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Numerical simulation of bubble formation and condensation of steam air mixture injected in subcooled pool

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HIGHLIGHTS

- Bubble formation and condensation process injected from a nozzle is studied numerically.
- Euler-Euler two-fluid free surface model and species model from are coupled together.
- Influence of non-condensable gas is considered.
- Bubble shape variation histories are shown in comparison with experiments.

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ABSTRACT

Bubble formation and condensation of steam-air mixture vertically injected in a subcooled water pool was simulated, combining thermal phase change model into the two continuous phase free surface model of ANSYS CFX 17.1. Continuous surface force model was used to calculate surface tension force and the influence of non-condensable gas was accounted for by component transportation equation and assumption of interface temperature equal to saturation temperature at local partial steam pressure. The thermal phase change model includes an experimental correlation for liquid side sensible heat transfer. Based on available experiment data from literatures, singular pure steam bubble and steam-mixture bubble in a pool were first simulated to see the predictability of the proposed method and then, the same method was applied to the bubble formation, detachment and condensation process of injected steam air mixture from a nozzle. Bubble dimeter, water subcooling and non-condensable gas concentration studied range from 4.9 mm to 50 mm, 12 K to 40 K, and 0 to 31.5% respectively. The results of the computations indicate that the present method can predict very well the bubble formation and condensation both for pure steam case and with non-condensable gas.

1. Introduction

Bubble formation, growth and its transfer in liquid is of vital importance in a variety of industries involving condensation and gas transport in liquid. Non-condensable gas bubbles exist in devices including bubble columns, gas-liquid stirred vessels and separation equipment, in which the knowledge of bubble size distribution is one of the main design parameter. Steam bubble with phase change is another significant industrial interest, because it plays a critical role in the flow, heat and mass transfer characteristics in process devices. For instance, in subcooled boiling flow, the steam bubbles, which are generated from superheated wall and condense subsequently in bulk fluid, control the pressure drop and heat removal capacity, especially in cases of small or micro scale tube that is commonly encountered in electrical cooling devices (El Mghari and Louahlia-Gualous, 2016; Fan et al., 2016; Zhang et al., 2016). Further, phase changing bubbles can also be encountered in direct contact condensation, where steam is usually injected into subcooled liquid through nozzle or orifice, where bubbles appear at low flow rates or steam jet at high steam flow rate and sometimes with oscillations due to unstable interface.

The formation of air bubbles injected from a submerged orifice was numerically and experimentally investigated by Buwa et al. (2007) and Gerlach et al. (2007). Using an in-house computer code, they combined volume of fluid (VOF) method and level set (LS) method, thus taking the advantages of the mass conservation

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features of VOF and accurate interface capture features of LS, respectively. They showed different bubble formation regimes, mainly the period-1 and period-2 regimes (period-1 means every single bubble detaches nozzle evenly and period-2 means every two succeeding bubbles coalesce or pair near nozzle exit before continue to rise), based on observed different periods of bubble formation and these findings agree well with their experiment. Also, in the so-called period-1 regime, they investigated the influence of orifice diameter, flow rate, orifice contact angle and fluid properties on the bubble detachment volume and frequency.

There have been many studies focusing on the bubble collapse after nucleate boiling in subcooled water (Anglart and Nylund, 1996; Bode, 2008; Tu and Yeoh, 2002; Zeitoun and Shoukri, 1996), and number of correlations (Kalman, 2003; Kalman and Mori, 2002; Kar et al., 2007; Kim and Park, 2011; Warrier et al., 2002) have been developed to predict heat transfer based on the experiments. However, these studies only focus on the bubble condensation behaviors after bubble or jet formation, while the formation process outside injection nozzle is also important to understand the bubble or jet size and their effect on the subcooled water pool. For example, in nuclear power plant safety a suppression pool (large subcooled water pool) is used to condense steam in order to reduce the reactor pressure vessel pressure and maintain containment pressure. The surface temperature of the suppression pool determines the containment pressure which is related to pool stratification. The bubble characteristics at the injection point including detachment volume frequency, velocity, interfacial instability impact the stratification in the pool (Norman and Revankar, 2010).

The influences of non-condensable gas on the behaviors of condensing bubble is challenging to study since the content and distribution of NC gas in the bubble is hard to control or measure. On the other hand, the bubbles from injection usually show very different characteristics than that from nucleate boiling, including the initial bubble size and velocity. Al Issa et al. (2014) performed a visual investigation of condensing steam bubble injected through three different nozzles, with bubbles' equivalent diameters covering the range between 5 and 50 mm, a size impossible to obtain in nucleate boiling flow. Tang et al. (2015a,b) studied the microbubble emission boiling(MEB) phenomena of condensing injected steam bubbles, and indicated that MEB may be attributed to the violent condensation of the boiling film based on the fact that the condensing bubbles generate secondary tiny bubbles just like the emission of microbubble in film boiling. They (Tang et al., 2015a,b) also measured the acoustic characteristics of condensing bubbles, distinguishing four condensation patterns containing smooth bubble regime, shape oscillation regime, transition regime and capillary wave regime.

The condensation of steam bubbles has been numerically explored by many authors with different methods (Tian et al., 2010; Wei et al., 2011; Yang et al., 2008). Recently, Jeon et al. (2011), Pan et al. (2012) and Qu et al. (2015) have all successfully simulated the condensing bubbles using the VOF method, and the influence of non-condensable gas on condensing bubble (Qu et al., 2015). However, all their simulations were based on specific experimental correlation for one single bubble and can only apply to single bubble condensation in their respective limited ranges, and the method used is called lumped correlation method. Applying evaporation heat transfer coefficient to account for the mass transfer (Hardt and Wondra, 2008), the condensation simulation has been extended to multi-bubbles case by Liu and Palm (2016) using Fluent a, commercial CFD. Samkhaniani and Ansari (2016) and Zeng et al. (2015) have used Open-FOAM for multi bubble condensation simulation. However, the evaporation heat transfer coefficient in their method is still not universal and a proper choice of this value is vital to obtain successful simulation. In the present study, the focus is on bubbles formed by submerged injection of steam, and the influence of non-condensable gas on the bubble formation. Four different experimental works on condensation of single bubble (Xu, 2004; Kim and Park, 2011; Qu et al., 2015; Tang et al., 2015a,b) are considered in order to develop generic predictive capability on bubble formation at the nozzle while condensation proceeds. Experimental works of Qu et al. (2015) and Kim and Park (2011) are used to access the predictabilities of single condensing bubble, with and without non-condensable air respectively. Experiments in Tang et al., 2015a,b employed a nozzle with a diameter of 4 mm, through which bubbles form and condense in stagnant water. In Xu (2004), he considered the influence of non-condensable gas with nitrogen, using a larger nozzle diameter of 17.3 mm. This paper firstly briefly shows the development of the numerical model using the commercial software ANSYS CFX 17.1, and then the model is applied to the simulation of bubble condensation for comparison with four different experimental results from literatures.

2. Mathematic models

A Euler-Euler based two-fluid model (Chahed et al., 2003) is used in this study, with both the gas and liquid phases taken as continuous phases in the calculations. Material properties including density, viscosity, thermal conductivity, and enthalpy of the steam in the gas phase and the water in the liquid phase are calculated using the IAPWS-97 database, which can be regarded as a kind of real gas model and thus reduces errors caused by material properties as much as possible. Surface tension coefficient of the water is based on its temperature and its value varies with different experimental cases. Outside the nozzle, wall contact model is used with a constant contact angle. Nitrogen and air are considered as ideal gas, which are used as the non-condensable gas in the experimental studies by Xu (2004) and Qu et al. (2015), respectively.

Different from the common use of VOF model in the numerical simulation of bubble behavior (Jeon et al., 2011; Pan et al., 2012), which is indeed a homogeneous model with no velocity slip among phases, the present study instead uses the inhomogeneous free surface model of CFX, allowing slip velocity between the two phases. The use of VOF for the bubbles generated at flow boiling scenario is reasonable because of small deviation between gas and liquid velocities. In contrast, the bubbles in case of injection have inherently high phasic velocity, especially near nozzle exit, so an inhomogeneous momentum model is more appropriate. Other than this and the differences of interphase surface construction method (which can be referred to the user manual of ANSYS), the free surface model resembles VOF model. The continuum surface force (CSF) model proposed by Brackbill and Kothe (1992) is used for the surface tension, which results in a source term in momentum equations and is expressed as a volume force.

Thermal phase change model (Gulawani et al., 2006; Shah, 2010) is used to calculate the condensation mass transfer. This model assumes the difference of sensible heat transfer on each sides of the interface caused by the condensation latent heat transfer. On liquid side, the heat transfer from the interface to the bulk fluid is calculated by the Hughmark (1967) model, while on gas side, the zero resistance model is applied meaning the sensible heat transfer is omitted whenever the gas is pure steam or with non-condensable gas. This is true because the sensible transfer rate at liquid side is much larger than gas side and details of the magnitude analysis can be found in Meier (1999). When gas is composed of steam and non-condensable, the composition is always changing with condensation of steam, so the component transportation equation is used to account for this composition varia-