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Measurement of sliding bubble behavior on a horizontal heated tube using a stereoscopic image processing technique

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ABSTRACT

The significance of the sliding bubble effect on boiling heat transfer has been reported by a number of precedent studies through experiments and numerical analyses. However, the experimental data and mechanistic boiling heat transfer models considering sliding bubbles on horizontal tube outer surfaces are insufficient. In the present study, therefore, the behavior of sliding bubbles on a horizontal tube heater is measured at nearly saturation temperature and atmospheric pressure for various flow conditions; liquid velocity (14.7–27.6 mm/s), wall heat flux (67–129 kW/m^2), and the location of nucleation site (45° and 90° from the bottom of the heater). A thin film heater with a narrow heating strip was proposed to generate boiling bubbles in a restricted region on a horizontal heater. This improved the quality of the visualization of the sliding bubbles. Two synchronized high-speed cameras were used to capture the behavior of the bubbles from two perpendicular measurement angles. The configurations of the bubbles were identified by an image processing method based on shadowgraphy from the two images, and the results of the image processing elicited various boiling bubble parameters, such as the bubble diameter transient, bubble velocity, bubble frequency, etc. In particular, the volume of the nonspherical bubble was measured by a three-dimensional reconstruction method which defines a specific cross-section configuration at each elevation using stereoscopic images. Two verification steps confirmed that the reconstruction method has allowable errors and also indicated the limitation of the monoscopic visualization method for deformed bubble measurement. According to the result of this measurement, the location of the nucleation site is a principal factor affecting the life cycle of a sliding bubble on a horizontal tube. Under the present experimental conditions, a bubble generated on the lower half of the tube showed the lift-off from the heating surface twice during its life cycle; the first is due to the contact pressure force and the inertia of the surrounding liquid caused by bubble shape change shortly after the nucleation, and the second is mainly due to the lift force after being accelerated by the sliding motion. In contrast, bubbles occurring at the side of the tube did not show sliding motion, but rather rose without confinement by the wall after the lift-off. The effects of the bulk liquid velocity and wall heat flux on bubble behavior were investigated and the results are discussed in this paper. This experimental observation can be used to improve understanding of the boiling heat transfer mechanism on a horizontal tube and the bubble dynamics of a sliding bubble on a downward heating surface.

1. Introduction

Boiling bubble behavior on heating surfaces has been studied intensively in the field of engineering to accumulate knowledge of the boiling heat transfer mechanism and to develop a better model based on the bubble dynamics. There has been significant progress in the study of two-phase flow and boiling heat transfer with advances in the experimental techniques and modeling capability with CFD (Computational Fluid Dynamics). The advanced experimental instruments, such as high-speed cameras, PIVs (Particle Image Velocimetry), infrared cameras, etc., enable the production of high-resolution local information of boiling bubble behavior, such as bubble configuration, velocity, and bubble-wall interaction (Okawa et al., 2005; Duan et al., 2013; Yoo et al., 2014; Jung et al., 2016; Chu et al., 2016). In conjunction with these improvements in experimental techniques, various attempts have been made to predict the boiling heat transfer using a CFD code in a mechanistic approach by considering the bubble behaviors on the heating surface, such as departure, lift-off, and sliding (Kurul et al., 1990; Sateesh et al., 2005; Luke et al., 2000; Sugrue et al., 2014). However, these experimental and modeling efforts have been principally focused on horizontal plates or vertical channels, and not many studies have

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been conducted for the outer surface of a horizontal heater in spite of its practical importance in heat exchanger design and analysis.

In particular, an advanced pressurized light water nuclear reactor APR+ (Advanced Power Reactor +) incorporates a passive auxiliary feedwater system, which supplies feedwater to a steam generator using gravitational force and natural circulation without any electrical power for active driving mechanisms (Kang et al., 2012). This system includes a horizontal tube bundle submerged in a large water pool. Boiling occurs outside of these heat exchanger tubes by the heat transferred from the tube, where high pressure steam condensation occurs. For this reason, understanding of the boiling heat transfer on a horizontal tube surface became an important issue to evaluate the performance of the passive system of the advanced nuclear reactor (Jeon et al., 2015). This background motivated the present study to visualize a boiling bubble and its sliding motion on a horizontal heater.

A simulation of boiling heat transfer using the two-fluid model (or time-averaged model) of a CFD code, requires the boiling heat transfer model to evaluate the phase change rate under given flow and wall conditions. The widely accepted boiling heat transfer model for CFD codes is the heat partitioning model (or RPI model) proposed by Kurul et al. (1990), which decomposes the boiling heat transfer into three mechanisms; evaporation, transient heat conduction, and single-phase convection. Since its development, a number of modifications were made for this model to improve its accuracy and applicability. For example, Basu et al. (2005) proposed a modified heat partitioning model with the addition of a heat transfer term influenced by a sliding bubble. However, most of these models were developed and validated for plates or vertical channels and few models are available for a horizontal tube outer wall boiling bubble. Sateesh et al. (2005) proposed a modified heat partitioning model applicable to not only vertical plates, but also a horizontal tube. The model considers the sliding bubble motion and the resulting thermal boundary layer disruption, and it was validated against two horizontal tube boiling experiments performed by Barthau and Hahne (2000) and Luke and Gorenflo (2000). Luke and Gorenflo (2000) also proposed heat partitioning model considering bubble sliding motion of a horizontal tube.

The key submodels of these heat partitioning models are related to bubble behavior, including the bubble growth, departure, sliding, and lift-off, since they affect the boiling heat transfer significantly. The understanding of this boiling bubble behavior, therefore, is a crucial factor in predicting the boiling heat transfer rate accurately. Since the bubble parameters are determined by competition among forces exerted on the bubble, predicting these parameters using the force balance equation has been endeavored. Klausner et al. (1993) proposed a widely accepted bubble force balance model under the saturated forced convection condition on a horizontal plate. The forces acting on an asymmetric single bubble were analyzed with bubble configuration and flow conditions and the bubble departure and lift-off diameters can be predicted as a result. This model is applicable to both pool boiling and flow boiling conditions, and was validated based on data from tests performed with refrigerant R113 as the working fluid. Yeoh and Tu (2004) extended Klausner's force balance model to a vertical heating surface and applied the modified model to a CFD simulation of subcooled boiling at low pressure in a vertical annulus channel. Yun et al. (2012) improved the force balance model to extend its applicability to subcooled boiling at high pressure in a vertical pipe. Recently, Surge et al. (2014) established and extended the force balance model to predict the bubble departure and lift-off at various surface orientations. However, further investigation and validation are required in order to extend its applicability to a horizontal heat exchanger tube because most of the validation works have been conducted with plate geometries or vertical channels.

Table 1 summarizes experimental efforts to visualize the boiling bubble behavior on a heating surface and its condensation after lift-off. Thorncroft et al. (1998) examined the boiling phenomena on a vertical heating surface in the upward and downward forced convection conditions, as well as pool boiling conditions. The bubble growth, departure, lift-off, waiting time, etc. were measured using a high-speed camera. The bubble growth and its deformation during sliding were observed furthermore. Situ et al. (2005, 2008) also measured various bubble behavior parameters from the side in parallel with the heater and proposed correlations for the parameters with respect to flow conditions.

Recently, there are some previous studies which applied a stereoscopic method, which observes a single object in different directions, in order to consider the deformation of sliding or rising bubbles (Zaruba et al., 2007; Murai et al., 2001; Maurus et al., 2004; Fujiwara et al., 2004; Bian et al., 2013). These works pointed out the limitation of the monoscopic observation method when it was applied to a nonspherical bubble. Okawa et al. (2005) observed a sliding bubble inside a vertical cylindrical tube using two synchronized cameras installed in the tangential and normal directions to the heating surface. The shape of a bubble was considered to be an ellipsoid which has three different axis lengths obtained from two images. Yoo et al. (2014) investigated the bubble behavior on a vertical plate under forced convection conditions. According to this observation at the moment of bubble departure, the bubble shape in the image obtained from the view parallel to the heating surface approximates an ellipse, but that from the perpendicular view shows a circle. Thus, the bubble was regarded as a prolate or oblate ellipsoid for volume evaluation. Kim et al. (2011) measured the condensation rate in the subcooled boiling condition after bubble departure in the bulk liquid region. The stereoscopic method, followed by the three-dimensional image reconstruction method, was proposed for an accurate measurement of the condensation rate. Imaginary phantoms were used to quantify the uncertainties of the stereoscopic observation method depending on the deformation extent. Since the deformation of a bubble is significant in boiling on a horizontal tube according to open literatures (Cornwell et al., 1982; Kang, 2005), Kim et al.'s reconstruction method for a deformed bubble was adopted in the present experiment.

There are experimental visualization results for the sliding bubble motion on a downward facing inclined heating surface. Qiu and Dhir (2002) performed a pool boiling experiment with an inclined plate with a refrigerant as the working fluid. Bouncing motion of the bubble during sliding was observed and the mechanism was expressed with the lift force and recoil force. Sugrue et al. (2014) conducted a series of subcooled boiling experiments in forced convection and measured the bubble departure diameter under various flow, subcooling, heat flux, and pressure conditions. These experimental observations of bubbles on inclined plates have given important insight to understand bubble motion including sliding on a horizontal tube heater. However, the inclination of a horizontal tube surface varies continuously along the circumference and therefore, the findings of the inclined channel tests may not be applied directly to horizontal tube boiling. In this context, there are not sufficient experimental data on horizontal tube boiling, and are even less on the detailed bubble motions. This lack of experimental data on horizontal tube boiling and the bubble behavior became the motivation for an experiment which can provide detail information on bubble behaviors for the force balance model validation and improvement.

The objectives of the present experiment are to visualize the behavior of boiling bubbles on the lower part of a horizontal tube heater, and to establish the measurement technique to provide quantitative information on the sliding bubble motion required for the force balance model, such as bubble volume, interface area,