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Axisymmetric simulation of bubble condensation of pure steam and steam–air mixture

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ABSTRACT

A coupled compressive interface capturing scheme and dual-time preconditioned approach was developed for the two-dimensional axisymmetric computation of compressible interface flows with mass transfers. The fully-compressible three-phase homogeneous mixture flow model was implicitly solved using the dual-time preconditioned technique on generalized curvilinear grids. The interfaces between the three phases were captured by the solution of two interface advection equations using a compressive high resolution interface capturing method. The predictive capabilities of the numerical scheme were examined for a series of bubble condensations of pure steam and steam–air mixtures in different thermal and hydrodynamic subcooled boiling flows. Reasonably good agreement with the experimental data was obtained. Subsequently, several test cases on the condensation of single steam–air mixture bubbles were performed to investigate the effects of non-condensable gases on the characteristics of a condensing bubble. The numerical results revealed a nearly linear decrease of the condensation rate with an increase of the non-condensable gas void fraction in the mixture bubble.

1. Introduction

A fundamental understanding of bubble condensation in subcooled boiling water is essential to predict the performance of heat and mass exchange devices. From the computational point of view, bubble condensation can be modeled with the use of an appropriate mathematical model, which can be generally classified into four categories: (1) fully incompressible flow models, where all phasic properties are assumed to be independent of pressure and temperature (Ganguli et al., 2012; Gibou et al., 2007; Pan et al., 2016; Tian et al., 2010); (2) isothermal compressible flow models, where phasic properties are only dependent on pressure (Ahuja et al., 2001; Venkateswaran et al., 2002); (3) fully compressible flow models, where all phasic properties depend on both pressure and temperature (Föll et al., 2014; Ha et al., 2015; Jin et al., 2017; Li et al., 2017; Lindau et al., 2001), and (4) mixture incompressible–compressible models, where one phase is treated as an incompressible fluid and the other is treated as either an isothermal fluid (Lind et al., 2016; Neusser and Schleper, 2017) or a fully compressible fluid (Boger et al., 2015). The main difficulty in the simulation of bubble formation is the existence of interfaces between the phases, which represent a discontinuity of the flow field quantities. The complexity of the problem increases with increasing interface deformation, especially in the presence of mass and heat transfer across the interfaces. An effective numerical scheme should be capable of handling a number of different interface flow features, such as reasonably sharp and accurate interface topology representation, large jumps in phasic properties across the interface, and all-speed flows associated with compressibility effects. For a brief review of the advantages and disadvantages of the current numerical methods for capturing/tracking interface flows, readers are referred to Ha et al. (2017).

Condensation of pure steam bubbles has been extensively studied both experimentally (Al Issa et al., 2014; Chen and Mayinger, 1992; Kalman, 2003; Kamei and Hirata, 1990; Kim and Park, 2011; Tang et al., 2015a,b; Xu, 2004; Yuan et al., 2009) and numerically (Bahreini et al., 2015; Guo et al., 2011; Jeon et al., 2011; Pan et al., 2012; SalaiSargunan et al., 2018; Tian et al., 2010; Wei et al., 2011; Yang et al., 2008). However, only few studies have been published on the condensation of gas mixture bubbles. Condensation of steam bubbles in the presence of non-condensable gases is often encountered in many industrial applications, including bubble column reactors, chemical reactors, gas-liquid stirred tank reactors, and industrial boilers. Bubble characteristics, such as, bubble size, bubble shape, rise velocity, and void distribution, have significant impact on the hydrodynamics and transport of mass and/or heat (Bai, 2010). Therefore, quantitative knowledge of such characteristics is of considerable importance for safety and optimum design analysis. To our knowledge, the effect of a non-condensable gas on a condensing bubble was first experimentally and numerically investigated by Qu et al. (2015). In their simulations,

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the volume of the air and steam mixture was explicitly tracked by the volume of fluid (VOF) incompressible two-phase flow model while the steam mass fraction was obtained by solving an additional transport equation using another numerical method. From the numerical point of view, there is no guarantee that the steam fraction obtained by the VOF solution and that obtained by the solution of the additional conservation for steam are the same, owing to the difference in the numerical errors of each solution. As the results, the constraint, i.e., the sum of the void or mass fractions of all phases being equal to unity, can be violated. This leads to either loss of accuracy or loss of stability of the numerical solution. The loss of symmetry of the predicted steam mass fraction in the bubble presented in this work has showed an evidence. More recently, Qu et al. (2017) carried out the same simulation for a single non-condensable steam mixture bubble using a compressible two-fluid model. However, this study was limited to the use of two-phase flow, where the steam–air mixture was simplified as a single fluid phase. As a consequence, the air and steam cannot be distinguished. In order to properly model the condensing non-condensable gas steam bubble, either a three-phase flow mathematical model or two-field approach with a transport equation for the non-condensable gas in the steam field are generally necessary. The numerical solution of such flow models, without introducing large errors, presents significant challenges (Ha and Park, 2016; Hérard, 2007; Vuyst et al., 2005).

The aim of this study is to extend our previously developed compressive interface- capturing scheme to the computation of interface flows separating three different phases with mass transfers. To achieve this objective, a numerical solution of the fully compressible mixture of three fluids in mechanical and thermodynamic equilibrium, coupled with that of two volume interface advection equations was implemented. The developed scheme is then examined for either two-phase or three-phase flows, including bubble condensation of single pure steam and steam–air mixtures.

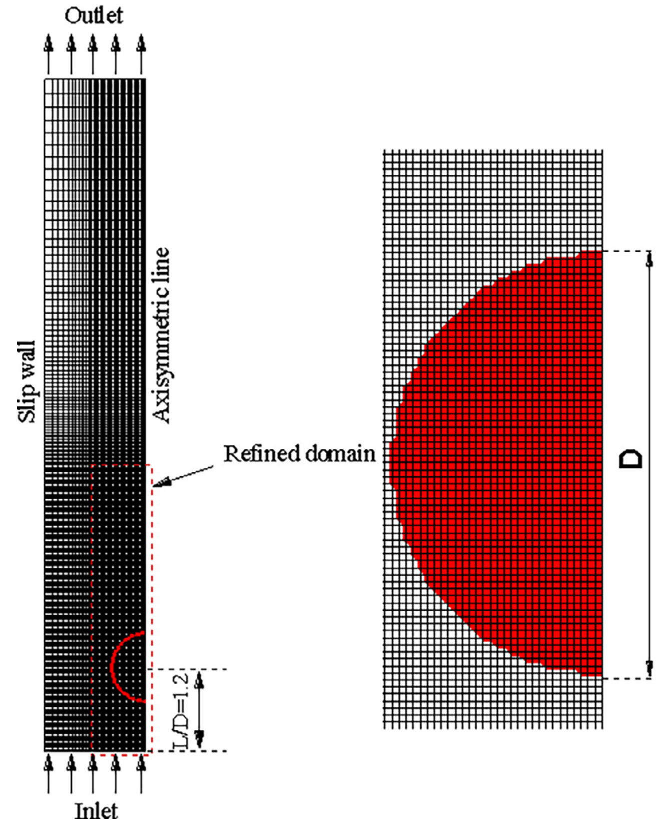

Fig. 1. Computational domain for bubble simulation.

Table 1
Initial flow conditions for steam bubble condensation simulation.

Case no.	Subcooling temperature, ΔT_{sub} (K)	Mass flux (kg/ $m^{-1}.s^{-1}$)	Saturation pressure, P_{sat} (MPa)	Bubble diameter, D (mm)
A1	25.0	400.0	0.130	1.008
A2	12.8	118.0	0.101	0.950
A3	10.6	100.4	0.102	0.800

2. Governing equations

The mathematic model consists of a multiphase flow model and separate interface advection equation for steam and air. The multiphase flow model is based on a dual-time, fully compressible three-fluid water/steam/gas mixture model (Ha et al., 2017). In this model, the flow of water, steam, and air is assumed to be in thermal and dynamical equilibrium. For a two-dimensional (2D) axisymmetric flow, the multiphase model consists of six conservative equations for mass, momentum, and energy. These conservation equations are written in generalized coordinates as follows:

$$\Gamma_e \frac{\partial \hat{Q}}{\partial t} + \Gamma \frac{\partial \hat{Q}}{\partial \tau} + \frac{\partial \hat{E}}{\partial \xi} + \frac{\partial \hat{F}}{\partial \eta} = \frac{\partial \hat{E}^v}{\partial \xi} + \frac{\partial \hat{F}^v}{\partial \eta} + \hat{S} + P_\sigma \left(\frac{\partial \hat{H}_\xi}{\partial \xi} + \frac{\partial \hat{H}_\eta}{\partial \eta} \right) \tag{1}$$

$$\hat{Q} = \frac{1}{J}\begin{pmatrix} p \\ u \\ v \\ T \\ Y_v \\ Y_g \end{pmatrix}, \hat{E} = \frac{1}{J}\begin{pmatrix} Y_w \rho U \\ \rho u U + \xi_x p \\ \rho v U + \xi_y p \\ \rho h_0 U \\ Y_v \rho U \\ Y_g \rho U \end{pmatrix}, \hat{F} = \frac{1}{J}\begin{pmatrix} Y_w \rho V \\ \rho u V + \eta_x p \\ \rho v V + \eta_y p \\ \rho h_0 V \\ Y_v \rho V \\ Y_g \rho V \end{pmatrix} \tag{2}$$

$$\hat{E}^v = \frac{1}{J}\begin{pmatrix} 0 \\ \xi_x \tau_{xx} + \xi_y \tau_{xy} \\ \xi_x \tau_{yx} + \xi_y \tau_{yy} \\ \xi_x b_x + \xi_y b_y \\ 0 \\ 0 \end{pmatrix}, \hat{F}^v = \frac{1}{J}\begin{pmatrix} 0 \\ \eta_x \tau_{xx} + \eta_y \tau_{xy} \\ \eta_x \tau_{yx} + \eta_y \tau_{yy} \\ \eta_x b_x + \eta_y b_y \\ 0 \\ 0 \end{pmatrix} \tag{3}$$

$$\hat{H}_\xi = \frac{1}{J}\begin{pmatrix} 0 \\ \xi_x \alpha_{vg} \\ \xi_y \alpha_{vg} \\ 0 \\ 0 \\ 0 \end{pmatrix}, \hat{H}_\eta = \frac{1}{J}\begin{pmatrix} 0 \\ \eta_x \alpha_{vg} \\ \eta_y \alpha_{vg} \\ 0 \\ 0 \\ 0 \end{pmatrix}, \hat{S} = \frac{1}{J}\begin{pmatrix} \dot{m} - Y_w \rho v / y \\ \rho g_x - (\rho u v - \tau_{xy})/y \\ \rho g_y - (\rho v^2 - \tau_{yy})/y \\ \dot{m} h_{lv} + (u\tau_{xy} + v\tau_{yy} - \rho h_0 v - q_y)/y \\ -\dot{m} - Y_v \rho v / y \\ -Y_g \rho v / y \end{pmatrix} \tag{4}$$

$$b_{x_i} = u_j \tau_{x_i x_j} - q_{x_i}$$

$$h_0 = h + \tfrac{1}{2}(u^2 + v^2) \tag{5}$$

$$U = \xi_x u + \xi_y v, \; V = \eta_x u + \eta_y v \tag{6}$$

$$Y_v = \alpha_v \rho_v / \rho, \quad Y_g = \alpha_g \rho_g / \rho \tag{7}$$

$$\alpha_g + \alpha_v + \alpha_w = 1, \quad Y_g + Y_v + Y_w = 1 \tag{8}$$

Interface advection equation for condensable phase (steam phase):