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CFD of dilute gas–solid two-phase flow using Lagrangian algebraic slip mixture model

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ABSTRACT

A Lagrangian algebraic slip mixture model (LASMM) has been employed to study gas–solid two-phase flows. In this model the slip velocity between gas and solid particles was derived from Lagrangian form. Hence the accelerations of various forces on the particle were considered through the single solid particle Lagrangian movement equation. Owing to the governing equations of LASMM based on Euler equations, this model therefore realized the connection between Eulerian model and Lagrangian model. Through the comparisons of the numerical simulations to the experiments and two-fluid models, this model was validated.

1. Introduction

In engineering, gas–solid two-phase flow can be encountered in many industrial processes such as fluidized beds, coal combustion boilers, food and commodity transfers, solid rocket jets, pharmaceutical granulators, the dryers and filters in oil and gas. In a gas–solid two-phase flow system, solid particles are usually transported by flowing gas. Such two-phase flow is widely encountered in pipe flows.

In gas–solid two-phase flows, the solid particle usually is grounded into fine powder which is from several micrometers to several hundred micrometers in size. During the flowing, these fine powders have not only the interactions with gas phase but also the collisions with each other. Therefore the flow phenomena of gas–solid two-phase flows are very complex.

The experiment methods usually were employed to explore the complex internal flow structure of gas–solid two-phase flows. Ruck and Makiola [1] used laser-Doppler anemometry (LDA) to measure the velocity distributions of solid particles behind the backward-facing step. Hernandez-Jimenez et al. [2] employed particle image analysis and velocimetry (PIV) measuring technique to do the experiments for a fluidized bed. They measured the velocity field of the solid particles. Laverman et al. [3] used the positron emission particle tracking (PEPT) method, which is a kind of non-invasive measuring technique, to measure the velocity vectors and the average velocity distribution of the solid particles. From experiments, the flow structure and specific physical parameters can be measured directly. However, the cost of doing experiments is very high. Following the advantage of computer technology, the flow structure and specific physical parameters of gas–solid two-phase flows can be simulated numerically based on computational fluid dynamics (CFD) methodology [4–6].

The accuracy of CFD will depend on the models, for example, mixture, two-fluid and Eulerian–Lagrangian models, which are able to perform the numerical simulations for two-phase flows [2,5,7]. Within these models, Eulerian–Lagrangian model is accurate but the computing cost is high; two-fluid model is popular but complex; mixture model is simple but the accuracy is difficult to be guaranteed. It is because in mixture model the algebraic slip mixture model (ASMM) is often employed. However in traditional ASMM, the interfacial forces, such as drag force, lift force, virtual mass force and turbulent dispersion force etc., are not included. Hence the accuracy of the traditional ASMM will be affected [8].

Against the disadvantages of low accuracy of the traditional ASMM, a Lagrangian algebraic slip mixture model (LASMM) was developed in this paper for gas–solid dilute two-phase flow according to the former studies by the authors for gas–water two-phase flows [8]. It employed a mixture model to describe the two-phase flows based on Eulerian model. The slip velocity, which can be developed from the dynamic equation of the dispersed phase based on Lagrangian model, was introduced to represent the difference between dispersed and continuous phases. Owing to the Lagrangian model, the interfacial forces, such as buoyancy, drag force, lift force, virtual mass force and turbulent dispersion force etc., are able to be involved. LASMM therefore overcomes the disadvantages of low accuracy of the traditional mixture model. Through comparisons of numerical simulations using LASMM

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to experiments and two-fluid models on gas–solid two-phase flows, this model was validated.

2. Mathematical model

The time averaged conservation equations of mass, momentum and energy as well as the turbulent kinetic energy equation and the turbulent kinetic energy transport equation for the mixture model of a turbulent multi-component multi-phase flow with one continuous phase and several dispersed phases can be written as follows.

$$\partial\rho_m/\partial t + \nabla\cdot(\rho_m U_m) = 0 \tag{1}$$

$$\begin{aligned}\partial(\rho_m U_m)/\partial t + \nabla\cdot(\rho_m U_m U_m) &= -\nabla p + \rho_m g \\ &+ \nabla\cdot\left[(\mu_m+\mu_t)\left(\nabla U_m + \nabla U_m^T\right)\right] - \nabla\cdot\sum\alpha_k\rho_k U_{km}U_{km}\end{aligned} \tag{2}$$

$$\begin{aligned}\partial(\rho_m h_m)/\partial t + \nabla\cdot(\rho_m U_m h_m) &= q + \nabla\cdot\left[\left(\frac{\mu_m}{\Pr}+\frac{\mu_t}{\Pr_t}\right)\nabla h_m\right] \\ &-\nabla\cdot\sum\alpha_k\rho_k h_k U_{km}\end{aligned} \tag{3}$$

$$\partial(\rho_m k)/\partial t + \nabla\cdot(\rho_m U_m k) = \nabla\cdot\left[\left(\mu_m+\frac{\mu_t}{\sigma_k}\right)\nabla k\right] + G - \rho_m\varepsilon \tag{4}$$

$$\partial(\rho_m \varepsilon)/\partial t + \nabla\cdot(\rho_m U_m \varepsilon) = \nabla\cdot\left[\left(\mu_m+\frac{\mu_t}{\sigma_\varepsilon}\right)\nabla \varepsilon\right] + \frac{\varepsilon}{k}(C_1 G - C_2\rho_m\varepsilon) \tag{5}$$

in which

$$\rho_m = \sum\alpha_k\rho_k \tag{6}$$

$$\mu_m = \sum\alpha_k\mu_k \tag{7}$$

$$\rho_m U_m = \sum\alpha_k\rho_k U_k \tag{8}$$

$$U_{km} = U_k - U_m \tag{9}$$

$$G = \frac{1}{2}\mu_t\left[\nabla U_m + (\nabla U_m)^T\right]^2 \tag{10}$$

$$\mu_t = C_\mu\rho_m\frac{k^2}{\varepsilon} \tag{11}$$

where, ρ is the density, U are the velocity vectors, α is the volumetric fraction, p is pressure, g is the gravitational acceleration vector, U_{km} is the diffusion velocity vector of the kth dispersed phase relative to the averaged mixture flow, h is enthalpy, q is heat input, μ is viscosity, μ_t is turbulent viscosity, Pr is molecular Prandtl number, Pr_t is turbulent Prandtl number, G is stress production. C_μ, σ_k, σ_ε, C_1, C_2 are constants for standard k-ε turbulence model [9], shown in Table 1. The subscript m stands for the averaged mixture flow, and k stands for the kth 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

Additional to the above equations, the following conservation equation for each phase is also necessary.

$$\partial(\alpha_k\rho_k)/\partial t + \nabla\cdot(\alpha_k\rho_k U_m) = \Gamma_k - \nabla\cdot(\alpha_k\rho_k U_{km}) \tag{12}$$

where Γ_k is the generation rate of k-phase.

For the closure of the governing Eqs. (1)–(12), it is necessary to determine the diffusion velocities U_{km}. The following equation is employed to convert the diffusion velocities to slip velocities that can be defined as $U_{kl} = U_k - U_l$.

$$U_{km} = U_{kl} - \sum\frac{\alpha_k\rho_k}{\rho_m}U_{kl} \tag{13}$$

Actually the above equation can be developed from the definition of the mixture density (Eq. (6)), the definition of mixture mass flux (Eq. (8)), the diffusion velocity (Eq. (9)) and the slip velocity (U_{kl}). In gas–solid two-phase flow system, the subscript k can be p (particle) and l can be g (gas). Once the slip velocities are obtained, the whole governing equations will be in closure.

The slip velocities present the difference of the movement between the dispersed phase and the continuous phase. For example, in gas and solid particle two-phase flow system, the dispersed phase can be presented as many individual solid particles flowing with the continual gas flow. The movement of the single particle can be described by Lagrangian motion equation.

$$F_p = F_{buoyancy} + F_{drag} + F_{virtual} + F_{lift} + F_{dispersion} + \cdots \tag{14}$$

where F_p is the force acting on the particle due to its acceleration, $F_{buoyancy}$ is the force due to gravity and buoyancy, F_{drag} is force due to drag by the continuous liquid, $F_{virtual}$ is the force due to virtual mass effect, F_{lift} is the force due to slip shear lift, $F_{dispersion}$ is the turbulent dispersion force due to the movement of the turbulent eddies, and so on the other forces can be added into Eq. (14).

In this paper, only the forces of buoyancy, drag, virtual mass, slip shear lift and turbulent dispersion were considered. The expanded description about these forces can be represented by the following equations [10].

$$F_p = m_p\frac{dU_p}{dt} \tag{15}$$

$$F_{buoyancy} = m_p\left(1-\frac{\rho_g}{\rho_p}\right)g \tag{16}$$

$$F_{drag} = m_p\frac{U_g - U_p}{\tau_p} \tag{17}$$

$$F_{lift} = \frac{\pi}{8}d_p^3\rho_g C_{sl}\left(U_g - U_p\right)\times\nabla\times U_g \tag{18}$$

$$F_{virtual} = m_p\frac{\rho_g}{\rho_p}\frac{dU_p}{dt} \tag{19}$$

$$F_{dispersion} = m_p C_{td}\frac{\mu_t}{\sigma_{pg}\rho_g\rho_p\tau_p}\left(\frac{\nabla\alpha_g}{\alpha_g}-\frac{\nabla\alpha_p}{\alpha_p}\right) \tag{20}$$

where, in Eqs. (15)–(20), g is gravity, τ_p is the particle relaxation time, d_p is solid particle diameter, m_p is the mass of the solid particle and σ_{pg} is the dispersion Prandtl number. C_d is drag force coefficient, C_{sl} is slip shear lift force coefficient and C_{td} is the turbulent dispersion coefficient.