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Visualization study on bubble dynamical behavior in subcooled flow boiling under various subcooling degree and flowrates

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ABSTRACT

An experimental study was conducted to investigate the characteristics of bubble dynamical behavior in subcooled flow nucleate boiling in an upward annular channel. The bubble dynamical behavior under wide ranges of subcooling degrees (ΔT_{sub} = 5–50 K) and flowrates (v_m = 0.1–0.8 m/s) were observed and recorded with high spatial and temporal resolutions by using a high speed video camera and a Cassergrain microscopic lens. The bubble behaviors at different subcooling degrees and flowrates were found to be quite different. At a medium subcooling degree, the bubble deformation at upstream-side interface during its growing and departure period was observed and was attributed to the condensation caused by the cold liquid coming from the subcooled bulk flow. At high subcooling degrees and low flowrates, contracting deformation was found in both upstream and downstream bottom of the bubble, the phenomenon of two successive bubbles was also observed. At high subcooling degrees but high flowrates, bubble was strongly pushed by the incoming liquid flow and concave deformation in the middle of bubble upstream-side interface was observed. At lower subcooling degrees, bubble behaviors at different flowrates are quite similar. The bubble shape was very close to a sphere, only very weak deforming phenomena was observed.

1. Introduction

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 microprocessors. The high heat transfer efficiency 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.

Subcooled 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 [1,2], heat transfer characteristic at various boiling regimes [3–5], the critical heat flux (CHF) [6–9].

The bubble dynamical 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 is necessary, because the size of bubble in subcooled flow boiling is in millimeter scale and its lifetime is about several milliseconds.

An investigation of forced-convective subcooled nucleate boiling was carried out by Bibeau and Salcudean [10] using high speed photography. Experiments were performed using a vertical circular annulus at atmospheric pressure, for mean flow velocities of 0.08–1.2 m/s and subcoolings of l0–60 K. They found that bubbles detach from the nucleation site and start to slide almost immediately after nucleation, then it detach from the heated wall as they are ejected into the flow. Bubbles become elongated in the vertical

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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 ejection. The bubble diameter at ejection is smaller than the maximum diameter, since the bubble condenses on the wall while sliding.

Thorncroft et al. [11] carried out experimental investigations on characteristics of bubble growth and detachment over a commercially finished nichrome heating surface in both vertical upward and downward channel using FC-87 as working fluid. The liquid flow was slightly subcooled (ΔT_{sub} = 1.0–5.0 K). They found that the 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. However, in the downward flow, the bubbles either lift off directly from the nucleation sites, or firstly slide and then lift off, depending on the flow and thermal conditions.

Prodanovic et al. [12] carried out experimental studies on subcooled flow boiling in an upward annular channel over a wide range of experimental conditions. The bubble behavior was captured by a high speed camera at frequencies of 6000–8000 frames per second. Bubble growth rate and condensation rate, variation of bubble lifetime and size with flow rate, subcooling, heat flux and pressure were examined. New correlations for the maximum diameter, detachment diameter, and bubble lifetime have been proposed. In another study of Prodanovic et al. [13], they attempted to relate the boiling heat transfer process and the transition from partial to fully developed boiling with bubble behavior. Within the partial nucleate boiling region, bubbles barely change in size and shape while sliding a long distance on the heater surface. The bubble growth rates increase significantly with increasing heat flux, or reducing flowrate. Bubbles slid during growth regime, then detach from the heater, and finally collapse in the bulk fluid. 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.

Maurus et al. [1] conducted experiments on subcooled flow boiling of water in a test section of horizontal rectangular channel heated from one side by a copper strip. They used a high speed camera and a low-speed high-resolution camera for capturing the images of bubbles from two directions. The high speed camera recorded the dynamical behaviors of bubble growth, detachment and collapse while the low speed camera from the perpendicular view acquired additional data like number of bubbles, bubble size and density distribution, average spacing of bubbles and local vapor content. They found that 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. In their later research [14], 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 bubble behaviors were also affected by the temperature profile in the thermal boundary layer and the turbulent intensity.

Subcooled flow boiling of water was investigated in a vertical annular channel by Situ et al. [15]. The highest subcooling degree was 6.6 K, and liquid velocities were set to be around 0.5 m/s in their experiments. 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. 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 [16], they found that bubble lift-off diameter increased with increasing the inlet temperature and heat flux and decreasing inlet fluid velocity by investigation on bubbles of 91 test conditions. A force balance analysis of a growing bubble was also performed to predict the bubble lift-off size.

Bubble dynamics in water subcooled flow boiling was investigated by Ahmadi et al. [17] 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.

Other studies on dynamical parameters and behaviors of bubbles in subcooled flow boiling have also been conducted in recent years [18–22]. These research works reviewed above have studied the bubble dynamical behaviors under various experimental conditions and in various boiling regimes. Correlations and models were also proposed to predict the bubble dynamical parameters. In the present study, the characteristics of bubble dynamical behavior in subcooled flow boiling of water under wide range of subcooling degree and flowrate were studied by using a high speed video camera and Cassegrain microscopic lens, several interesting phenomena of the bubble were observed for the first time. The bubble behaviors at low, medium and high subcooling degrees were compared and were found to be quite different, meanwhile, the effect of flowrates were also analyzed.

2. Experimental apparatus

An experimental system has been built for studying the bubble dynamical 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 l, which is large enough for storing sufficient amount of working fluid and keeping the water temperature stable 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 1000 mm long vertical annular channel consisting of a transparent round tube made of acrylic resin with an insides 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