ARTICLE IN PRESS

PTEC-11504; No of Pages 10

Powder Technology xxx (2016) xxx–xxx

Contents lists available at ScienceDirect

Powder Technology

journal homepage: www.elsevier.com/locate/powtec

Study on two-way coupling of gas–solid two-phase flow of cylindrical particles

Jie Cai [a,b,*], Zhulin Yuan [a], Xiaobao Zhao [b]

[a] School of Energy & Environment, Southeast University, Nanjing 210096, Jiangsu, PR China

[b] School of Energy & Mechanical Engineer, Nanjing Normal University, Nanjing 210042, Jiangsu, PR China

ARTICLE INFO

Article history:
Received 4 September 2015
Received in revised form 5 February 2016
Accepted 13 February 2016
Available online xxxx

Keywords:
Gas–solid two-phase flow of cylindrical particles
DEM
Two-way coupling correlation
Rigid Dynamics
Fluidization properties

ABSTRACT

This article proposed a three-dimensional model of gas–solid two-phase flow of cylindrical particles based on Discrete Element Method (DEM), Rigid Dynamics and κ–ε model. In this model, the two-way coupling correlation between cylindrical particles and turbulent flow was established according to the correlation between Lagrangian time scales and κ–ε model, the force and motion model of cylindrical particles was established according to Rigid Dynamics, and the inter-cylindrical particle collision was taken into account by using the Rigid Impact Dynamics and modified Nanbu collision method. The model was verified by a cold-state experiment of gas–solid two-phase flow of cylindrical particles in a fluidized bed. In addition, some fluidization properties of gas–solid two-phase flow of cylindrical particles were obtained. Experiment results and simulated results both proved that the axes of most cylindrical particles are closely parallel to z-axis when cylindrical particles move up in the riser during the fluidization; there is an evident horizontal transfer of cylindrical particles from radial central regions to near-wall regions during the fluidization, and the number concentration of cylindrical particles in radial central regions is lower than that in near-wall regions. Simulated results showed that the volume fraction of turbulent flow in radial central regions is higher than that in near-wall regions and it will change evidently over time; the velocity and pressure of local turbulent flow field will decline evidently where there is a residence of some cylindrical particles.

1. Introduction

Circulating fluidization of cylindrical particles is applied widely in industries, such as combustion of biomass stalks, molding and drying of troches, and drying or wetting of cut-tobacco. The key issues on the gas–solid two-phase flow of cylindrical particles are modeling of force, modeling of motion, modeling of coupling correlation between cylindrical particles and turbulent flow, and modeling of inter-cylindrical particle collision.

There are two ways for force analysis of a cylindrical particle in a flow field. One is slender-body theory, which was initiated by Burgers and improved by Broersma [1–2]. And it had been revived and developed by Tuck [3], Tillett [4], Batchelor [5], Cox [6–7], Roger and Weidman [8], Bringley and Peskin [9], Bouzarth and Minion [10], Srivastava [11], et al. Slender-body theory analyzes the force of a cylindrical particle in a flow field by solving an equations set proposed by Batchelor [5]. The equations set aim at finite discrete positions along the length of the cylindrical particle. Each solution of the equations set stands for the fluid force around the perimeter at each discrete position on the cylindrical particle. The total fluid force acting on the cylindrical particle is obtained by vector adding the force around the perimeter at all discrete positions. Therefore it is difficult for slender-particle theory to establish two-way coupling model between cylindrical particles and turbulent flow field.

Folgar et al. proposed a mathematical model to predict the orientation distribution function of rigid fibers in concentrated suspensions [10]. Butler et al. modeled the linear rotational velocities of rigid fibers based on the slender-body theory [11]. Saintillan et al. simulated the concentration fluctuations and the microstructure in dilute sedimenting suspensions of orientable and deformable particles at zero Reynolds number. The concentration instability of suspensions of spheroids had been captured in the simulations [12]. Zak et al. presented a novel two-section based method for statistical characterization of the fiber-orientation distribution within short-fiber composites [15]. Camassa et al. provided an exact solution of trajectory and flow properties for a rod spinning in a viscous fluid on the basis of slender-body theory [16].

The other method is DEM, which was originated by Cundall in the light of molecular dynamics and which was firstly used by Tsuji in numerical study of gas–solid two-phase flow of spherical particles [17–18]. Now DEM has advanced to the study of two-phase flow of irregularly-shaped particles. DEM approximatively treats an irregularly-shaped particle as the geometric assembling of finite discrete elements, then analyzes the

* Corresponding author at: School of Energy & Environment, Southeast University, Nanjing 210096, Jiangsu, PR China.
E-mail address: caijie@njnu.edu.cn (J. Cai).

http://dx.doi.org/10.1016/j.powtec.2016.02.025
0032-5910/

Please cite this article as: J. Cai, et al., Study on two-way coupling of gas–solid two-phase flow of cylindrical particles, Powder Technol. (2016), http://dx.doi.org/10.1016/j.powtec.2016.02.025

force acting on each discrete element respectively, and then obtains the force acting on the cylindrical particle by vector adding the force acting on all discrete elements. As for a cylindrical particle, the configuration can be assembled by finite discrete elements along its axis. DEM provided an effective way to directly structure the coupling correlation between each discrete element of an irregularly-shaped particle and flow field, which is based on the coupling correlation between Lagrangian time scales and κ–ε model. But DEM cannot give detailed attitude information of a cylindrical particle during its movement. Langston et al. simulated the movement of non-spherical particles involving friction in 3D based on DEM, and the simulation was verified by experimental results [19]. Zhong and Zhang et al. simulated the cylindrical particles flow in a fluidized bed with DEM [20].

Rigid Dynamics is a branch of dynamics, studying the movement behaviors of a rigid-body under the external force [21]. It is the mechanical basis of the movement attitude study of aircrafts such as secondary planets, airplanes, rockets and so forth. As shown in Fig. 1, there are, in Rigid Dynamics, two reference frames, one is the body axes of which 3 axes are ξ-axis, η-axis and ζ-axis, and the other is the fixed reference frame of which 3 axes are x-axis, y-axis and z-axis. The rigid-body is fixed in the body axes, and the attitude of the rigid-body is described by relative attitude between the two reference frames with 3 Euler angles that are precession angle (ψ), nutation angle (θ) and spin angle (φ). If a cylindrical particle is fixed in the body axes, with its centroid overlapping the origin of the body axes and its axis being along the ζ-axis, the nutation angle is just the angle between the axis of a cylindrical particle and the z-axis of the riser. Literature [22] proposed a single-way coupling three-dimensional model of gas–solid two-phase flow of cylindrical particles based on DEM, Rigid Dynamics and κ–ε model.

As described above, by far numerical study on dense or semi-dense gas–solid two-phase flow of cylindrical particles based on DEM is still at the preliminary stage, and there is no efficient two-way coupling model for the study of gas–solid two-phase flow of cylindrical particles. But some studies indicated that even though for dilute phase flow, the existence of cylindrical particles in the flow field would affect the flow field evidently [23]. So it is necessary to establish the coupling correlation between cylindrical particles and turbulent flow.

In this study, a three-dimensional two-way coupling model of gas–solid two-phase flow of cylindrical particles was proposed. In this model, the two-way coupling correlation between cylindrical particles and flow field was established according to the coupling correlation between Lagrangian time scales and κ–ε model, the force and motion model of cylindrical particle was established according to Rigid Dynamics, and the inter-cylindrical particle collision was taken into account by using the Rigid Impact Dynamics and modified Nanbu collision method. The simulated results were well consistent with the experimental results. It is found that the axes of most cylindrical particles are closely parallel to z-axis when cylindrical particles move up in the riser during the fluidization; there is an evident horizontal transfer of cylindrical particles from radial central regions to near-wall regions during the fluidization, and the number concentration of cylindrical particles in radial central regions is lower than that in near-wall regions; the volume fraction of turbulent flow in radial central regions is higher than that in near-wall regions and it will change evidently over time; the velocity and pressure of local turbulent flow field will decline evidently where there is a residence of some cylindrical particles.

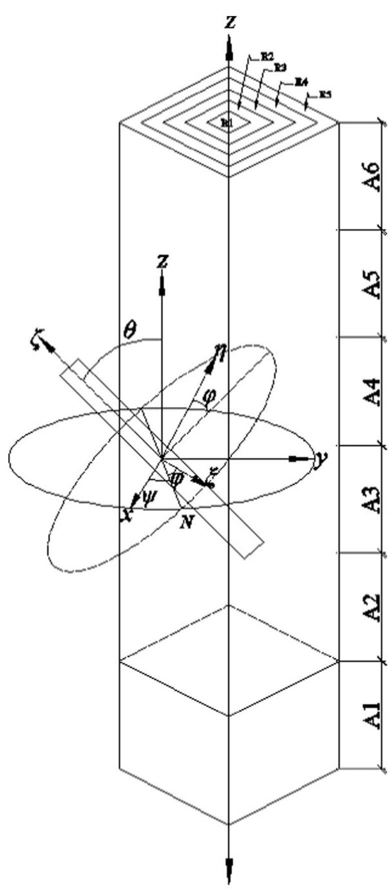

Fig. 1. Nutation angle between the body axes and the fixed reference frame.

2. Mathematical models

The coupling correlation between cylindrical particles and turbulent flow field was established by setting up the coupling correlation between each discrete element of cylindrical particles and turbulent flow. Every cylindrical particle is discretized into finite discrete elements along its axis; the force acting on each discrete element by local flow field is calculated separately, at the same time the reaction force and the volume of each discrete element is recorded; the force acting on the cylindrical particle is obtained by vector adding the force acting on all discrete elements, meanwhile the torque is calculated; then the translation and rotation of the cylindrical particle is calculated according to Rigid Dynamics. Simultaneously, for each flow field grid, the volume fraction is gained by counting the volume of discrete elements in this grid, and the reaction force exerted by cylindrical particles is got by vector adding all reaction force exerted by all discrete elements in this grid; the reaction force is the source term of time-averaged N–S equations, and then the source terms of κ–ε equations are calculated.

2.1. Gas-phase models

Continuity equation is given as:

$$\frac{\partial}{\partial t}\left(\phi_g\rho_g\right)+\nabla\cdot\left(\phi_g\rho_g\mathbf{v}_g\right)=0 \tag{1}$$

where ϕ_g is the volume fraction of flow field; $\mathbf{v}_g$ is the flow field velocity, m/s.

Time-averaged N–S equation is:

$$\begin{aligned}&\frac{\partial}{\partial t}\left(\phi_g\rho_g\mathbf{v}_g\right)+\nabla\cdot\left(\phi_g\rho_g\mathbf{v}_g\mathbf{v}_g\right)\\&=-\phi_g\nabla p+\nabla\cdot\left[\phi_g(\mu+\mu_t)\left(\nabla\mathbf{v}_g-\frac{2}{3}\rho_g k\delta_{ij}\right)\right]+\phi_g\rho_g\mathbf{g}+\mathbf{f}_{sg}\end{aligned} \tag{2}$$

where p is the pressure of flow field, Pa; μ is the dynamic viscosity of fluid, Pa·s; μ_t is the turbulent viscosity, Pa·s; $\boldsymbol{f}_{sg}$ is interaction force between phases, $\mathbf{f}_{sg}=K_{sg}(\boldsymbol{v}_s-\boldsymbol{v}_g)$, N; K_{sg} is the momentum exchange coefficient, kg/s [17]; $\boldsymbol{v}_s$ is the average of velocities of all discrete elements in the local flow field, m/s. The empirical correlation for K_{sg},