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Numerical investigation of single and multiple bubble condensing behaviors in subcooled flow boiling based on homogeneous mixture model

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ABSTRACT

Numerical investigations of the condensing behaviors of a single bubble and multiple bubbles under different subcooled flows were conducted using the compressible homogeneous mixture method. The surface tension between the liquid and vapor phases was determined using the continuous surface force method. An implicit dual-time technique was applied to solve the two-phase compressible flow model. A sensitivity study of the empirical coefficients used to access the predictive capacity of the existing mass transfer models was conducted. The numerical simulation results were compared with experimental data. The obtained results agreed well with the experimental results. Additionally, the bubble condensation behavior was investigated for different initial subcooled temperatures, bubble diameters, and velocities. Subsequently, the effect of multiple bubble interactions on their condensation was studied. The condensation rate of the lower bubbles increased compared to the other bubbles as a result of induced random perturbation. When the gap between the bubbles was large, a negligible amount of condensation occurred between the bubbles.

1. Introduction

In the field of nuclear engineering, researchers are extremely focused on designing features that ensure the safety of nuclear reactor core cooling systems. This could be attributed to bubble dynamics, which has a significant impact in the presence of vapor bubbles and influences the heat transfer characteristics, including pressure drop and flow instability. Understanding the bubble condensation in subcooled flow boiling is essentially considered to describe heat and mass transfer phenomena, because it can be applied to many industrial applications such as nuclear reactors, boilers, and a new generation of cooling systems for electronic devices.

Mainly, research has focused on theoretical studies, experimental analysis, and numerical simulations. Theoretical studies on stationary bubble condensation and dynamic bubble condensation were conducted by Zuber [1] and Okhotsimskii [2]. Over the last two decades, the level of understanding of bubble behavior has progressed with the technological advancements of measuring and monitoring instruments. Kim and Park [3] correlated the interfacial heat transfer coefficient at low pressure in a subcooled boiling flow with the condensate Nusselt number, which was obtained as a function of a bubble's local Jacob number, local liquid Prandtl number, and Reynolds number from the experimental results. Lucas and Prasser [4] investigated the structure of a steam-water flow in a vertical pipe using novel wire-mesh sensors for high pressure/temperature operation. They found that bubble break-up had a strong influence on the condensation process because of the change in the interfacial area. Harada et al. [5] carried out visualization experiments to investigate the dynamics of vapor bubbles generated during water pool boiling. Brucker and Sparrow [6] used experimental studies to investigate the behavior of bubbles in relation to their size history, shape, velocity, collapse time, and interfacial heat transfer coefficient under high-pressure conditions.

From the aforementioned perspective, the behavior of bubbles was investigated using the bubble shape, velocity, size, collapse, and interfacial heat transfer coefficient under different conditions. However, it was impossible to obtain all the information about bubble behavior because the shape of the bubbles and interfacing area was too complicated to measure. As a bubble grows and condenses in less than a microsecond, it is very difficult to accurately capture a condensing bubble using an advanced high-speed camera. Hence, numerical simulation was used to determine the bubble dynamics.

Tian et al. [7] simulated the condensation behavior of a single steam bubble in subcooled water using the moving particle semi-implicit method. The liquid phase was modeled using moving particles, and a movable boundary method was applied to track a two-phase interface through the topological position of the interfacial particles. The interfacial heat transfer was determined based on the heat condition through the interfacial liquid layer, and the coupling between the momentum

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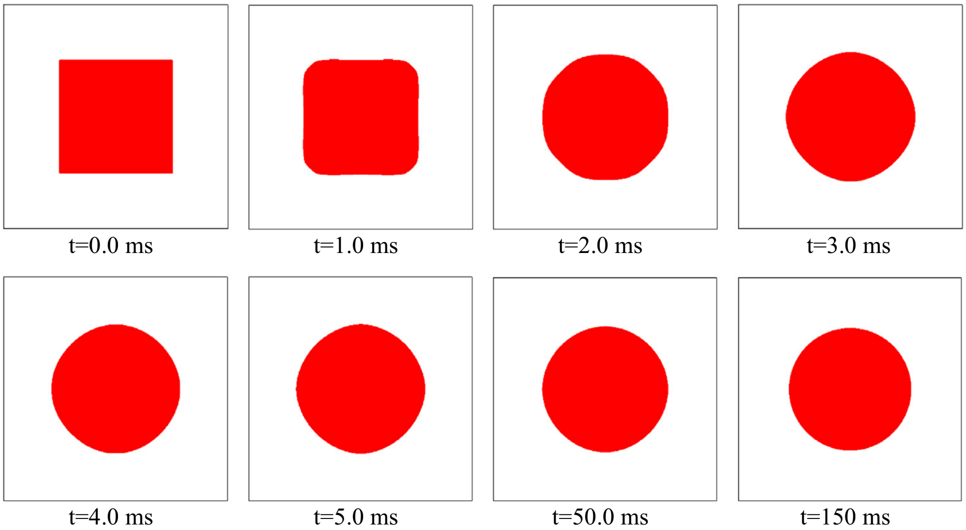

Fig. 1. Time evolution of transformation of square droplet to circular droplet.

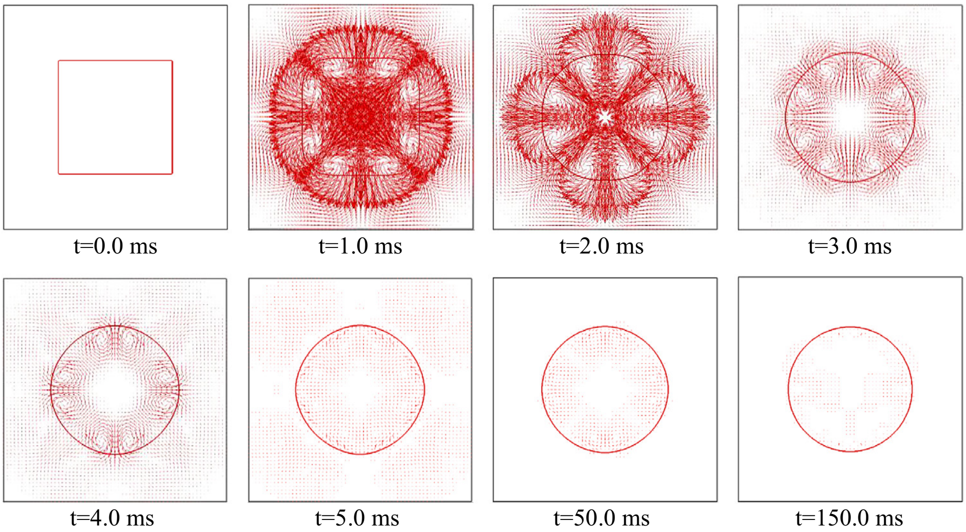

Fig. 2. Velocity vector computed around bubble interface.

and energy was specially treated. Furthermore, the moving particle semi-implicit method was applied in a two-dimensional domain simulation of a pair of bubbles rising in a stagnant liquid on coalescence. Subcooled liquid simulations were performed for nucleating flow boiling by Chena et al. [8, 9]. Junali et al. [10] conducted a two-dimensional simulation of the single bubble rising behavior in a metal liquid.

Moreover, Jeon et al. [11] performed a subcooled boiling flow simulation of bubble condensation using direct numerical simulation, and the amount of condensation was determined using the interfacial heat transfer coefficient obtained from the liquid temperature, bubble velocity, and bubble diameter at every time step. Eames [12] categorized the possible bubble vortex generation mechanisms. Lucas et al. [13] focused on the derivation of equations to extend the inhomogeneous MUSIG model and presented verification and validation results. Ganguli et al. [14] and Bahraini et al. [15] performed experiments and computational fluid dynamic simulations on the bubble dynamics of a single condensing vapor bubble from a vertically heated wall in a subcooled pool boiling flow. The heat source was modeled using a simple heat balance, and the rising behavior of condensing bubbles was studied. Kharangate and Mudawar [16] addressed the computational modeling of bubble nucleation, growth and departure, film boiling, flow boiling, and flow condensation, and discussed the validation of their predictions against experimental data. Liu et al. [17] performed a numerical simulation of the condensation of multiple bubbles in a subcooled flow boiling and its effect on the condensation rate. Qu et al. [18] performed a simulation of the bubble formation and condensation in a steam air mixture injected into a subcooled water pool.

This study is based on the simulation of single- and multi-bubble condensation using a numerical simulation approach under low- and high-pressure operating conditions. Bubble condensation was the key parameter for describing the heat and mass transfer phenomena. To determine the condensing vapor bubble behavior, a homogeneous mixture model was used for these simulations. Simulations were performed to determine the bubble behavior under low pressure, with various bubble sizes, subcooled temperatures, and velocities. A bubble life comparison was made under different subcooled temperatures for single bubbles, and simulations were conducted of multi-bubble behavior with various gaps between the bubbles, bubble sizes, and velocities.

The in-house code of the condensation model was validated for a vapor bubble condensed in liquid. For the interfacing of liquid and vapor phases, a compressive interface-capturing scheme was applied in the simulation. A brief review of the advantages and disadvantages of this