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Visualization study of bubble behavior in a subcooled flow boiling channel under rolling motion

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A B S T R A C T

Boiling heat transfer equipment in a vessel can be affected by the additional force which is generated by the rolling, swing and heaving motion of the vessel. Bubble behavior is very important for the research of boiling phenomenon. Bubble behavior under rolling motion condition is experimentally studied by using a high speed camera. The experiment is conducted in a subcooled flow boiling rectangular channel, and the cross section size of the channel is 2 mm $\times$ 40 mm. Two types of bubbles with large discrepancies in sliding and condensation behaviors can be observed in the captured images. The first type bubbles disappear quickly after generation and the slide distance is only a few times of bubble maximum diameter, while the second type bubbles can survive a longer time after leaving the nucleation site and slide for a long distance with the flowing fluid. Bubble characteristics under rolling motion are separately studied for different type bubbles based on the above reasons. The results show that the lifetime, maximum diameter, nucleation frequency and sliding velocity of the first type bubble are periodically fluctuated and the period is same with the rolling motion. The fluctuation intensity of the bubble lifetime and maximum diameter can be enhanced by the increase of the rolling amplitude. The peak value of bubble lifetime, maximum diameter, and nucleation frequency appears when the rolling platform plate rolls to the maximum positive angle, while opposite trend can be observed in the variation of bubble sliding velocity. In view of the characteristics of the second type bubbles, lifetime and maximum diameter are not measured. And the variation of nucleation frequency and sliding velocity of the second type bubbles under the effect of rolling motion is same with the first type bubbles. Furthermore, the effects of additional force, variation of local pressure and flow rate oscillation on bubble behavior are analyzed. The results indicate that the fluctuations of the bubble parameters can be generated by the variation of local pressure caused by rolling motion even no influential flow rate fluctuation occurs. The effect of the acceleration variation vertical to the heated surface on bubble behavior is unclear and need more researches in the future work.

1. Introduction

In the research of the subcooled flow boiling, bubble behaviors not only decide the performance of the heat transfer and the pressure drop of the channel, but also affect the boundary of the flow instability and the thermal neutron flux level in a nuclear reactor core. Heat transfer characteristics of the devices in ship power equipment under the effect of additional force caused by ocean condition are different from that of the land based devices. Numerous researchers had done many studies on the flow resistance, heat transfer coefficient and natural circulation capacity under rolling, heaving and inclination condition using many methods, such as experimental study, theoretical analysis and numerical simulation (Isshiki, 1966; Ishida et al., 1990; Murata et al., 2002; Si-chao et al., 2009a,b; Yan et al., 2011; Wang et al., 2013; Xing et al., 2013a,b). Both single phase flow and two phase flow were studied.

The study of bubble behavior was driven by the curious on the boiling phenomenon itself and the need to identify the heat transfer ratio of the subcooled boiling. Other reason for the study of the bubble behavior was the development of the two-fluid-model, which can offer more accurate analysis for two phase flow system. Bubble information was required to construct the transport equation of the two-fluid-model, namely the interfacial area transport equation and bubble number density transport equation (Ishii and Hibiki, 2005). The study of the bubble behavior in a subcooled flow boiling was related to the bubble nucleation, growth, departure and lift-off, condensation and interaction among bubbles.

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Bubble nucleation density and nucleation frequency has been studied by many researchers through experiment and theoretical analysis (Hibiki and Ishii, 2003; Situ et al., 2008; In-Cheol et al., 2011). Growth of a bubble near a heated surface exhibits two stages, where the first is a very rapid, inertia-controlled growth and the second is a heat-transfer-controlled process (Carey, 2008). Analytical treatments of heat-transfer-controlled bubble growth in the non-uniform temperature field near a superheated wall have been presented by Zuber (Zuber, 1961) and Mikic and Rohosenow (Mikic et al., 1970), in which Zuber's correlation has been widely applied in many predication models. Bubble departure diameter and/or lift-off diameter are two of the key parameters in the source and sink terms of interfacial area transport equation of bubbly flows. Models based on bubble force balance to determine these two diameters during subcooled flow boiling have always been the subject of numerous investigators (Klausner et al., 1993; Situ et al., 2005; Cho et al., 2011). Shrinking and collapsing of vapor bubbles can be observed after they depart from the heated surface and eject into the subcooled bulk flow. Warrier (Warrier et al., 2002) has combined the correlation of forced convection cooling around a solid sphere and the experimental data of subcooled flow boiling to develop a mechanistic model for the bubble condensation process. Some other correlations of the bubble condensation have also been proposed by Kalman (Kalman and Mori, 2002) and Kim (Kim and Park, 2011). Summarized these mentioned researches, a common point could be found that all of them were carried out under normal and uniform gravitational field, which means only land-based channel considered.

Some works on bubble behaviors under ocean condition had been conducted by researchers because of the demand for the development of power system on vessels. Qin (Qin and Gao, 2008) calculated the bubble forces under rolling motion and pointed out that the effect of additional force may be neglected when comparing with other forces acting on bubbles. But they noted that the fluctuation of flow rate caused by additional force was obvious in a natural circulation system. Thus the rolling motion has great influence on bubble departure and lift-off due to the variation of bubble forces associated with flow velocity. Wei (Wei et al., 2011) used numerical simulation based on VOF (Volume-of-Fluid) method to study the bubble behaviors in subcooled flow boiling in a rectangular channel under rolling motion. A similar bubble force analysis of Qin (Qin and Gao, 2008) was adopted to evaluate the effects of additional force. The results implied that the fluctuation of mass flow rate under rolling motion has more influences on shear lift force, drag force and hydrodynamic pressure force acting on bubbles. Thus the bubble sliding and detachment, the heat transfer near heated wall and the pressure drop under motion condition would fluctuate and different from that of static condition eventually. In the calculations of bubble forces in Qin's and Wei's research, the flow rate fluctuation amplitudes were 4.4% and 60%, respectively. Forced convection subcooled flow boiling experiments under heaving motion were conducted by Hong (Hong et al., 2012a,b) to assess the potential effects of ocean condition on bubble characteristics. Bubble size, bubble velocity and bubble number density was statistically analyzed under various having conditions and at different flow rates in order to gather more bubble information recorded in the experiments. An increase of the oscillation frequency would cause an increase fluctuation of the above three bubble parameters. And the fluctuation of bubble size and bubble velocity was weakened by increasing mass flow rate. A correlation based on the experimental data has been fitted to describe the effects of heaving motion on the fluctuation of bubble size. Subsequently, Hong (Hong et al., 2012a,b) discussed the bubble departure size under heaving condition. The results indicated that bubble departure size was affected by additional heaving acceleration and flow rate fluctuation. By considering the additional force and the flow rate fluctuation caused by heaving motion, a model to predict the bubble departure diameter under heaving condition was proposed. Hong's works mentioned above were conducted in a narrow rectangular channel near atmosphere pressure, in which the flow rate fluctuation could be 3.9–6%. Bubble number density and bubble size in an up-flow subcooled flow boiling channel under rolling motion was experimental studied by Li (Li et al., 2014) by using the high speed camera in combination with the digital image processing technology. The experimental results indicated that bubble number density and bubble size periodically fluctuated under the effect of rolling motion and the period of the fluctuation was identical with that of rolling motion. Compared to smaller fluctuation amplitude of the mass flow rate (less than 1%), the fluctuation of the bubble parameters was rather obvious (about 50%). Therefore, the main reason for bubble behavior fluctuations could be ascribed to the fluctuation of the effective wall superheat induced by the variation of wall temperature and local pressure.

Although a number of investigations performed on bubble behaviors, most of them were carried out under static state condition for land-based application. To expand the understanding on the effect of ocean condition, the existing achievements are still insufficient. In addition, more experiments under rolling condition should be conducted to validate the numerical simulation results. In this paper, a visualization experiment on bubble behaviors under rolling motion during subcooled flow boiling is carried out to explore the general influence of rolling motion on bubble behaviors.

2. Experimental setup

2.1. Experimental loop

The experimental loop used in this study was composed of a main circulation flow loop and a cooling loop, as indicated in Fig. 1. The part circulated by the dashed line was fixed in rolling platform to simulate the effect of ocean condition. The main flow loop was a closed loop which consisted of a rectangular test section, an electrical heated preheater, a condenser, a centrifugal pump with 45 m pressure head and a pressurizer. Deionized water was used as the working fluid in this experiment and a primary degasification process was completed before injecting the water into the main flow loop. The test section was a single-side heated visualization rectangular channel, which was formed by a stainless steel heated plate and a rectangular groove etched on a quartz glass. The vertical length of the test channel was 550 mm and the cross-sectional area was $2 \times 40\ mm^2$. For the purpose of eliminating the heat losses to the environment, the backside of the test section was surrounded by some thermal insulation materials. Furthermore, experimental raw data are collected only if the differences between the calculated and measured exit fluid bulk temperatures are less than ±5%. A wide range of heat fluxes was supplied to the test channel with a DC power through two copper electrodes welding on the heated plate, and the heat flux could be measured by the ratio of the heat power (obtained by the product of the voltage and current across the heated plate) and the area of active heating surface. The heated surface temperature was detected by ten N type shielded thermocouples with 1 mm outer diameter which were calibrated by a standard mercury thermometer before embedded in the outer surface of the heated plate.

The main function of the preheater was to adjust the inlet fluid temperature of the test section to a desired value. Besides, a secondary degassing process was completed using the preheater through boiling the water into saturation state. The non-condensable gas could be removed by opening the vent of the experimental loop, which was located at the outlet of the test section. Steam-water mixture generated from the boiling channel was then condensed into single-phase water in the condenser. The