Numerical Tests for the Lift, Wall Lubrication, and Turbulence Dispersion Forces in the CUPID

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1. Introduction

In a two phase flow momentum equation, the most important term to be modeled by a constitutive relation is the generalized drag force which specifies the interfacial surface forces. This force can be formulated as the linear combination of various known interfacial forces as a sum of the standard drag force, the lift force, the wall lubrication force, the turbulent dispersion force, and so on [1]. In the current version of CUPID[2], the standard drag force and the virtual mass force have been implemented, but the lift force, the wall lubrication force, and the turbulence dispersion force were omitted temporally. In this paper these three forces were implemented and tested.

2. Mathematical Model

2.1 Governing Equation

The governing equations of the two-fluid, three-field model are similar to those of the time-averaged two-fluid model derived by Ishii and Hibiki[3]. The momentum equation for the k-phase is given by

$$\frac{\partial}{\partial t}(\alpha_k\rho_k\underline{u}_k)+\nabla\cdot(\alpha_k\rho_k\underline{u}_k\underline{u}_k)=-\alpha_k\nabla P+\nabla\cdot[\alpha_k\tau_k]$$
$$+\alpha_k\rho_k\underline{g}+P\nabla\alpha_k+M_k^{mass}+M_k^{drag}+M_k^{non-drag} \quad (1)$$

where, α_k, ρ_k, u_k, P are the k-phase volume fraction, density, velocity, pressure. M_k represents the interfacial momentum transfer due to a mass exchange, a standard drag force, and several drag forces except the standard drag force virtual mass. $M_k^{non-drag}$ includes the virtual mass force, the lift force, the wall lubrication force, and turbulence dispersion force.

$$M_k^{non-drag}=M_k^{VM}+M_k^{L}+M_k^{WL}+M_k^{TD} \quad (2)$$

$M_k^{L}, M_k^{WL}, M_k^{TD}$ will be discussed in the following section. Further detailed two-phase flow mathematical descriptions are given in Ref. [3].

2.1 Lift Force

The lift force[4] pushes the bubble with perpendicular to the liquid motion. The lift force is given in terms of the slip velocity and the curl of the continuous phase velocity by:

$$M_l^{L}=-\alpha_g\rho_l C_L\left(\vec{u}_g-\vec{u}_l\right)\otimes\left(\vec{\nabla}\otimes\vec{u}_l\right) \quad (3)$$

Here C_L is 0.5 for an inviscid flow around a sphere, but it can have values between 0.01 and 0.05 for a viscous flow. In this paper, the simple formulation of C_L without the directional change was tested and the sophisticated formulation of C_L including the change of the direction will be tested later.

2.3 Wall Lubrication Force

The gas fraction distribution in the near wall region is important for the general flow structure in the case of the pipe flow. It mainly determined by the lift and the wall forces. In this paper, the correlation like that by Antal et al.[5] are tested as

$$M_l^{WL}=\frac{-\alpha_g\rho_l\left|\vec{u}_g-\vec{u}_l\right|^2}{d}\max\left(0, C_1+C_2\frac{d_{bubble}}{y_{wall}}\right)\vec{n} \quad (4)$$

with C1 =-0.01, C2 =0.05. The wall lubrication force is limited within $y_{wall}<5d_{bubble}$, the region less than 5 particle diameters from the wall. This force can be seen on fine grids by considering the bubble diameter. The more sophisticated model will be tested later.

2.4 Turbulence Dispersion Force

Considering the turbulence dispersion force by Bertadano[6], Burns et al.[7] suggested the model for the turbulence dispersion force as following:

$$M_l^{TD}=-C_{TD}C_D\frac{\nu_{T,g}}{Sc_{T,g}}\left(\frac{\nabla\alpha_l}{\alpha_l}-\frac{\nabla\alpha_g}{\alpha_g}\right) \quad (5)$$

where, $C_{TD}, C_D, \nu_{T,g}, Sc_{T,g}$ indicates turbulence dispersion coefficient(~1), the drag coefficient(~2), the turbulence kinematic viscosity for gas, turbulent Schumidt number or turbulent Prandtl number(~0.9). This formulation has an advantage in that it does not need the turbulence kinetic energy and it can work with a zero equation turbulence model. In this paper, the turbulence dispersion force model by Burns et al. was tested and another model will be tested in the future.

The non-drag forces for the gas phase have the same magnitude and an opposite sign as follows.

$$M_g^{non-drag}=-M_l^{non-drag} \quad (6)$$

3. Qualitative Verification

An air/water two-phase flow through 2-dimensional duct of 0.28m x 1.6 m was simulated. The geometrical condition for this calculation and the gas volume fraction contours for the steps of the non-drag force implementations are presented in Figure 3. The 24 x 24 cells were used for this calculation. The void fraction and the inlet velocity were 0.2 and 0.2 m/sec, respectively. Figure 4 clearly shows the effect of each non-drag force and their sum.

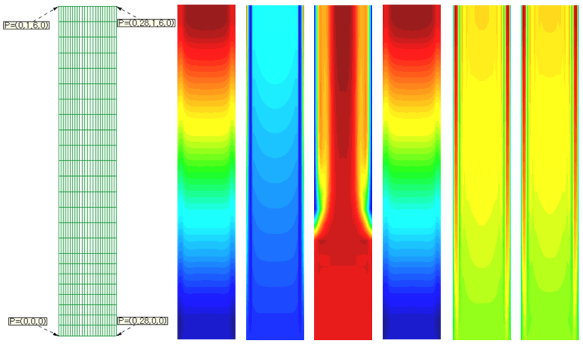

Fig. 3. Mesh and Gas Volume Fractions for Various Non-drag Models (None, Lift, Wall, Dispersion, Lift +Wall, Lift+Wall+Dispersion).

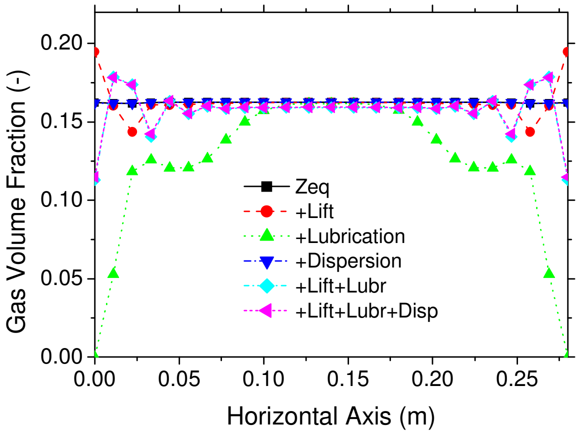

Fig. 4. Horizontal Gas Volume Fractions for Various Non-drag Models

The void fraction without non-drag forces distributes nearly uniform over the perpendicular direction to the primary flow. The lift force pushed the vapor bubble towards the wall. An increase of the void fraction was observed in the near wall region, which is driven by the large liquid velocity gradient at the near wall. The lubrication force expelled the gas at the near wall into the central region by the force which pushed the liquid into the wall. The volume fraction of the dispersed vapor phase, the phasic relative velocity, the bubble diameter, the distance from the wall, and the velocity gradient of the continuous liquid phase are related to this wall lubrication force. The turbulence dispersion force is created by the volume fraction gradient of the continuous liquid phase and the turbulent kinetic energy. The combination of the lift force and the wall lubrication force make the gas fraction peaked at the near wall. The volume fraction of the dispersed gas fraction in the central region and at the very near wall is relatively lower than that of the gas peaking region.

4. Conclusions

A component-scale two-phase analysis code, CUPID, has been developed for realistic simulations of transient two-phase flows in light water nuclear reactor components. The non-drag forces such as the lift force, the wall lubrication force, and the turbulence dispersion force were implemented and verified based upon a zero equation turbulence model by using an air-water flow. The gas volume fraction contours and the horizontal gas volume fraction distributions show that each force and the sum of all these 3 forces were implemented properly and worked effectively. After further validations against air-water flow tests and/or steam-water flow tests, these implementations can be adapted for a realistic simulation of transient two-phase flows.

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ACKNOWLEDGMENTS

This study has been carried out under the nuclear R&D program by the Korean Ministry of Education, Science and Technology.

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