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Assessment of the Wall Drag and Form Loss Partitioning Methods for Dispersed Flow

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1. Introduction

Recently, Kim et al. (2013) derived the volume-averaged momentum equations working at dispersed flow. Since the equations are based on the equation of a particle motion, each force term can be exactly identified and interpreted. The dispersed phase equation is expressed in terms of the continuous phase pressure and viscous stress. As a result, it was shown that the pressure drop by the wall in a 1D flow should be apportioned to each phase in proportion to its volume fraction.

The form loss denotes the momentum loss related to flow separation by the interaction between the continuous phase and the surrounding wall. The momentum loss occurs in which the flow area changes abruptly or the pipe is bent.

This study demonstrates the validity of the wall drag partitioning method suggested by Kim et al. (2013). In addition, the inconsistencies of the existing form loss formulation is discussed. To overcome this, a new form loss calculation method is proposed.

2. Wall Drag and Form Loss

2.1 Wall Drag

Kim et al. (2013) showed that when neglecting the phase change, the horizontal 1D momentum equation for phase k is given by

$$\alpha_k \rho_k \left(\frac{\partial v_k}{\partial t} + v_k \frac{\partial v_k}{\partial x} \right) = -\alpha_k \frac{\partial p}{\partial x} - \alpha_k F_{wt} - f_{ik} \qquad (1)$$

where F_{wt} and f_{ik} represent the total pressure drop by the wall drag and the interface drag force. The second term on the right-hand side means that the total wall drag is apportioned to each phase in proportion to its volume fraction. For steady flow, the first two terms on the right-hand side sum to zero. However, CATHARE, TRACE and COBRA codes do not consider the wall drag term in the dispersed phase momentum equation. In this case, the motion of the dispersed phase can be predicted unphysically.

2.2 Form loss

Usually, the contribution of the form loss is added to the momentum equation in a following form:

$$\alpha_k \rho_k \left(\frac{\partial v_k}{\partial t} + v_k \frac{\partial v_k}{\partial x} \right) = -\alpha_k \frac{\partial p}{\partial x} - \alpha_k F_{wt} - f_{ik} - \frac{K_k}{2L} \alpha_k \rho_k v_k^2 \qquad (2)$$

where K_k is the form loss factor and L is computational momentum cell length.

Consider a steady bubbly flow at the region in which K_k is a non-zero value while the flow area does not change. This situation is encountered at the bending region of a pipe. For simplicity, consider a hypothetical situation in which K_k is a non-zero in a straight pipe. In this case, Eq. (2) can be written as

$$0 = -\alpha_d \frac{\partial p}{\partial x} - \alpha_d F_{wt} - f_{id} - \frac{K_d}{2L} \alpha_d \rho_d v_d^2 \qquad (3)$$

$$0 = -\alpha_c \frac{\partial p}{\partial x} - \alpha_c F_{wt} - f_{ic} - \frac{K_c}{2L} \alpha_c \rho_c v_c^2 \qquad (4)$$

where d and c stand for the dispersed and continuous phases, respectively.

The pressure drop results from the wall drag and the form loss. The linear relation is assumed as follows:

$$-\frac{\partial p}{\partial x} = \left(-\frac{\partial p}{\partial x} \right)_w + \left(-\frac{\partial p}{\partial x} \right)_K \qquad (5)$$

Substituting Eq. (5) into Eqs. (3) and (4) and using the relations $(-\partial p / \partial x)_w = F_{wt}$ and $f_{ic} = -f_{id}$, we can have

$$0 = \alpha_d \left(-\frac{\partial p}{\partial x} \right)_K - f_{id} - \frac{K_d}{2L} \alpha_d \rho_d v_d^2 \qquad (7)$$

$$0 = \alpha_c \left(-\frac{\partial p}{\partial x} \right)_K + f_{id} - \frac{K_c}{2L} \alpha_c \rho_c v_c^2 \qquad (8)$$

If we multiply the first equation by α_c and the second by α_c and subtract the first equation from the second, the pressure gradient term is eliminated. The resulting equation can be arranged to give

$$f_{id} = \frac{\alpha_c \alpha_d}{2L} \left(K_c \rho_c v_c^2 - K_d \rho_d v_d^2 \right) \approx \frac{\alpha_c \alpha_d}{2L} K_c \rho_c v_c^2 \qquad (9)$$

The last approximation is due to fact that the bubble density is much smaller than the water density. Accodingly,

$$f_{id} = C_{id} \, | v_d - v_c | (v_d - v_c) = \frac{\alpha_c \alpha_d}{2L} K_c \rho_c v_c^2 > 0 \, . \qquad (10)$$

This means that the bubble is faster than the water. However, this prediction seems unphysical. Since the flow area remains unchanged and the form loss can be treated as another form of the wall drag, it is anticipated that the dispersed phase velocity is the same as the continuous phase velocity in a fully-developed flow. Therefore, the form loss formulation such as Eq. (2) should be corrected.

Let us look again at Eqs. (7) and (8). To make two velocities equalize, the total form loss (F_{loss}) is first computed and is apportioned to each phase in proportion to its volume fraction.

$$0 = \alpha_d \left(-\frac{\partial p}{\partial x} \right)_K - f_{id} - \alpha_d F_{loss} \qquad (11)$$

$$0 = \alpha_c \left(-\frac{\partial p}{\partial x} \right)_K + f_{id} - \alpha_c F_{loss} \quad (12)$$

Note that the pressure gradient term naturally corresponds to F_{loss}. Thus, the first and third terms on the right-hand side in Eqs. (11) and (12) sum to zero; two velocities become identical.

3. Result

To demonstrate the validity of the wall drag and form loss partitioning method, various tests were perform in a horizontal pipe, contraction, and expansion, using SPACE code. The contraction cases are provided in this study. The test geometry covers the lower plenum and the core, which was taken from SPACE input for Shin-Kori 3 and 4 units. For the lower plenum, the hydraulic diameter and flow area are 3.3m and 8.54m^2, respectively. For the core, the hydraulic diameter and flow area are 9.5mm and 5.8m^2.

At the lower plenum inlet, the bubble fraction is 0.05 and the two velocities are 1.0m/s. Tests were done at 70 bar saturated condition. To exclude any other effects such as gravity and phase change, the interface heat transfer is turned off and the horizontal stratification is set not to occur.

Figure 1 shows the result when the wall drag is not applied to the bubble phase. The k-factors for grid spacers are not considered.

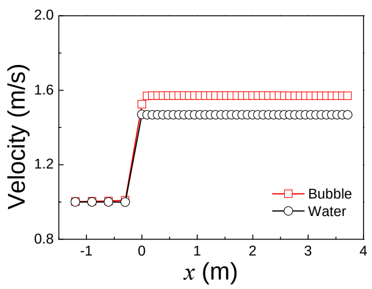

Fig. 1. Velocity when the wall drag applies only to the water.

The flow area reduces at x=0.0m. In the lower plenum (x<0m), the difference between two velocities is not distinguishable, which is attributed to the fact that the pressure drop by the wall drag is very small in that region. However, the pressure drop by the wall drag becomes considerable at the core. Therefore, neglecting the wall drag term for the dispersed phase leads to faster bubble velocity against the surrounding water. Figure 2 shows the result when the total wall drag is apportioned to each phase in proportion to its volume fraction. As seen, two velocities are the same in the whole region. Strictly speaking, the bubble velocity is faster the water velocity in the contraction, which becomes more apparent when the flow area changes largely and the water velocity becomes higher.

Now, a k-factor (=1.2) is applied to the spacer grids in the core while the flow area does not change in the core. The wall drag is apportioned to each phase in

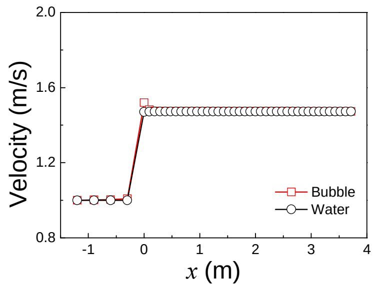

Fig. 2. Velocity when the total wall drag is apportioned to each phase in proportion to its volume fraction.

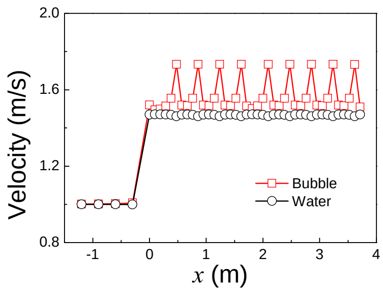

Fig. 3. Form losses are computed using Eqs. (7) and (8).

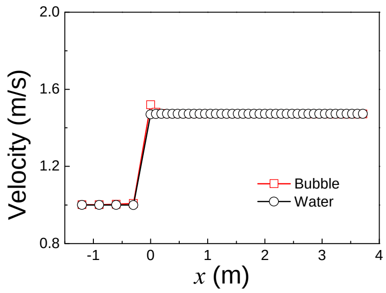

Fig. 4. Form losses are computed using Eqs. (11) and (12).

proportion to its volume fraction. Figure 3 shows the result when the form losses are computed using Eqs. (7) and (8). As expected, the bubble is faster than the water at every spacer grid. However, when the form losses are computed using Eqs. (11) and (12), two velocities becomes equal.

3. Conclusions

In the one-dimensional dispersed flow, the total wall drag and the total form loss should be apportioned to each phase in proportion to its volume fraction.

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REFERENCES

[1] B. J. Kim, J. W. Kim, K. D. Kim, On the Wall Drag Term in the Averaged Momentum Equation for Dispersed Flow, submitted, 2013.