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Original Article

NEW WALL DRAG AND FORM LOSS MODELS FOR ONE-DIMENSIONAL DISPERSED TWO-PHASE FLOW

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It had been disputed how to apply wall drag to the dispersed phase in the framework of the conventional two-fluid model for two-phase flows. Recently, Kim et al. [1] introduced the volume-averaged momentum equation based on the equation of a solid/fluid particle motion. They showed theoretically that for dispersed two-phase flows, the overall two-phase pressure drop by wall friction must be apportioned to each phase, in proportion to each phase fraction. In this study, the validity of the proposed wall drag model is demonstrated though one-dimensional (1D) simulations. In addition, it is shown that the existing form loss model incorrectly predicts the motion of the dispersed phase. A new form loss model is proposed to overcome that problem. The newly proposed form loss model is tested in the region covering the lower plenum and the core in a nuclear power plant. As a result, it is shown that the new models can correctly predict the relative velocity of the dispersed phase to the surrounding fluid velocity in the core with spacer grids.

1. Introduction

Most thermal-hydraulic codes for nuclear reactor safety analysis are based on two-fluid equations which are obtained by averaging the local instantaneous conservation equations in time, space, or some combination of the two. A key assumption in the standard two-fluid model is that even a dispersed phase is treated as a continuous phase. Therefore, the same averaging process is applied to both phases.

However, that assumption may yield physically-incorrect predictions. One example is the wall drag treatment in the one-dimensional momentum equation for dispersed flows. The methods of determining the wall drag acting on the dispersed phase vary from code to code. The TRACE [2], CATHARE [3], and COBRA-TF [4] do not consider the wall drag force for the dispersed phase based on observations that most droplets/bubbles do not touch the wall. However, this wall drag treatment causes the dispersed phase to be faster than the carrier in a fully-developed horizontal bubbly flow in a pipe with constant area for which two phase velocities are considered to be equal. The local bubble velocity must not exceed the local water velocity in a fully-developed horizontal

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bubbly flow in a pipe with constant area [5,6]. Thus, the wall drag must not be set to zero. The RELAP5 [7] imposes a wall drag force on the bubbles based on the wetted perimeter concept, but the magnitude of the wall drag for the bubbles is even smaller than the physically-correct value.

A question is then raised: what value should we assign to the wall drag force for the dispersed phase? To answer this question, Kim et al. [1] considered different one-dimensional momentum equations based on the equation of a fluid particle motion. They insisted that the magnitude of the wall drag force acting on each phase is the phasic volume fraction multiplied by the overall two-phase pressure drop induced by the interaction between the continuous phase and the wall.

Meanwhile, the form loss designates the loss of momentum due to obstruction or flow separation in nonstraight channels in which the flow area changes abruptly or the pipe is being bent. The existing form loss formulation for a two-phase flow takes the form similar to that used for a single-phase flow. However, such formulation incorrectly predicts the bubble/droplet velocity against the surrounding fluid velocity.

The purpose of this study is to demonstrate the validity of the wall drag model proposed by Kim et al. [1], and to propose a new form loss model for dispersed flows. The concept of the wall drag and form loss are needed only for one-dimensional modeling. Therefore, various one-dimensional simulations were performed using the SPACE code [8] in order to validate the proposed wall drag and form loss models. Fundamental tests were performed in a pipe, contraction, and expansion to validate the new wall drag model. In addition, separate effect tests were carried out in the region covering the lower plenum and the core with grid spacers in a nuclear power reactor, to demonstrate the validity of the new form loss model.

2. Wall drag and form loss for dispersed flow

2.1. Wall drag

This section summarizes the work done by Kim et al. [1]. Unless phase change is considered, the standard volume-averaged momentum equation for phase k can be written as [9]:

$$\alpha_k\rho_k\frac{\partial \mathbf{v}_k}{\partial t} + \alpha_k\rho_k\mathbf{v}_k\cdot\nabla\mathbf{v}_k + \nabla\cdot\left(\alpha_k\tau_k^{\mathrm{Re}}\right) = -\alpha_k\nabla p_k + \nabla\cdot(\alpha_k\tau_k) - \mathbf{f}_{ik} + \alpha_k\rho_k\mathbf{g}, \tag{1}$$

where α_k, ρ_k, $\mathbf{v}_k$, p_k, τ_k, $\mathbf{f}_{ik}$, τ_k^{Re}, and $\mathbf{g}$ are the volume fraction, density, velocity vector, pressure, viscous stress tensor, interface force, volume-averaged Reynolds stress, and gravitational acceleration, respectively.

Meanwhile, based on the equation of a solid/fluid particle motion [10,11], the volume-averaged momentum equation for an adiabatic dispersed two-phase flow is derived as follows [1,12–14]:

$$\alpha_k\rho_k\frac{\partial \mathbf{v}_k}{\partial t} + \alpha_k\rho_k\mathbf{v}_k\cdot\nabla\mathbf{v}_k + \nabla\cdot\left(\alpha_k\tau_k^{\mathrm{Re}}\right) = -\alpha_k\nabla p_c + \alpha_k\nabla\cdot\tau_c - \mathbf{f}_{ik} + \alpha_k\rho_k\mathbf{g}. \tag{2}$$

Each variable is a volume-averaged quantity. Subscripts d and c are used to indicate the dispersed and continuous phases, respectively.

Comparing Eq. (2) with Eq. (1), one can notice the differences in the second terms on the right-hand sides: (1) α_k is outside the divergence operator with regard to the viscous stress tensor, whereas it is inside the divergence operator in Eq. (1); and (2) the dispersed phase equation is expressed in terms of the pressure and viscous stresses for a continuous phase instead of those for a dispersed phase.

Eq. (2) reduces to the following one-dimensional equation:

$$\alpha_k\rho_k\frac{\partial v_k}{\partial t} + \alpha_k\rho_k v_k\frac{\partial v_k}{\partial x} = -\alpha_k\frac{\partial p}{\partial x} - \alpha_k F_{wt} - f_{ik} + \alpha_k\rho_k g_x. \tag{3}$$

Each of the variables are one-dimensional volume-averaged quantities. The x-direction is the main flow direction. p_c is expressed by p. τ_k^{Re} is neglected because of one-dimensional modeling. f_{ik} is the interface force acting on phase k. In Eq. (2), $\nabla\cdot\tau_c$ is the divergence of the volume-averaged viscous stresses. Thus, it is evaluated as:

$$\nabla\cdot\langle\tau_c\rangle = \langle\nabla\cdot\tau_c\rangle = -F_{wt}, \tag{4}$$

where $\langle\ \rangle$ means the volume averaging over the control volume. F_{wt} is the overall pressure drop induced by the shear of the continuous phase at the wall, which is defined to be a positive value. Consequently, the term $-\alpha_k F_{wt}$ in Eq. (3) indicates that the overall two-phase pressure drop by wall friction is apportioned to each phase in proportion to each phase fraction. This wall drag partition model correctly predicts the relative motion of a bubble/droplet against the surrounding fluid. For a steady horizontal bubbly flow, the bubbles become faster than the water in a contraction whereas the bubble becomes slower in an expansion. For a steady horizontal droplet flow, the droplet is slower than the gas in a contraction whereas the droplet is faster in an expansion. These behaviors are attributed to the fact that compared with the lighter fluid, the heavier fluid slowly accelerates or decelerates in response to the changes in circumstances. Of course, two velocities become equal for a fully-developed flow in a pipe with constant area. A detailed theoretical discussion is described in Kim et al. [1].

2.2. Form loss

The form loss designates the loss of momentum due to an obstruction or flow separation in nonstraight channels in which the flow area changes abruptly or the pipe is being bent. The contribution of the form loss is usually added to the one-dimensional momentum equation as follows:

$$\alpha_k\rho_k\frac{\partial v_k}{\partial t} + \alpha_k\rho_k v_k\frac{\partial v_k}{\partial x} = -\alpha_k\frac{\partial p}{\partial x} - \alpha_k F_{wt} - f_{ik} + \alpha_k\rho_k g_x - \frac{K_k}{2L}\alpha_k\rho_k\left|v_k\right|v_k. \tag{5}$$

The last term accounts for the form loss, where K_k is the form loss factor for phase k in the channel length L. Consider a fully-developed horizontal bubbly flow at the region in which K_k has a nonzero value whereas the flow area remains unchanged. This situation may be encountered at the bending