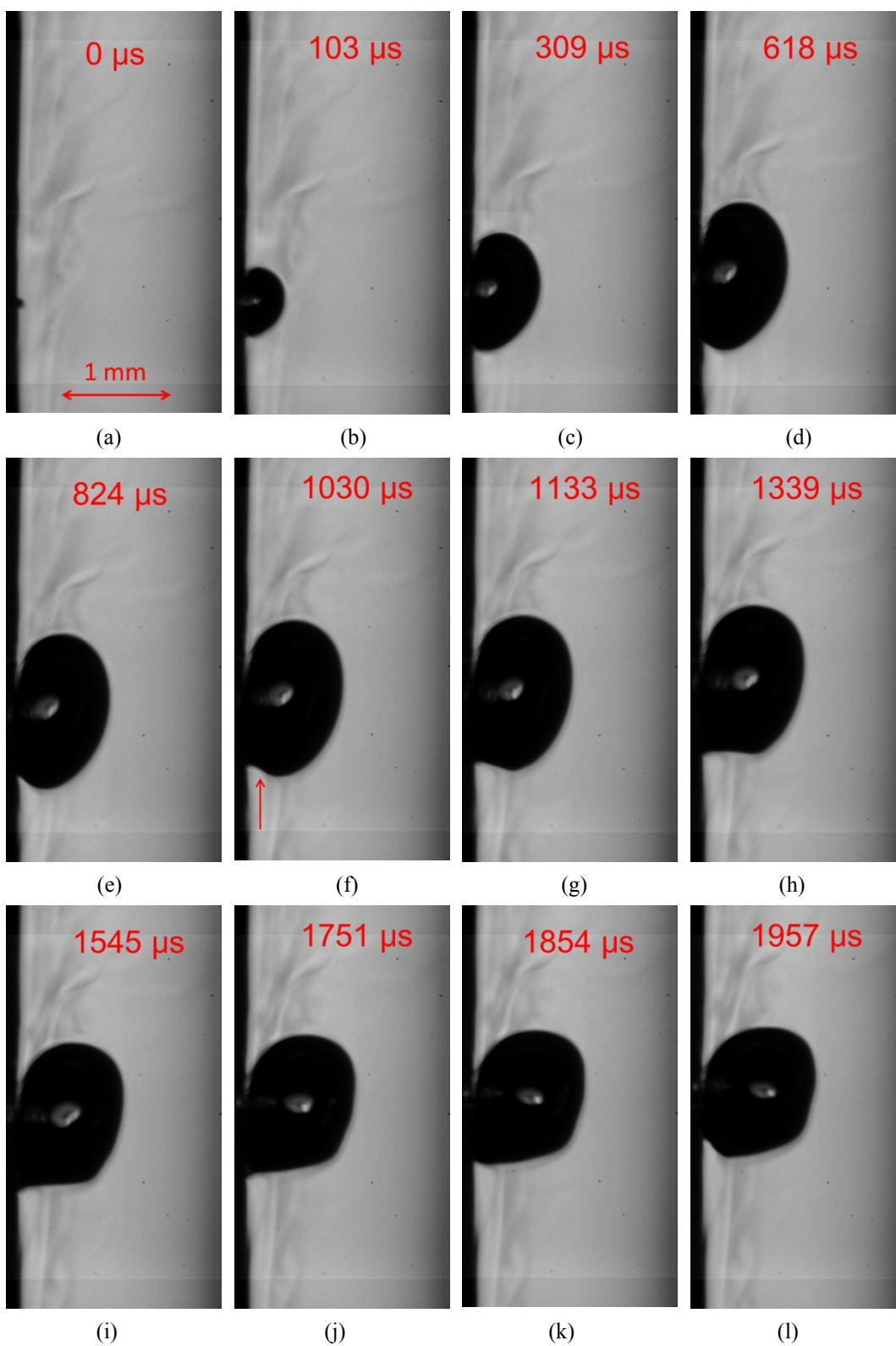
3.2.1.2 At high flow rates

The typical bubble behavior in subcooled flow boiling at medium subcooling degrees but high flow rates was given in Fig. 3.2. The nucleating site was about 25 mm downstream from the beginning of the heating section of the heater rod. The average heat flux q was 310 kW/m^2 , and subcooling degree ΔT_{sub} was about 19.0 K, the mean liquid velocity v_m in the annular channel was 0.55 m/s.

Compared with the bubbles at the similar subcooling degrees but lower flow rates, the effect of the flow shearing on the bubble behaviors is very eminent during the

whole lifetime of the bubble. Even in the rapid growth period of the bubble preliminary stage, as shown in Fig. 3.2 (a) ~ (f), the bubble exhibited an asymmetry shape, the upstream part of the bubble was a little bit longer and thinner than the downstream part because of the flow shearing effect. From Fig. 3.2 (f), a small concave deformation of the bubble at the upstream side bottom was observed, as pointed out by the red arrow, and this deformation developed along the upstream side interface from bottom to top, as shown in Fig. 3.2 (f) ~ (l), this deformation process can also be attributed to the condensation of bubble at the upstream side bottom caused by the low temperature liquid from the subcooled bulk flow, as discussed for the bubble in low flow rate of the medium subcooling degrees given in Sec. 3.2.1.1. The difference was that at high flow rate the bubble has a strong tendency of moving or rolling towards the downstream side on the heating wall, because of the strong shearing effect of the bulk flow, finally the upstream side surface of the bubble was not a curvilinear line any longer, but deformed to a straight line, as shown in Fig. 3.2 (i), (j), and (k), which was very different with the other parts of the bubble surface.

During the growth and departure period of the bubble, as can be seen in Fig. 3.2 (a) ~ (n), the bubble rolled on the heating wall and slid towards the downstream side, under the shearing effect of the liquid flow, furthermore, the deformation in the upstream side bubble surface makes the bubble easier to roll on the heating wall under the flow shearing effect. Finally, at the time when the bubble lifted off from the heating wall, it was quite far away from the original position of its nucleating site. It was also found by Bibeau and Salcudean [3.2] that bubbles depart away from the nucleation site because of the shearing effect of the bulk flow and start to slide almost immediately after nucleation. Generally, the bubble behavior at medium subcooling degrees and high flow rates was a combination of the deformation on the upstream side bubble surface caused by the condensation process and the bubble rolling and sliding towards the downstream side on the heating wall caused by the shearing effect of the bulk liquid flow.



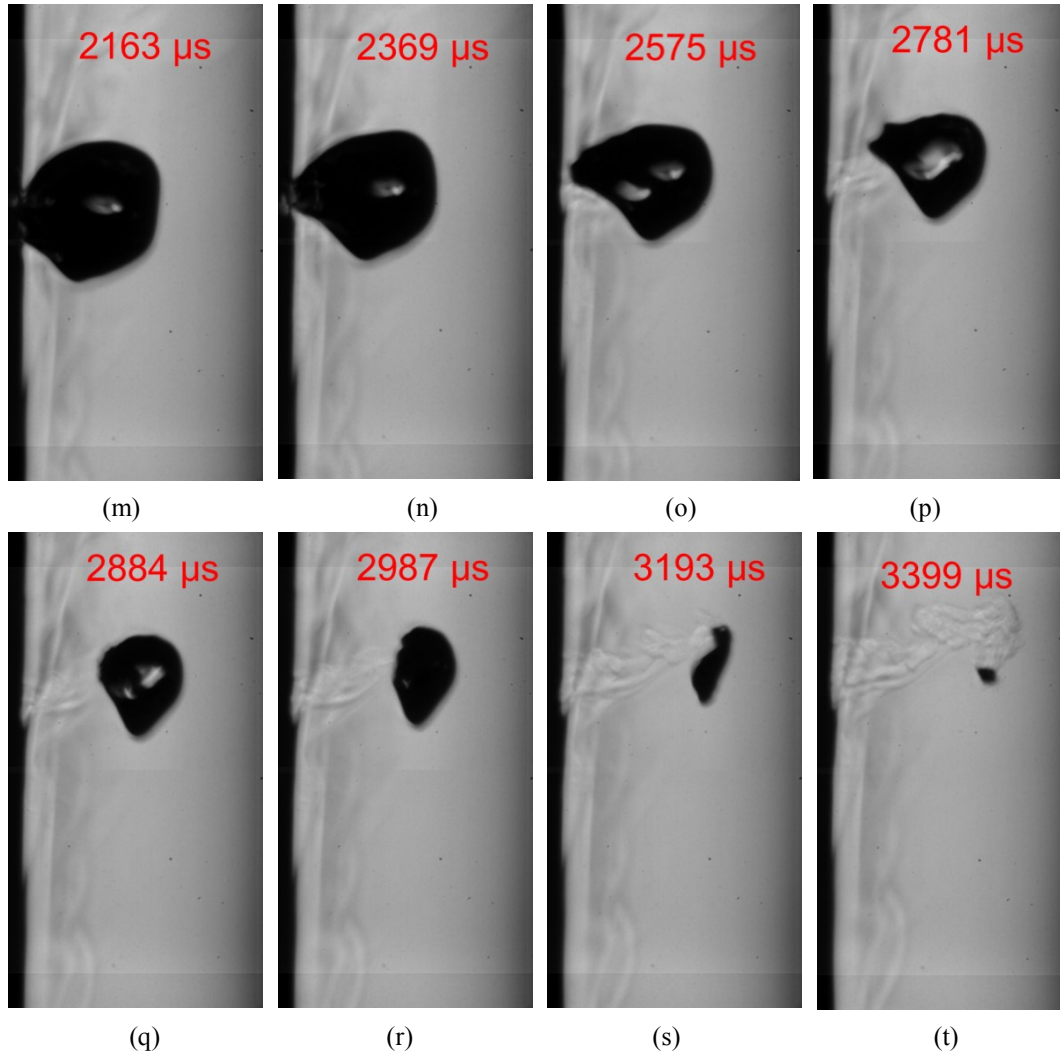


Fig. 3.2 Sequential images of bubble behavior,
 $\Delta T_{\text{sub}}: 19.0 \text{ K}$, $v_m: 0.55 \text{ m/s}$, $q: 310 \text{ kW/m}^2$

3.2.2 Bubble behaviors at high subcooling degrees

In this part, the bubble behavior at high subcooling degrees ($\Delta T_{\text{sub}} > 30 \text{ K}$) were discussed. At low flow rate (mean velocity less than 0.3 m/s), the contraction and elongation deformation of bubble was observed and also the phenomena of two successive bubbles is common at high subcooling degrees. At high flow rate the bubble concave deformation was found on the middle of the bubble upstream side surface because the highly subcooled bulk flow can directly hit the bubble upstream side surface.

3.2.2.1 At low flow rates

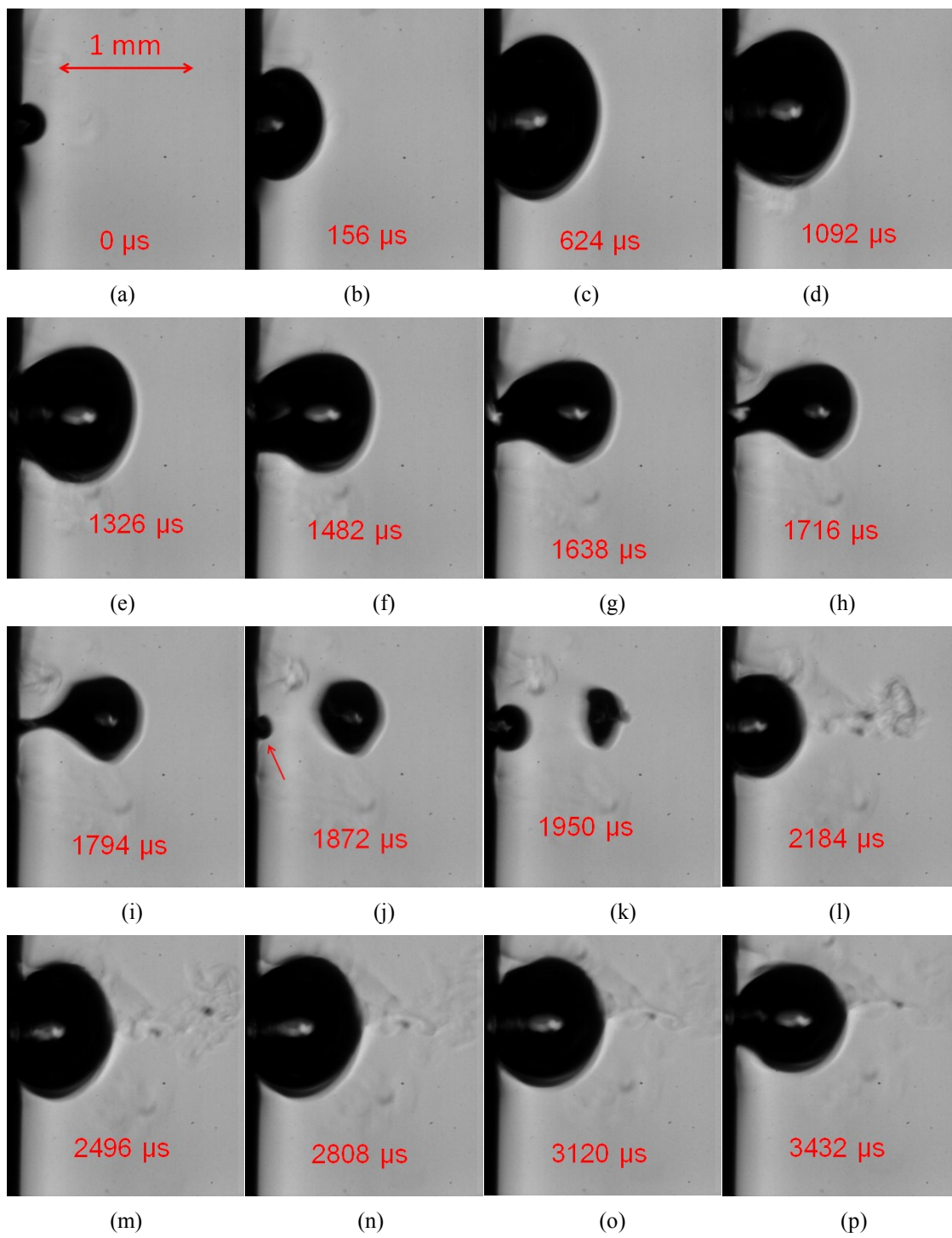
The images in Fig. 3.3 showed the bubble behavior in subcooled flow boiling at a high subcooling degree ($\Delta T_{\text{sub}} = 39.3 \text{ K}$) and a low flow rate, the mean liquid velocity in the annular channel of the test section v_m was 0.15 m/s, the heat flux applied on the heater surface was 185 kW/m^2 .

As shown in Fig. 3.3 (a) ~ (d), after the bubble embryo appeared at the heating wall, the bubble size increased very rapidly and reached its maximum in a very short time, about $1100 \mu\text{s}$. The bubble was of oblate shape during this rapid growth period, because of the very thin superheated layer at high subcooling degrees. From Fig. 3.3 (e) ~ (i), a contracting deformation at the bubble bottom was observed, firstly a small concave deformation on the upstream side surface was found, as in Fig. 3.3 (e), then the deformation at downstream-side surface of the bubble also occurred, as in Fig. 3.3 (h), the deformation became more and more serious, finally when the bubble was lifting off from the wall, the bubble bottom became very thin and long, like a thread connecting the bubble to the wall, as shown in Fig. 3.3 (i). Then the threadlike bubble bottom broke apart, and the bubble departed from the wall and condensed in the subcooled bulk flow rapidly as shown in Fig. 3.3 (j), (k).

The contracting deformation was attributed to the condensation occurred at the bubble bottom. Because the subcooling degrees was very high, around 40 K, so the temperature gradient in direction normal to the heating wall was very large and the superheated boundary layer was very thin, as shown in Fig. 3.4. During the rapid growing period, the liquid surrounding the bubble could be pushed or agitated by the quick bubble movement and volume expansion. After the bubble reached its maximum size, it deformed from an oblate ellipse to a sphere under the effect of surface tension, so some subcooled liquid was entrained to the region near the bubble bottom and caused the condensation occurring at the bottom region of the bubble, resulting in contracting deformation of the bubble bottom. Finally when the bubble was about to lift off from the heating wall, very long and thin bubble neck was formed, like a thread fastening the

bubble to the heating wall like a balloon, as shown in Fig. 3.3 (i). This deformation phenomena and the long thin bubble neck was very common in bubbles of high subcooling degrees, Fig. 3.5 shows the bubble images at departure time at different subcooling degrees (30 K, 40 K, 50 K) and flow rates (0.14 ~ 0.28 m/s). At the high subcooling cases, the deformation caused by the thermos-capillary flow of Marangoni effect as in medium subcooling cases should also exist, since the temperature gradient was even larger. The bubble images given in Fig. 3.5 were not exactly symmetry, in the upstream side its deformation was a little severer, this might be caused by the additional deformation in the upstream side of the bubble caused by the Marangoni effect. Then at some time the long and thin bubble neck broke apart and the bubble lifted off from the heating wall. After the bubble lifted off from the wall, a small part of vapor was left on the heating wall, as marked by the red arrow in Fig. 3.3 (j). Then this small part of bubble grew larger very quickly, as shown in images (j) ~ (n) of Fig. 3.3, finally the second bubble also departed from the heating wall and condensed in the subcooled bulk flow. This is the two successive bubbles phenomenon, which was very common in subcooled flow boiling at high subcooling degrees and low flow rates. This phenomenon of two successive bubbles will be discussed in detail in Chapter 4.

In subcooled flow boiling of high subcooled degree, the condensation process starts very early, much earlier than the bubble departure time, this can be verified by the bubble volume at departure time, as you can see in Fig.3.3 (d), (i), the bubble volume at departure time is much smaller than the bubble maximum volume. Actually the condensation occurred not only at the bubble bottom, but also other parts of the bubble, such as the bubble top. Since the thickness of superheated boundary layer in subcooled flow boiling of high subcooling degrees was very thin, so the bubble top was very easy to get out of the superheated thermal boundary layer and touch the subcooled bulk liquid and resulted in condensation, in Fig. 3.3 (e) ~ (i) it can be clearly seen that the top part of the bubble was also getting smaller.



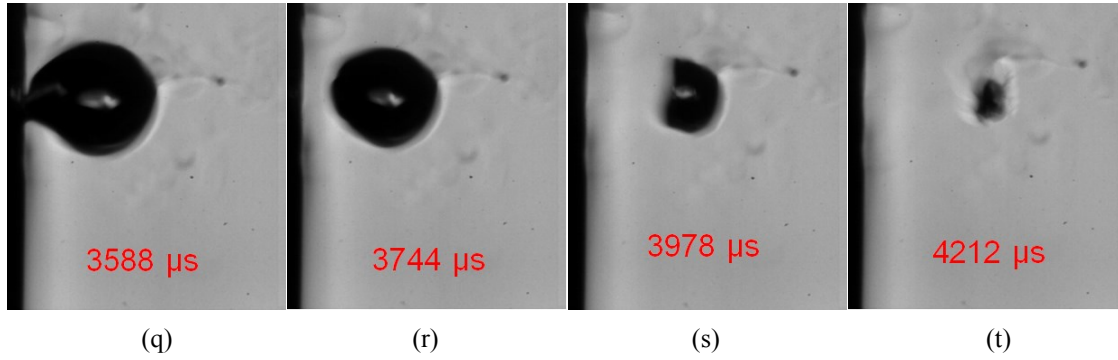


Fig. 3.3 Sequential images of bubble behavior,
 $\Delta T_{\text{sub}}: 39.3 \text{ K}$, $v_m: 0.15 \text{ m/s}$, $q: 185 \text{ kW/m}^2$

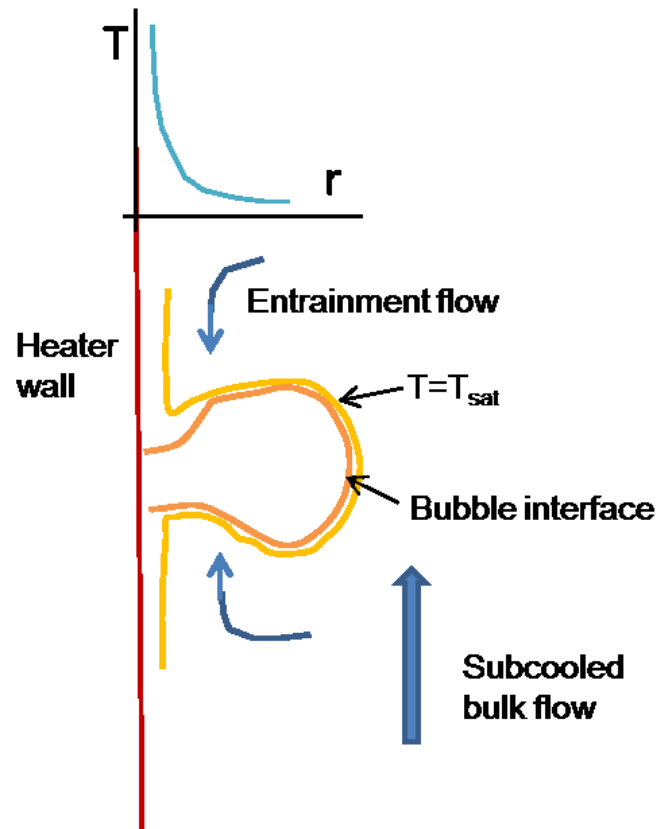


Fig. 3.4 Schematic of bubble deformation mechanism in high subcoolings

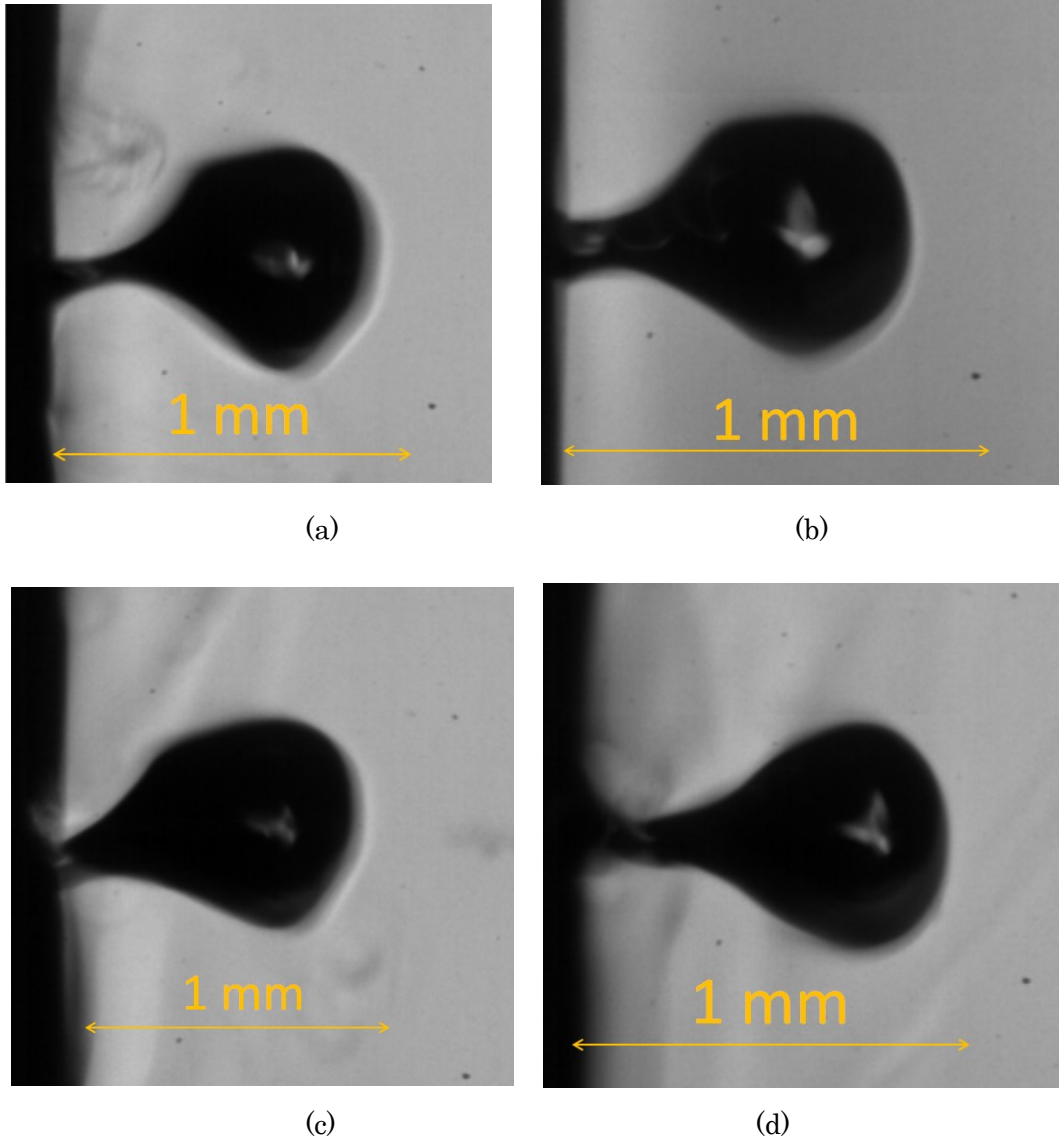


Fig. 3.5 Bubble images when lifting off at different experimental conditions

- (a) $\Delta T_{\text{sub}}: 40\text{K}$, $v_m: 0.14\text{m/s}$, $q: 185\text{kW/m}^2$
- (b) $\Delta T_{\text{sub}}: 40\text{K}$, $v_m: 0.28\text{m/s}$, $q: 270\text{kW/m}^2$
- (c) $\Delta T_{\text{sub}}: 30\text{K}$, $v_m: 0.14\text{m/s}$, $q: 155\text{kW/m}^2$
- (d) $\Delta T_{\text{sub}}: 50\text{K}$, $v_m: 0.21\text{m/s}$, $q: 309\text{kW/m}^2$

3.2.2.2 At high flow rates

The bubble behavior in subcooled flow boiling at a relatively high subcooling degree ($\Delta T_{\text{sub}} = 39.1\text{ K}$) and a high liquid flow rate was given in Fig. 3.6. The mean liquid velocity in the annular channel v_m was 0.35 m/s , the heat flux applied to the

heater surface was 290 kW/m^2 .

Compared with the bubbles in low flow rates of similar subcooling degrees, the shearing effect of bulk liquid flow was significant when the flow rate was high. Like boiling bubbles under other experimental conditions, the bubble grew very quickly to its maximum size in a very short time after it nucleated on the heating wall, as shown in Fig. 3.6 (a) ~ (c), the influence of the liquid flow was negligible during this period. A small concave deformation in the middle of the bubble upstream side surface was observed, as pointed out by the red arrow in Fig. 3.6 (d). Then the concave deformation developed larger and larger, as shown in Fig. 3.6 (e) ~ (h), finally a dimple shaped interface was formed in the upstream side of the bubble, this is quite different with the smooth downstream side surface of the bubble. During this process, the bubble was pushed strongly by the incoming bulk liquid flow from the upstream side, changing from a shape of approximate sphere to a long and thin shape at the time when the bubble was lifting off from the heating wall as shown in Fig. 3.6 (i), the bubble volume was also reduced a lot during this deforming period. After departing from the heating wall, the bubble condensed rapidly in the highly subcooled bulk flow, after condensation, two non-condensed air spots were observed as shown in Fig. 3.6 (l).

The concave deforming phenomenon of the bubble in the middle of the upstream side surface was found to be the typical behavior of bubbles in subcooled flow boiling of high subcooling degrees and high flow rates, and this was attributed to the condensation caused by the highly subcooled liquid flow hitting the bubble upstream side surface directly. Since in the high subcooling case, the temperature of liquid bulk flow was very low, and the liquid flow rate was also very high, so the thermal boundary layer was very thin compared with the relatively low subcooling and low flow rate cases, so when the bubble size was getting larger, it can get out of the superheated boundary layer very easily and the low temperature liquid can directly hit the upstream side surface of the bubble and caused the occurrence of the condensation there, and because of the condensation in the middle of the bubble upstream side interface, the bubble can even be intersected into two or more parts, so after condensation, two or more

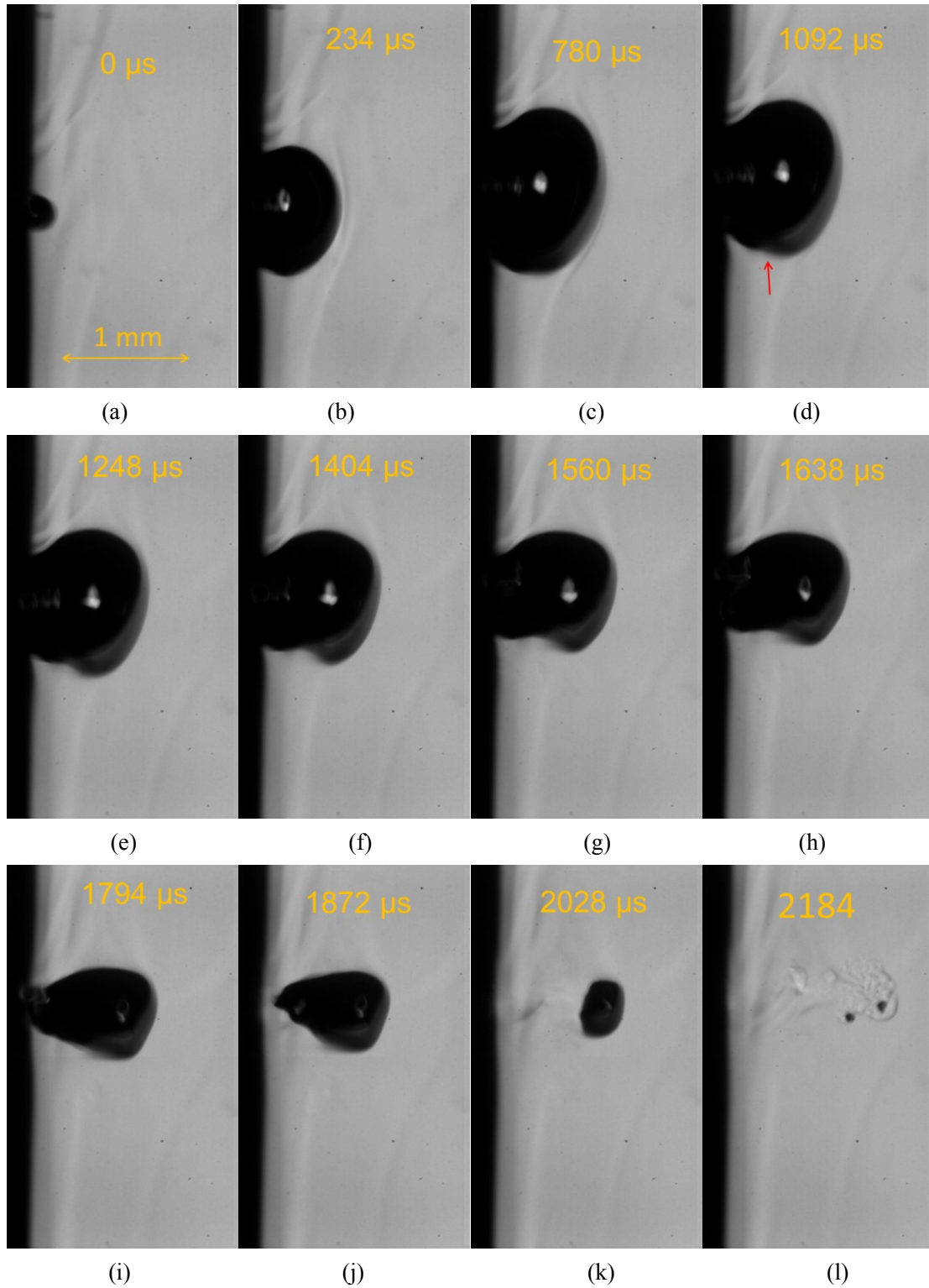


Fig. 3.6 Sequential images of bubble behavior,
 ΔT_{sub} : 39.1 K, v_m : 0.35 m/s, q : 290 kW/m²

non-condensed air spots can be observed.

The flow effect on the bubble behavior at high subcooling and high flow rate was different with that of medium subcooling and high subcooling degrees. At medium subcooling degrees and high flow rate, the bubbles move or slide towards the downstream side under the shearing effect of the high flowrate bulk flow, bubbles were observed to be elongated in the flow direction. However, at high subcooling degree and high flowrate, the bubble was hit by the subcooled bulk flow and condensed in the middle of the upstream side surface, because at high subcooling cases, the bubble has a strong tendency of elongation in the vertical direction, as discussed in previous section, so the bubble was easy to be condensed in the middle of the upstream side surface.

3.2.3 Bubble behaviors at low subcooling degrees

The bubble behaviors in subcooled flow boiling of low subcooling degrees were also investigated by the visualization experiments. The sequential images of bubble dynamic behavior during its whole lifetime at low flow rate ($v_m = 0.14$ m/s) and high flow rate ($v_m = 0.44$ m/s) were given in Fig. 3.7 and Fig. 3.8, respectively, the temporal variation of equivalent diameter of the bubbles shown in Fig. 3.7 and Fig. 3.8 were given in Fig. 3.9.

The bubbles of the low subcooling degrees in both low and high flow rates exhibited a rapid growth period after nucleation, the bubble size increase a lot in a short time, as shown in Fig. 3.7 and Fig. 3.8 or by the quantitative data of bubble equivalent diameter given in Fig. 3.9. The equivalent diameter of bubbles in low and high flow rates coincided with each other from bubble nucleation until 1.0 ms, as shown in Fig. 3.9, which means the flow rates have almost no influence on the bubble growth during this preliminary stage of the bubble lifetime, this is because the bubbles were very small and existed in the superheated boundary layer, so the effect of the flow shearing can be neglected. The effect of flow shearing on bubble growth became quite significantly during the later period of the bubble lifetime. As can be clearly seen in Fig. 3.9, the growth duration of the bubble at low flow rates was longer than that of the bubble at

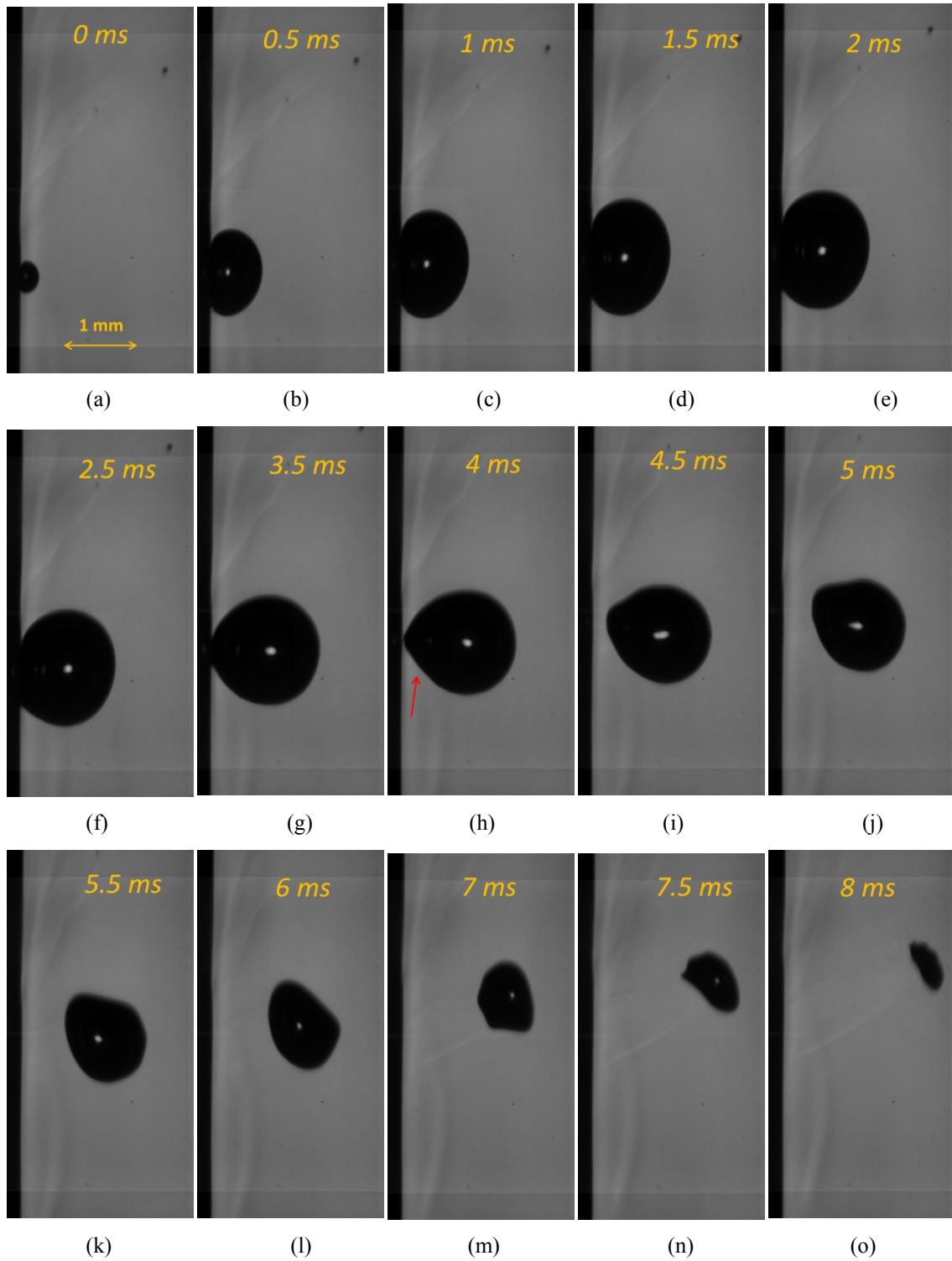


Fig. 3.7 Sequential images of bubble behavior,
 $\Delta T_{\text{sub}}: 5 \text{ K}$, $v_m: 0.14 \text{ m/s}$, $q: 54 \text{ kW/m}^2$

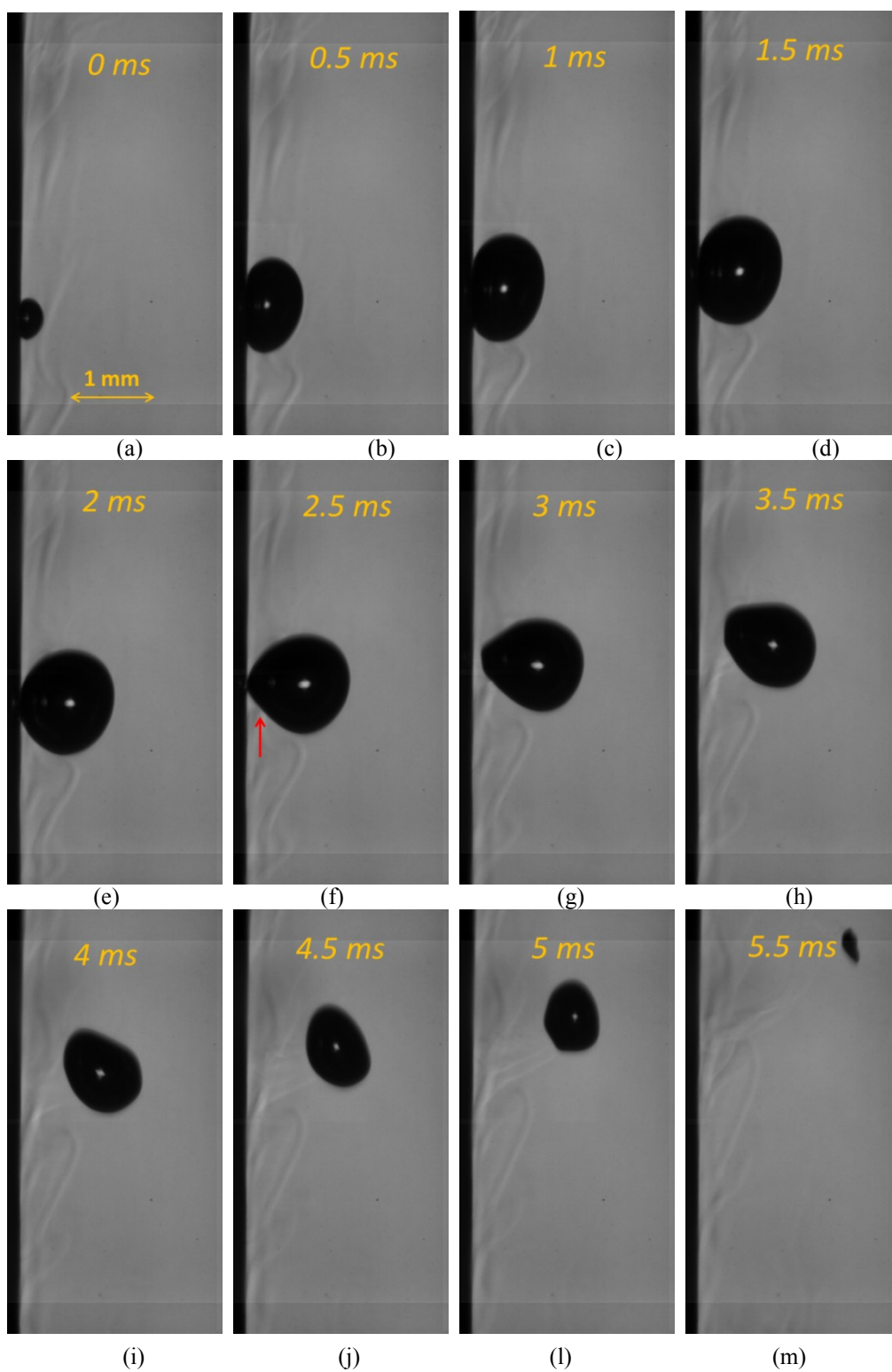


Fig. 3.8 Sequential images of bubble behavior,
 $\Delta T_{\text{sub}}: 5 \text{ K}$, $v_m: 0.44 \text{ m/s}$, $q: 110 \text{ kW/m}^2$

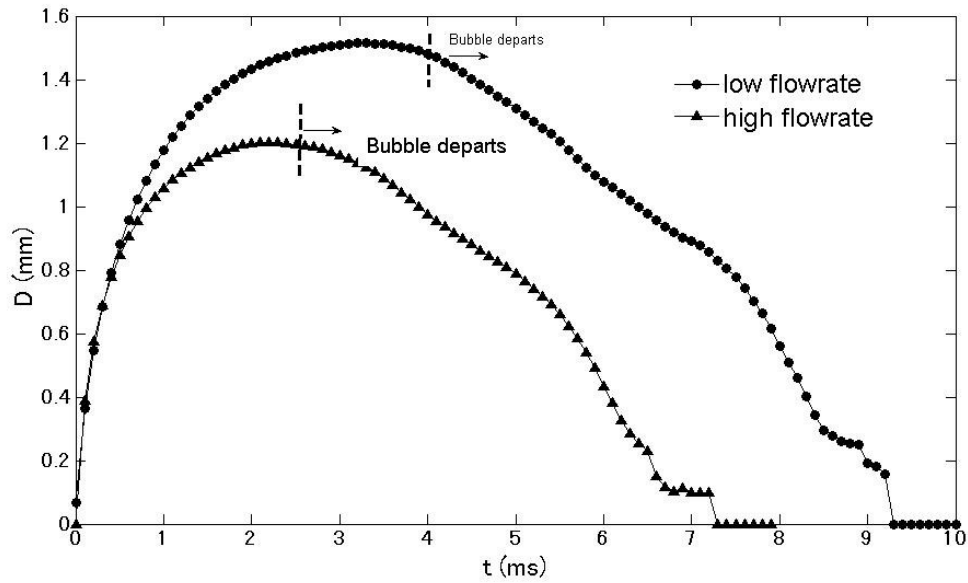


Fig. 3.9 Equivalent diameter variation of bubbles show in Fig. 3.7 and Fig. 3.8

high flow rate, leading to that the maximum size of the bubble at the low flow rate was larger. The condensation duration and the total lifetime of the bubbles at low flow rates were also longer than those of bubbles at high flow rates.

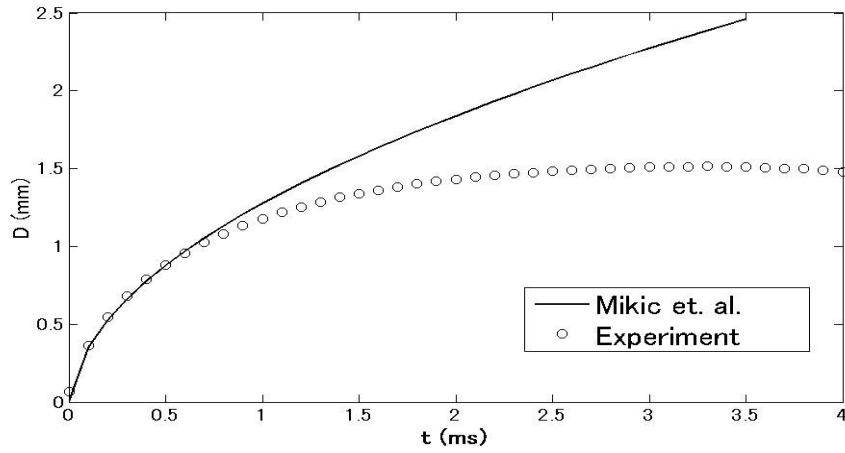
From comparing the bubble behaviors shown in Fig. 3.7 and Fig. 3.8, it is seen that at low degrees of subcooling, the bubble shape and behaviors at different flow rates were quite similar. The bubble shape was very close to spherical shape, no very severe deformation was observed as that for the bubbles in medium and high subcooling cases, only very weak deformation at the upstream side bottom of the bubble was found when it was lifting off from the wall, as marked by red arrows in Fig. 3.7 (h) and Fig. 3.8 (f), this weak deformation was also caused by the condensation as analyzed for bubbles of medium subcooling degrees, the difference is that it is very weak in low subcooling case. At low subcooling degrees, the temperature gradient in the direction normal to the heating wall was much smaller than that of the high subcooling cases, and the subcooling degree of the bulk liquid was not very high, almost no cold liquid can reach the bubble upstream side bottom region, so the deformation of the bubble was much weaker than bubbles in relatively high subcooling cases.

Almost at the time when the bubbles reached the maximum size, the bubbles

departed away from the heating wall and then the condensation process started, this can be verified by the images shown in Fig. 3.7 and Fig. 3.8 or quantitatively by variation of equivalent diameters in Fig. 3.9. For bubbles in low subcooling degrees, the maximum size time and bubble lift off time were very close, so some studies on bubble dynamics treat the bubble maximum diameter and the bubble departure diameter as the same as long as the degree of subcooling was low enough. Compared with bubbles in medium and high subcoolings, the bubbles in low subcooling cases have longer growth time until the lifting off time, thence the bubbles in low subcooling cases can reach much larger size than the bubbles in high subcooling degrees, and the condensation time and total lifetime was also much longer. Since the subcooling degree was low, the condensation process took quite a long time, in Fig. 3.7 and 3.8 the bubbles rotate after lifting off from the heating wall and enter the subcooled bulk flow region quickly without floating a long distance, in this case, the bubble are often extinct much quicker by condensation. However, in some cases, especially when the bubble size is large, the rotation can be very slow and the bubble floats to downstream for quite a long distance before extinct in the bulk liquid.

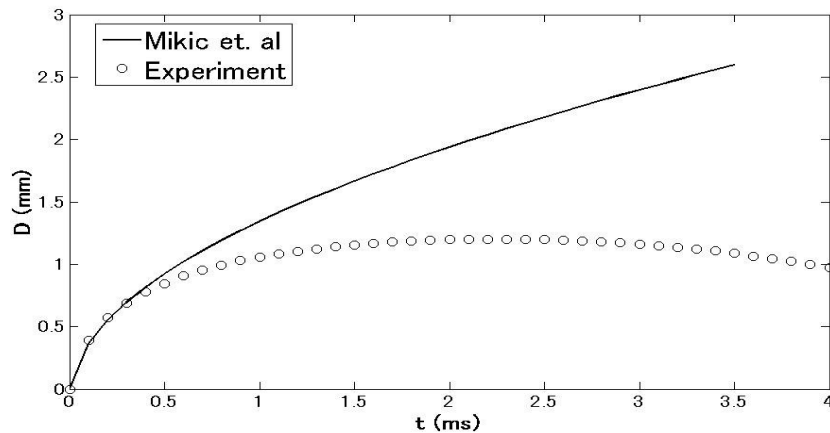
The bubble growth was also compared with the semi-empirical model which was developed from saturated pool boiling by Mikic et. al. as shown in Fig. 3.10. As can be seen, the growth of the bubble obtained from the experiments at subcooling degree of 5 K agrees quite well with the curve predicted by the Mikic model only at the beginning period of the growth regime, this period is very short, about 0.6 ms for bubbles at low flow rate as in Fig. 3.10 (a) and about 0.4 ms for bubbles at a higher flow rate as in Fig. 3.10 (b). The growth of bubbles in subcooled flow boiling at the early stage is very similar with bubbles in pool boiling cases, this means the subcooled flow has no effect on the bubble growth, because the bubble was quite small and submerged in the superheated layer near the wall during this period. Comparing (a) and (b) of Fig. 3.10, it can be found the growth rate of bubble at high flow rate became slower at earlier time than that of bubble at a lower flow rate, even though the subcooling degree was the same, this means flow rate has obvious effect on bubble growth, the thickness of the

superheat layer might be decreased by the high flow rate. After this short period, the bubble growth rate was much lower than that predicted by Mikic model, the bubble growth was suppressed by the subcooled bulk flow as the bubble was growing larger and its size might exceed the thickness of the superheat layer. This proves that the modes developed from saturated pool boiling cannot be used for prediction of the bubble growth in subcooled flow boiling except for the short period at the beginning of bubble growth regime, even though the subcooling degree was lower, if the subcooling degree was increased higher, the bubble growth rate would be decreased more severe and at an earlier time.



(a)

Experimental conditions, ΔT_{sub} : 5 K, v_m : 0.14 m/s, q : 54 kW/m²



(b) Experimental conditions, ΔT_{sub} : 5 K, v_m : 0.44 m/s, q : 110 kW/m²

Fig. 3.10 Comparison of bubble growth with Mikic model

3.2.4 Quantitative analysis of the bubble behaviors

For analyzing the bubble behaviors quantitatively, an image processing program was developed by using the MATLAB Simulink toolbox computer vision system to extract the quantitative data from the images obtained by the high speed image system.

3.2.4.1 The effect of subcooling degree

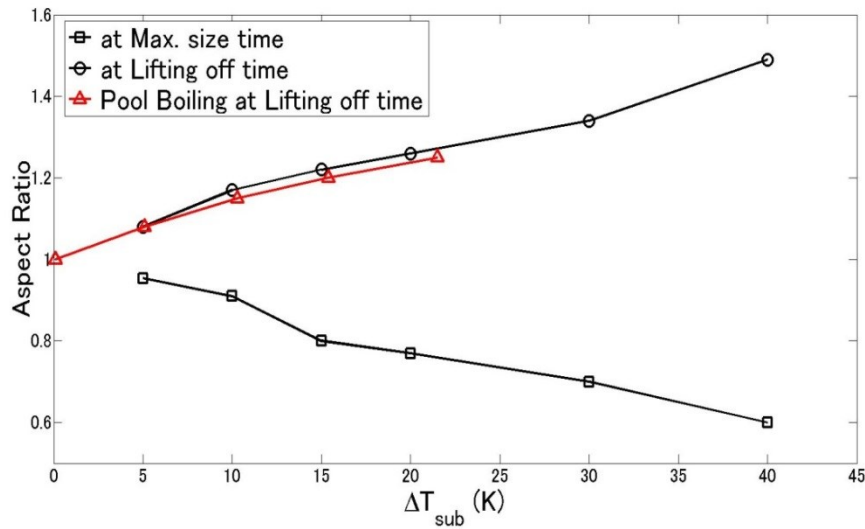


Fig. 3.11 variation of bubble aspect ratio as subcooling degree

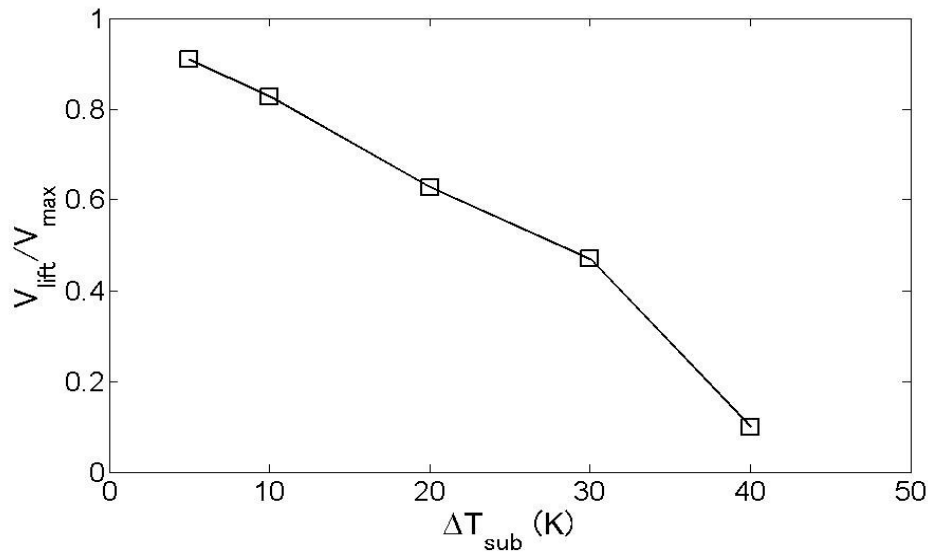


Fig. 3.12 variation of volume reduction ratio as subcooling degree

As shown in the previous section, the subcooling degree has an important influence on the bubble shape and behavior. As discussed above, at low subcooling degrees, the bubbles were close to spherical shape, while at high subcooling degrees, the bubbles were elongated and deformed severely. The aspect ratio was chosen as an index to indicate the extent of bubble deformation, and it was defined as the ratio of bubble height to its width, namely the ratio of lengths in vertical direction to the heating wall and the direction along the heating wall. Two values of the aspect ratio of a bubble were obtained at the bubble maximum size time and the time when the bubble was lifting off from the heating wall. These two kinds of aspect ratio were shown in Fig. 3.11 at different subcooling degrees. The values of bubble aspect ratio at each subcooling degree were obtained by averaging over at least 30 bubbles of the same experimental conditions. The experimental conditions of these bubbles at different subcoolings were shown in Tab 3.1 in detail, the flow rate was chosen to be the same ($v_m = 0.14$ m/s) for eliminating the effect of flow rate and only studying the effect of the subcooling degree, however, the heat flux applied on the heater surface was adjust in a narrow range to provide the energy needed for generating the bubbles, since at different subcooling degrees, heat flux needed to generate the bubbles are very different, so the heat flux cannot be the same, as can be seen in Tab. 3.1.

As illustrated in Fig 3.11, the aspect ratio at the bubble lifting off time increases with increasing the subcooling degree, however, the aspect ratio at bubble maximum size time showed an opposite tendency, it decreases with the increase of the subcooling degree. The reason is that, at maximum size time the bubble exists in the superheated layer near the heating wall, the higher the subcooling degree, the thinner the superheated layer, so at high subcooling degrees, the bubble is much easier to grow in the direction along the heating wall and the growth in the vertical direction was strongly suppressed by the thin thermal boundary layer, so when the bubble reaches its maximum size, it forms an oblate shape with a low aspect ratio. When the subcooling degree is getting higher, the superheated layer is getting thinner and the bubble is more flattened, so the aspect ratio is also getting lower.

When the bubble reaches its maximum size, most of the bubbles in subcooled flow boiling deformed and even elongated in the vertical direction during the bubble growth and departure period as discussed in previous section. At higher subcooling degrees, the temperature gradient in the vertical direction to the heating wall is much larger, so the bubble elongation and deformation is also much severer than in low subcooling cases, consequently, the aspect ratio at lifting off time is higher. At low subcooling degrees, the superheat layer was thicker, and the temperature gradient in the flow region near bubble nucleation was not so steep, so the bubble was almost spherical shape without obvious deformation as shown in the images of Fig. 3.7 and 3.8, so the aspect ratio at lifting off time and maximum size time at low subcooling degrees was close to 1 as shown in Fig. 3.11. The variation of aspect ratio shown in Fig. 3.11 agrees with the previous qualitative analysis of bubble behaviors under various subcooling degrees.

In Fig. 3.11, the aspect ratio at lifting off time of pool boiling bubbles were also plotted, as can be seen, there is no obvious difference between the aspect ratio of pool boiling bubbles and that of flow boiling bubbles, meaning that the flowrate less impact on aspect ratio than subcooling degree.

ΔT_{sub} (K)	V_m (m/s)	Q (kW/m ²)	Position (mm)	No. of Bubbles
5	0.14	44.5 - 46.8	54	35
10	0.14	54.0 - 72.2	46	50
20	0.14	81.8 - 142.0	30	99
30	0.14	128.6 - 156.2	39	33
40	0.14	218.1	28	41

Tab. 3.1 Experimental conditions of bubbles for quantitative analysis

The condensation process starts earlier than the bubble lifting off time, especially at higher subcooling degree cases, the bubble condensed even when it was attached to the heating wall, the condensation process is accompanied by the bubble

deformation and departure process. So the bubble volume at lifting off time is usually much smaller than the bubble maximum size, especially at higher subcooling degrees. The ratio of bubble volume at lifting off time and the maximum bubble volume was also calculated and illustrated as a function of subcooling degree in Fig. 3.12. The bubble volumes at maximum time and lifting off time were calculated by assuming the bubble an ellipsoid shape, since the equivalent diameter and aspect ratios of the bubble can be obtained by the image processing program. As can be seen, the ratio of bubble volumes decrease sharply as the increase of subcooling degree, at highest subcooling degree (40 K), the ratio was less than 0.2, this means the bubble condensed and shrunk a lot on the heating wall before departure. However, at lowest subcooling degree (5 K) in Fig. 3.3, the ratio was close to 1, which means the bubble lifting off volume was almost the same as the bubble maximum volume. As mentioned in previous section, some researches on bubble behaviors of saturated flow boiling or subcooled flow boiling of very low subcooling degrees treated the bubble lifting off size the same as the bubble maximum size.

3.2.4.2 The effect of bulk liquid flow rate

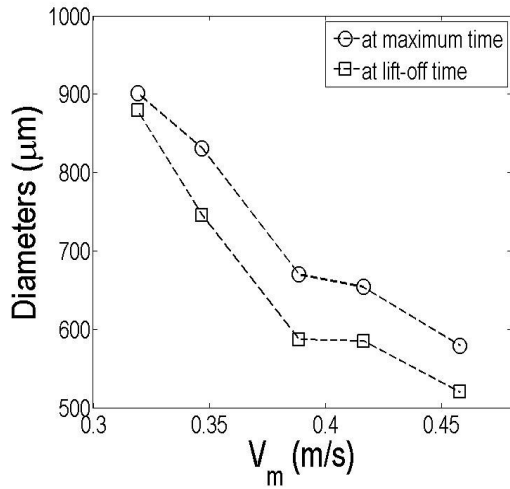
The effect of flow rate of the bulk liquid flow on the bubble parameters were investigated by extracting the quantitative data from the images through using the image process program. The variation of the basic bubble parameters, namely the bubble lifting off diameter, maximum diameter, bubble growth and condensation time, aspect ratio at lifting off time, with the bulk liquid flow rate at the subcooling degree of 15.9 K were illustrated in Fig. 3.13, The results were obtained on the analysis of at least 20 bubbles for each experimental condition, the heat flux applied on the heater surface was 235 kW/m^2 , the mean velocity of bulk liquid flow in the channel of test section is from $0.32 \sim 0.46 \text{ m/s}$.

As can be seen, the bubble diameter, including lifting off diameter and maximum diameter exhibit a decrease tendency as the flow rate of the bulk liquid flow increase. This agrees with the conclusion of some previous research work, e.g.

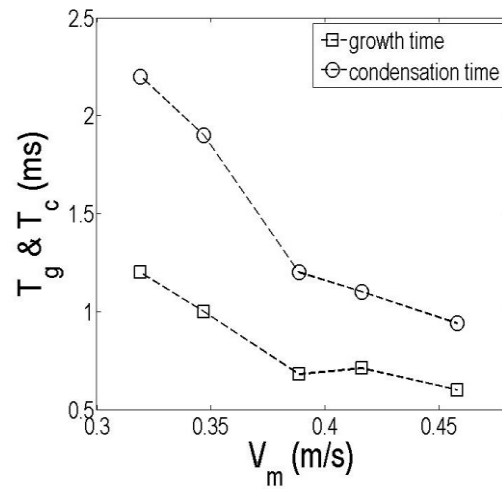
Thornicroft et al [3.3], Prodanovic et al. [3.4]. The effect of the bulk liquid flow rate is similar as the subcooling degree, the increase of the flow rate leads to the decrease of the superheated layer thickness, so the bubble size was getting smaller as increasing the flow rate. At the same experimental conditions, the bubble lifting off diameter is smaller than the correspondent maximum diameter, this means the condensation process already started when the bubble is still on the heating wall, as discussed in previous section.

The growth time and condensation time showed the same general tendency as the bubble diameters, as can be seen in Fig. 3.13 (b). When the bubble size was getting smaller at high flow rates, the growth time and condensation time of the bubble also reduced, However, the growth time of bubble at high flow rate regions (mean velocity v_m from 0.38 - 0.46 m/s) the growth time was almost the same, or even longer at about v_m 0.42 m/s, this may be caused by the slowdown of the bubble growth rate because the increase of the subcooled liquid flow rate might decrease the superheat degree in the boundary layer.

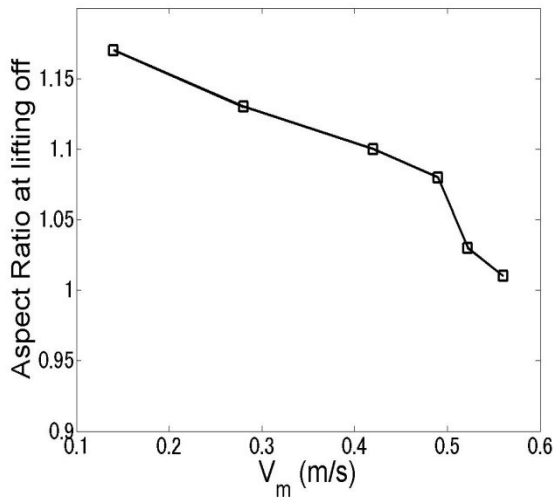
The aspect ratio of bubble at the lifting off time was given in Fig. 3.13 (c), as can be seen, it decrease as the bulk liquid velocity increase, the reason is because the shearing effect of the flow is enhanced at high flowrate, the superheated layer near the heating wall was also getting thinner, so the tendency of bubble elongation in the vertical direction was depressed at higher bulk liquid flowrate.



(a)



(b)



(c)

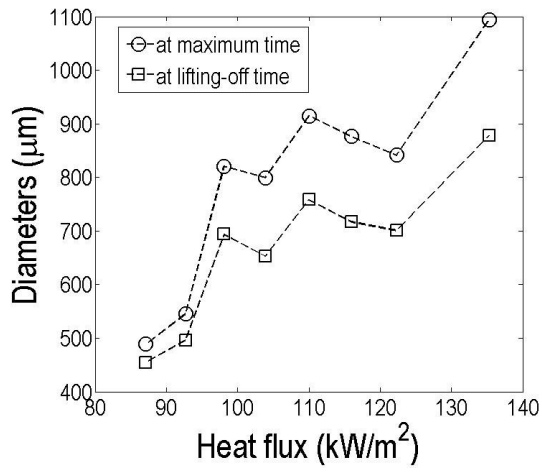
Fig. 3.13 Effect of flow rate on bubble parameters, $\Delta T_{\text{sub}} = 15.9 \text{ K}$, $q = 235 \text{ kW/m}^2$
 (a) Variation of bubble diameters, (b) Variation of growth time and condensation time
 (c) Aspect ratio at lifting off time

3.2.4.3 The effect of heat flux

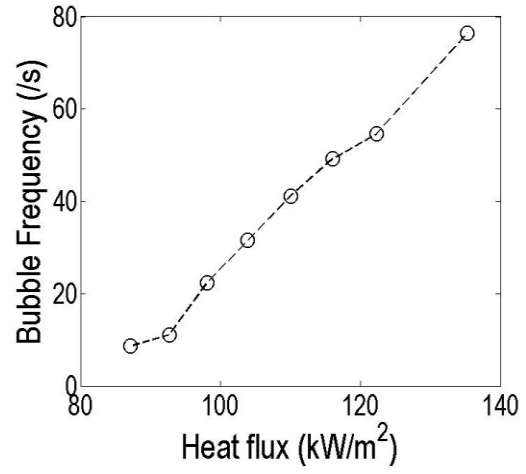
The effect of heat flux applied on the heater surface on the bubble parameters was also investigated, as shown in Fig. 3.14 and Fig. 3.15, the bubble diameters (maximum diameter and lifting off diameter), bubble frequency, growth time and condensation time were illustrated, the subcooling degree was around 20 K, and mean velocity were 0.14 m/s and 0.43 m/s, respectively. Every value of the bubble parameter

was obtained by averaging over at least 20 bubbles at the same experimental conditions.

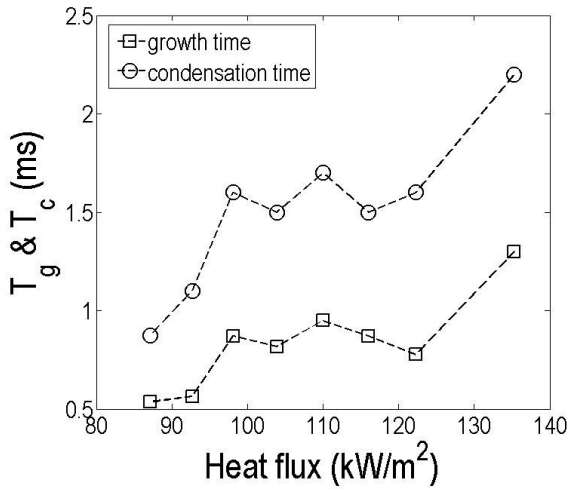
The bubble diameters increased with the increase of heat flux, as shown in Fig. 3.14 (a) and Fig. 3.15 (a). Although the curves given in Fig 3.14 (a) showed some decrease in some local area, the general increase tendency can be verified, for high flow rate case ($v_m = 0.43$ m/s), it was obvious in Fig. 3.15 (a) that the bubble diameters increase monotonously as the increase of the heat flux. The maximum diameter and the lifting off diameter exhibit the similar tendency of variation as the heat flux, although the lifting off diameter at each condition was relatively smaller than the maximum bubble diameter. The bubble frequency increase drastically when the heat flux was increased at both low and high flow rate as shown in Fig 3.14 (b) and Fig. 3.15 (b). This is because at high heat fluxes, the superheated thermal boundary layer needed for bubble nucleation can be reconstructed in a shorter time, in other words, the waiting time between two nucleating bubbles was decreased by the increase of the heat flux. The growth time and condensation time of the bubble also exhibit an increase tendency as the heat flux increases and the variations were quite similar as the bubble diameters, this is reasonable because the larger bubbles normally need longer time for growing and condensing.



(a)



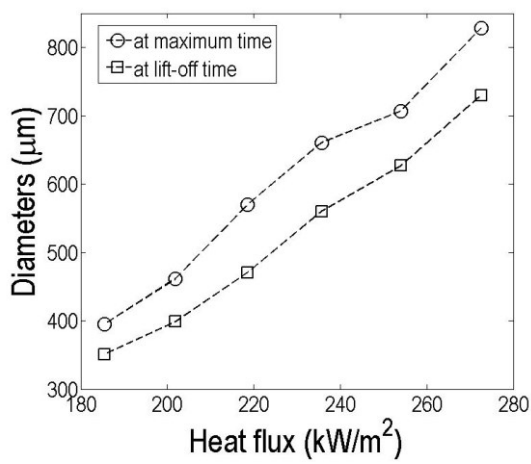
(b)



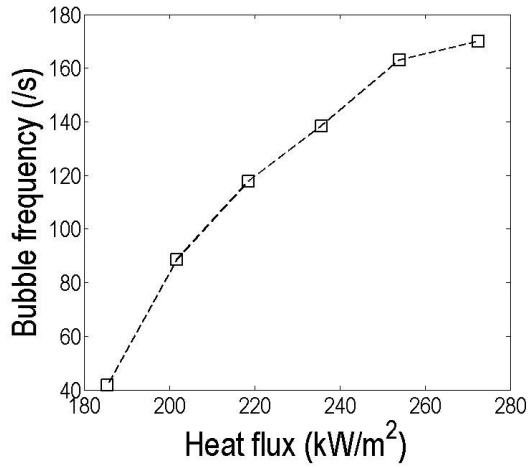
(c)

Fig. 3.14 Effect of heat flux on bubble parameters, $\Delta T_{\text{sub}} = 21.4 \text{ K}$, $v_m = 0.14 \text{ m/s}$

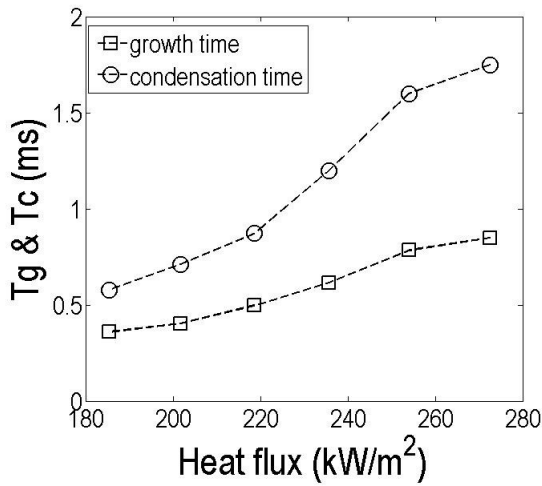
(a) Diameters, (b) Bubble frequency (c) Growth time & condensation time



(a)



(b)



(c)

Fig. 3.15 Effect of heat flux on bubble parameters, $\Delta T_{\text{sub}} = 19.9 \text{ K}$, $v_m = 0.43 \text{ m/s}$

(b) Diameters, (b) Bubble frequency (c) Growth time & condensation time

3.2.5 Summary

In this Section, the bubble behaviors in subcooled flow boiling of three different subcooling degrees and flow rates were investigated. Bubble behavior characteristics at different subcooling degrees were very different, and the effect of the flow rates was also important. At medium subcooling degrees and low flow rates, the deformation at the upstream side bottom of the bubble was observed and attributed to the condensation

caused by cold liquid from the subcooled bulk flow. The bubble behavior at medium subcooling degrees but high flow rates was a combination of the upstream side interface deformation caused by the condensation and the bubble movements of sliding and rolling on the heating wall caused by the flow shearing effect. At high subcooling degrees and low flow rates, the bubbles exhibit contracting and elongation deformation at the bottom during the bubble growth and departure period, because of the very thin superheated boundary layer and the entrainment of the highly subcooled liquid caused by bubble's rapid movement. The bottom of bubble can become very long and thin at the moment of departing from the wall. A successive bubble can grow from the remaining part of the first bubble. At high flow rates, the effect of flow is also significant, a concave deformation at the middle of the bubble's upstream side surface was found when the bubble size was getting large, which attributes to the condensation caused by the highly subcooled bulk flow. The bubble behavior at low subcooling degrees was quite regular, there is no severe deformation like that in bubbles of high and medium subcooling cases. For low subcooling cases only the bubble size was affected by the flowrates, bubble behaviors were quite similar at different flowrates. Bubbles were very close to spherical shape during most of the lifetime and most of bubbles departed the heating wall at the maximum-size time.

The quantitative data of the bubble were also extracted, the effect of the subcooling degree, flow rate, and heat flux on bubble behaviors was investigated. The subcooling degree has an important effect on the bubble shape, this was verified by the aspect ratio and the bubble equivalent diameters, accordance between the quantitative variables and the qualitative analysis was obtained. The flow rate also influences the bubble behaviors, when the flow rate is increased, the bubble size and the growth and condensation period is getting smaller. The heat flux has a positive effect on the bubble size, frequency, the growth and condensation period were also getting longer since the bubble size increase as the heat flux increases.

3.3 Bubble deformation caused by Marangoni effect

In this Section, the typical behavior of bubbles in subcooled flow boiling at a medium subcooling degree, namely the deformation on the upstream side of the bubble, were discussed. The bubble deformation results from the condensation occurred there caused by the thermal-capillary flow of Marangoni effect along the bubble surface from the bubble bottom to the top. Numerical simulation of bubble growth and departure in subcooled flow boiling was also carried out to verify and provide evidence to the explanation of the bubble deformation mechanism, since no sufficient evidence can be obtained directly from the current experimental results.

3.3.1 Deformation phenomenon and mechanism

The temporal serial images of bubble behavior in subcooled flow boiling at an medium subcooling degree (around 20 K) were shown in Fig. 3.16 during its whole lifetime, including nucleation, growing up, departure and finally extinction due to condensation in the subcooled bulk flow. The images were extracted from the video clip recorded by the high speed video image system. The bubble nucleating position was about 30 mm downstream from the beginning of the heating section of the heater rod. The average heat flux q applied to the heater surface was 110 kW/m^2 , and the degree of subcooling ΔT_{sub} was about 21.2 K based on the temperature of the bulk liquid at the inlet of the test section. Mass flow flux was $142 \text{ kg/m}^2\text{s}$, which corresponded to the mean velocity v_m in the annular channel of 0.14 m/s. The elapse time from the appearance of the bubble embryo was marked in each image of Fig.3.16. Every image in was composed of 256×256 pixels, and the spatial resolution is 8.13 micron/pixel, so the size of the image in Fig. 3.16 is about $2.1 \text{ mm} \times 2.1 \text{ mm}$, the length scale is also given in Fig. 3 (a).

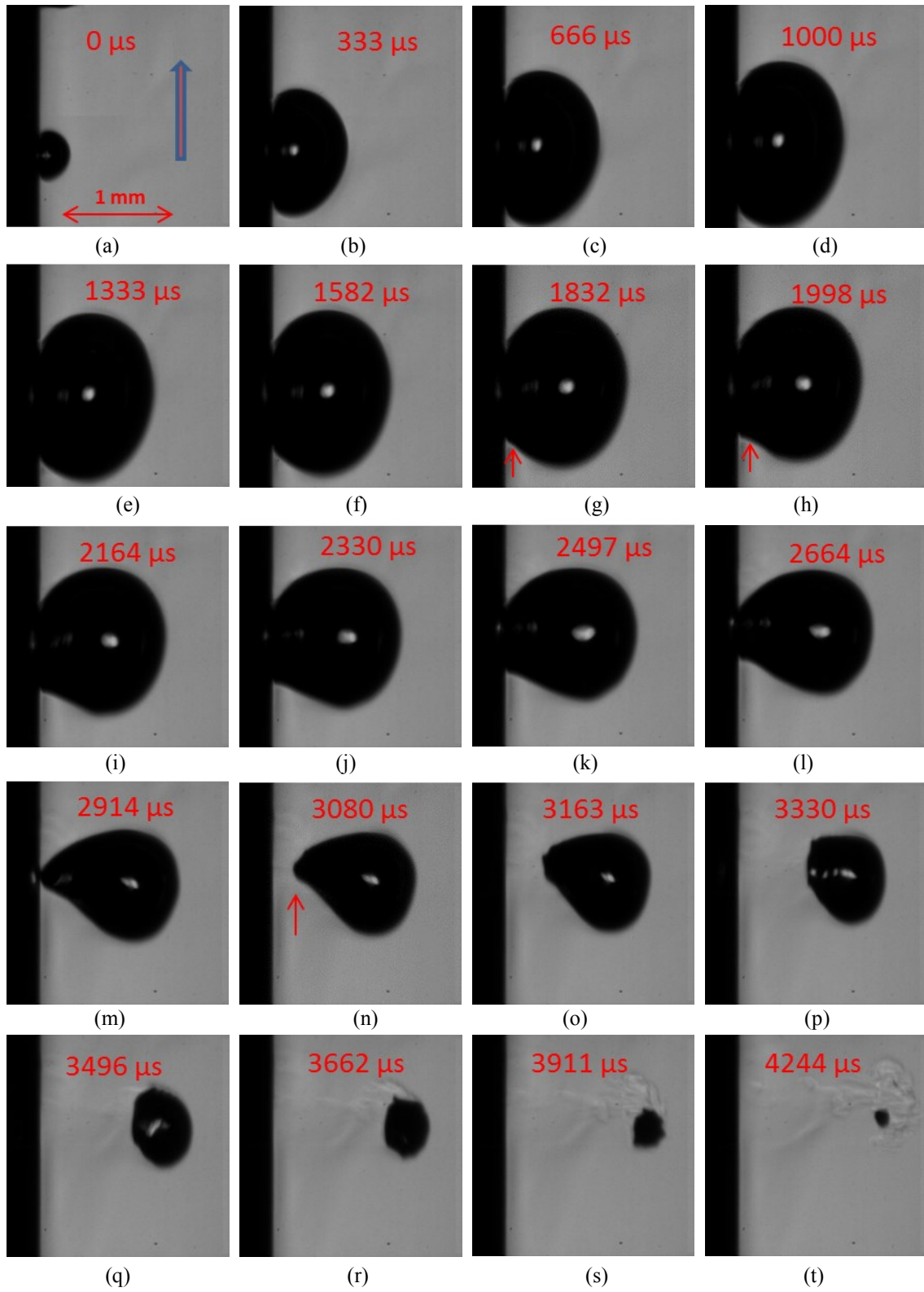
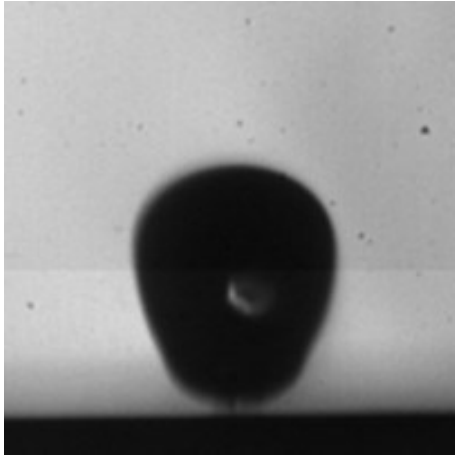
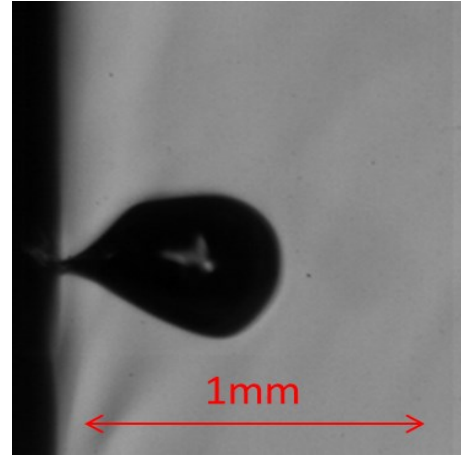


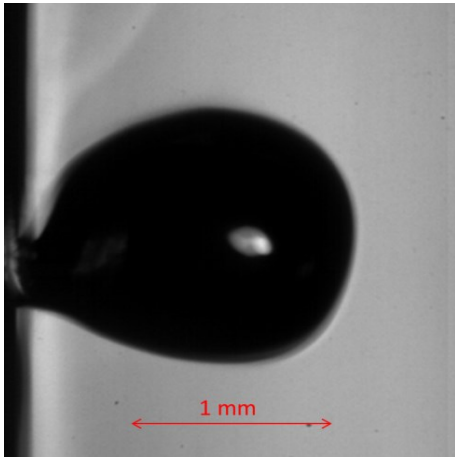
Fig. 3.16 Sequential images of bubble behavior,
 ΔT_{sub} : 21.2 K, v_m : 0.14 m/s, q : 110 kW/m²



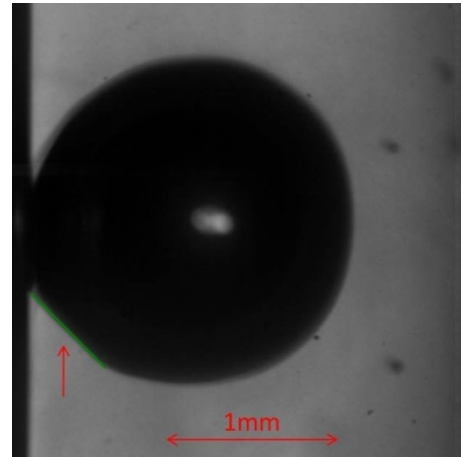
(a)



(b)



(c)



(d)

Fig. 3.17 bubble images when departing from heating wall

(a) Pool boiling, ΔT_{sub} : 15.4 K, q : 250 kW/m² (Kawara (2007))

(b) Flow boiling, ΔT_{sub} : 29.4 K, v_m : 0.15 m/s, q : 156 kW/m²

(c) Flow boiling, ΔT_{sub} : 15.9 K, v_m : 0.14 m/s, q : 128 kW/m²

(d) Flow boiling, ΔT_{sub} : 6.1 K, v_m : 0.21 m/s, q : 72.3 kW/m²

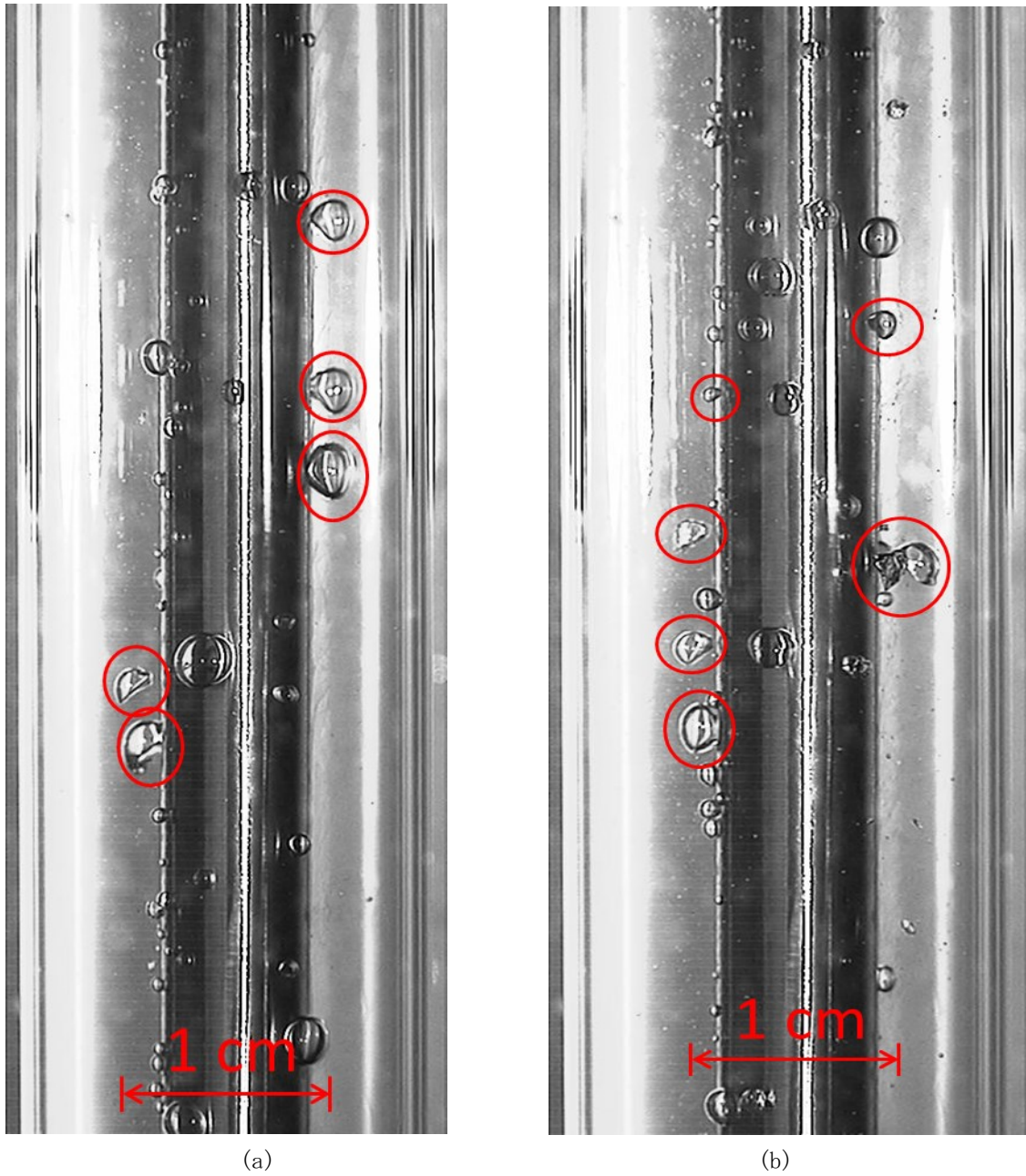


Fig. 3.18 bubble images when departing from heating wall

(a) ΔT_{sub} : 14.5 K, v_m : 0.28 m/s, q : 156 kW/m²

(b) ΔT_{sub} : 14.5 K, v_m : 0.28 m/s, q : 203 kW/m²

As shown in images from (a) to (e) of Fig. 3.16, the bubble grew rapidly after nucleating on the heating wall, the size of the bubble increased a lot in a short time (about 1300 μs). After this rapid growth period, the change of bubble size was not so

obvious until it departing the heating wall, which can be seen in Fig. 3.16 (e) ~ (m). However, during this bubble departure period, the shape of the bubble varied significantly. As marked by the red arrows in Fig. 3.16 (g) and (h), a concave deformation of the bubble interface was observed at the bottom of the upstream side of the bubble, and this deformation of bubble interface became larger and larger in the later images, finally when the bubble was about to lift off from the heating wall, as shown in Fig. 3.16 (m), the upstream side part of the bubble was very different compared with the downstream side. The bubble shape was like an eggplant, and it is very different from the shape of bubbles in a pool boiling case, which was like a pear shape when it was lifting off from the heating wall as shown in Fig. 3.17 (a) [3.5].

The deformation on the upstream side of the bubble during the period of growth and departure was not an occasional phenomenon, actually this phenomenon was observed in quite a lot of bubbles of subcooled flow boiling under a wide range of experimental conditions. The images of bubble deformation phenomenon at three different experimental conditions were also given in Fig. 3.17 (b), (c), and (d). As you can see, the upstream side deformation of the bubbles were confirmed at different subcooling degree: $\Delta T_{\text{sub}} = 29.4 \text{ K}$, 15.9 K and 6.1 K , respectively, even though the bubble size was very different at different degrees of subcooling. In addition, it was very clear that the deformation of bubble in high subcooling case, as shown in Fig. 3.17 (b), was much severer than that of bubble in a lower subcooling case, e.g. 6.1 K , as shown in Fig. 3.17 (d). The bubble deformation at $\Delta T_{\text{sub}} = 6.1 \text{ K}$ was very weak, only the bottom part of the bubble upstream sides was a little bit deformed, as marked by red arrow in the image. Images of bubbles of subcooled flow boiling obtained in a much larger observation scope by using a normal lens were also given in Fig. 3.18, the subcooling degree is 14.5 K , and the flow rate is 0.28 m/s , the heat fluxes are 156 kW/m^2 and 203 kW/m^2 , respectively. As marked by the red circles, many bubbles in the images exhibited an obvious deformation on the upstream side at the moment they departed from the heated wall.

The deformation on the upstream side of bubbles in subcooled flow boiling

when lifting off from the heating wall results from the condensation process occurred there induced by the thermo-capillary flow from the bubble bottom to the top driven by the Marangoni effect, which is the motion of liquid near the two phase interface due to the interfacial tension gradient caused by the temperature difference or composition concentration variation along the interface. According to the basic theory of the bubble nucleation, the interface temperature of the vapor and the surrounding liquid must be constant because of the saturation vapor there. However, if this is correct, there is no Marangoni flow, so this theory is correct only for the zero-thickness interface hypothesis, it is known that the real interface has a finite thickness, so the temperature in the interface is not constant. In this sense, the temperature along the bubble surface is influenced by the temperature of the liquid surrounding the bubble, which strongly relates to the existence of thermal boundary layer along the bubble. Therefore, it can be considered that the temperature difference in the thin interface along the bubble exists.

The convection of Marangoni effect is the motion of liquid near the two-phase interface due to interfacial tension gradient along the interface, which could be caused by the temperature difference or composition concentration variation along the interface. When the interface tension gradient is caused by the temperature gradient along the two phase interface, the convection of liquid was also called thermos-capillary flow. The liquid in regions of low interfacial tension is pulled towards the regions of high interfacial tension along the two phase interface. The Marangoni flow phenomena of the liquid surrounding a boiling bubble was found to be quite common, because the existence of temperature gradient in the thermal boundary layer. Some researchers also studied the effect of Marangoni flow on heat transfer performance in pool boiling case. McGrew [3.6] proposed that the Marangoni convection serves as a primary factor of heat transfer mechanism for the situation when the bubbles remain on the heating wall for a relatively long time. However, Kenning [3.7] suggested this was not an important

mechanism based on their theoretical estimates. Petrovic [3.8] conducted the experimental study on the Marangoni heat transfer in subcooled nucleate pool boiling, the presence of Marangoni convection was confirmed and it significantly influenced the heat transfer in subcooled pool boiling.

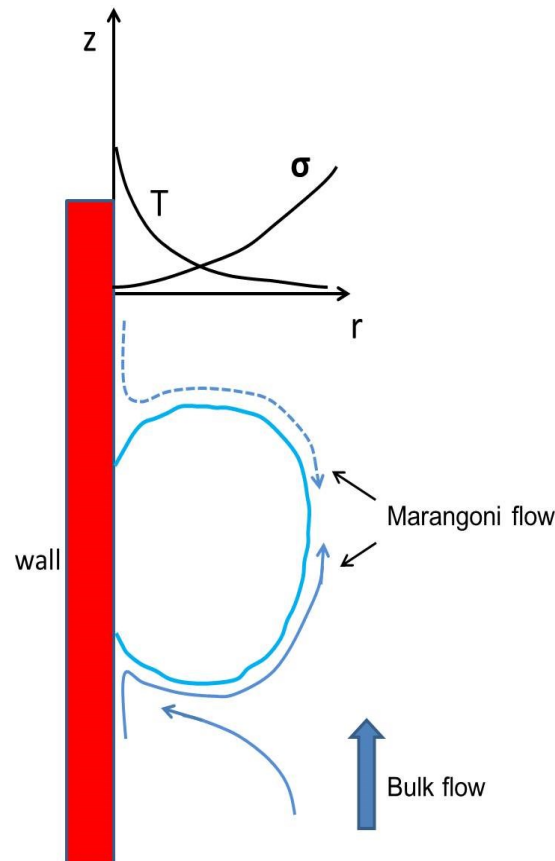


Fig. 3.19 Schematic of bubble deformation caused by Marangoni flow

The schematic of bubble deformation mechanism was given in Fig. 3.19. In subcooled flow boiling, the heating wall and the boundary layer region close to the heating wall are superheated, but the bulk flow region far away from the heating wall is subcooled, thus the temperature difference is quite large. The surface tension coefficient of pure water increases with decreasing the temperature, therefore, the temperature gradient in the vertical direction to the heating wall causes a surface tension gradient along the bubble interface, the liquid near the bubble interface was pulled from the

region of low surface tension (the bubble bottom region) to the region of high surface tension (the bubble top region) and this forms the thermo-capillary flow flowing from the bubble bottom to the top near the bubble interface as indicated by the arrows in the schematic of Fig. 3.19. According to the conservation of mass, since the liquid near the bubble bottom flows to the bubble top region by the Marangoni effect, some liquid of lower temperature from the bulk flow may be “sucked” to the bottom region of the bubble for compensation, and this low temperature liquid might lead to the condensation occurred at the bubble bottom. At first the condensation might be very weak, but since the specific volume of the vapor is much larger than the water, so the space of vapor after condensation needs to be filled by more liquid water, so more low temperature liquid was “sucked” from the bulk flow, since the supply of low temperature liquid is quite sufficient from the subcooled bulk flow, the condensation makes the surface of the bubble in the upstream side deforming from a convex shape to a concave one, as shown in Fig. 3.16 (g) ~ (m). As for the downstream side of the bubble, the flow caused by Marangoni effect may also exist, but because the subcooled bulk flow was flowing away from the bubble, so the low temperature liquid from the bulk liquid flow may be difficult to reach the bottom region directly in the downstream side, the nearby liquid in the superheated boundary layer might flow to the bubble bottom in the downstream side for compensation. Therefore, so there is almost no or less condensation occurring at this side of bubble. From Fig. 3.16 (g) ~ (m), it can be seen the deformation of bubble caused by the condensation was firstly initialed at the bottom of the bubble and then developed gradually to the whole upstream side of the bubble. This also proved that this deformation was caused by the Marangoni flow. Considering the fact that the deformation of bubbles in high subcooling degree case was much severer than that of bubbles in lower subcooling degree cases, as shown in Fig. 3.17 (b), (c), (d), this also proved indirectly the mechanism explained by Marangoni effect. The temperature gradient in high subcooling case along the bubble interface is larger, which results in larger surface tension gradient and stronger Marangoni flow, so the deformation of bubbles in high subcooling case was much severer.

3.3.2 Simulation of the bubble deformation

3.3.2.1 Configuration and conditions of numerical simulation

Since the thermos-capillary flow along the bubble interface caused by Marangoni effect as discussed above cannot be directly observed in the video images obtained in the present experimental system, there is no direct evidence to confirm the bubble deformation mechanism given in Section 3.3.1., so the numerical simulation of the behavior of bubble in subcooled flow boiling during growth and departure regimes was carried out for the purpose of providing the direct evidence to the explanation of bubble deformation mechanism.

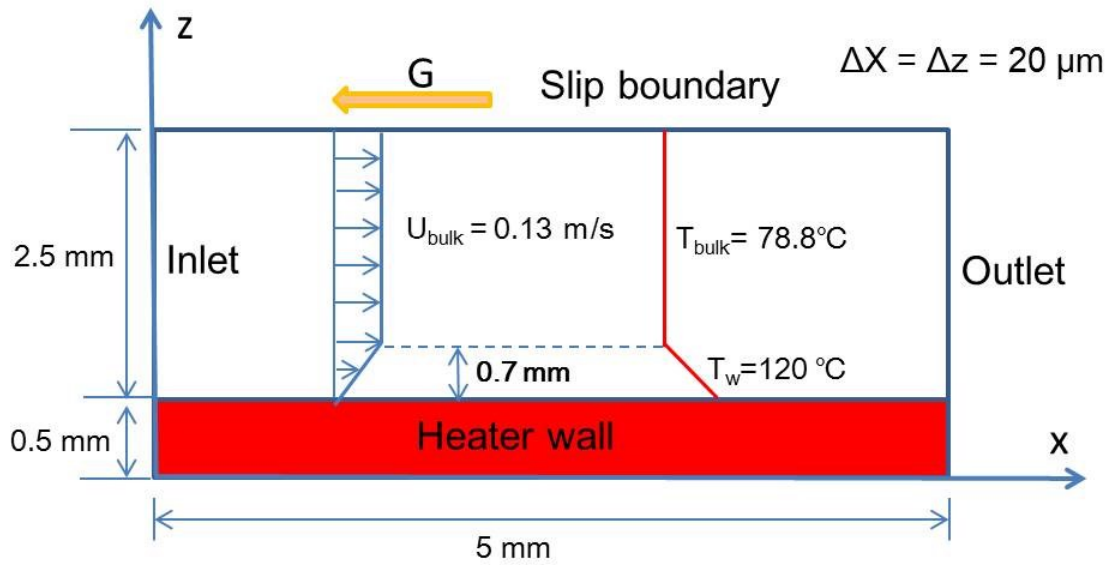


Fig. 3.20 Configuration schematic of computation

The configuration schematic of numerical computation model was given in Fig. 3.20. The computational geometry was a two dimensional rectangular area ($5 \text{ mm} \times 3 \text{ mm}$), only the local flow region near the bubble nucleation site was simulated because of the limitation of the capability of the super computers, the axis direction of the channel is put in x direction, and accordingly the gravity was applied in negative x

direction to form the upward flow configuration, which is in accordance with the present experimental system. The boundary conditions of the channel inlet and outlet were set to be constant velocity and constant pressure, respectively. The velocity and temperature fields in the bulk flow were set to be uniform, initial values were 0.13 m/s and 78.8 °C respectively, according to the experimental conditions. Since the length of computational geometry in the x direction (flow direction) was not long enough to form the boundary layer by the numerical computation itself, so the hydraulic and thermal boundary layer was given by setting the initial values of velocity and temperature in the boundary layer, the thickness of boundary layer was set to be 0.7 mm based on the consideration with the actual Re of liquid flow and the hydraulic diameter of the channel in the present experimental system, and the profiles of velocity and temperature in the boundary layer were assumed to be a linear distribution. The red region in Fig.3.20 was set to be solid region simulating the heater rod, the initial temperature on the heating surface was set to be 120 °C, the heat flux applied on the heater was set to be 110 kW/m². The uniform grids were used in the simulation, and grid size was finally chosen to be 20 microns by giving consideration to both the accuracy and efficiency of the simulation, thus a total of 37500 grids were used in the simulation computation.

In order to verify the effect of the Marangoni flow on the bubble behavior in subcooled flow boiling, the running of simulations was conducted in pairs. A pair of simulations was carried out under the same geometry configuration and initial and boundary conditions except for the surface tension coefficients, in one simulation case, the surface tension coefficient of water was set to be constant, so no surface tension gradient occurs and consequently no Marangoni effect arise. In the other case, the surface tension coefficient is set to be temperature dependent, so the interface tension can be generated by the temperature difference and Marangoni convection of liquid can be simulated in the computation. The numerical models and method of this simulation work was developed by Kunugi and Ose [3.9, 3.10], which is already introduce in detail in Chapter 2.

3.3.2.2 Results of numerical simulation

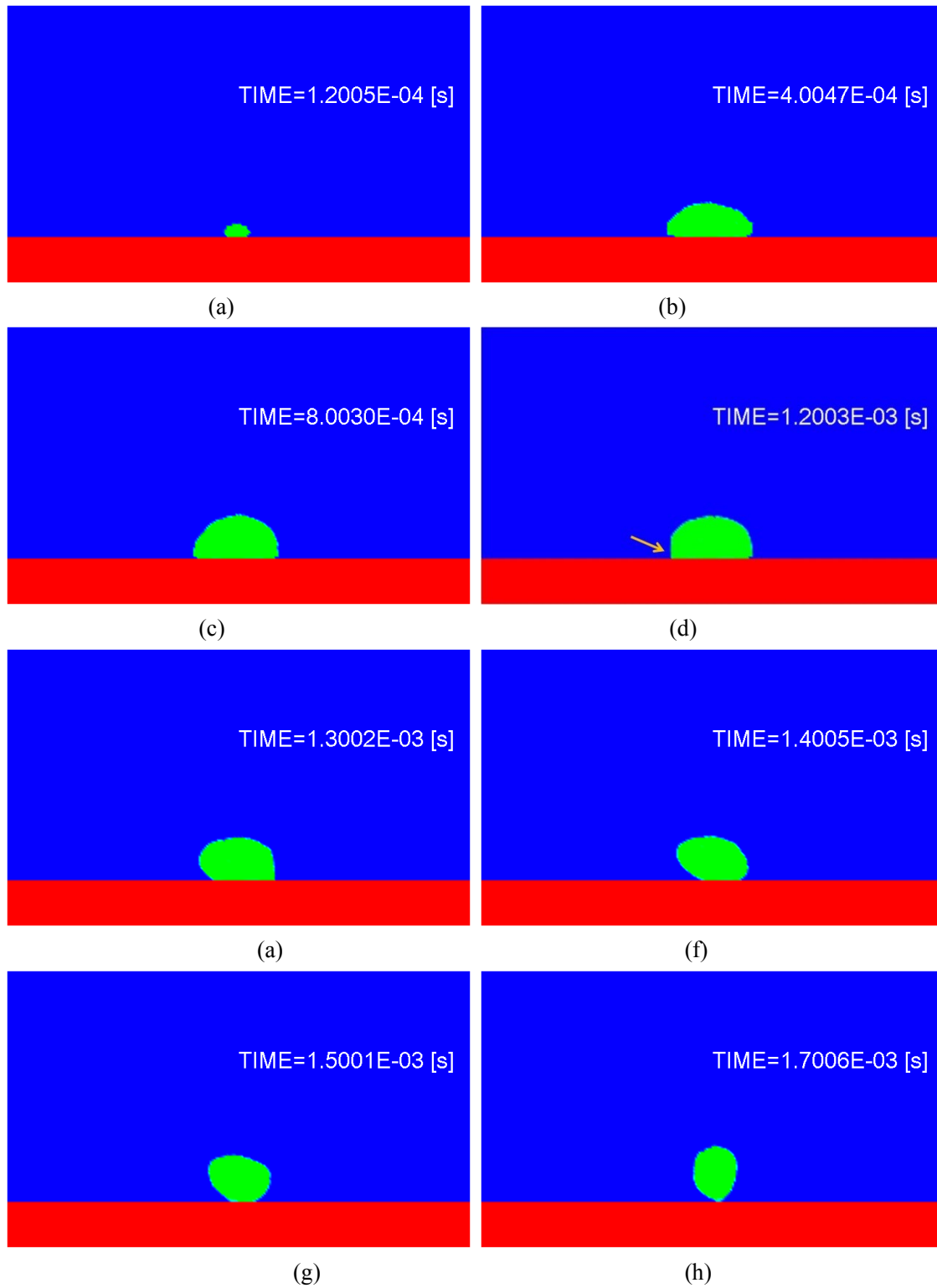


Fig. 3.21 Simulated bubble behavior with Marangoni effect

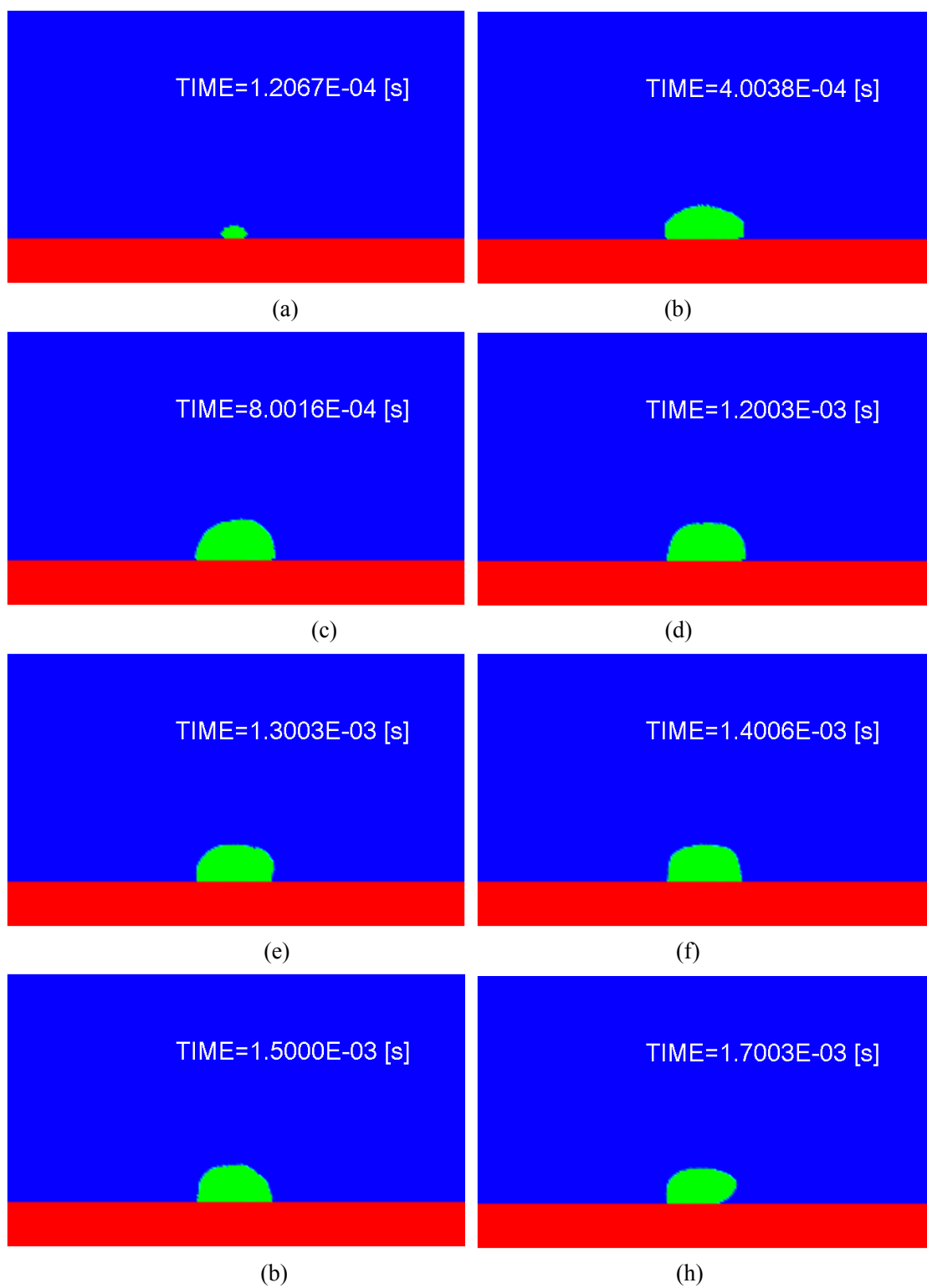
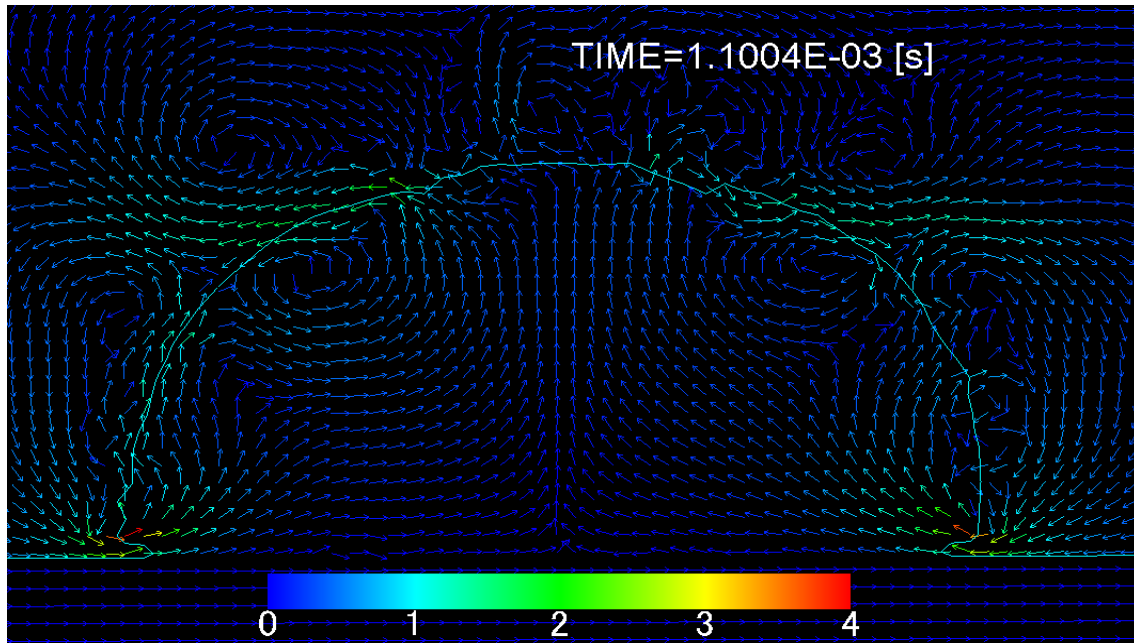


Fig. 3.22 Simulated bubble behavior without Marangoni effect

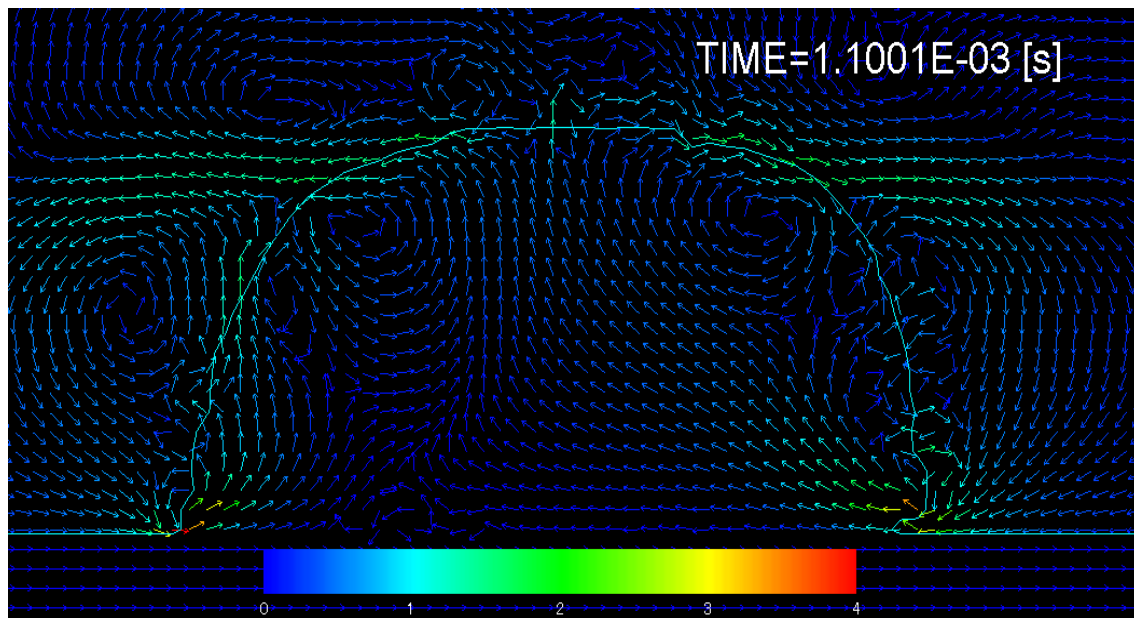
The temporal serial images of bubble behaviors in subcooled flow boiling from nucleating to lifting off from the heating wall obtained from the numerical simulation with and without Marangoni effect were given in Fig. 3.21 and Fig. 3.22 respectively. Comparing the first three images (images (a), (b), (c)) of Fig. 3.21 and Fig. 3.22, the bubbles behaviors in the initial period of growth regime were quite similar, both presenting an extension in horizontal direction firstly and then a nearly hemispherical shape under the effect of surface tension. This is also accordance with the experimental results. From images (d) of Fig. 3.21 and Fig. 3.22, the bubbles behaviors show some difference because of the difference in the surface tension coefficient setup in the simulation. When the surface tension coefficient was set to be temperature dependent, this means the Marangoni effect was turned on, the upstream side bottom part of the bubble surface deformed to a straight line, as pointed by the yellow arrow in image (d) of Fig. 3.21, this is also agree with the experimental results (e.g. Fig. 3.16 (h), (i), (j)) and can be viewed as the starting of the bubble deformation, hereafter, as shown in Fig. 3.21 (d) ~ (f), the bubble deformation became more and more severe and developed to the whole upstream side surface of the bubble, the upstream side surface shows a concave shape and the whole bubble is asymmetry when departing from the heating wall, this deformation process and the bubble shape when departing from the heating wall were in good agreement with the bubble behaviors and shape in the images obtained from the experiments.

However, when the surface tension coefficient of water in the numerical simulation is set to be constant in the simulation, which means the Marangoni effect is turned off, the bubble behavior was quite different, as can be seen in images (d) ~ (f) of Fig. 3.22, there was no deformation at all on the bubble surface, the bubble was always keeping an stable hemispherical shape on the heating wall and cannot even lift off from the wall. From the comparison of bubbles behaviors in the simulations with and without Marangoni effect, as shown in Fig. 3.21 and Fig. 3.22, it is confirmed that the Marangoni effect have an important influence on the bubble behaviors, and the deformation on the upstream side surface of bubble during the growth regime was

indeed caused by the Marangoni flow around the bubble as was discussed in Section 3.3.1.



(a) Simulation with Marangoni effect



(b) Simulation without Marangoni effect

Fig. 3.23 Velocity vector near the bubble surface before the bubble deformation

The distribution of velocity vectors in the simulation with and without Marangoni effect was given in Fig. 3.23 (a) and (b) respectively, the time was about 1.1 ms, a little earlier than the starting time of bubble deformation. As can be seen in Fig. 3.23 (a), when the Marangoni effect was turned on, there were a flow along the upstream side bubble surface from bottom to top, this is corresponding to the Marangoni flow caused by the surface tension gradient which is caused by temperature difference. The vortex in front of the bubble was also deformed by the Marangoni flow. However, when the Marangoni effect was not turned on, there is no such flow along the bubble surface, as shown in Fig. 3.23 (b), many of the velocity vectors go across the bubble surface, and the vortex was not deformed. The velocity distributions near the downstream side of bubble surface were quite similar, no matter the Marangoni effect was turned on or not, many velocity vectors in this region were perpendicular to the bubble surface and no flow along the bubble surface was found, this is because in the downstream side of bubble, the bulk liquid flow away from the bubble and no sufficient liquid can reach the bubble bottom of the downstream side to maintain an sustainable Marangoni flow along the bubble surface as discussed in Section 3.3.1.

3.3.3 Calculation of area or volume reduced by deformation

The deformation on upstream side bottom of bubble caused by condensation would slow down the growth rate of bubble, but the heat transfer performance in subcooled flow boiling between the bubble and the heating wall could be enhanced by the condensation deformation caused by the thermo-capillary flow. The reduced area (2 dimensional volume) of bubble caused by condensation deformation could be calculated by the method shown in Fig. 3.24, a typical deformed bubble on the upstream side was shown in Fig. 3.24 (a), as we discussed in previous section, the downstream side of the bubble was almost no deformation, so the bubble was symmetry if no deformation occurred in the upstream side, like the bubble shape of pool boiling. By flipping the downstream part of the bubble according to the horizontal center axis of the bubble to

the upstream side, we can get the virtual bubble shape without deformation in Fig. 3.24 (b), the red line indicates the contour line of the virtual bubble without deformation, the green line is the contour of real deformed bubble, so the grey area between these two contour lines as marked in Fig. 3.24 (b) was the reduced area by the condensation. By using some image processing software, the real deformed bubble area and the virtual non-deformed bubble area can be obtained, so the reduced area can be calculated easily. A variable R_D could be defined as the ratio of reduced area and the real bubble area, to represent the extent of the bubble condensation deformation. The variation of real deformed area and virtual symmetry area of the bubble in Fig. 3.16 from nucleating to lifting-off was shown in Fig. 3.25, together with the variation of R_D . The difference between these two lines in Fig. 3.25 represents the area reduced by the condensation deformation, these two lines diverged at about 1.8 ms from nucleating, after the maximum value of these two lines. Also the bubble deforming process could be verified by the variation of R_D shown in Fig. 3.25, as you can see, the reduced area could reach as much as 18% of the bubble real area at the time when the bubble is lifting off from the wall. By this method we can obtain the two dimensional volume (area) reduced by the condensation deformation of the bubbles.

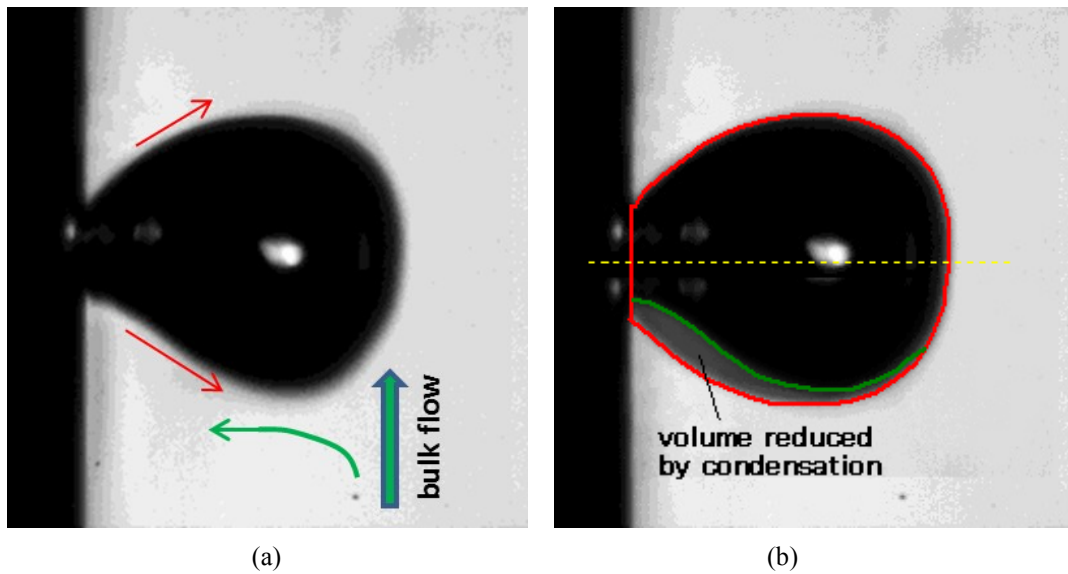


Fig. 3.24 Schematic of calculation method of the reduced area

Because of the irregular shape of the bubbles with the condensation deformation in subcooled flow boiling, especially at high subcooling degrees, it is not easy to obtain an accurate calculating method of the three dimensional volume reduced by the condensation deformation, except for some very simple cases, e.g. the bubbles in subcooled flow boiling of very low subcooling degrees case, as the bubble shown in Fig. 3.17 (d), the bubble is very close to a spherical shape even when it is lifting off from the wall, because the subcooling degree is only 6.1 K, there is almost no deformation except for the slightly deformed region at the bottom of bubble as point out by the red arrow in the image. The deformed section of the bubble surface is a straight line as marked by the green line in Fig. 3.17 (d), in actual 3D case, it should be can be treated as a plane. For the imaginary bubble without condensation deformation, it is ok to be treated as a sphere shape, so we can obtain the three dimensional volume reduced by the condensation deformation, through considering the deformation part as the segment being cut off along the plane of deformation line (green line in Fig. 3.17 (d)) from the sphere of virtual non-deformation bubble, as illustrated in Fig. 3.26.

Using the image processing software, the diameter R and the length of deformed surface L can be obtained, and then the height of the segment H can be calculated and then the volume of the segment can be calculated by:

$$V_R = \pi H^2 (R-H/3) \quad (3.1)$$

By calculating with this method, the volume reduced by condensation deformation of the bubble at subcooling degree of 5 K was about 0.2% of the total bubble volume, this proportion is not high, because the bubble was generated in subcooled flow boiling of very low subcooling case, the condensation deformation of the bubble by the thermo-capillary flow was not so severe. As long as the volume reduced by condensation was known by the way given above, the heat released by the condensation could also be calculated by

$$Q = \rho h V_R \quad (3.2)$$

Where, h and ρ is the latent heat and density of purified water, respectively

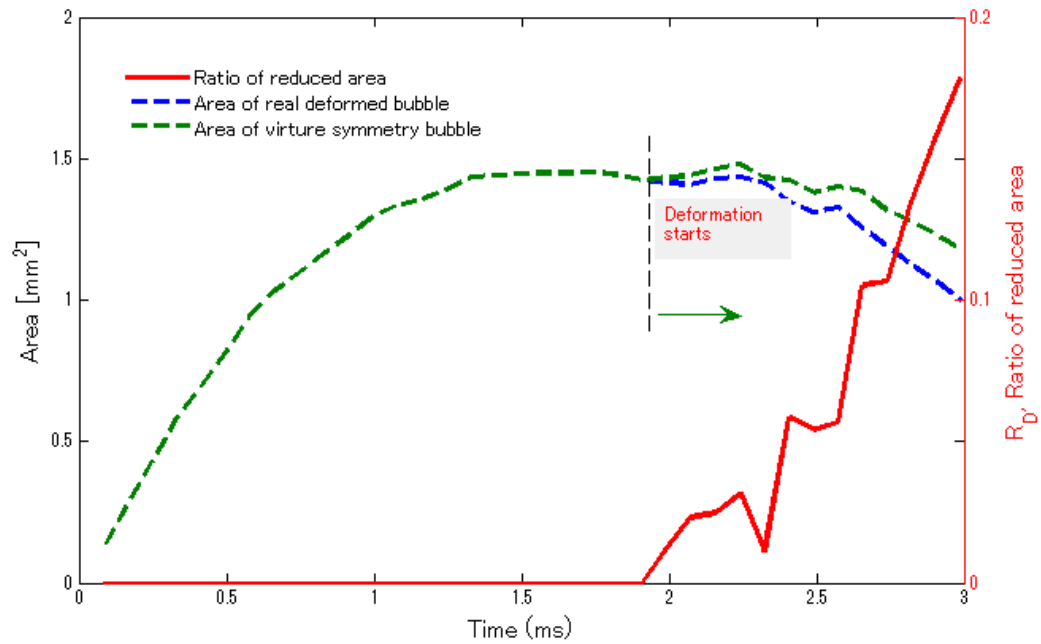


Fig. 3.25 Variation of bubble area and ratio of reduced area as time before lifting off

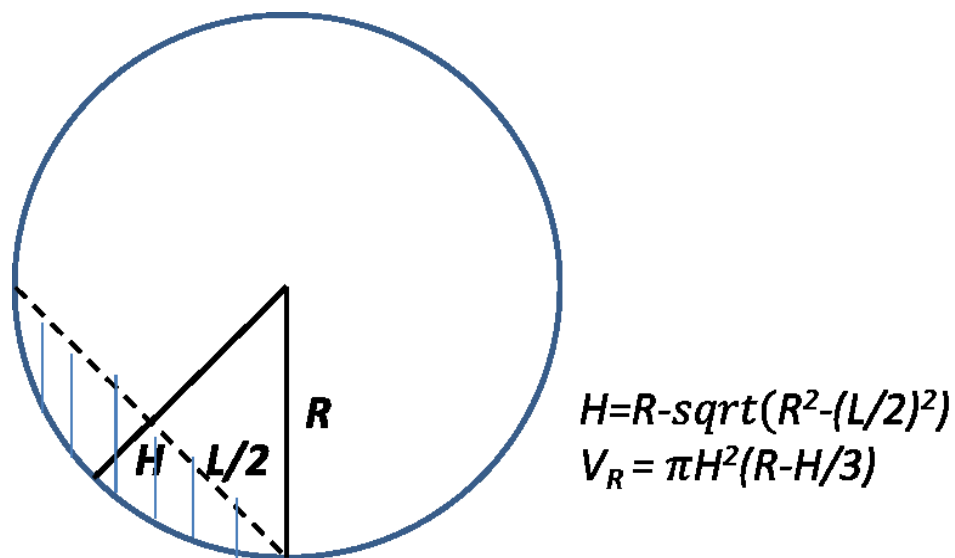


Fig. 3.26 Schematic of calculation of bubble reduced volume

The ratio of reduced area caused by the condensation deformation R_D was calculated at different subcooling degrees (5 K, 10 K, 16 K, 21 K, 30 K). At each subcooling degrees, the ratio R_D was calculated by averaging over at least 20 bubbles, the results were showed in Fig. 3.27. As can be seen, the ratio increase rapidly as the subcooling degree increase, indicating the subcooling degrees has an important effect on the bubble deformation, confirming the previous discussion that the bubble deformation in the upstream side bottom was caused by the thermos-capillary flow of Marangoni effect. The increase of R_D from subcooling degree 16 K to 30 K was not so steep as that of subcooling degree from 5 K to 16 K, this is because at higher subcooling degrees, the deformation of bubble occurs not only at the upstream side of the bubble, instead all the bubble bottom was deformed by the entrainment flow as discussed in Sec 3.2.2.1 for bubble behaviors in subcooled flow boiling of high subcooling degree cases, the total bubble volume was already decreased a lot, so the ratio of reduced bubble area by the condensation deformation on the upstream side of the bubble was not so significant.

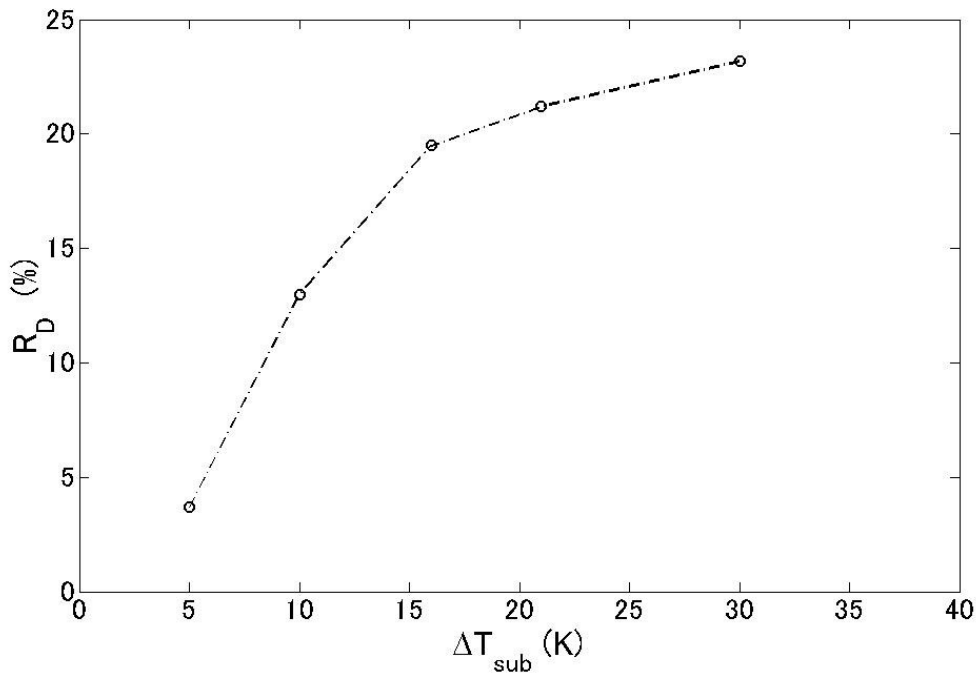


Fig. 3.27 ratio of bubble reduced area at various subcooling degrees

3.3.4 Summary

In this part, the condensation deformation of bubble on the upstream side part was discussed in detail, the bubble deformation was caused by the condensation occurred there, which was induced by the thermos-capillary flow along the bubble surface from the bottom to the top, caused by the surface tension gradient in the vertical direction along the bubble surface.

Since the thermo-capillary flow of Marangoni effect along the bubble surface cannot be observed in the video images of bubbles obtained by the present forced convection subcooled boiling experimental system, so no direct evidence can be obtained to support the proposed explanation of the bubble deformation mechanism with the Marangoni effect. Therefore, the numerical simulation of bubble behavior in subcooled flow boiling was carried out, the surface tension coefficient was set to be constant or temperature dependent with all the other configuration and condition the same in the simulations in order to investigate the effect of the Marangoni effect. From the simulation results, it is confirmed that the bubble deformation on the upstream side of the bubble was indeed caused by the thermos-capillary flow of Marangoni effect.

The computing method of the reduced bubble area or volume by the condensation deformation was also proposed. At low subcooling degree cases, the reduced bubble volume is only small portion of the total bubble volume. Statistical value of the ratio of reduced bubble area or volume was also obtained, and it was found to be increase with the increase of the subcooling degree, this is consistent with the qualitative visualization results of bubbles at various subcooling degrees given in Sec 3.2

3.4 Wave propagation during condensation

In the previous section, the bubble behaviors before it lifts off from the heating wall were discussed under a wide range of experimental conditions, however, after the bubble departs from the heating wall, interesting phenomena was also observed, namely, the wave propagating on the bubble surface during the condensation process. As we know, the bubble condensed rapidly in the subcooled bulk flow region after departure from the heating wall, the images of the bubble condensation after its departure was shown in Fig. 3.27 ~ 3.29, corresponding to different subcooling degree cases: 15.9 K, 29.4 K, 6.1 K. From the elapse time given in each image and the length scale marked in the first image of Figs. 3.27 ~ 3.29, it can be seen that the size and lifetime of the bubbles under different degrees of subcooling degrees were very different, but the wave propagating phenomenon was observed in all these cases.

As shown in Fig. 3.27, when the bubble was about to lift off from the heating wall, the bubble was a little bit elongated in the vertical direction to the heating wall, only one small tip at the bubble bottom was attached to the heating wall. After the bubble complete departed from the heating wall, the wave was generated first at the bubble bottom by the strong recoil force when the attached bubble tip suddenly lifted off from the wall. As can be seen, the wave was firstly generated at the bottom-tip of the bubble when it pinched off from the heating wall, and then it propagated on the bubble surface to the bubble top very quickly. At higher subcooling degree cases, as can be seen in Fig. 3.28, the recoil force was even stronger, since the elongation deformation of bubble when departing from the heating wall was much obvious and severer than that of low subcooling degree cases, a wave of ring shape was generated at the bottom part of the bubble after it departed from the heating wall, and this ring shaped wave rolled up from the bottom of the bubble to the whole surface of the bubble.

The wave propagation features on the bubble surface at lower subcooling degree cases were also a little different. Since the bubble at low subcooling degrees were not so deformed and elongated when departing from the heating wall, so the recoil force was

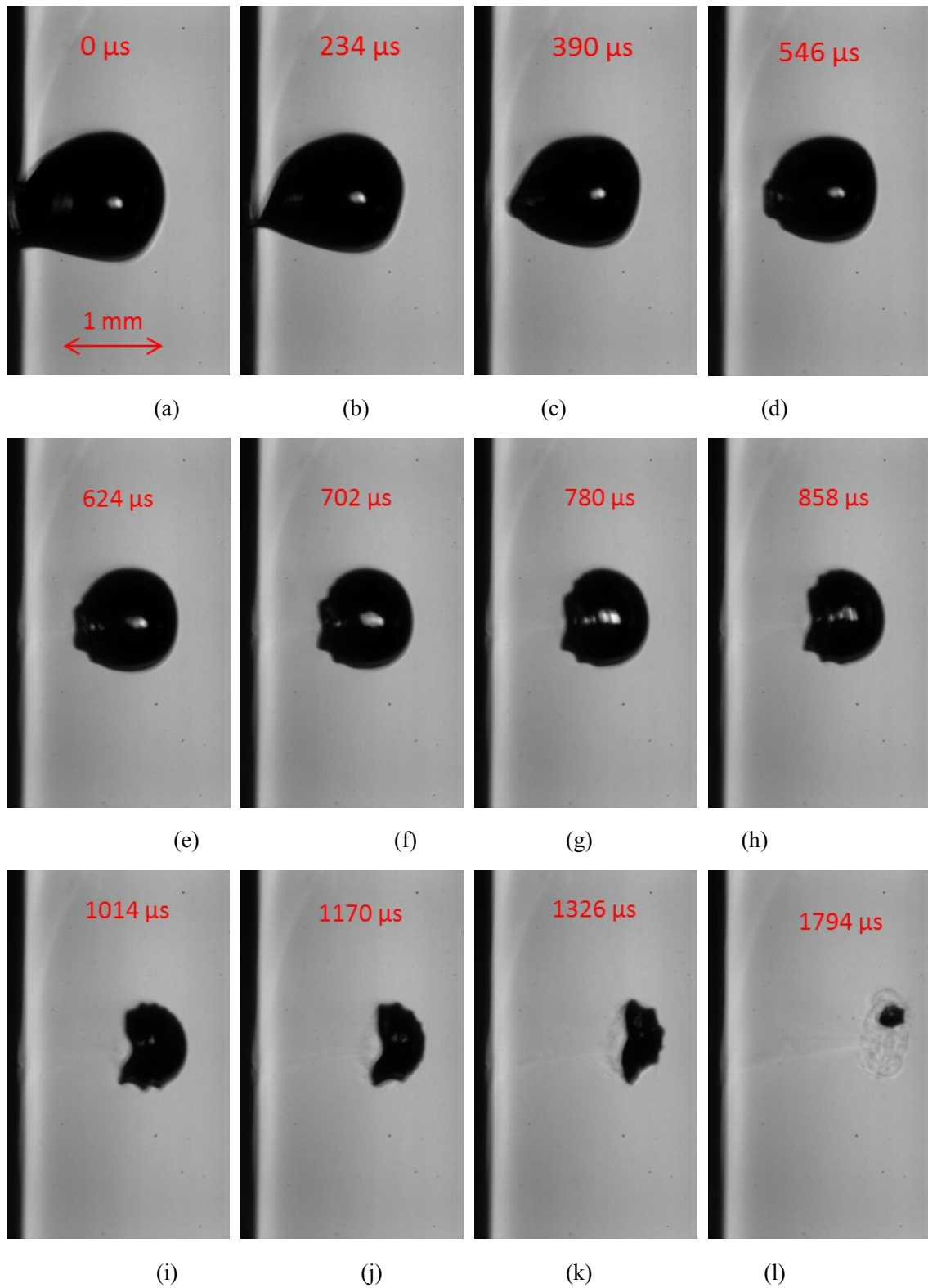


Fig. 3.27 Sequential images of bubble behavior after lifting-off

ΔT_{sub} : 15.9 K, v_m : 0.14 m/s, q : 128 kW/m²

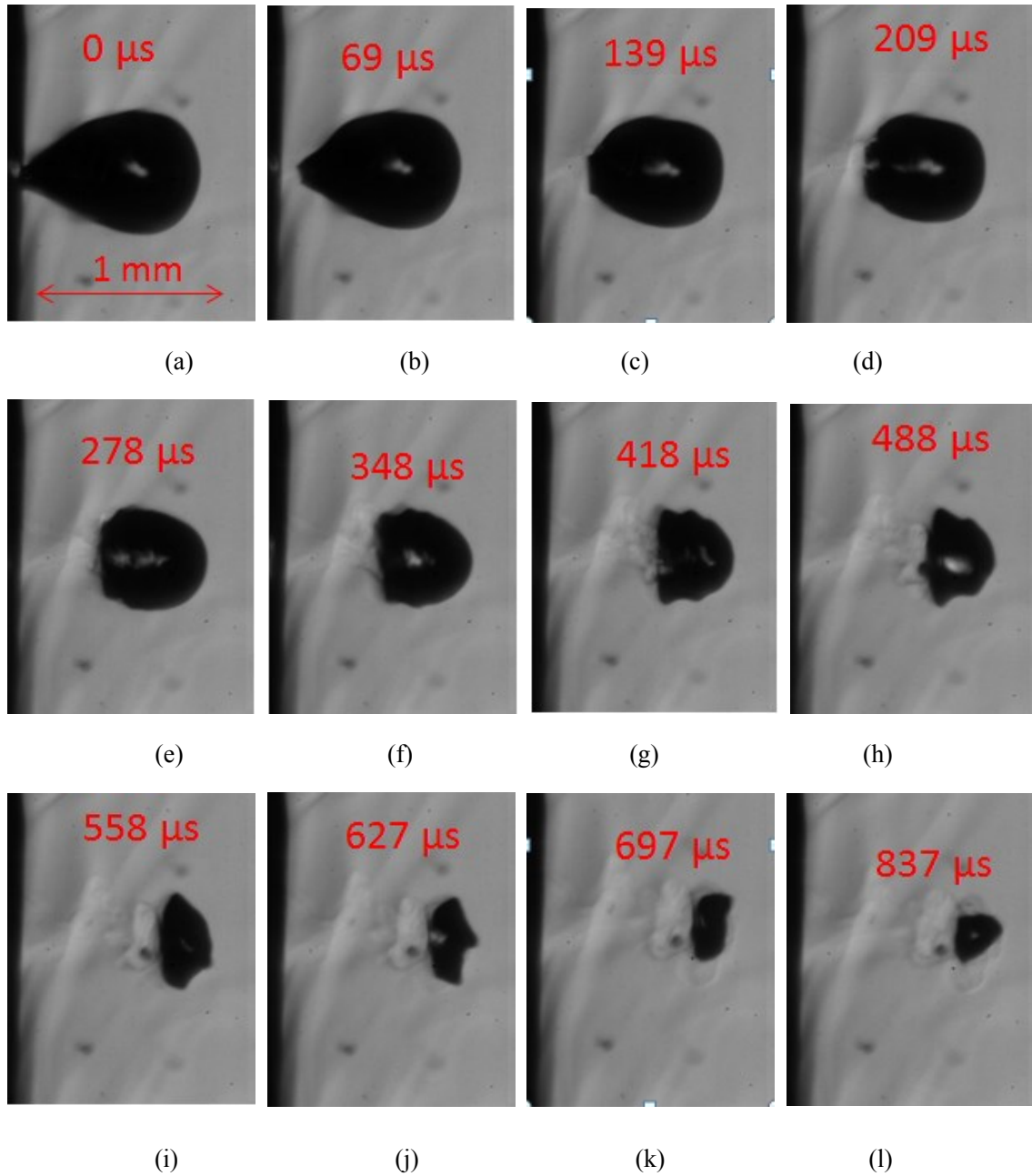


Fig. 3.28 Sequential images of bubble behavior after lifting-off

$\Delta T_{\text{sub}}: 29.4 \text{ K}, v_m: 0.15 \text{ m/s}, q: 156 \text{ kW/m}^2$

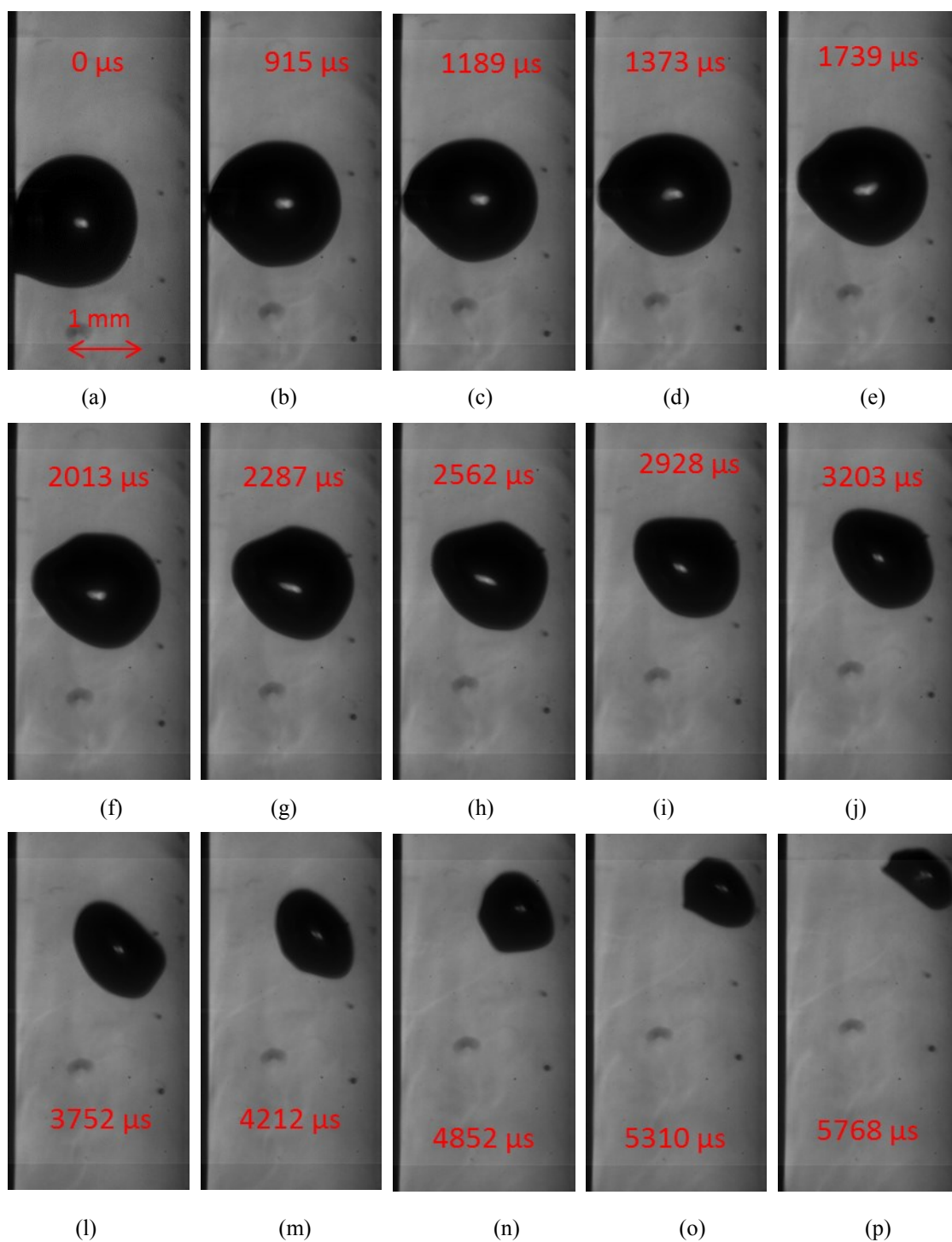


Fig. 3.29 Sequential images of bubble behavior after lifting-off,

$$\Delta T_{sub}: 6.1 \text{ K}, v_m: 0.21 \text{ m/s}, q: 72.3 \text{ kW/m}^2$$

not so strong when it lifts off from the wall so the wave was not obvious at the moment just after departure. However, though the bubble deformation at low subcooling case was only slightly deformed, after the bubble departing from the heating wall, it has a tendency to become a spherical shape under the effect of the surface tension, so the bubble shape also changed rapidly during the condensation process, this also enhanced the propagation of wave on the bubble surface.

The wave propagated on the bubble surface very quickly, making the surface wrinkled, not as smooth as that in the bubble growth period. The wave propagation makes the surface area of bubble being much larger than the surface area of a spherical bubble with the same volume, and also the bubble surface was highly vibrated and deformed by the rapid wave propagation. This enlarged surface area and the rapid vibration and deformation of the bubble surface enhanced the heat transfer performance between the bubble and the bulk subcooled liquid. Therefore it is reasonable that bubble condensation rate was enhanced by the wave propagation on bubble surface.

3.5 Conclusion

In this Chapter, the bubble behaviors in subcooled flow boiling were investigated under various subcooling degrees and flow rates. Bubble behavior characteristics at different subcooling degrees were very different, the effect of the flow rates was also important.

At medium subcooling degrees and low flow rates, deformation at the upstream side bottom of the bubble was observed and attributed to the condensation induced by thermo-capillary flow or by Marangoni effect caused by the surface tension gradient along the bubble surface in the vertical direction to the heating wall. The bubble behavior at medium subcooling degrees but high flow rates was a combination of the upstream side deformation and the bubble movements of sliding and rolling on the heating wall caused by the shearing effect of bulk liquid flow.

At high subcooling degrees and low flow rates, the bubbles exhibit contracting and elongation deformation at the bottom during the growth and departure period, because of the very thin superheated boundary layer and the entrainment of the highly subcooled liquid caused by the bubble's movement of rapid growth. The bottom of bubble can become very long and thin when departing from the wall. A second successive bubble can grow from the remaining part left by the previous bubble. At high flow rates, the effect of flow becomes significant, a concave deformation at the middle of the bubble's upstream side surface was found when the bubble size was getting large, this is because the low temperature liquid can hit the bubble upstream side surface directly when the bubble was getting larger.

The bubble behavior at low subcooling degrees was quite regular compared to that of high subcooling cases. There is no severe deformation, bubbles were close to spherical shape during the lifetime and some bubbles depart from the heating wall and enter the bulk liquid flow region rapidly and condensed quickly but some bubble may float a long distance before condensation. The bubble size at lifting off time is close to the maximum bubble size means there is almost no condensation occurred when the

bubble is attached to the heating wall. At low subcooling cases only the bubble size was affected by the flow rates, bubble behaviors were quite similar at different flow rates.

The effect of subcooling degree, flow rate and heat flux on the bubble behaviors were also investigated in a quantitative way, some basic parameters of the bubble dynamics were studied and conclusion agrees well with most of the previous research work.

The condensation deformation on upstream side of the bubble at a medium subcooling degree cases was discussed in detail, the deformation mechanism of bubble was explained by the thermo-capillary flow of Marangoni effect. the bubble deformation was caused by the condensation occurred there, which was induced by the thermos-capillary flow along the bubble surface from the bottom to the top, caused by the surface tension gradient in the vertical direction along the bubble surface.

Since the thermo-capillary flow of Marangoni effect along the bubble surface cannot be observed in the video images of bubbles obtained by the present forced convection subcooled boiling experimental system, so no direct evidence can be obtained to support the proposed explanation of the bubble deformation mechanism with the Marangoni effect. Therefore, the numerical simulation of bubble behavior in subcooled flow boiling was carried out, the surface tension coefficient was set to be constant or temperature dependent with all the other configuration and condition the same in the simulations in order to investigate the effect of the Marangoni effect. From the simulation results, it is confirmed that the bubble deformation on the upstream side of the bubble was indeed caused by the thermos-capillary flow of Marangoni effect.

The computing method of the reduced bubble area or volume by the condensation deformation was also proposed. At low subcooling degree cases, the reduced bubble volume is only small portion of the total bubble volume. Statistical value of the ratio of reduced bubble area or volume was also obtained, and it was found to be increase with the increase of the subcooling degree, this is consistent with the qualitative visualization results of bubbles at various subcooling degrees given in Sec 3.2.

The wave propagation phenomenon on the bubble surface during the bubble condensation process was also observed under various experimental conditions. The enlarged area of the bubble surface and the rapid vibration and deformation caused by the wave propagation during condensation process can enhance the heat transfer performance between the bubble and the bulk subcooled liquid. Therefore it is reasonable that bubble condensation rate was enhanced by the wave propagation on the bubble surface.

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Chapter 4

Two-Successive Bubble Phenomena at High Subcooling Degrees

4.1 Introduction

The typical behaviors of bubbles in subcooled flow boiling of high subcooling degrees ($\Delta T_{\text{sub}} > 30 \text{ K}$) are the obviously contraction deformation and elongation in the vertical direction to the heating wall during the growth regime of the bubble. After the bubble departs from the wall, a new bubble grows up from the remaining vapor left by the previous departed bubble. This causes the appearance of the two successive bubbles phenomena, which is quite common in subcooled flow boiling at relatively high subcooling degrees. In this chapter, the characteristic of bubble behaviors in subcooled flow boiling of relatively high subcooling degrees ($\Delta T_{\text{sub}} > 30 \text{ K}$) were discussed in detail, the phenomena of two successive bubbles were analyzed in a quantitative way.

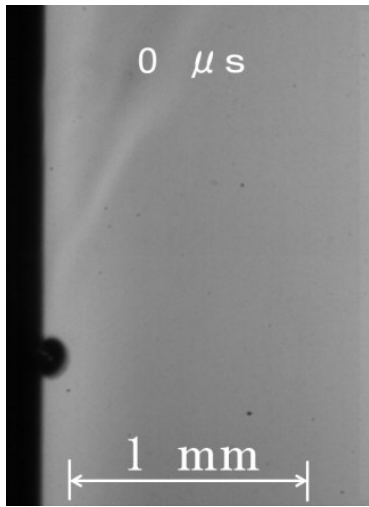
4.2 Contraction and elongation deformation

The sequential images of typical bubble behaviors in subcooled flow boiling at relatively high subcooling degree were shown in Fig. 4.1. The experimental conditions were as follows: the subcooling degree measured at the inlet of test section was 29.6 K, the average heat flux applied on the surface of the heating wall was 156 kW/m^2 and the average flow velocity of liquid in the annular channel was 0.14 m/s. The observation and recording position was about 20 mm above the beginning of the heating section of the heater. The temporal variation of equivalent diameter of the bubbles shown in Fig. 4.1 was given in Fig. 4.2.

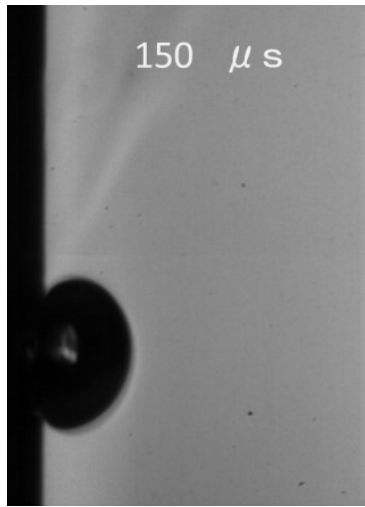
As we can see from images (a) to (d) of Fig. 4.1, after the bubble embryo nucleated at the heating wall, the bubble grew very rapidly and reached its maximum size in a very short time, about 600 μ s, this is also illustrated by the variation of equivalent diameter of the bubble given in Fig. 4.2. The bubble shape at its maximum size is not spherical but an oblate ellipse, as can be seen in Fig. 4.1 (d), this is because in subcooled flow boiling of high subcooling degree, the superheated thermal boundary layer near the heating wall is very thin, so that the growth rate of bubble in direction along the wall was much faster than that in the direction normal to the heating wall.

After the bubble reaches its maximum size, the bubble shape changed from an oblate ellipse to a sphere because of the effect of surface tension, however it was not an perfect sphere, as shown in images (d), (e) of Fig. 4.1, there was some slight deformation because of the adhesion effect of the wall to the bubble bottom and the upstream and downstream sides of the bubble were not symmetry, because of the flow shearing effect. From images (f) to (h) of Fig. 4.1, the contraction and elongation deformation of the bubble bottom was observed, firstly a small concave deformation on the upstream side surface was found, as marked by the arrow in image (f) of Fig. 4.1, then this deformation became larger and larger, and finally when the bubble was lifting off from the wall, the bubble bottom became very thin and long, like a thread connecting the bubble body to the wall, also the bubble volume became much smaller than the maximum bubble volume, as shown in images of Fig. 4.1 or the quantitative data of bubble equivalent diameter in Fig. 4.2. After this, the long and thin bubble bottom which connects the bubble to the heating wall broke apart and then the bubble condensed in the subcooled bulk flow rapidly, as shown in images (h) (i) of Fig. 4.1.

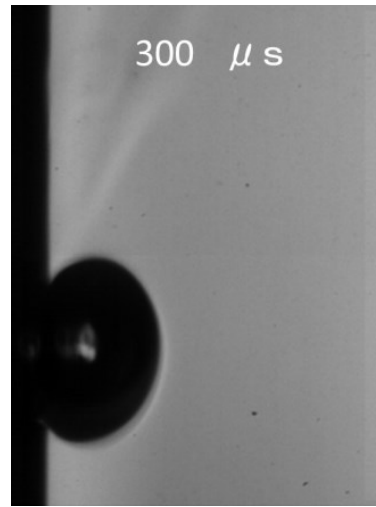
This kind of contraction and elongation deformation of bubble was not a occasional special case, instead it was quite common in subcooled flow boiling at the high subcooled degrees, normally above 30 K. This phenomenon has been observed in quite a lot of bubbles in our experiments. The contraction deformation of bubble at high subcooling cases can be attributed to the condensation occurred at the bottom region.



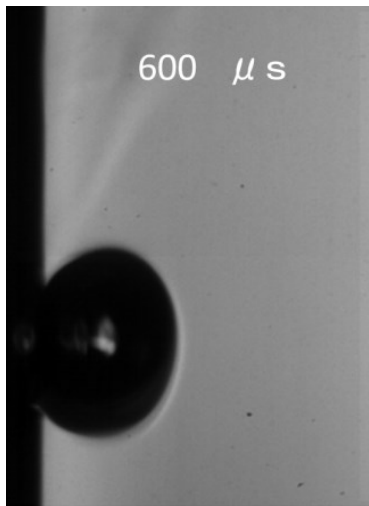
(a)



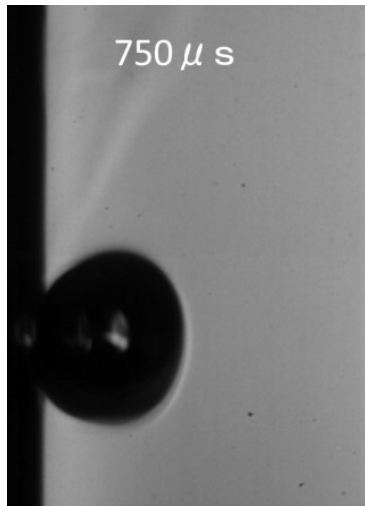
(b)



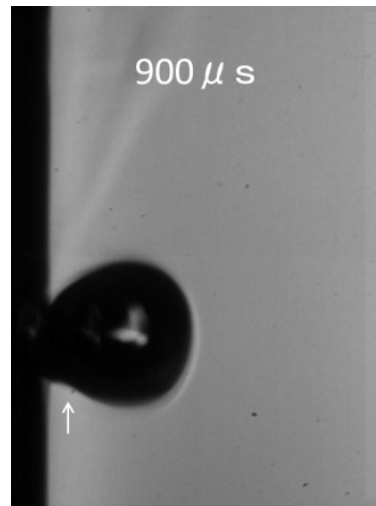
(c)



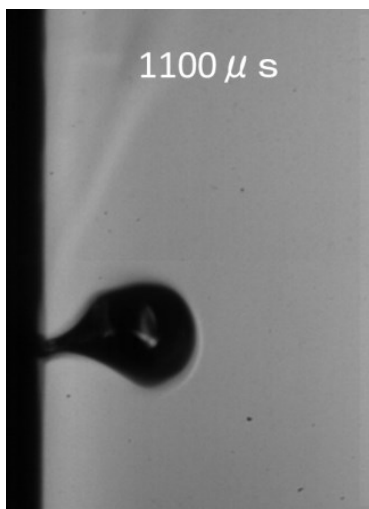
(d)



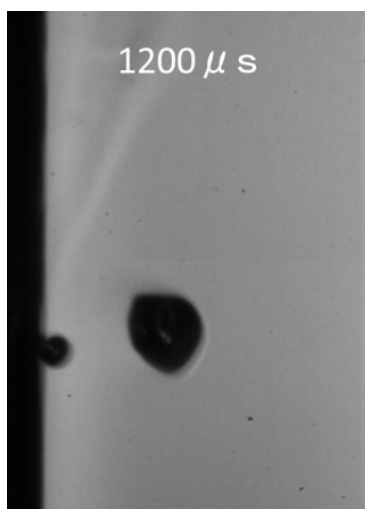
(e)



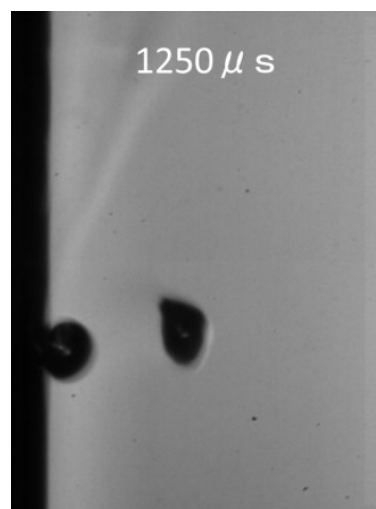
(f)



(g)



(h)



(i)

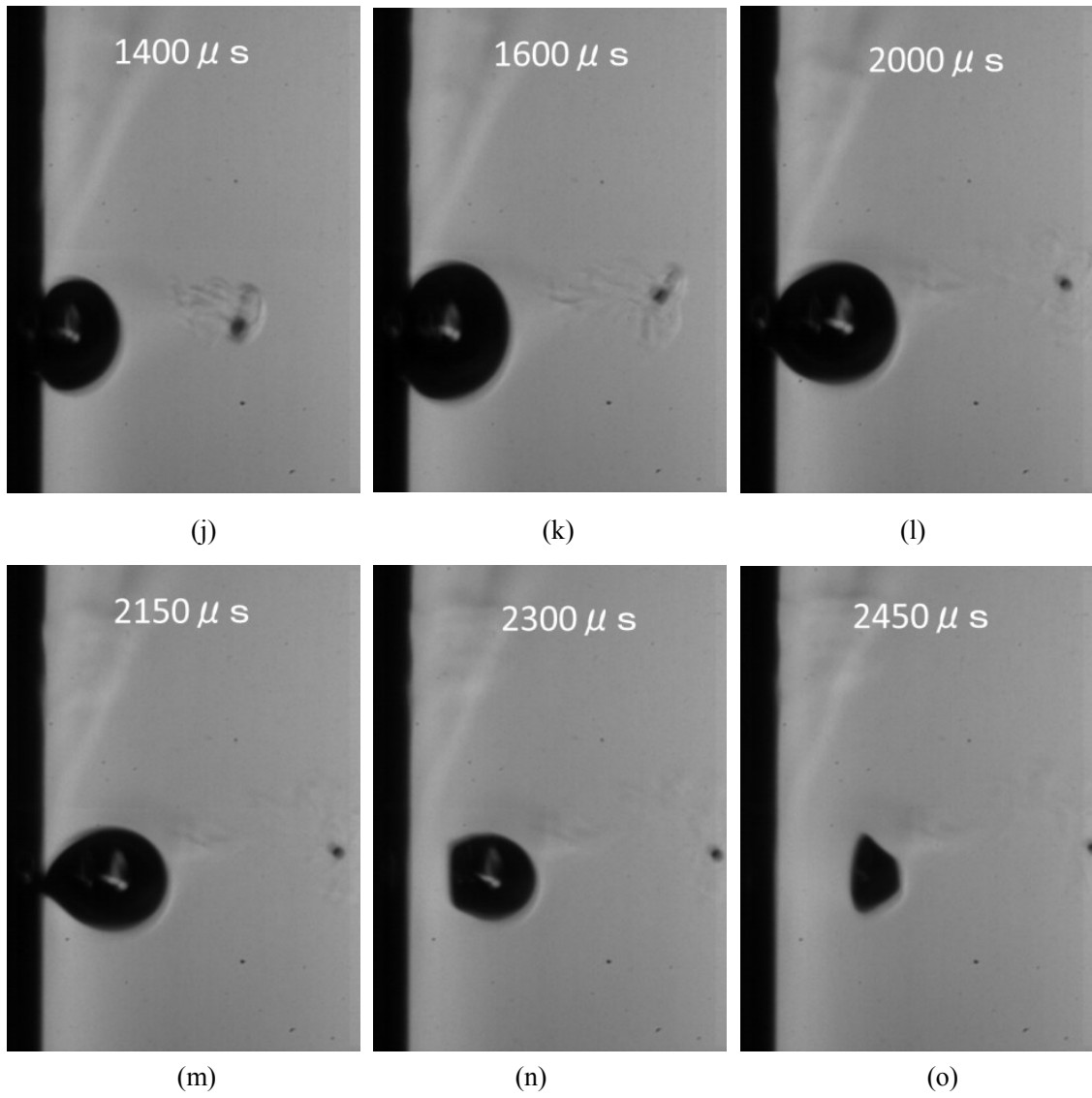


Fig. 4.1 Images of two successive bubbles

ΔT_{sub} : 29.6 K, v_m : 0.14 m/s, q : 156 kW/m²

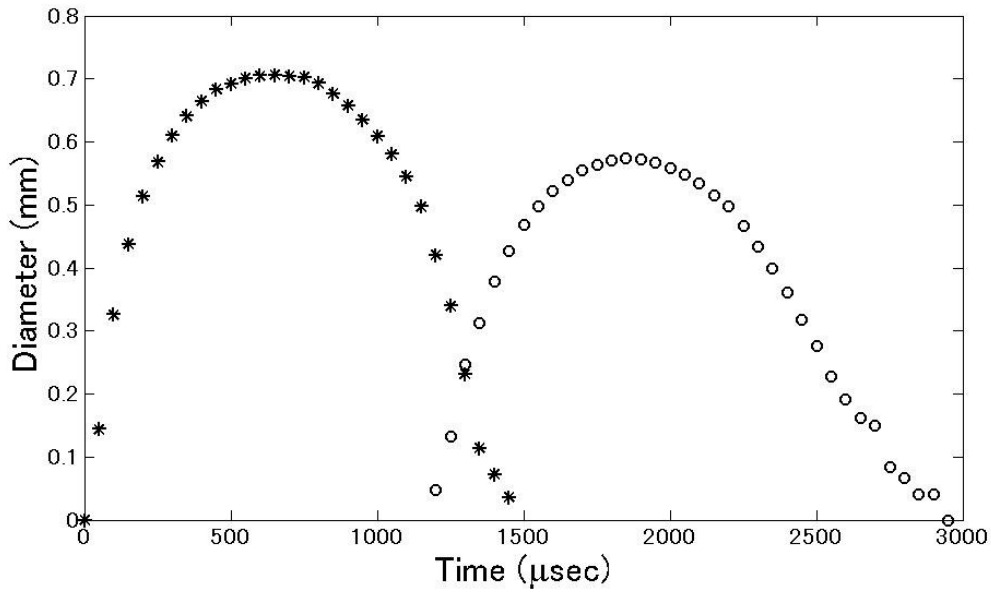
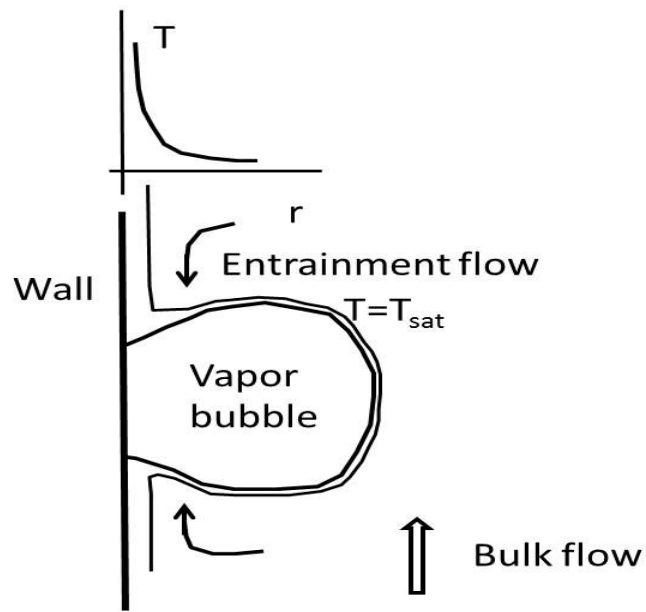
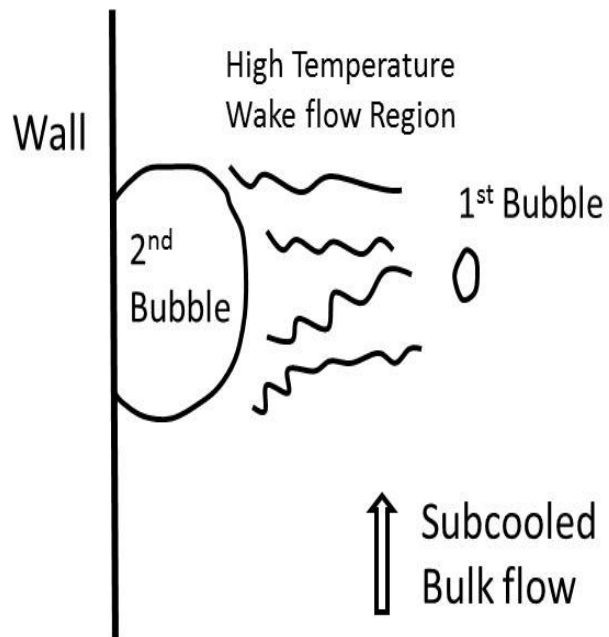


Fig. 4.2 Temporal variation of equivalent diameter the bubbles shown in Fig. 4.1

Because the subcooling degrees in these cases were very high, at least 30 K, the bulk liquid flow region was highly subcooled, however, for bubbles nucleating on the heating wall, the heating wall and near-wall boundary layer should be highly superheated, so the temperature difference between the heating wall and the bulk liquid flow region was very large, and the superheated boundary layer was very thin as mentioned above, the schematic of the temperature distribution and isotherm line around the bubble were given in Fig. 4.4 (a). During the rapid bubble growing and deforming process, the liquid surrounding the bubbles could be pushed or attracted by the rapid bubbles movement. As we discussed above, after the bubble reached the maximum size, its shape changed from oblate ellipse to a sphere shape under the effect of surface tension, so during the bubble deforming process some low temperature liquid could also be entrained to the bottom region from the subcooled flow region. So the low temperature liquid flow may cause the condensation occurring at the bottom region of the bubble and make the bottom of bubble gradually deforming to a very long thin shape, finally like a thread connecting the bubble to the heating wall. Actually, the condensation occurred not only at the bottom of the bubble, from images (e) to (g) of Fig. 4.1 or the temporal variation of bubble equivalent diameter in Fig. 4.2, we can see obviously that accompanying the



(a)



(b)

Fig. 4.3 Schematic of bubble behaviors

(a) Deformation of first bubble

(b) Growth of second bubble

bubble deforming process, the bubble volume was also getting smaller and smaller, which proved that the condensation was already started, from about 750 μs , since the superheated layer near the heating wall in the subcooled flow boiling of high subcooling degree is very thin, the bubble became longer in the normal direction to the wall under the effect of surface tension during the deforming process, the top of bubble may get out of the thin superheated layer easily.

4.3 The phenomena of two successive bubbles

In the previous section, the typical bubble behaviors in subcooled flow boiling at relatively high subcooling degrees, namely contraction and elongation deformation phenomena was discussed, this was caused by the condensation occurred at the bubble bottom region during the bubble's growing regime, the bubble bottom becomes very thin and long when it is lifting off from the heating wall, so it is very easy to break apart, as you can see in image (h) of Fig. 4.1. After the bubble broke apart away from the heating wall, a small part of vapor was left on the heating wall as shown in Fig. 4.1 (h). This small amount of vapor grows larger very quickly and reached its maximum size in a short period of time, as shown in images from (h) to (k) of Fig. 4.1. However, the maximum size of this new bubble is a little bit smaller than the maximum size of its predecessor, which can also be verified from the equivalent diameter in Fig. 4.2 and the bubble shape when it was lifting off from the heating wall was also different from the previous bubble, as shown in image (m) of Fig. 4.1, only a slight deformation at the bubble bottom was observed, the deformation was not so severe as that of its predecessor. This phenomenon of a second new bubble growing immediately following a predecessor bubble was named two successive bubbles, which was observed quite common in the subcooled flow boiling at relatively high subcooling degrees.

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. 4.4 (b), the first bubble has a great effect on the second bubble during its whole lifetime, including the nucleation, growth and departure. Strictly speaking, the second bubble was not a new

nucleated bubble, for there is no nucleation process at all, the second bubble just 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 the 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 temporal variation of equivalent diameter of a bubble nucleated at the same site within a period of 0.15 s was shown in Fig. 4.4. 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. 4.4. From an investigation over 105 bubbles at the same nucleate site under the experimental conditions (the degree of subcooling 30K, the average liquid velocity 0.14 m/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 of appearance of the single bubble and two-successive bubble was about 3:4.

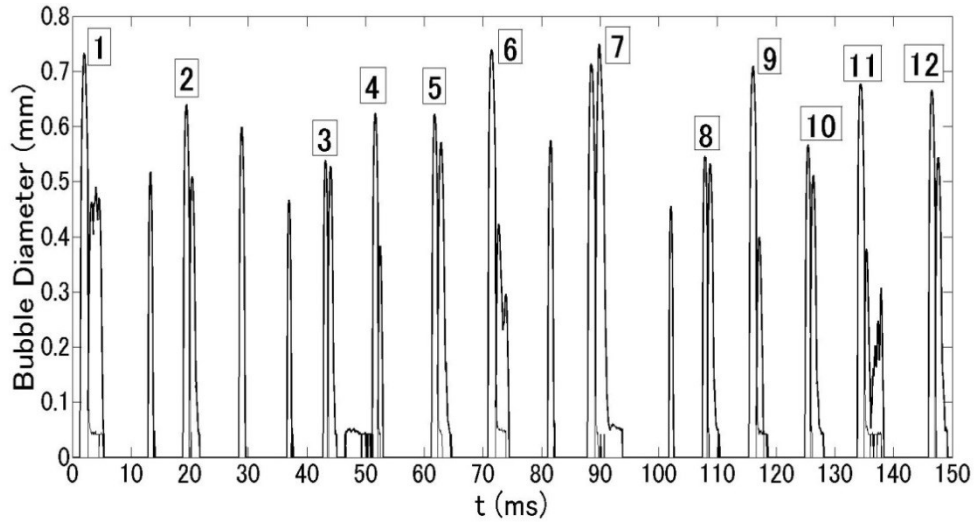


Fig. 4.4 Diameter variation of bubble at the same nucleate site

For getting a better understanding of the two successive bubble phenomena some quantitative data were obtained for discussion. 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. 4.5 shows the distribution of the diameter of the first bubble obtained from 46 group data, it can be seen that the distribution of the bubble diameters is close to standard normal distribution, so the statistical data obtained from 46 group data are credible.

From Fig. 4.1, it can be seen that the maximum diameter of the second bubble is a little smaller than the first one, which can also be verified in Fig. 4.2 quantitatively, this is because the second bubble grows immediately after the first bubble departed from the heating wall, and there was no waiting time between these two bubbles, namely 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. 4.4 (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 (represented by D1, D2 respectively) from the 46 groups of two successive bubbles were given in Fig. 4.6 (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.

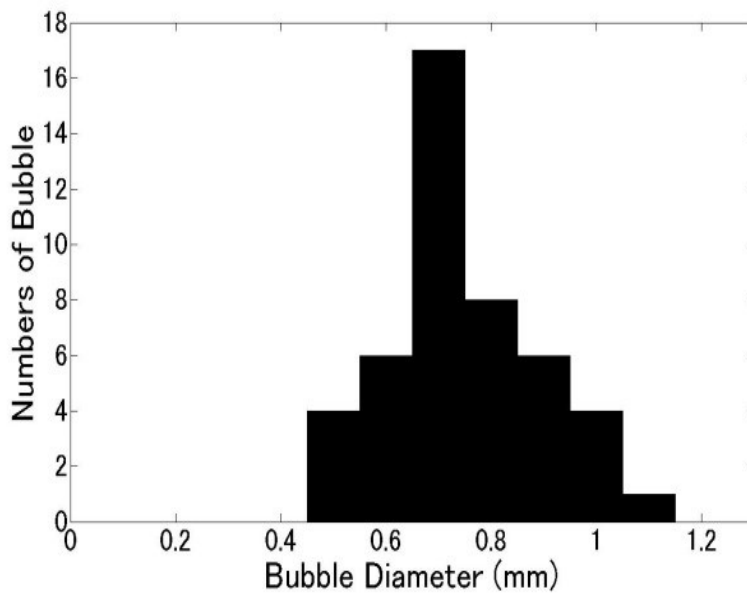
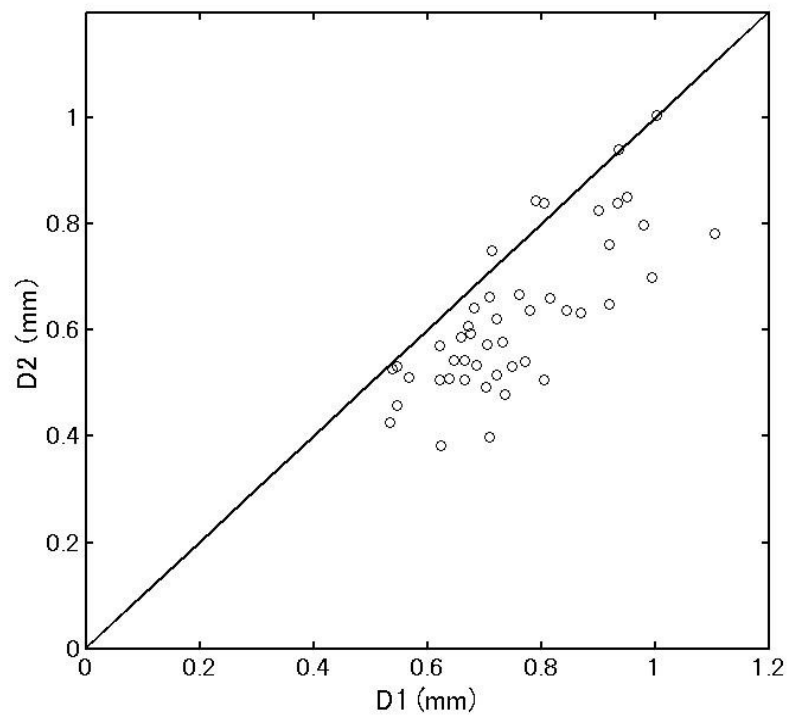
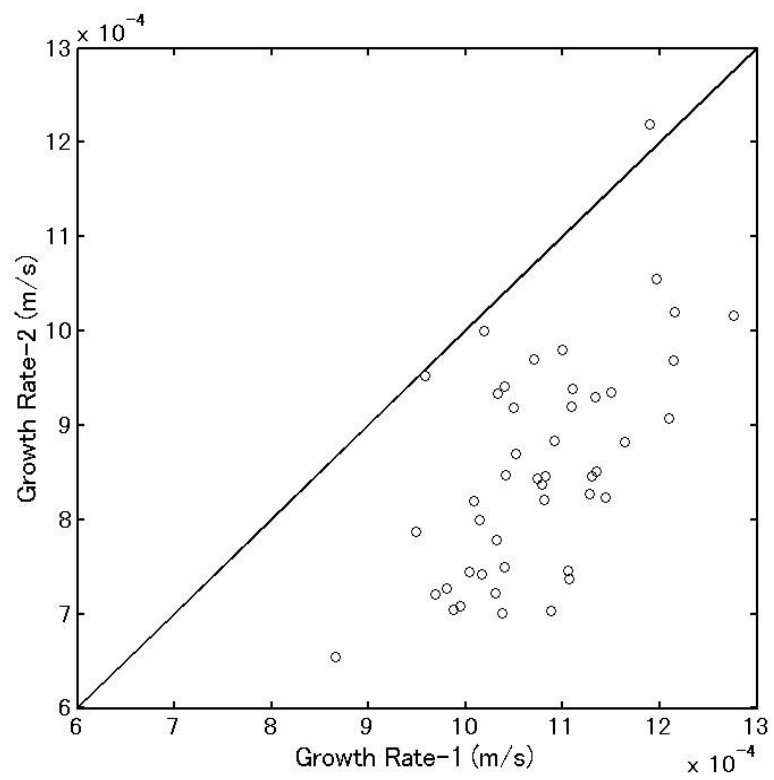


Fig. 4.5 Distribution of bubble diameter

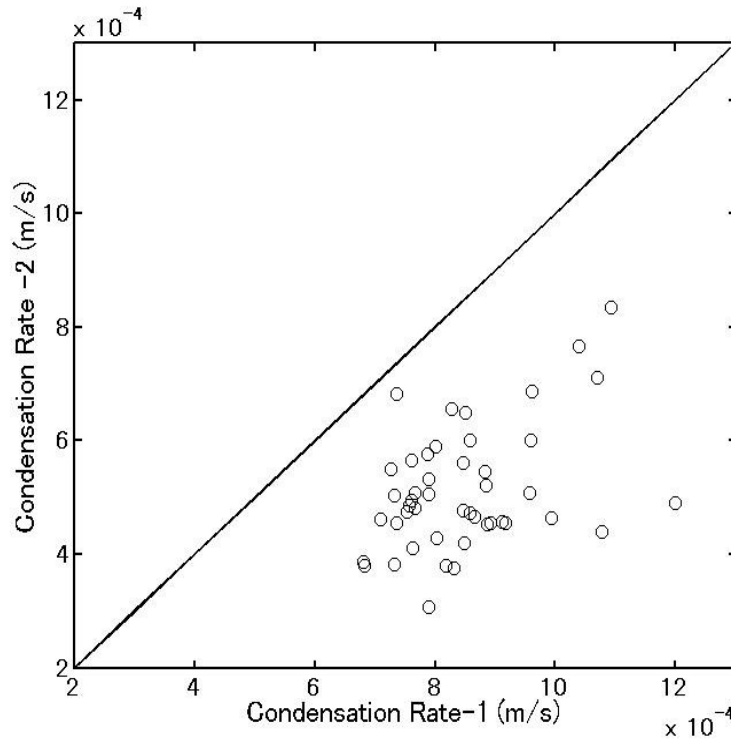
The growth rates of the first bubble and second bubble from the 46 groups of data were also acquired, as shown in Fig. 4.6 (b). The growth rate of a bubble is defined as the increment of the bubble diameter per unit time, the average growth rates of the first and second bubble were 1.10 m/s and 0.86 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. 4.6 (b), most of the dots, lie in the downside of the diagonal line. The reason why the growth rate of the second bubble is



(a) Maximum diameter of first and second bubbles



(b) Growth rate of first and second bubbles



(c) Condensation rate of bubbles

Fig. 4.6 Comparison of bubble parameters of 1st and 2nd bubbles

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 not enough time to recover the wall temperature, so as mentioned above, the growth of the second bubble consumes 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. 4.7 (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.

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. 4.1 (l) (m), this is because the second bubble submerged in the high temperature wake region of the first bubble during its whole lifetime, 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 not 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.

4.4 Conclusion

An experimental study on the bubble behaviors in subcooled flow boiling under relatively high subcooling degrees was carried out. The subcooling degree was above 30 K. The interesting phenomenon of two successive bubbles was observed, and this phenomenon was caused by the severe contraction and elongation deformation of the first bubble when it was growing and departing from the heating wall, the second bubble grows from the remaining vapor of the first bubble after it departed from the wall, and its behaviors were strongly influenced by the first bubble. The quantitative data of the first and second bubble from a group 46 pairs of the two successive bubbles were 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 behaviors of subcooled flow boiling at high degrees of subcoolings. Moreover, the bubble behavior characteristic observed in the present study can also be used as a benchmark for numerical studies on bubble dynamics in subcooled flow boiling at high subcooling degrees.

Chapter 5

Multiple bubble behaviors

5.1 Introduction

In this chapter, the multiple bubble behaviors was discussed, including the interacting behavior between the neighborhood bubbles and also the coalesce behaviors. New bubbles were easier to nucleate at the separation flow region in front of and after the pre-existing bubbles and new bubbles grow larger quickly and will probably coalesce with the pre-existing bubble before departure from the heating wall. Multiple bubbles images of larger view area was also given, variation of multiple bubbles behavior as the heat flux increases was also discussed.

5.2 Coalescence of Bubbles

5.2.1 Coalescence of two bubbles

Fig. 5.1 shows the interacting and coalescing phenomenon of two bubbles which nucleated at the adjacent sites on the heating wall. The experimental conditions were as follows: the mean velocity of the liquid flow in the annular channel of the test section v_m was about 0.45 m/s, the heat flux q applied on the heating wall of heater rod was 185 kW/m², the temperature of the liquid entering the inlet of the test section was 89.5 °C, corresponding to a subcooling degree ΔT_{sub} of 10.5 K. The observation position was about 29 mm downstream from the beginning of the heat section of the heater rod. The system pressure was 1 atm. The elapse time and spatial scale of the bubble images were also marked in Fig. 5.1.

As shown in Fig. 5.1 (a) ~ (c), a bubble first nucleated on the heating wall and

grew bigger rapidly, then a new bubble nucleated at the adjacent position of the heating wall at the downstream side of the first larger bubble, as can be seen in Fig. 5.1 (c), the nucleation site of the new bubble was very close to the position of the first bubble, approximately in the wake separation region of the first bubble. The new bubble grew so quickly that the liquid surrounding the bubble was suddenly pushed away, the first bubble was also pushed strongly by the rapid growing of the new bubble and its downstream side surface was deformed severely, as can be seen in Fig. 5.1 (d) and (e). The deformation at the downstream side surface of the first bubble caused the wave propagating on the surface of the first bubble, as can be seen in Fig. 3 (d) ~ (k), during the process, the shape of the first bubble was irregular and changed severely, and the bubble surface was also wrinkled, because the wave was propagating on the bubble surface. In image (k) of Fig. 5.1, one salient point on the surface of the first bubble first hit the surface of the new bubble, and the two bubbles contacted and coalesced into one bubble finally. The coalesced bubble became an irregular shape and the bubble surface was also wrinkled because of the effect of the coalescing process of the two bubbles, and the wave propagation on the first bubble before coalescence. After coalescence, the bubble was extinguished in the near wall region by the condensation very rapidly. The condensation process was faster than the condensation of one single bubble, because the interacting of the two bubbles, the wave propagation and the coalescing of the two bubbles have an positive effect on performance of the heat transfer between the bubble and the surrounding liquid, so the condensation can be faster, from (d) ~ (k) of Fig. 5.1, it can be seen that the volume of first bubble was reduced by the wave propagation on the bubble surface during the deformation process.

It was found that a new bubble nucleating at the downstream wake separation region of one previous grown-up bubble and the interacting and coalescing phenomenon of the two bubbles were quite common in the experiments, the time of the new bubble nucleating on the heating wall was approximately the moment when the first bubble reached its maximum size, as shown in Fig. 5.1. When the first bubble grew larger and reached its maximum size, some secondary flow or vortex flow can be formed in the

separation flow region of the bubble, so the heat transfer between the heating wall and the near wall flow region can be enhanced by the secondary flow or vortex flow in the

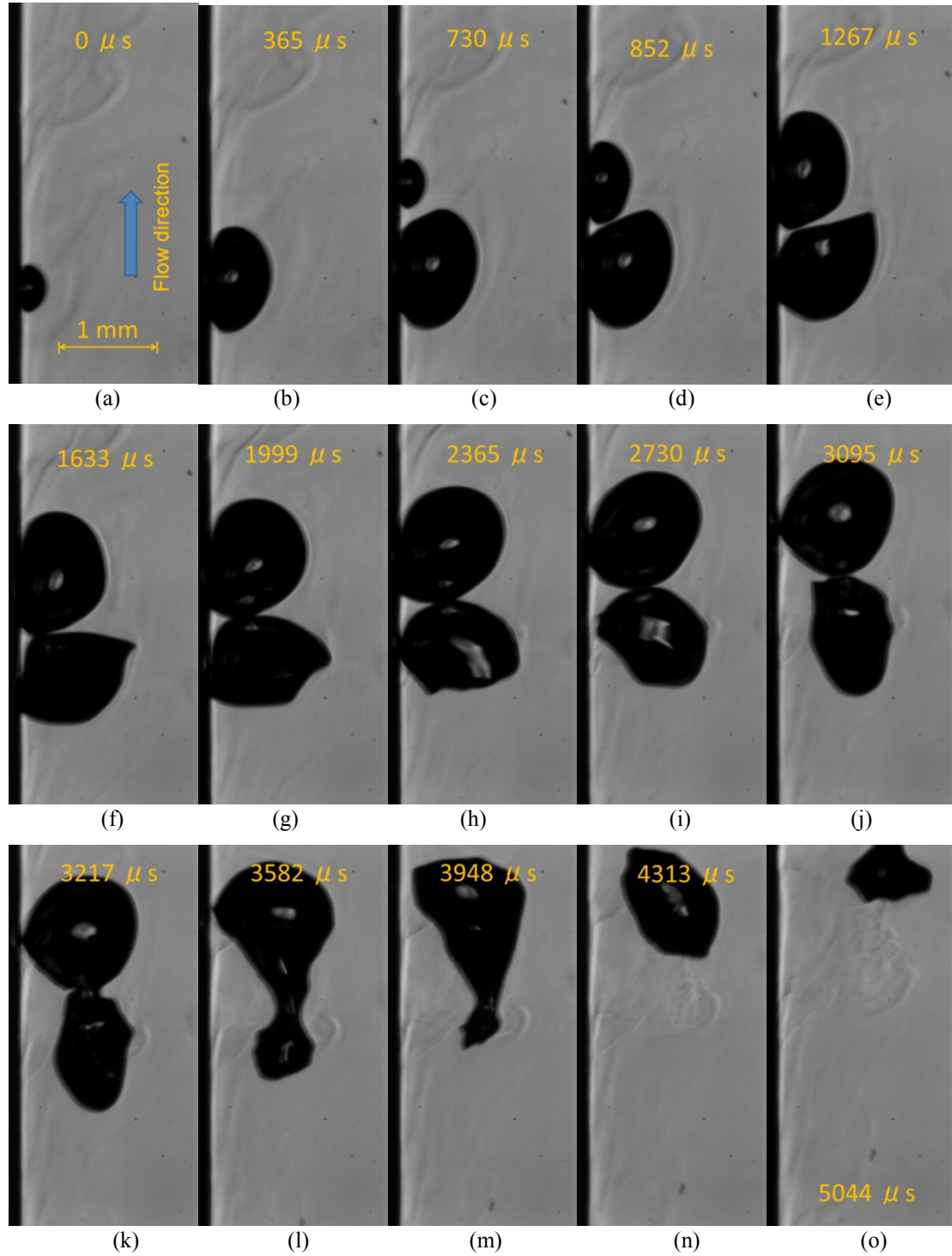


Fig. 5.1 Coalesce phenomenon of bubbles at adjacent sites

ΔT_{sub} : 10.5 K, v_m : 0.45 m/s, q : 185 kW/m²

wake separation region of the first bubble, so the temperature in this region could be increased and the condition for new bubble nucleation become easier to be satisfied, compared with the other near wall region far away from the first bubble. Since the new bubble nucleates at the position quite close to the first bubble and its growth rate is very high, so there is a very high probability that the new bubble and the first bubble will coalesce before they depart from the heating wall. The rapid growth of the new bubble will cause the deformation and wave propagation on the surface of the first bubble. The bubble deformation and wave propagating on the bubble surface can enhance the heat transfer rate between the bubble and the surrounding liquid, that is why the bubble formed by coalescence collapses rapidly in the near-wall region.

5.2.2 Coalescence of more bubbles

In the case shown in Fig. 5.1, a new bubble nucleated at the downstream side separation region of the first bubble, but in some other cases, the new bubbles can even nucleate at the upstream side or both side separation region of a large grown-up bubble.

Fig. 5.2 shows the coalescing phenomenon of three bubbles. The experimental conditions were as follows: the mean velocity of the liquid in the annular channel v_m was 0.31 m/s, the heat flux q applied on the heating wall was 155 kW/m², the subcooling degree ΔT_{sub} at the inlet of the test section was 10.3 K. The observation position was about 30 mm downstream from the beginning of the heating section of the heater rod. As shown in Fig. 5.2 (a) ~ (c), a bubble nucleated on the heating wall and grew up quickly, then a new bubble nucleated on upstream side of the first bubble, as can be seen in Fig. 5.2 (c), and then another new bubble was observed on the downstream side of the first bubble as in Fig. 5.2 (d). The nucleating sites of the new bubbles were very close to the first bubble, and the rapidly growth of the two new bubbles occupied the space of the first bubble and deformed it severely. The bubbles coalesced when they were in the growing regime, much earlier than the two-bubble coalescence cases shown in Fig. 5.1. Finally the three bubbles coalesced into one oblong bubble, whose surface was also very coarse, as shown in Fig. 5.2 (i) ~ (l). Then

the bubble formed by coalescence condensed in the near wall region very quickly as in Fig. 5.2 (l) ~ (p).

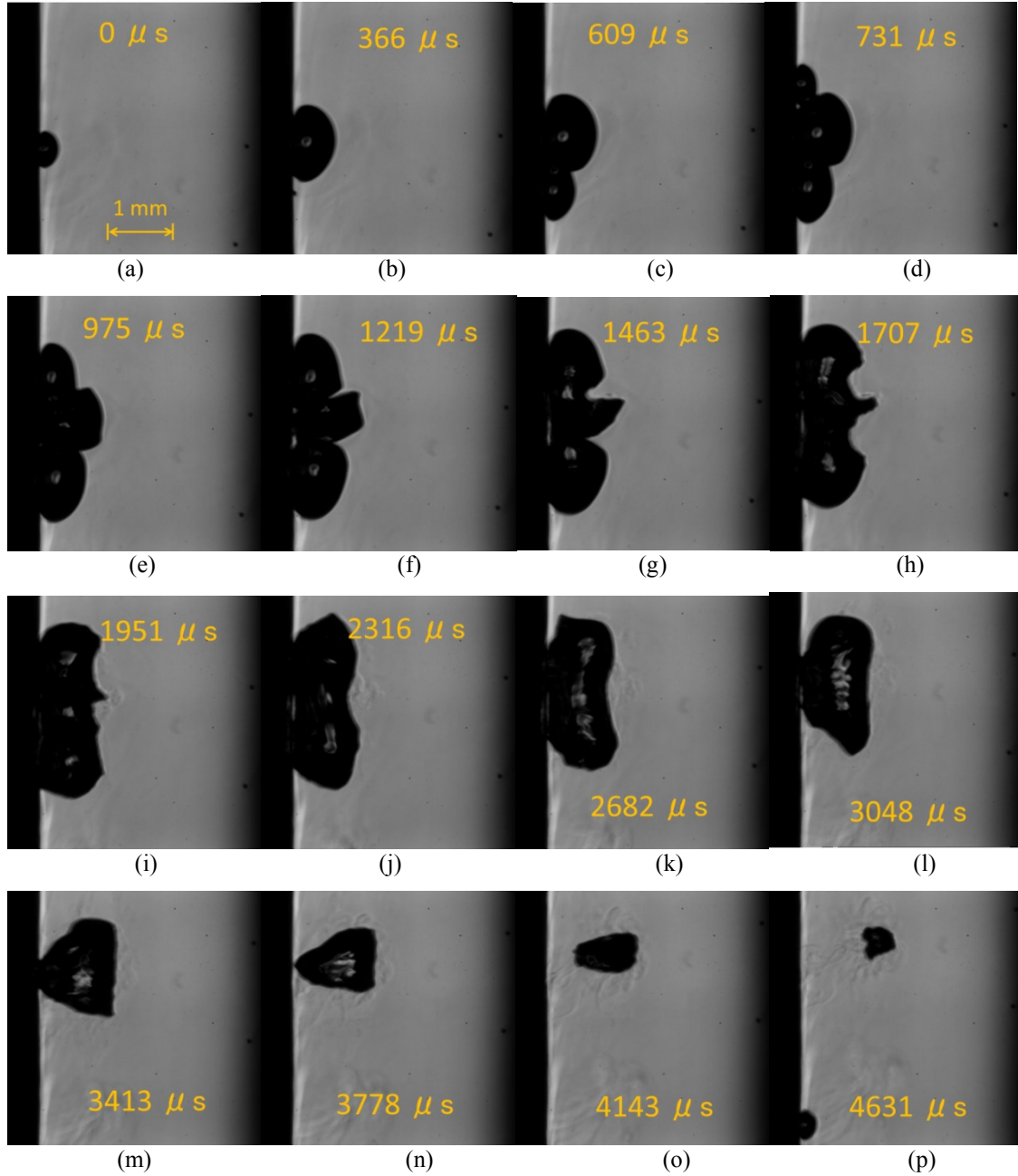


Fig. 5.2 Coalesce phenomenon of three bubbles at adjacent nucleating sites
 ΔT_{sub} : 10.3 K, v_m : 0.31 m/s, q : 155 kW/m²

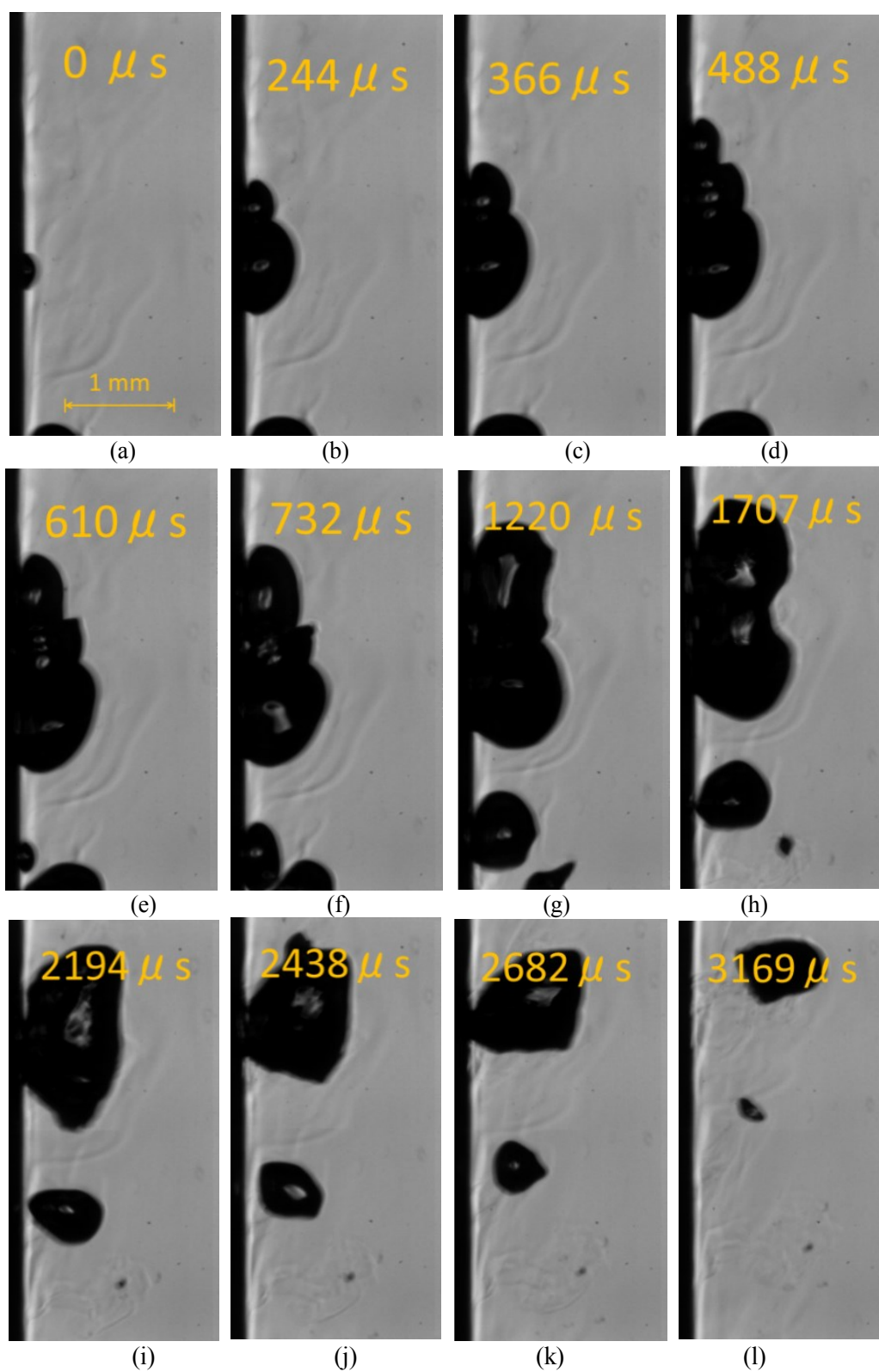


Fig. 5.3 Coalesce phenomenon of three bubbles at adjacent nucleating sites

ΔT_{sub} : 10.2 K, v_m : 0.55 m/s, q : 217 kW/m²

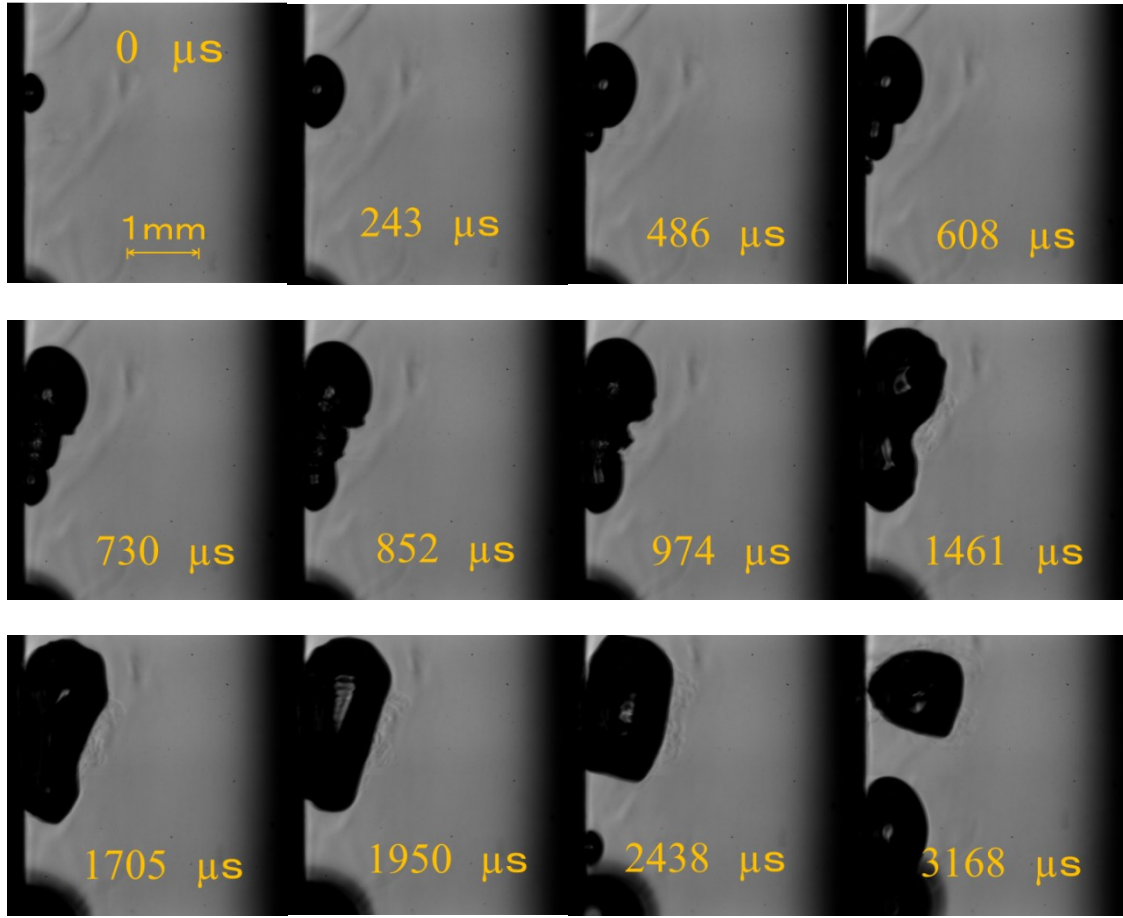


Fig. 5.4 Coalesce phenomenon of three bubbles at adjacent nucleating sites

ΔT_{sub} : 11.2 K, v_m : 0.28 m/s, q : 136 kW/m²

The case shown in Fig. 5.2, in which two new bubbles nucleated at each side of the first grown-up bubble, was observed quite often in the experiments. However, sometimes the new bubbles also nucleate sequentially on the same side of the first bubble as shown in Fig. 5.3 and Fig. 5.4. The images of coalescence phenomenon of three bubbles, where two new bubbles nucleated sequentially on the downstream side separation region of the first bubble was given in Fig. 5.3, the subcooling degree ΔT_{sub} was 10.2 K, mean liquid velocity v_m is 0.55 m/s, and heat flux q was 217 kW/m². Fig 5.4 shows another coalescence phenomenon of three bubbles, where two new bubbles nucleated sequentially in the upstream side of the first bubble, the subcooling degree at the inlet of the test section ΔT_{sub} was 11.2 K, the mean liquid velocity v_m is 0.28 m/s, and heat flux was q 136 kW/m². These phenomena verified directly that the new

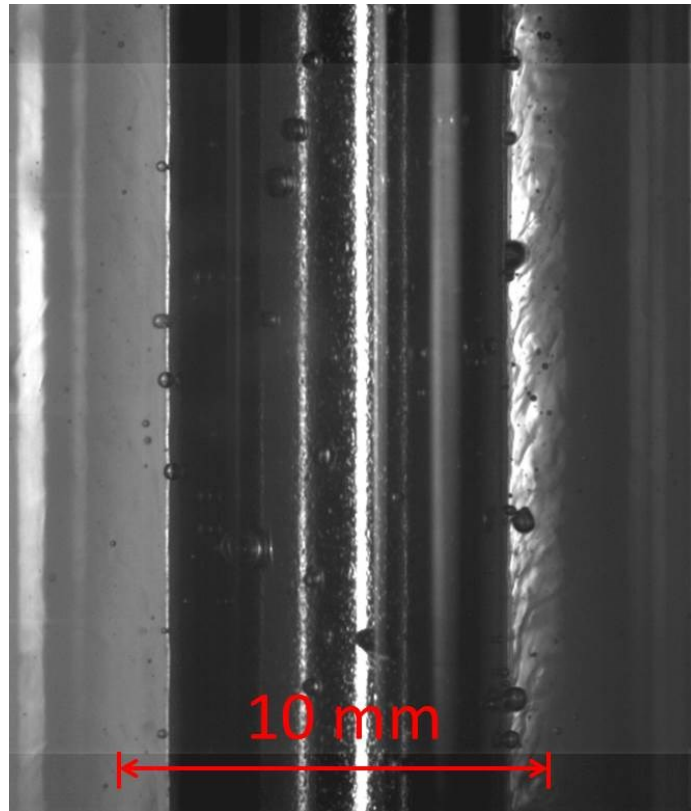
bubbles were easier to be nucleated in the separation region in upstream or downstream side of a large grown-up bubble. The new bubbles can nucleate in downstream and even upstream side separation regions of the first bubble, because the heat transfer between the wall and the liquid in the separation regions is enhanced by the vortex flow existing in these regions, such as the horseshoe vorticity, which exists in front of an obstacle in the fluid flow, might also exist in the upstream of the grown-up bubbles. Since these bubbles nucleate at adjacent sites on the wall, they would coalesce before departing from the wall and form a long plug-shaped vapor clot near the heating wall. This phenomenon of bubbles coalescence and generating the long plug-shaped vapor clot may be considered as one of the precursor phenomena of the Departure from Nucleate Boiling (DNB), which indicates the start of transition from nucleate boiling to film boiling.

5.3 Multiple bubble behaviors at different heat flux

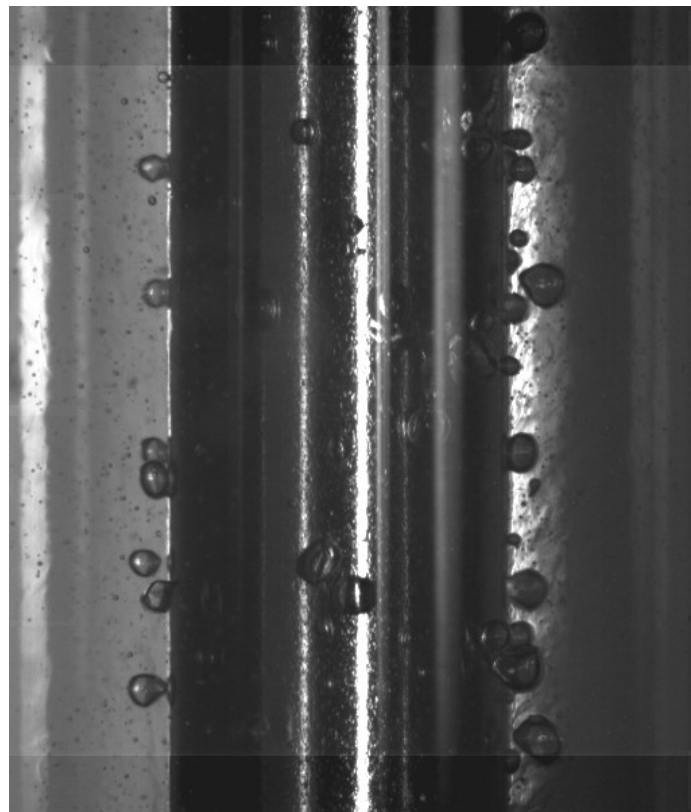
The video images of many bubbles in subcooled flow boiling obtained in a much larger view area was shown in Fig. 5.5, the length scale was given in image (a), the subcooling degree ΔT_{sub} was 21.0 K, mean velocity of liquid in the annular channel was 0.43 m/s and the heat flux applied on the heating wall surface was also given in the sub-title of each image.

In image (a) of Fig. 5.5, the heat flux applied on the heating wall was low, the boiling regime is close to ONB (Onset of Nucleate Boiling) so the bubble size was very small, and nucleation site density is also low, the bubbles slide along the heating wall and cannot departed from the wall. As the heat flux increases, the bubble size is getting larger and the nucleation site density also increase, as shown in images (b),(c) of Fig. 5.5, but the bubbles were still independent with each other, no obvious bubble coalesce phenomena was observed, so this mean the isolated bubble boiling region.

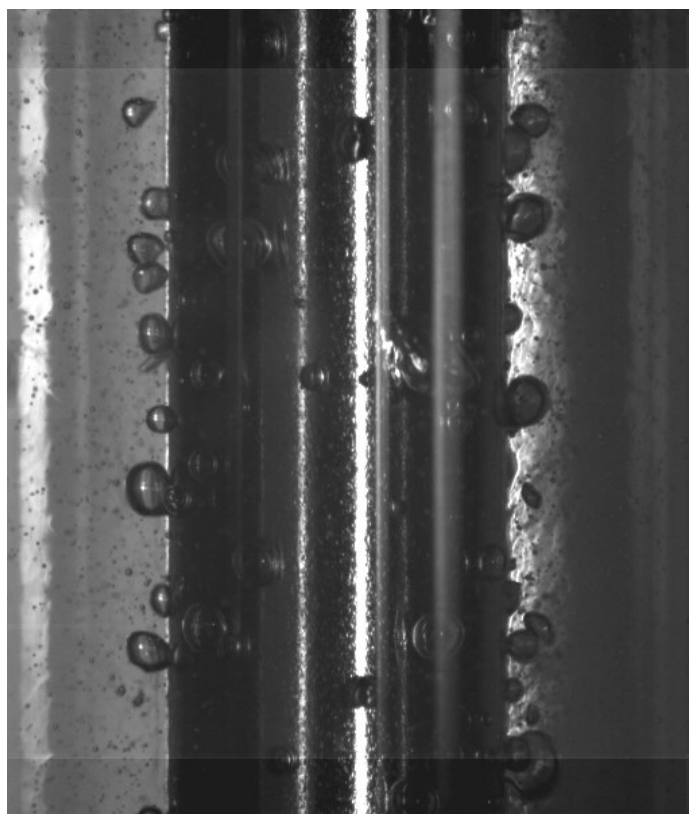
As the heating flux continues to increase, the bubble nucleation site is getting more and more, spreading widely on the heating wall, as can be seen in Fig. (d), (e),



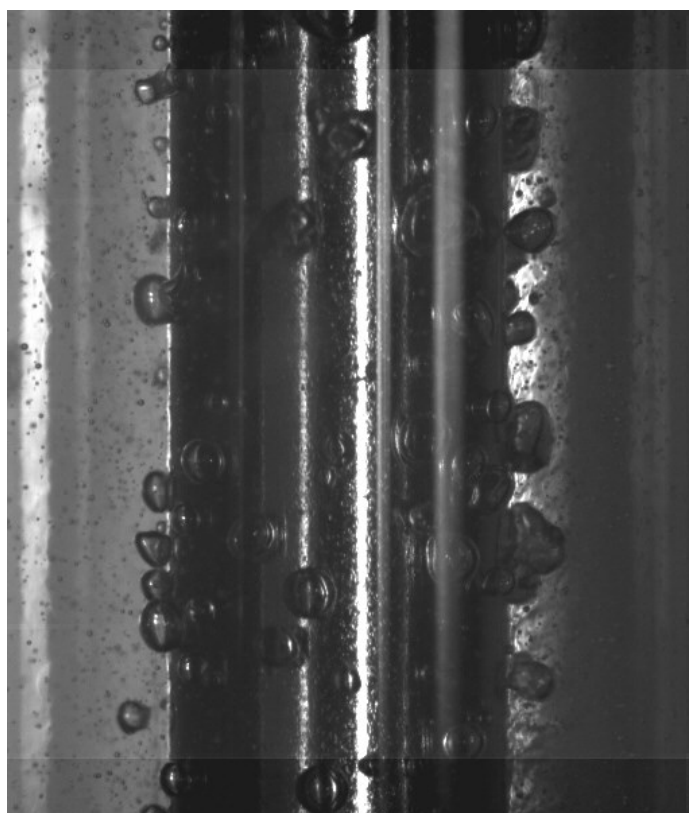
(a) $q: 175 \text{ kW/m}^2$



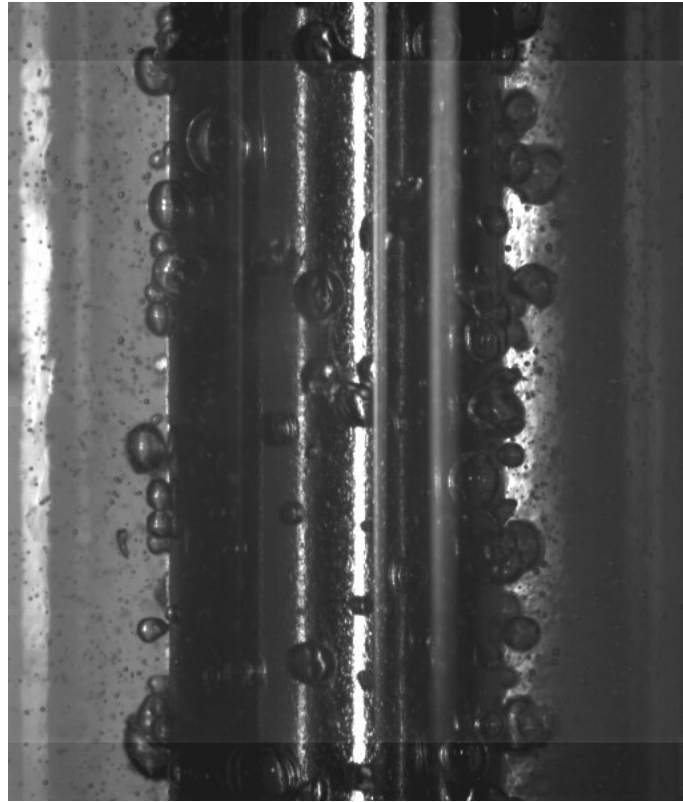
(b) $q: 253 \text{ kW/m}^2$



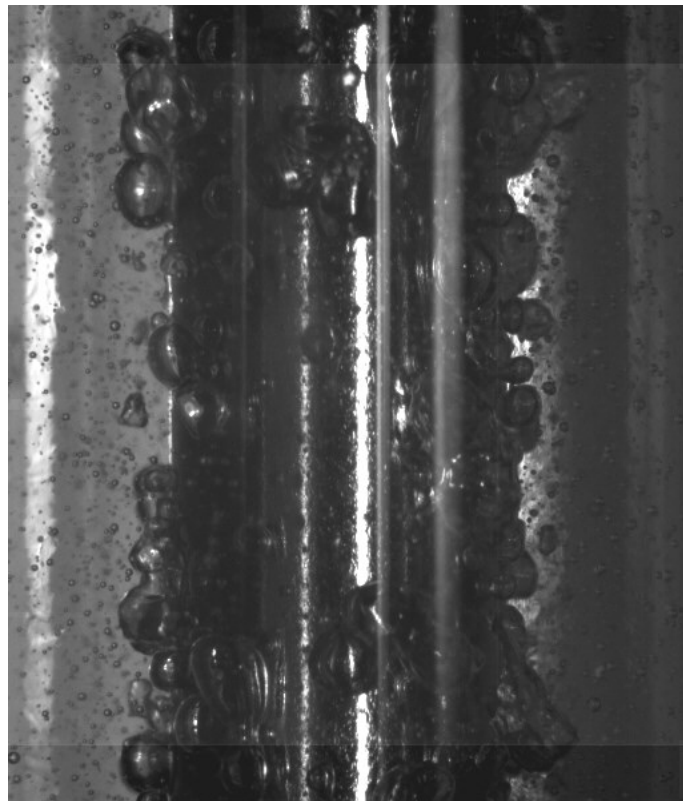
(c) q : 306 kW/m²



(d) q : 345 kW/m²



(e) q : 452 kW/m²



(f) q : 522 kW/m²

Fig. 5.5 Multiple bubble behaviors at different heat flux, ΔT_{sub} : 21.0 K, v_m : 0.43 m/s

Bubble clusters consisting of many bubbles of different sizes can be observed existing in several regions of high nucleation site density on the heating wall, this phenomenon of bubble cluster agrees with the observed phenomena that new bubbles are prone to nucleate in the upstream and/or downstream side separation flow region of a large bubble discussed in the Sec 5.2. The bubble coalesce is getting more and more common, as in Fig. 5.5 (f), the nucleation site density is so high that almost all the bubble coalesced with the neighborhood bubbles when they grew up. Vapor clot generated by the bubble coalescence existed in the near wall flow region before extinction by condensation. The heating wall was almost covered by the vapor clot, so it can be imaged that as the heat flux continues to go up, more and larger vapor clot may generated by the fierce bubble coalescence and finally a vapor layer might be formed by the merging of the vapor clot and all the surface area of the heating wall can be covered by the vapor layer, and then the liquid might be separated by the vapor layer and difficult to re-wet the heating wall, this can cause the occurrence of CHF (Critical Heat Flux). When the CHF occurs, the surface temperature of the heating wall may rise up abruptly to a very high value, and the heater rod can even broke if the surface temperature exceeds the melting temperature of the heater material.

5.4 Conclusion

In this chapter, the interacting and coalescing phenomena of bubbles at adjacent nucleating sites of the heating wall in subcooled flow boiling were investigated by experimental visualization. It was found that when a certain nucleate bubble reaches its maximum size, some new bubbles were often generated in the downstream separation region of that bubble and sometimes even in the upstream of it. The new bubbles grow rapidly and reach its maximum size in a short period before the first bubble departs from the wall. The reason is because the secondary flow or vortex flow generated in the up- or down-streams side of the first large bubble enhances the thermal mixing of the liquid in that region and also the heat transfer performance between the heating wall and

the near wall liquid was also enhanced, the temperature in the separation flow region in up- or downstream side of the first grown up bubble becomes higher so the new bubbles are easier to be generated there, compared with other near wall regions. There is a high probability that the new nucleated bubbles and the first bubble will coalesce before they depart from the heating wall and the coalescence of bubbles forms a long plug-shaped vapor clot near the heating wall, this may be considered as one of the precursor phenomena of the Departure from Nucleate Boiling (DNB) which indicates the start of transition from nucleate boiling to film boiling. The interaction and coalescence of bubbles also causes the wave propagation on the bubble surface and makes the bubble deform strongly. This wave propagating on bubble interface and bubble deformation can enhance the heat transfer between the bubble and the surrounding liquid, so the coalesced bubble collapses rapidly in a short time.

The multiple bubble behaviors were also discussed as the increase of the heat flux from the images of a larger view area. The variation of bubbles behavior from sliding bubbles, isolated bubbles, bubbles coalescence to vapor clot was discussed qualitatively, CHF might be induced if the heat flux continue to increase.

Chapter 6

Conclusions

6.1 Summary of the dissertation

The understanding on behavior characteristic of bubbles in subcooled flow boiling was very important to investigating the forced convection subcooled flow boiling heat transfer, visualization studies on bubble behaviors were carried out, in order to improve the understanding on the behavior characteristic of the bubbles. Numerical simulation of bubble behavior in subcooled flow boiling was also carried out to compare with the experimental results and supply the information which cannot be obtained in experiments. In the first chapter of the present dissertations, the review on boiling studies, including pool boiling and flow boiling was given, emphasis was put on the subcooled flow boiling. In the second chapter, the experimental system, including the water cycling and boiling generation system and high speed video image system was introduced, also the numerical simulation procedure was also given.

The bubble behavior under wide ranges of experimental conditions: subcooling degrees from 5 K to 50 K, mean velocity of bulk liquid flow from 0.14 m/s to 0.8 m/s, were observed and recorded with high spatial and temporal resolutions. Based on the experimental results, the main achievements in each part could be summarized as follows:

1). Single bubble behaviors

The behavior of single bubble in subcooled flow boiling was introduced in Chapter 3. The contents of this chapter can be divided into three parts, the bubble behavior at different subcooling degrees and flow rates, the detailed explanation of bubble deformation on the upstream side surface and the wave propagation phenomena

during the condensation.

The bubble behavior characteristics at different experimental system were found to be quite different. At a medium subcooling degree, the bubble deformation at upstream side bottom of the bubble during its growing and departure period was observed and was attributed to the condensation induced by the thermo-capillary flow of Marangoni effect. Numerical simulation of the bubble behaviors in subcooled flow boiling was also carried out to provide the evidence for the proposed explanation of bubble deformation mechanism. At high subcooling degrees, contracting deformation was observed in the bottom of the bubble, and very thin and long bubble bottom was formed when the bubble was lifting off from the heating wall, the phenomenon of two successive bubbles was also observed. At high subcooling degrees and high flowrates, bubble was strongly pushed by the incoming liquid flow and concave deformation in the middle of bubble upstream side surface was observed. At low subcooling degrees, the bubble shape was very close to a sphere, only very weak deforming phenomena was observed, bubble behaviors at different flow rates are quite similar, only bubble size were affected by the flow rate.

The wave propagation phenomenon during the condensation process was found to be very common. The wave propagation makes the surface area of bubble being much larger than the surface area of a spherical bubble with the same volume, and also the bubble surface was highly vibrated and deformed by the rapid wave propagation, so the heat transfer performance between the bubble and the bulk subcooled liquid can be enhanced. Therefore it is reasonable that bubble condensation rate was enhanced by the wave propagation on bubble surface.

2). Phenomena of two successive bubbles

The phenomenon of two successive bubbles was observed in subcooled flow boiling of high subcooling degrees, and it was caused by the severe contraction and elongation deformation of the first bubble when it was departing from the heating wall, the second bubble grows from the remaining vapor of the first bubble after it departed from the wall, and its behaviors were strongly influenced by the first bubble. 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 also slower than the first bubble. The deformation of the second bubble when lifting off from the heating wall was not so severe as that of the first bubble, because the second bubble submerged in the wake flow of relatively high temperature of the first bubble.

3). Multiple bubble behaviors

Behaviors of multiple bubbles were also investigated. It was found that new bubbles were prone to nucleate at the separation flow region in upstream or downstream side of a pre-existing large grown-up bubble. Since the nucleation sites of the new bubbles are very close to the pre-existing bubbles, so there is a high probability that the new nucleated bubbles and the pre-existing bubble would coalesce before they depart from the heating wall and the coalescence of bubbles forms a long plug-shaped vapor clot near the heating wall, this may be considered as one of the precursor phenomena of the Departure from Nucleate Boiling (DNB) which indicates the start of transition from nucleate boiling to film boiling.

6.2 Recommendation for the future work

Although the studied on bubble behaviors in subcooled flow boiling has been conducted by many researchers, it is still necessary to continue the research work because of its importance in understanding the mechanism of flow boiling heat transfer. the future research work should be carried out in the following aspect:

1). More experiments should be conducted in larger ranges of conditions

From review of the literature, it can be known that most of the research work were only carried out at a narrow range of working conditions, so it is insufficient for understanding completely the bubble behaviors and heat transfer mechanism of subcooled flow boiling and it is difficult to establish the reliable models or correlations based on the limited experimental data.

2). Method of accurate temperature measurement

The temperature distribution and variation information at the heating wall and in

the thermal boundary layer is very important to investigate the bubble behaviors, however, the accurate temperature measurement is difficult in visualization experimental system, since the installation of the thermal couple can have an impact on the flowing and temperature field and even the bubble behavior, for reducing the influence thermal couples with very thin probe is needed.

3). Numerical approach needs to be improved

The numerical simulation is an very important tool for studying the bubble behaviors, since the velocity and temperature information which is very difficult to measure in experiments can be obtained directly in simulation results. However, limited by the capability of the computers, the 3 dimensional simulation is difficult even for one single bubble, numerical code of parallel computation should be developed. In addition, phase change model should be modified for accurate simulating the evaporation and condensation processes, e.g. incorporating the micro-layer evaporation model.

4). Experiments with other working fluid

Most of the experimental studies on bubble behaviors used the water as working fluid, however, bubble behaviors of other working fluids should also be investigated and compared with bubble behaviors of water for clarifying the effect of physical properties of fluids on bubble behaviors.

Nomenclature

Latin

C_{pl}	Specific heat of liquid
F_i	Volume fraction of the i th fluid
F_V	Volume force of surface tension
G	Gravity
h_{lg}	Latent heat
n	Normal vector of the interface
P	Pressure
P_{sat}	Saturation pressure
Q	Heat source term
q	Heat flux
T	Temperature
t	Time
ΔT_{sub}	Degree of subcooling
u	velocity
v_m	Mean velocity
v	Specific volume
v_l	Specific volume of liquid

Greek

θ	Contact angle
ρ	density
ρ_l	Liquid density
ρ_g	Vapor density
τ	Viscous stress tensor

κ	curvature
φ	Material properties of liquid or vapor

Subscript

g	Vapor/gas
l	Liquid
v	Vapor
sat	Saturation
sub	Subcooling
m	Average value
n	Normal direction
t	Tangible
w	wall