Modified Reynolds Stress Model for Turbulent Bubbly Flows

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1. Introduction

Two-fluid equations are the basic and the only model for the two-phase flow analysis in nuclear reactor systems. Following is the two-fluid momentum equation derived in [1, 2].

$$\begin{aligned}&\frac{\partial}{\partial t}(\alpha_k \rho_k \mathbf{u}_k) + \nabla\cdot(\alpha_k \rho_k \mathbf{u}_k \mathbf{u}_k)\\ &= -\alpha_k \nabla p_k + \nabla\cdot(\alpha_k \boldsymbol{\tau}_k) + \nabla\cdot(\alpha_k \boldsymbol{\tau}_k^{\mathrm{Re}}) ,\\ &+\alpha_k \rho_k \mathbf{g} + \mathbf{f}_{ik}\end{aligned} \quad (1)$$

where, α , ρ , $\mathbf{u}$, p , $\boldsymbol{\tau}$, $\boldsymbol{\tau}^{\mathrm{Re}}$, $\mathbf{g}$, and $\mathbf{f}_{ik}$ are the phase fraction, density, velocity vector, pressure, viscous stress tensor, Reynolds stress tensor, gravitational acceleration, and interfacial momentum transfer, respectively.

Another approach is the derivation from the particle-based theorem, since the disperse phases such as bubbly and mist flows are not may proper for the continuum-based derivation [3-5]. Using the concept in [3-5], unreal velocity deviation in gas and liquid flows are fixed [6-7].

In this paper, the numerical suggested Reynolds stress model in [6] are validated against experiment in [8-9].

2. Modified Momentum Equation

Equation (2) shows the two-fluid density transport equation where the subscript *k* means the phases: *l* for liquid and *g* for vapor.

$$\frac{\partial}{\partial t}(\alpha_k \rho_k) + \nabla\cdot(\alpha_k \rho_k \mathbf{u}_k) = 0 , \quad (2)$$

Equations (3)~(5) show the convectional continuum-based, particle-based with convectional Reynolds stress model, and particle-based with the modified Reynolds stress model momentum equation, respectively. The meaning of Eq. (5) is that the disperse phases are governed by the movement of the surrounding phase.

All equations have interfacial transfer terms such as interfacial drag, interfacial non-drag, and virtual mass terms.

$$\begin{aligned}&\frac{\partial}{\partial t}(\alpha_k \rho_k \mathbf{u}_k) + \nabla\cdot(\alpha_k \rho_k \mathbf{u}_k \mathbf{u}_k)\\ &= -\alpha_k \nabla p + \nabla\cdot[\alpha_k(\boldsymbol{\tau}_k + \boldsymbol{\tau}_k^{\mathrm{Re}})] + \alpha_k \rho_k \mathbf{g} ,\\ &+\mathbf{M}_k^{\mathrm{drag}} + \mathbf{M}_k^{\mathrm{ndrag}} + \mathbf{M}_k^{\mathrm{VM}}\end{aligned} \quad (3)$$

$$\begin{aligned}&\frac{\partial}{\partial t}(\alpha_k \rho_k \mathbf{u}_k) + \nabla\cdot(\alpha_k \rho_k \mathbf{u}_k \mathbf{u}_k)\\ &= -\alpha_k \nabla p + \alpha_k \nabla\cdot\boldsymbol{\tau}_c + \nabla\cdot(\alpha_k \boldsymbol{\tau}_k^{\mathrm{Re}}) + \alpha_k \rho_k \mathbf{g} ,\\ &+\mathbf{M}_k^{\mathrm{drag}} + \mathbf{M}_k^{\mathrm{ndrag}} + \mathbf{M}_k^{\mathrm{VM}}\end{aligned} \quad (4)$$

$$\begin{aligned}&\frac{\partial}{\partial t}(\alpha_k \rho_k \mathbf{u}_k) + \nabla\cdot(\alpha_k \rho_k \mathbf{u}_k \mathbf{u}_k)\\ &= -\alpha_k \nabla p + \alpha_k \nabla\cdot\boldsymbol{\tau}_c + \alpha_k \nabla\cdot\boldsymbol{\tau}_c^{\mathrm{Re}} + \alpha_k \rho_k \mathbf{g} ,\\ &+\mathbf{M}_k^{\mathrm{drag}} + \mathbf{M}_k^{\mathrm{ndrag}} + \mathbf{M}_k^{\mathrm{VM}}\end{aligned} \quad (5)$$

3. Validation

The modified Reynolds stress model is validated against the experiment by Kocamustafaogullari [8].

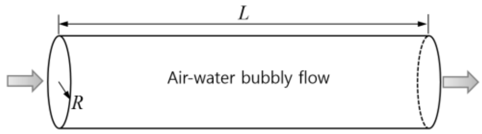

Fig. 1. Schematic draw for the experiment [8].

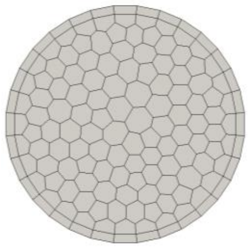

Fig. 2. Mesh generation using CUPID-POP.

Figure 1 shows a horizontal pipe of the experiment [8] where *L*=12.7 m and *R*=25.12 m. Bubbly flow comes in from the left face and goes out through the right face.
Figure 2 shows the computational mesh for CUPID calculations. The total number of cells is 19177. The initial conditions are as follows:

- Test1

Void fraction=0.0850
Gas Velocity=4.9412 m/s

Liquid Velocity=5.1038 m/s

・ Test2
Void fraction=0.2048
Gas Velocity=5.8936 m/s
Liquid Velocity=5.8727 m/s

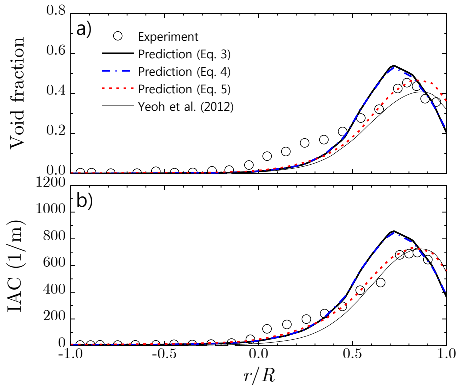

Fig. 3. Non-drag coefficient estimation.

Figure 3 shows the adaptation of the non-drag coefficients for this horizontal pipe flow case (Test1). The coefficients are as follows:

C_L =-0.2, C_{WL} =1.0, C_1 = -0.01, C_2 =0.05, C_{TD} =0.35

Figure 4 shows the velocity comparison for Test2. Figure 4c is the final result of the modified Reynolds stress model. The previous two models (Fig. 4a~b) show a big deviation especially in upper region of the horizontal pipe.

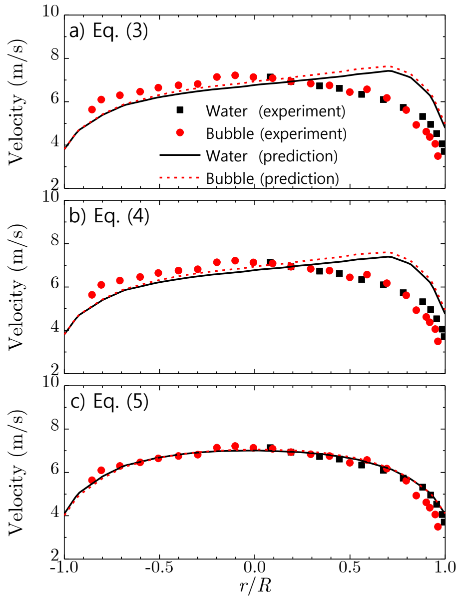

Fig. 4. Comparison of velocity distribution

4. Conclusions

In this study, the modified Reynolds stress model is validated. The experiment of Kocamustafaogullari [8] was tested for the validation. Throughout the investigation, the present modification can correct the velocity distribution to make the upper part slower the lower part. Therefore, the modified model is reasonably recommended to be used in analyzing bubbly flows.

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