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Two-phase turbulence models for simulating dense gas–particle flows

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ABSTRACT

The two-fluid model is widely adopted in simulations of dense gas–particle flows in engineering facilities. Present two-phase turbulence models for two-fluid modeling are isotropic. However, turbulence in actual gas–particle flows is not isotropic. Moreover, in these models the two-phase velocity correlation is closed using dimensional analysis, leading to discrepancies between the numerical results, theoretical analysis and experiments. To rectify this problem, some two-phase turbulence models were proposed by the authors and are applied to simulate dense gas–particle flows in downers, risers, and horizontal channels; Experimental results validate the simulation results. Among these models the USM-Θ and the two-scale USM models are shown to give a better account of both anisotropic particle turbulence and particle–particle collision using the transport equation model for the two-phase velocity correlation.

1. Introduction

Dense gas–particle flows are commonly encountered in fluidized bed combustors, riser and downer reactors, dense gas–solid cyclones, blast furnaces, pneumatic transport, and the near-wall zone of dilute gas–particle flows. Both gas–particle turbulence and particle–particle collision play important roles in the behavior of dense gas–particle flows. There are two approaches for simulating these kinds of flows: Eulerian–Lagrangian (E–L) and Eulerian–Eulerian (E–E, or two-fluid). In the E–L approach, numerous discrete particles are tracked, and inter-particle collisions are simulated using either a hard- or soft-sphere model. This approach, called the discrete element method (DEM) or discrete particle simulation (DPS), was originally proposed by Tsuji, Kawaguchi, and Tanaka (1993) and was recently developed further and applied to various engineering processes by Zhang, Chu, Wei, and Yu (2008). The advantage of the E–L model is its ability to give details of particle behavior using fewer closure models, but requires large computation times. In the E–E approach, the particles are simulated using a pseudo-fluid model. The advantage of the E–E approach is its ability to simulate large-scale engineering processes with acceptable computation requirements, but the main problem is its complex closure models, needing further improvement and experimental validation. In the E–E approach, the kinetic theory of dense gas–particle flows proposed by Gidaspow (1994) was widely adopted in the 1990s to simulate particle–particle collision without accounting for the effect of gas–particle turbulence. Lun, Savage, Jeffrey, and Chepurniy (1984) and Gidaspow (1994) derived the full set of equations of the kinetic theory for granular flows. Sinclair and Jackson (1989) first applied this theory to set up a laminar gas-phase and laminar particle-phase model to simulate fully developed flows in vertical pipes. Considering the effect of gas turbulence, Bolio, Yasuna, and Sinclair (1995) accounted for both gas turbulence, modeled by a low-*Re* k–ε model, and the particle fluctuation due to collision. Samuelsberg and Hjertager (1996) simulate gas–particle flows in risers using the kinetic theory, whereas gas turbulence is modeled using the large eddy simulation (LES).

For high-velocity dense gas–particle flows in risers, downers, and channels, besides gas turbulence, an account is necessary of both small-scale particle fluctuations due to particle–particle collision and large-scale particle fluctuations due to particle turbulence. Zhou (1993) proposed a k–ε–k_p model and a unified second-order moment (USM) model (Zhou & Chen, 2001) to simulate particle turbulence for dilute gas–particle flows. In recent years, different investigators have developed two-phase turbulence models for simulating dense gas–particle flows. Cheng, Guo, Wei, Jin, and Lin (1999) proposed a k–ε–k_p–Θ (Θ – particle pseudo-temperature) model by combining the k–ε–k_p two-phase turbulence model proposed by Zhou with the Θ model proposed by Gidaspow (1994) to account for both collisions and turbulence. Zheng, Wan, Qian, Wei, and Jin (2001) proposed a k–ε–k_p–ε_p–Θ model that includes the effect of particle collisions on particle turbulence. In both k–ε–k_p–Θ

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Nomenclature

c	coefficients
D	diffusion term
G	phase interaction source term
g	gravitational acceleration
k	turbulent kinetic energy
P	production term
p	pressure
T	phase interaction term
t	time
U, u, v	velocity components and their fluctuations
x	coordinates

Greek symbols

α	volume fraction
β	coefficient
Γ	coefficient
δ_{ij}	kronic delta
ε	dissipation rate
μ	dynamic viscosity
ν	kinematic viscosity
Π	pressure–strain term
ρ	density
τ_r	relaxation time

Superscript

$\bar{}$	filtered value
$'$	fluctuation value in time averaging
$''$	fluctuation value in mass-weighted averaging

Subscripts

g	gas
i, j, k	components in coordinate directions
p	particle

and k–ε–k_p–ε_p–Θ models the two-phase velocity correlation $\overline{v_{pi}v_{gi}}$ is simply closed using semi-empirical expressions, such as $\sqrt{k_g k_p}$ and $ck_g - k_p$, based on dimensional analysis. If the particle turbulent kinetic energy is different from the gas turbulent kinetic energy anywhere in the flow field, then the source term in the k_p equation due to two-phase velocity correlation can be positive or negative. However, it was observed in experiments and found by theoretical analysis that the two-phase velocity correlation is always smaller than the gas and particle Reynolds stresses; the particle-source term in the particle turbulent kinetic energy equation should always be dissipative. Thus, the two-phase velocity correlation should be modeled by transport equations, or algebraic expressions simplified from these equations, rather than obtained from dimensional analysis.

To improve the closure for the two-phase velocity correlation, a k–ε–k_p–k_{pg}–Θ model is proposed to use the k_{pg}-equation closure instead of empirical closures. For most practical gas–particle flows in pipes, the turbulence is not isotropic; the radial component is roughly one-fifth of the axial component. Therefore, isotropic models over-estimate lateral particle mixing. To further improve the two-phase turbulence models for dense gas–particle flows, a two-phase turbulence model, called the USM-Θ model, combining the USM two-phase turbulence model for dilute gas–particle flows with the particle kinetic theory for inter-particle collisions, is proposed. Particle–particle collisions are modeled by the particle kinetic theory, whereas gas–particle turbulence is simulated using the USM model. The two-phase velocity correlation is simulated by the transport equations using a two-time-scale dissipation closure. As an alternative, a two-scale particle turbulence model accounting for large-scale particle fluctuation due to particle turbulence and small-scale particle fluctuation due to particle–particle collision is also developed. The merit of the latter is using a unified treatment of two-phase turbulence instead of simply merging the dilute two-phase turbulence model with the kinetic theory modeling of inter-particle collision. Therefore, in this paper, the development of the k–ε–k_p–k_{pg}–Θ model, USM-Θ model, and two-scale particle turbulence model for simulating dense gas–particle flows in downers, risers, and horizontal channels will be presented. The description of these models, their application, and experimental validation will be discussed.

2. The k–ε–k_p–k_{pg}–Θ model

The k–ε–k_p–k_{pg}–Θ model uses all equations of the k–ε–k_p–Θ model except that the k_{pg} equation required for closure of two-phase velocity correlation is used instead of the empirical expression in the k–ε–k_p–Θ model. The k_{pg} equation is written as

$$\frac{\partial}{\partial t}(k_{pg}) + (\overline{u_{gk}} + \overline{u_{sk}})\frac{\partial}{\partial x_k}(k_{pg}) = D_{pg} + P_{pg} + T_{pg} - \varepsilon_{pg} \quad (1)$$

where $D_{pg} = \frac{\partial}{\partial x_k}[(\mu_e + \mu_p)(\partial k_{pg}/\partial x_l)]$, $P_{pg} = -(1/2)(\overline{u''_{pk}u''_{gi}}(\partial \overline{u_{pi}}/\partial x_k) + \overline{u''_{gk}u''_{pi}}(\partial \overline{u_{gi}}/\partial x_k))$,

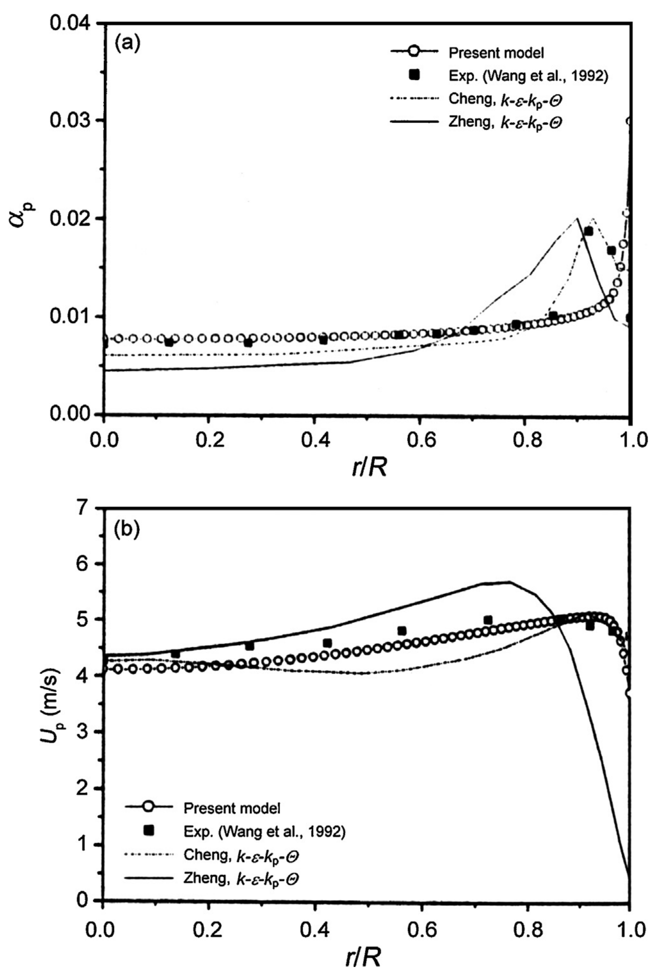

Fig. 1. Particle volume fraction (a) and velocity (b) distributions in a downer.