Nuclear Engineering and Design 285 (2015) 188–196

Contents lists available at ScienceDirect

Nuclear Engineering and Design

journal homepage: www.elsevier.com/locate/nucengdes

Experimental and numerical investigations on the air–steam mixture bubble condensation characteristics in stagnant cool water

Xiao-hang Qu, Mao-cheng Tian*, Guan-min Zhang, Xue-li Leng

School of Energy and Power Engineering, Shandong University, Jingshi Road No. 17923, Jinan 250061, Shandong, PR China

HIGHLIGHTS

- Air–steam mixture bubble condensation behavior is studied by visual experiment.
- VOF and species models are coupled to simulated mixture bubble condensation.
- Condensation is model as source terms based on correlation from experiment.
- Simulation results agree well with experimental results.
- Steam concentration distribution in bubble is analyzed using numerical method.

ARTICLE INFO

Article history:
Received 30 July 2014
Received in revised form 23 October 2014
Accepted 20 December 2014

ABSTRACT

In this study, condensation of air–steam mixture bubble with mass fraction of steam above 0.5 was investigated first by a visual experiment at atmosphere. Then a 3-D numerical model based on volume of fluid (VOF) model and species model was developed to simulate the bubble condensation. In order to model steam condensation, mass and energy transfer between phases were modeled as source terms of conservation equations, using a correlation obtained from the experiment to predict the condensation heat transfer coefficient (HTC). After validation of the numerical model with the experimental results, influences of steam fraction and diameter of bubble on condensation characteristics are studied numerically. Moreover, steam concentration distribution in bubble was also analyzed along the time series of bubble condensation process. It was found that condensation HTC decreases with the increase of bubble diameter. With increase of steam fraction in bubble, the bubble volume shrinks more quickly due to the increased condensation rate, and the bubble accelerates more quickly reaching a higher terminal velocity. Aggregation of non-condensable air inside the bubble near the gas and water interface deteriorates the condensation heat and mass transfer.

1. Introduction

Bubble condensation is a kind of micro heat transfer encountered in a lot of industrial processes such as subcooled flow boiling and direct contact condensing (DCC), both of which are important issues in the nuclear systems safety and reactors optimum design. In most cases, a condensing bubble consists of not only pure water vapor but also some amounts of non-condensable gases like nitrogen and air which may come from systems leakage or chemical process reacting in the core. Study on the complex behavior of pure steam bubble condensing and its heat and mass transfer characteristics through bubble interface has drawn many attentions in the past years, while there are rarely any studies on the condensation of steam bubble with the presence of non-condensable gases. As a result, we need to enhance our understanding of the effect of non-condensable gases on the condensing of steam bubble.

Many researchers have investigated bubble condensing phenomenon in the past decades (Florschuetz and Chao, 1965; Isenberg and Sideman, 1970; Kar et al., 2007; Theofanous et al., 1970; Zeitoun et al., 1995). In modern time, the bubble condensation process is usually studied by visual experiment based on holographic interferometry or high-speed cinematography due to their ability of capturing very fast and transient processes. By photographing the generating and collapsing processes of vapor bubbles on a heated copper surface submerged in water pool using dual high speed cameras, Bode (2008) obtained single vapor bubble dynamic behavior and pressure oscillations in the water pool with the help of a hydrophone. Combining the time series of bubble images from

* Corresponding author. Tel.: +86 531 88395421; fax: +86 531 88395421.
E-mail address: tianmc65@sdu.edu.cn (M.-c. Tian).

http://dx.doi.org/10.1016/j.nucengdes.2014.12.031
0029-5493/

two perpendicular directions of a subcooled boiling flow in a rectangular channel and the local temperature measured using micro thermocouples, Kim and Park (2011) got a correlation predicting the condensing heat transfer coefficient (HTC) with respect to *Re*, *Pr* and *Ja*. Warrier et al. (2002) and Yuan et al. (2009) has also carried out similar experiments as Kim did, but their HTC correlations contain another non-dimensional number *Fo*, indicating time dependence. Kalman (2003) developed a theoretical model for condensing R113 bubble and the predicted bubble diameters and rising distances match reasonably well with his visual experiment.

Generally speaking, phase change involved in multiphase flows could be taken as a combination of bubble birth, death, coalesce and break up. Although most of the above mentioned researches focus on the bubble produced in a subcooled boiling flow, bubble condensation exists in multiphase flow in pipe, jet flow and so on. An experiment was conducted by Lucas and Prasser (2007) to study the steam injected into the upward subcooled water flow and the continuous changing interfacial area of the collapsing bubble was found to influence the condensation process strongly. Al Issa et al. (2014) performed a visual investigation of condensing steam bubble produced by three different nozzles and obtained *Nu* and *Re* correlation under different flow velocity or temperature conditions. The bubbles' equivalent diameters cover the range between 5 and 50 mm, a size too big to reach in subcooled boiling flow.

Moving particle semi-implicit (MPS) method (Tian et al., 2010), lattice Boltzmann method (Amaya-Bower and Lee, 2010) and level-set method (Wang and Tong, 2008) were all ever successfully used to capture the bubble behavior. The volume of fluid (VOF) multiphase model (Hirt and Nichols, 1981) is another numerical model very suitable for the simulation of bubble condensation. The influences of additional body forces on bubble sliding, detachment and coalescence behaviors in a subcooled boiling flow were investigated by Wei et al. (2011) using the VOF mode. Jeon et al. (2011) and Pan et al. (2012) simulated single vapor bubble condensation with VOF mode assuming a saturation status of the condensing bubble. The effects of initial bubble diameter, system pressure and water temperature and velocity distribution on the bubble volume decreasing, shape deformation and moving trajectory were studied thoroughly by both of them.

The presence of non-condensable gases was found to deteriorate the heat and mass transfer process seriously in cases of mixture gases condensing on a wall surface or in a tube (Dehbi et al., 2013; Lee and Kim, 2008; Li, 2013; Su et al., 2013). However, there are few public reports on the non-condensable gases' effects on the DCC or bubble condensation, which is a phenomenon as common and important as mixture gases condensing on surface. In this paper, a visual experiment is first conducted to record the condensing process and get a correlation to predict the heat transfer rate of an air–steam mixture bubble. Then, the mixture bubble condensation behavior has been simulated using the VOF and species model based on the commercial software Fluent 6.3.26. The correlation from the experiment predicting the HTC is compiled in the user defined function (UDF) to model the heat and mass transfer through the bubble interface. After validating the simulated result with experiment, the bubbles velocity and deformation characteristics are analyzed. Furthermore, the air and steam concentration in a condensing mixture bubble is shown, offering a deeper understanding of this condensation process.

2. Experiment

To investigate the mixture bubble condensing characteristics and correlate the condensing *Nu* number, experimental equipment was established. Instead of mixing the air and steam directly, the mixture was generated by vent air into a cluster of gas-washing bottles filled with water and submerged in a water bath which was maintained at boiling status. This method could produce mixture bubble containing air mass fraction from 0.1 to 0.5, which is representative and important in industrial applications. A high speed camera was used to photograph the images of the mixture bubble injecting from a vertical nozzle into stagnant cool water.

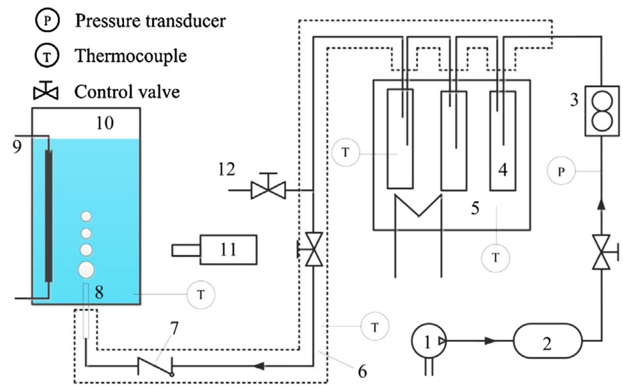

Fig. 1. Schematic of experiment: (1) air compressor; (2) surge tank; (3) rotor flow meter; (4) gas-washing bottle; (5) water bath; (6) heat tapes and insulated material; (7) check valve; (8) nozzle; (9) electric wire and heating rode; (10) glass water vessel; (11) high speed camera; (12) by pass.

2.1. Apparatus and instruments

A schematic view of the test equipment is shown in Fig. 1. Air was transported by an air compressor and flows successively through a surge tank, a rotor flow meter and a mixture gas production system before enters test section. Stable continuous production of air–steam mixture was ensured by a gas-washing system consisting of a thermostatic water bath and three gas-washing bottles. By maintaining the bath water boiling, the outlet gas of the third gas-washing bottle must be a mixture of air and water steam and the steam fraction of it wouldn't change as long as the bottle water temperature and the air flow rate remain constant. To prevent heat lose and any possible steam condensation before the test section, all tubes and valves between the mixture gas production system and test section were wrapped with heat tapes outside of which was thermal insulated materials. The heat tapes were powered by electricity and controlled by a PID controller, which helps maintain a temperature around 120 °C, high enough to ensure the mixture in the tube dry. The test section was a quartz glass vessel with dimensions of $150 \times 150 \times 400\,\text{mm}^3$, maintaining a water depth of 300 mm in testing. At the bottom of the vessel was a hole drilled to mount the injecting nozzle and the top of it was open to atmosphere so the pressure in the test section could be taken as 1 atm.

The water of the water bath and the test section were heated by electrical heating rod of 1.5 kW and 1 kW, respectively. With a PID temperature controller and a K type thermocouple, the temperature in the test section can be controlled within an error of 1 °C. Five T type thermocouples with an accuracy of 0.2 °C were mounted in the test section at five different positions to determine the cool water temperature. During the experiment, the five temperatures were found to be so close to each other (difference within 0.5 °C), so the cool water temperature was taken as the average of them. In order to obtain different size of bubbles, the air flow can be adjusted through a control valve and the flow rate can be measured using a rotor flow meter (uncertainty 2.5%) and a pressure transducer (uncertainty 1%). In addition, two nozzles of different diameters were used. Details of the test conditions are shown in Table 1, indicating a total of 14 different conditions were conducted.

A Memrecam HX-6 high speed camera made by NAC Company was used to capture the process of bubble condensation. HX-6 has