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A new centrifugal correction drag force model for gas solid-particle two-phase flow

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ABSTRACT

A new drag force model was developed to simulate gas-solid particle two-phase flows. The drag force model was based on the centrifugal correction, which can be presented by the gradients of the mixture velocities. For gas-solid particle two-phase flow, the effects of the centrifugal force on the solid particles were realized by the correction of the gradients of the mixture velocities. According to the corrections, the terminal velocities of the dispersed phase (solid particles) were able to be calculated in multi dimensions. Through the comparisons of numerical simulations to the experiments and the other models on 2D and 3D cases, this model was validated.

1. Introduction

Gas solid-particle two-phase flows can be encountered frequently in many chemical, petrochemical and biochemical industries, such as absorption, oxidation, hydrogenation, coal combustion boilers, food and commodity transfers, pharmaceutical granulators, the dryers and filters in oil & gas and aerospace propulsion systems [1]. Due to the complex flow phenomena of two-phase flows, a good understanding of the dynamics of solid particles inside the fluid flows will help the engineers to design the high efficient facilities under optimized operating parameters.

For studying the phenomena of gas solid-particle two-phase flows, the experimental facilities and methods, such as laser-Doppler anemometer (LDA), particle image analysis & velocimetry (PIV) measuring technique and positron emission particle tracking (PEPT) method, were used by Ruck and Makiola [2], Hernandez-Jimenez et al. [3] and Laverman et al. [4] respectively to study and measure the distributions of the transient velocity vectors of solid particles and the behaviors of solid particles under the fluidized regime.

Although some of useful information can be obtained by experiments at certain measurement points, it is difficult to have the details of the whole flow fields. Normally the cost of doing experiments is too high to measure the details of the flow fields. In the recent decades, a computational technology, called as computational fluid dynamics (CFD), was rapidly developed [1]. In CFD the approaches of Eulerian, Lagrangian and the couple Eulerian-Lagrangian were employed to simulate the details of the fluid flows [5–7]. Through the former studies using CFD simulations, it was found that the accuracy of the CFD simulations depends on the employed mathematical models [1,8–10]. A simple, efficient and accurate mathematical model can not only help CFD simulations to obtain the agreeable simulation results but also help to save the computing costs.

A new drag force model was developed in this paper. This model was based on the idea of Shang et al. [1,8–10]. It employed the gradient of the mixture velocity to revise the gravity for considering the natural curve movement of the droplets and particles. The effect of gravity with centrifugal correction was successful to be used into the drag force model. Based on this idea, in this paper, the revised gravity was used to calculate the terminal velocity from modifying the drift flux model and then the terminal velocity was used to calculate the drag force for gas liquid-droplet two-phase flows. For gas solid-particle two-phase flow, the revised gravity was directly used to calculate the terminal velocity and then the terminal velocity was used to calculate the drag force. Through comparisons to experiments and other model simulations on 2D and 3D cases, this model was validated.

2. Mathematical model

In this paper, the drag force model was developed based on Eulerian-Eulerian two-fluid model. Therefore the governing equations of the two-fluid model with Eulerian-Eulerian approach were employed. The time averaged conservation equations of mass, momentum, the turbulent kinetic energy equation and the turbulent kinetic energy transport equation can be written as the following.

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Mass equation of continuous phase:

$$\partial(\alpha_c\rho_c)/\partial t + \nabla\cdot(\alpha_c\rho_c\boldsymbol{U}_c) = 0 \tag{1}$$

Mass equation of dispersed phase:

$$\partial(\alpha_d\rho_d)/\partial t + \nabla\cdot(\alpha_d\rho_d\boldsymbol{U}_d) = 0 \tag{2}$$

Momentum equation of continuous phase:

$$\partial(\alpha_c\rho_c\boldsymbol{U}_c)/\partial t + \nabla\cdot(\alpha_c\rho_c\boldsymbol{U}_c\boldsymbol{U}_c) = -\alpha_c\nabla p + \alpha_c\rho_c\boldsymbol{g} + \nabla\cdot\left[\alpha_c(\mu_c+\mu_{tc})\left(\nabla\boldsymbol{U}_c+\nabla\boldsymbol{U}_c^T\right)\right] + \boldsymbol{F}_{cd} \tag{3}$$

Momentum equation of dispersed phase:

$$\partial(\alpha_d\rho_d\boldsymbol{U}_d)/\partial t + \nabla\cdot(\alpha_d\rho_d\boldsymbol{U}_d\boldsymbol{U}_d) = -\alpha_d\nabla p + \alpha_d\rho_d\boldsymbol{g} + \nabla\cdot\left[\alpha_d(\mu_d+\mu_{td})\left(\nabla\boldsymbol{U}_d+\nabla\boldsymbol{U}_d^T\right)\right] + \boldsymbol{F}_{dc} \tag{4}$$

Turbulent kinetic energy equation of continuous phase:

$$\partial(\alpha_c\rho_c k_c)/\partial t + \nabla\cdot(\alpha_c\rho_c\boldsymbol{U}_c k_c) = \nabla\cdot\left[\alpha_c\left(\mu_c+\frac{\mu_{tc}}{\sigma_k}\right)\nabla k_c\right] + \alpha_c(G_c-\rho_c\varepsilon_c) \tag{5}$$

Turbulent kinetic energy equation of dispersed phase:

$$\partial(\alpha_d\rho_d k_d)/\partial t + \nabla\cdot(\alpha_d\rho_d\boldsymbol{U}_d k_d) = \nabla\cdot\left[\alpha_d\left(\mu_d+\frac{\mu_{td}}{\sigma_k}\right)\nabla k_d\right] + \alpha_d(G_d-\rho_d\varepsilon_d) \tag{6}$$

Turbulent kinetic energy dissipation equation of continuous phase:

$$\partial(\alpha_c\rho_c\varepsilon_c)/\partial t + \nabla\cdot(\alpha_c\rho_c\boldsymbol{U}_c\varepsilon_c) = \nabla\cdot\left[\alpha_c\left(\mu_c+\frac{\mu_{tc}}{\sigma_{\varepsilon c}}\right)\nabla\varepsilon_c\right] + \frac{\alpha_c\varepsilon_c}{k_c}(C_{\varepsilon1}G_c-C_{\varepsilon2}\rho_c\varepsilon_c) \tag{7}$$

Turbulent kinetic energy dissipation equation of dispersed phase:

$$\partial(\alpha_d\rho_d\varepsilon_d)/\partial t + \nabla\cdot(\alpha_d\rho_d\boldsymbol{U}_d\varepsilon_d) = \nabla\cdot\left[\alpha_d\left(\mu_d+\frac{\mu_{td}}{\sigma_{\varepsilon d}}\right)\nabla\varepsilon_d\right] + \frac{\alpha_d\varepsilon_d}{k_d}(C_{\varepsilon1}G_d-C_{\varepsilon2}\rho_d\varepsilon_d) \tag{8}$$

in which

$$\mu_{tc} = C_\mu\rho_c\frac{k_c^2}{\varepsilon_c} \tag{9}$$

$$\mu_{td} = C_\mu\rho_d\frac{k_d^2}{\varepsilon_d} \tag{10}$$

$$\boldsymbol{F}_{cd} = -\boldsymbol{F}_{dc} \tag{11}$$

$$G_c = \frac{1}{2}\mu_{tc}\left(\nabla\boldsymbol{U}_c+\nabla\boldsymbol{U}_c^T\right):\nabla\boldsymbol{U}_c \tag{12}$$

$$G_d = \frac{1}{2}\mu_{td}\left(\nabla\boldsymbol{U}_d+\nabla\boldsymbol{U}_d^T\right):\nabla\boldsymbol{U}_d \tag{13}$$

where, ρ is the density, $\boldsymbol{U}$ are the velocity vectors, α is the volumetric fraction, p is pressure, $\boldsymbol{g}$ is the gravitational acceleration vector, $\boldsymbol{F}$ is the interfacial force, μ is viscosity, μ_t is turbulent viscosity, G is stress production. C_μ, σ_k, $\sigma_{\varepsilon c}$, $\sigma_{\varepsilon d}$, $C_{\varepsilon 1}$, $C_{\varepsilon 2}$ are constants for k-ε turbulence model [11], shown in Table 1. The subscript c stands for the continuous phase and d stands for the dispersed phase.

Table 1
Constants of standard k-ε turbulence model.

Variable	C_μ	σ_k	σ_ε	C_1	C_2
Constant	0.09	1.0	1.3	1.44	1.92

The interfacial forces $\boldsymbol{F}_{cd}$ and $\boldsymbol{F}_{dc}$ can be formulated through the interactions between continuous phase and dispersed phase. They have the same formulas but the sign is opposite. The total interfacial force $\boldsymbol{F}_{cd}$ can be described as the following equation.

$$\boldsymbol{F}_{cd} = \boldsymbol{F}_{cd}^{drag} + \boldsymbol{F}_{cd}^{virtual} + \boldsymbol{F}_{cd}^{lift} + \boldsymbol{F}_{cd}^{dispersion} + \cdots \tag{14}$$

where subscript cd indicates the interfacial force acting on continuous phase from dispersed phase, $\mathbf{F}^{drag}$ is interfacial force due to drag by the continuous liquid, $\boldsymbol{F}^{virtual}$ is the interfacial force due to virtual mass effect, $\mathbf{F}^{lift}$ is the interfacial force due to slip shear lift, $\boldsymbol{F}^{dispersion}$ is the interfacial turbulent dispersion force due to the movement of the turbulent eddies, and so on the other interfacial forces can be added into Eq. (14).

In this paper, only the interfacial forces of drag force, lift force and turbulent dispersion force were considered. The expanded description about these forces can be represented as the following equations [12].

$$\boldsymbol{F}_{cd}^{drag} = \frac{3\alpha_d\rho_c C_d|\boldsymbol{U}_c-\boldsymbol{U}_d|}{4d_p}(\boldsymbol{U}_c-\boldsymbol{U}_d) \tag{15}$$

$$\boldsymbol{F}_{cd}^{lift} = \alpha_d\rho_c C_l(\boldsymbol{U}_c-\boldsymbol{U}_d)\times\nabla\times\boldsymbol{U}_c \tag{16}$$

$$\boldsymbol{F}_{cd}^{dispersion} = C_{td}\frac{3\alpha_d\rho_c C_d|\boldsymbol{U}_c-\boldsymbol{U}_d|}{4d_p}\frac{\eta_{tc}}{\sigma_{tc}}\left(\frac{\nabla\alpha_c}{\alpha_c}-\frac{\nabla\alpha_d}{\alpha_d}\right) \tag{17}$$

in Eqs. (15), (16) and (17), d_p is dispersed phase diameter, σ_{tc} is the Prandtl/Schmidt number set to be 0.75 and η_{tc} is the turbulent diffusivity which can be simplified as $\eta_{tc}=\mu_{tc}/\rho_c$. C_d is drag force coefficient which should be modeled, C_l is lift force coefficient which is default as 0.5 and C_{td} is the turbulent dispersion force coefficient which is 1.0. These coefficients can be determined by mathematical models or constants.

3. Drag force coefficient

Based on the semi-empirical development, Krishna et al. [13] employed the drag force coefficient from the concept of terminal velocity, shown in Eq. (18).

$$C_d = \frac{4}{3}\frac{\rho_d-\rho_c}{\rho_c}gd_p\frac{1}{|\boldsymbol{U}_t|^2} \tag{18}$$

where $\boldsymbol{U}_t$ is the terminal velocity of droplets or particles. This drag force coefficient model was employed in this paper. However how to calculate the terminal velocity is the innovation in this paper. According to the different characteristics of droplets or particles, the terminal velocity will be calculated by different models.

The terminal velocity of solid particles can be modeled through the particle relaxation time [9,10,14]. In gas-solid particle flow system, the continuous phase is gas, subscripted as g and the dispersed phase is solid particle, subscripted as p.

$$\boldsymbol{U}_t = -\sqrt{\frac{\left(\rho_p-\rho_g\right)\mu_g \mathrm{Re}_p\tau_p|\boldsymbol{g}'|}{\rho_p\rho_g d_p}}\frac{\boldsymbol{g}'}{|\boldsymbol{g}'|} \tag{19}$$