Modeling of the Condensation Sink Term in the One-Dimensional One-Group Interfacial Area Transport Equation

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1. Introduction

In order to predict the interfacial area concentration mechanistically, it is necessary to introduce the interfacial area transport equation [1]. Some models for the source and sink terms have been developed based on the mechanism for fluid particle coalescence and disintegration by several researchers [2, 3] for various experimental conditions and test geometries. However, as the previous interests have been concentrated only on adiabatic conditions, it is necessary to develop IATE models for the source and sink terms to properly model the thermal-hydraulic phenomena in boiling and condensation conditions. The purpose of this paper is to solve the one-dimensional interfacial area transport equation for the condensation phenomena of bubbles in a subcooled liquid.

2. Mechanism of a Bubble Collapse

The condensation phenomena are divided into two regions: heat transfer-controlled region and the inertia-controlled region. Based on the bubble collapse phenomena, two regions are identified introducing the concept of a boundary bubble diameter, and then the bubble collapse time in a heat transfer-controlled region is calculated.

Figure 1 shows the typical variation of the bubble size during the boiling and condensation process.

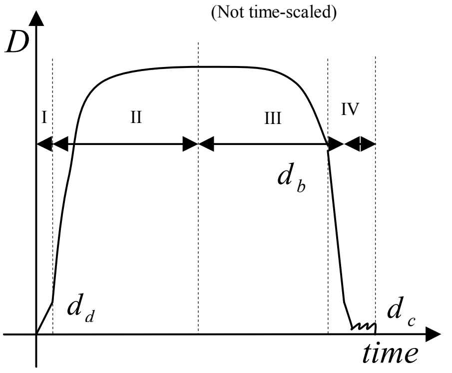

Fig. 1 Variation of the bubble size during the boiling and condensation process

From the previous research on a bubble in a subcooled liquid, it is assumed that there are four regions during the lifetime of a bubble. Region I is the bubble generation region, Region II the bubble growth region in a superheated condition, Region III the bubble shrink region in a subcooled condition, and Region IV the bubble collapse region in a subcooled condition. It is widely known that Region I and IV have a very short period of residence. In figure 1, d_d is the bubble size which is attained through the inertia-controlled bubble growth process during a nucleate boiling, d_b is the bubble size when the bubble begins to be controlled by inertia during a bubble condensation, and d_c is the critical collapsing bubble size. The condensing region in the subcooled condition can be divided into two regions: heat transfer-controlled region (Region III) and the inertia-controlled region (Region IV). In the heat transfer-controlled region, the Nusselt number approach is appropriate. However, in the inertia-controlled region, the mechanical force is balanced through the interface between bubbles and the surrounding liquid.

From the Rayleigh solution (1917), a rapid change of the bubble size occurs when the non-dimensional bubble diameter is between 0.4 and 0.6. Here, it is assumed that the non-dimensional bubble diameter is 0.4 at the region boundary.

The bubble collapse time is derived from the energy balance through the bubble interface. From the energy balance on the interfacial surface of the collapsing bubble, the following relationship is derived.

$$t_c = \frac{d_s^2 - d_{IC}^2}{4} \frac{\rho_g h_{fg}}{Nu_c \cdot k_f \Delta T} \tag{1}$$

3. Modeling of Condensation Sink Term in IATE

The one-dimensional interfacial area transport equation is expressed as follows.

$$\begin{aligned}
&\frac{\partial < a_i >}{\partial t} + \frac{\partial}{\partial z} < a_i ><< v_{iz} >>_a \\
&= \frac{2}{3}\left(\frac{< a_i >}{< \alpha >}\right)\left(\frac{< \Gamma_g >}{\rho_g} - \frac{< \alpha >}{\rho_g}\left(\frac{\partial \rho_g}{\partial t} + << v_{gz} >> \frac{\partial}{\partial z} < \rho_g >\right)\right) \\
&+ \frac{1}{3\psi}\left(\frac{< \alpha >}{< a_i >}\right)^2 \sum_j < R_j > + \pi < D_{bc} >^2 < R_{ph} > \\
&= \phi_{PC} + \phi_{PV} + \phi_{BC} + \phi_{BB} + \phi_{WN} + \phi_{CO}
\end{aligned} \tag{2}$$

The separate terms of the above IATE are explained as follows. ϕ_{PC} and ϕ_{PV} mean the source and sink terms of an expansion or shrinkage due to a phase change and a pressure change, respectively. ϕ_{BB} and ϕ_{BC} mean the source term due to a bubble breakup and the sink term due to a bubble coalescence, respectively. ϕ_{WN} and ϕ_{CO} mean the source term due to a bubble nucleation and the sink term due to a bubble condensation, respectively. The sink and source terms due to a bubble breakup and coalescence have been successfully modeled, particularly in bubbly flow regime [2]. The source and sink terms of ϕ_{PV} are given by an explicit function, and they thus can be estimated by a pressure change.

The fraction of bubbles with a smaller size than the boundary bubble size in the inertia-controlled region is defined as follows.

$$p_c = probability(D < d_b) \tag{3}$$

The probability can be calculated based on the bubble residence time of both regions. The time history of the collapsing bubble which was calculated by Rayleigh [4] is used to calculate the probability as follows

$$p_c = \frac{\Delta t_{c,in}}{\Delta t_{c,th} + \Delta t_{c,in}} = \frac{f(0) - f(\beta_b)}{f(0)} \tag{4}$$

The IAC sink term due to a condensation in the heat transfer-controlled region can be calculated as follows.

$$\phi_{PC} = (1 - p_c) \cdot n_b \cdot \frac{dA_i}{dt} = -4\pi \cdot (1 - p_c) \cdot n_b \cdot Nu_c \cdot Ja \cdot \alpha_t \tag{5}$$

The IAC sink term due to condensation in the inertia-controlled region can also be calculated as follows.

$$\phi_{CO} = R_{ph} \cdot \pi d_b^2 = -\pi d_b^2 \cdot \psi \cdot \frac{a_i^3}{\alpha^2} \cdot \frac{1}{t_c} \tag{6}$$

Figure 2 shows the calculated IAC changes and separate contributions of the pressure change, turbulence impact, random collision, and a condensation in the heat transfer-controlled region and in the inertia-controlled region for the case of Test Run C6 of Zeitoun [5]. For the case of Test Run C6 with the inlet pressure of 170000 pa, total mass flux of 492.39 $kg/m^2{-}s$, and inlet void fraction of 0.2402, the contributions of a turbulence impact and a random collision are negligibly small when compared with the others. The contribution of the pressure change is as low as below 2%. The main contribution is due to the condensation and a portion of the inertia-controlled region is about 16.8% for the case of Test Run C6. The overall agreement is reasonable between the simulated and measured data except for the exit region, where the measurement error of the experimental data seems to be the largest.

Figure 3 shows the overall comparison of the simulated IAC with the experimental data of Zeitoun [5]. The present model can reasonably predict almost all of the data. The standard deviation of the predictions of the present model from the experimental IAC is 19.9%.

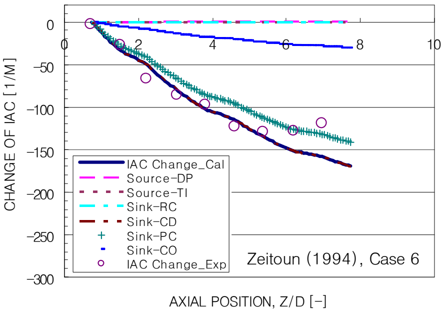

Fig. 2 Contributions of the Simulated IAC Source and Sink Terms and their Comparison with the Experimental Data of Zeitoun [5]: Run No. C6

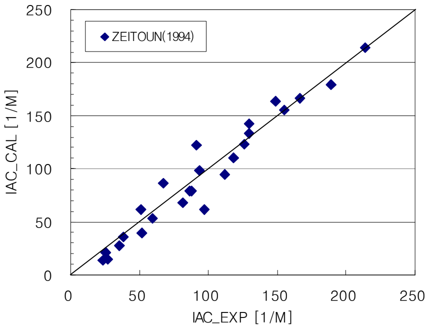

Fig. 3 Comparison of the Simulated IAC with the Experimental Data of Zeitoun [5]

5. Conclusion

The one-dimensional one-group interfacial area transport equation is solved with a new modeling on the condensation sink term of vapor bubble in a subcooled liquid. The present model can reasonably predict the data of Zeitoun [5]. The simulation results show that the present model would be a promising modeling approach for the condensation phenomena of vapor bubbles in a subcooled liquid.

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