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Effect of void fraction covariance on two-fluid model based code calculation in pipe flow

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ABSTRACT

Utilization of one-dimensional system analysis code such as TRACE, RELAP5, TRAC-BF1 to evaluate gas-liquid two-phase flow behaviors in nuclear power plants is crucial for the plant-level safety assessment. In the two-fluid model, interfacial momentum transfer between two phases is expressed under interfacial drag term in the momentum equation. For the rigorous and accurate expression of interfacial drag term and drift flux parameter, covariance due to the area averaging of void fraction distribution must be considered. In the present paper, an effect of the covariance on void fraction prediction in pipe flow was numerically assessed by implementing Hibiki and Ozaki's model into the interfacial drag term in the one-dimensional two-fluid model. For the low flow rate with high void fraction conditions, it was found that the inclusion of covariance model slightly underestimated void fraction value than that calculated by the drift-flux model. This underestimation comes from the momentum source term in the two-fluid model, which was derived under the assumption of uniform void fraction distribution. Therefore, in this paper, momentum source term was rederived with consideration of void fraction covariance and a complete set of momentum equation and constitutive formulations for the one-dimensional two-fluid model is presented.

1. Introduction

In order to evaluate the safety of nuclear power plants that possess highly complicated and large-scale systems, it is essential to utilize numerical simulation codes. Accidents in nuclear power plants can cause severe public hazards, and may lead to serious social and economic consequences. Hence, careful safety evaluation must be conducted using proper simulation method at the design stage of the plant. Also, those in charge of safety regulatory must consider the validity of the simulation methods upon their decision-making process. A method to evaluate the validity of numerical simulation is standardized in V&V (Verification and Validation) guideline (Boyack et al., 1989; AESJ, 2008, 2015). According to the guideline, thorough understandings of the uncertainties arise by the (1) lack of knowledge, (2) lack of the experimental database for model development, and (3) approximation for shortening iteration time, are crucial when numerically obtained results are compared to the exact solution.

Gas-liquid two-phase flow phenomena in the nuclear reactor are highly linked to the safety of nuclear power plants in terms of the plant's thermal power, fuel cooling, pressure loss, flow profiles within reactor core, flow-induced vibration characteristics, and so on. Hence, accurate two-phase flow simulation is indispensable for conducting a safety evaluation of nuclear power plants. Advanced thermal-hydraulics codes such as TRACE (USNRC, 2008), RELAP5 (ISL, 2001), and TRAC-BF1 (Borkowski and Wade, 1992) utilize interfacial drag term in the momentum equation to represent the interfacial momentum transfer between two phases. Interfacial drag term is the most important interfacial transfer term that governs velocity fields of two-phases, and it highly influences the void fraction prediction. Void fraction is one of the most important parameters to conduct plant's safety evaluation, it is typically categorized as the high ranked parameter in phenomena identification and ranking table (PIRT) for many associated evaluation events (Griffiths et al., 2014).

In general, safety evaluation of nuclear power plants is conducted by treating coolant flow within the reactor core and piping systems as one-dimensional flow, as is the case for the safety codes including TRACE (USNRC, 2008), RELAP5 (ISL, 2001), and TRAC-BF1 (Borkowski and Wade, 1992). The capability of three-dimensional CFD technique to simulate two-phase flow phenomena is still immature due to the high computational cost, and lack of the experimental database

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to perform benchmarking at a local level. Hence, it is still not a practical approach to conduct plant-level three-dimensional thermal-hydraulic analysis, despite the recent advancement in computational methodologies. In typical safety analysis codes, the one-dimensional two-fluid model is utilized. However, the interfacial drag term, which represents the interfacial momentum transfer between two-phases, is typically given as the area-averaged quantity, and such area-averaged approximation may influence the void fraction calculation results.

In order to eliminate the influence of area-averaged approximation, various works have been undertaken with the advancement of two-phase flow simulation capability. Covariance of the mixture volumetric flux and phase fraction profiles was defined as the distribution parameter for the general expression of the drift-flux model, and its relationship with respect to area-averaged void fraction was established (Zuber and Findlay, 1965). The area-averaged void fraction can be obtained from the distribution parameter, but it is highly dependent on channel geometry and flow conditions. Hence, various works have been undertaken to develop the constitutive equations for the distribution parameter (Ishii, 1977; Kataoka and Ishii, 1987; Hibiki and Ishii, 2003a,b; Ozaki and Hibiki, 2015). Additionally, Ishii and Mishima (1984) utilized the distribution parameter to develop area-averaged relative velocity model and contributed to the advancement of one-dimensional two-phase flow codes. However, Ishii and Mishima (1984) derived the area-averaged relative velocity term without considering the covariance of void fraction distribution (spatial auto-correlation of the void fraction). Hence, utilization of the Ishii and Mishima's model alone will not address the dependency of void fraction covariance on the local relative velocity expression.

Recent advancement of measurement technique enables one to conduct local time-averaged void fraction measurement (Garnier et al., 2001; Roy et al., 2002; Situ et al., 2004; Lee et al., 2009; Yun et al., 2010; Ozar et al., 2013), and the constitutive equations on void fraction covariance were developed based on such experimental database. Brooks et al. (2014) developed a covariance model based on the void fraction database obtained in adiabatic and boiling experiments performed in a circular pipe. Hibiki and Ozaki (2017) proposed the covariance model for subcooled boiling flow. By combining the model with the Brooks et al. (2014)'s, Hibiki and Ozaki (2017) extended their work to develop a new model that is applicable for entire dispersed bubbly flow regime. Hibiki and Ozaki (2017) clarified the relationship between the interfacial drag term of the one-dimensional two-fluid model and covariance term and formulated the interfacial drag term with covariance effect that can be embedded on system analysis codes such as RELAP5 and TRACE.

In this study, constitutive equations for covariance proposed by Hibiki and Ozaki (2017) were included in the one-dimensional two-fluid code, and the effect of covariance on circular round tube was evaluated. Based on the analysis, proper treatment of the interfacial drag term and formulation of the momentum equation in the two-fluid model were considered. The interfacial drag term with covariance effect proposed by Hibiki and Ozaki (2017) is comprehensive enough to conduct a quantitative evaluation using one-dimensional numerical code. On the other hand, in the original form of momentum equation, uniform void fraction distribution is assumed, and it is uniformly distributed to each phase to calculate wall shear force and viscous and turbulent shear stresses. This may create a discrepancy in the interfacial drag term calculated with covariance. In this paper, chapter 2 discusses the inclusion of interfacial drag term with covariance in the two-fluid model, and chapter 3 discusses the methodology of one-dimensional safety code analysis and the calculation domain nodalization. Chapter 4 discusses the cause of a discrepancy in void fraction calculations obtained using covariance and the drift-flux model, and new momentum equation formulation to resolve such issue is proposed.

2. Interfacial drag term for one-dimensional two-fluid model

2.1. Derivation of the interfacial drag term

To evaluate two-phase velocity fields using two-fluid model, proper usage of constitutive relation for the interfacial momentum transfer, especially the interfacial drag term, is indispensable. In the one-dimensional two-fluid model, interfacial drag term must be supplied as an area-averaged quantity over the flow channel of interest. Also, interfacial drag term should be expressed as a function of relative velocity due to its high dependency. The interfacial drag term also has an effect to suppress numerical instabilities. Based on above considerations, modeling of the interfacial drag term for the one-dimensional two-fluid model will be discussed in this section.

As was mentioned in Brooks et al. (2012), and Hibiki and Ozaki (2017), area-averaged interfacial drag force term used in the one-dimensional two-fluid model is expressed as follows:

$$\langle M_{ig}^D\rangle = -\langle C_i\rangle|\langle v_r\rangle|\langle v_r\rangle. \tag{1}$$

Here, M_{ig}^D , C_i and v_r are the interfacial drag force term, drag coefficient and relative velocity, respectively. The bracket of < > means the cross-sectional area averaging quantity. The area-averaged drag coefficient can be formulated as follows:

$$\langle C_i\rangle = \frac{\langle\alpha\rangle(1-C_\alpha\langle\alpha\rangle)^3\Delta\rho g}{\langle\langle v_{gj}\rangle\rangle^2} \tag{2}$$

Here, α, $\Delta\rho$, g, and $\langle\langle v_{gj}\rangle\rangle$ are the void fraction, the density difference between two phases, the gravitational acceleration, and the void fraction weighted mean drift velocity, respectively. C_α is the covariance in void fraction distribution arise by the area-averaging, which is defined as follows:

$$C_\alpha \equiv \frac{\langle\alpha^2\rangle}{\langle\alpha\rangle\langle\alpha\rangle} \tag{3}$$

Under the steady state condition, the interfacial drag force acting on bubbles is balanced with the buoyancy force as shown in Eq. (4).

$$\langle M_{ig}^D\rangle = -\langle\alpha(1-\alpha)\rangle\Delta\rho g = -\langle\alpha\rangle(1-C_\alpha\langle\alpha\rangle)\Delta\rho g \tag{4}$$

Substituting Eq. (4) into Eq. (1) yields the drag coefficient given by Eq. (2). Additionally, the area-averaged relative velocity can be expressed as a function of distribution parameter (C_0) and the covariance C_α defined in Eq. (3) as follows (Brooks et al., 2012, 2014):

$$\langle v_r\rangle = \frac{1-\langle\alpha\rangle}{1-C_\alpha\langle\alpha\rangle}\left(\frac{1-C_0\langle\alpha\rangle}{1-\langle\alpha\rangle}\langle\langle v_g\rangle\rangle - C_0\langle\langle v_f\rangle\rangle\right) \tag{5}$$

Here, v_g and v_f are, respectively, the gas velocity and the liquid velocity. By substituting Eqs. (2) and (5) into Eq. (1), one obtains an expression for the interfacial drag as follows:

$$\langle M_{ig}^D\rangle = -\frac{1}{C'_\alpha}\frac{\langle\alpha\rangle(1-\langle\alpha\rangle)^3\Delta\rho g}{\langle\langle v_{gj}\rangle\rangle^2} \times\left(\frac{1-C_0\langle\alpha\rangle}{1-\langle\alpha\rangle}\langle\langle v_g\rangle\rangle - C_0\langle\langle v_f\rangle\rangle\right)\left|\left(\frac{1-C_0\langle\alpha\rangle}{1-\langle\alpha\rangle}\langle\langle v_g\rangle\rangle - C_0\langle\langle v_f\rangle\rangle\right)\right| \tag{6}$$

Here, C'_α is the relative velocity covariance, which represents the effect of covariance C_α on the area-averaged relative velocity, and is defined as follows:

$$C'_\alpha \equiv \frac{1-\langle\alpha\rangle}{1-C_\alpha\langle\alpha\rangle} \tag{7}$$

As shown in Eq. (6), constitutive equations for C_0, $\langle\langle v_{gj}\rangle\rangle$, and C'_α are