Chinese Journal of Chemical Engineering 23 (2015) 1579–1586

Contents lists available at ScienceDirect

Chinese Journal of Chemical Engineering

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

Fluid Dynamics and Transport Phenomena

Comparison of numerical simulations and experiments in conical gas–solid spouted bed☆

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ARTICLE INFO

Article history:
Received 29 October 2014
Received in revised form 14 May 2015
Accepted 4 June 2015
Available online 16 July 2015

Keywords:
Fluidization
Simulation
Experiment
Conical spouted bed
Drag coefficient model
Computational fluid dynamics

ABSTRACT

Flow behavior of gas and particles in conical spouted beds is experimentally studied and simulated using the two-fluid gas–solid model with the kinetic theory of granular flow. The bed pressure drop and fountain height are measured in a conical spouted bed of 100 mm I.D. at different gas velocities. The simulation results are compared with measurements of bed pressure drop and fountain height. The comparison shows that the drag coefficient model used in cylindrical beds under-predicted bed pressure drop and fountain height in conical spouted beds due to the partial weight of particles supported by the inclined side walls. It is found that the numerical results using the drag coefficient model proposed based on the conical spouted bed in this study are in good agreement with experimental data. The present study provides a useful basis for further works on the CFD simulation of conical spouted bed.

1. Introduction

Spouted beds are often used in various industrial processes of gas–solid contacting operations, such as drying, coating, granulation, pyrolysis and gasification. This is because the significant advantage is their efficiency in contacting gas and coarse particles [1], for example, application of spouted bed elutriation in the recycling of lithium ion batteries [2], superheated steam drying of sawdust in continuous feed spouted beds [3], bio-oil production from rice husk fast pyrolysis in a conical spouted bed reactor [4], and conical spouted bed combustor for clean valorization of sludge wastes from the paper industry to generate energy [5]. Knowledge of gas and particle hydrodynamics in spouted beds is important for optimizing the bed performance [6]. Computational fluid dynamics (CFD) is a powerful tool for investigating the complex hydrodynamics and reaction kinetics, that is difficult to observe by experiments [7,8], in particular in spouted beds.

Now there are growing interests to use CFD to understand dense gas–solid two-phase flows in spouted beds [9]. The Eulerian–Eulerian (two-fluid) model with kinetic theory of granular flow (KTGF) is the most applicable approach to compute gas–solid flow in spouted beds. This model is particularly appropriate when the particle loading is relatively high and can be applied with reasonable computational loads. In the two-fluid model, the particles are treated as a continuum as in the gas phase. Thus, there are two interpenetrating phases (gas and solid) where each phase is characterized by its own conservation equation of motion. The interactions between the two phases are expressed as additional source terms added to the conservation equations. The kinetic theory of granular flow is used to define the fluid properties of the solid phase through constitutive equations. Detailed discussion on the development of granular flow models is provided by Gidaspow [10]. Lu *et al.* incorporated hydrodynamic modeling with a kinetic–frictional constitutive model of solids to simulate flow behavior of gas and particles in spouted beds [11]. Zhong *et al.* investigated flow behaviors of a large spout–fluid bed in a Eulerian–Eulerian frame. The gas phase was modeled with a k–ε turbulent model and the particle phase was modeled with KTGF [12,13]. Wu and Mujumdar simulated gas–particle flow behavior in a cylindrical spouted bed and a three-dimensional spout–fluid bed using the Eulerian–Eulerian two-fluid modeling approach, incorporating a kinetic–frictional constitutive model for dense assemblies of particulate solids [14]. Du *et al.* investigated the influences of drag coefficient correlations, frictional stress, maximum packing limit and restitution coefficient on the CFD simulation of spouted beds based on a gas–solid two-fluid approach using FLUENT [15]. Bettega *et al.* used the Eulerian–Eulerian 3D modeling to analyze the influence of the flat wall on the solid behavior inside a semi-cylindrical spouted bed by comparing numerical results with experimental data [16]. Duarte *et al.* simulated the dynamic behavior of gas and particles in conical and conical–cylindrical spouted beds using

☆ Supported by the National Natural Science Foundation of China (51206020), the Program for New Century Excellent Talents in University (NCET-12-0703) and the Northeast Petroleum University Foundation.
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http://dx.doi.org/10.1016/j.cjche.2015.07.006
1004-9541/

KTGF [17]. Gryczka *et al.* characterized the hydrodynamics of a prismatic spouted bed apparatus by applying the gas–solid two-fluid approach with KTGF [18]. Wang *et al.* discussed the impact of frictional stresses on the gas–solid flow by using a two-fluid model with the kinetic–frictional constitutive model of particles [19], and then simulated the flow behavior of gas and particles in spouted beds with a draft tube [20] and porous draft tube [21], respectively. An integrated granular phase source term was introduced into the momentum balance equation of the solid phase in the annulus region to simulate different flow patterns in the conical spouted bed [22]. Simulations show that the profiles of local velocity and solid volume fraction are required to use the source term that was obtained from the measured overall pressure drop over the spouted bed. Simon *et al.* introduced a new closure for the solid stress tensor for KTGF based on a two-fluid model to predict the flow in multiple-spout beds [23]. In their study, the impact of the solid shear stresses and the flux of fluctuation energy on boundary conditions were investigated.

Simulations mentioned above were compared to radial solid volume fraction distributions measured in spouted beds. Also, the comparisons of bed pressure drop between simulation and experiment are also required in spouted beds. In the present work, the bed pressure drop is measured in the conical spouted bed, and compared to simulations at various inlet gas velocities. In a conical based spouted bed, the partial weight of particles is supported by the inclined side walls, which causes the interaction force between the inclined walls and gas–particle mixture to vary in the vertical direction. To include the additional interaction force exerted by the tapered side wall on the gas–solid flow, a modified drag coefficient model is proposed based on the Ergun equation from the dynamic balance of forces exerted on particles in the conical spouted bed. The present drag coefficient model is an extension from cylindrical bed to conical bed. Flow behavior of gas and particles is simulated using a two-fluid model based on KTGF. The model is validated experimentally with comparison to numerical simulations.

2. Experimental Setup

Experiments were conducted in a conical spouted bed, as shown in Fig. 1. The spouted bed was a cylindrical column with an inside diameter of 155 mm and a height of 0.8 m, and with a tapering angle of 60° in the conical base with a height of 0.09 m. It was made of Perspex sheet to allow visual observation. The diameter of the conical base at the bottom was 15 mm. A 60-mesh screen at the bottom served as the support as well as the air distributor. Two pressure taps, one just above the distributor and the other at the top of the bed were provided to record the bed pressure drop. The bed pressure drop was measured by a manometer. Air at a temperature of around 28 °C was used as the fluidizing medium. It was passed through a silica gel tower to remove the moisture and a valve to control the air flow before entering the spouted bed. Two rotameters, one for the lower range (0–10 $m^3 \cdot h^{-1}$) and the other for the higher range (10–120 $m^3 \cdot h^{-1}$), were used to measure the air flow rates. Fluid cracking catalyst (FCC) particles with a diameter of 175.0 μm and density of 1650 $kg \cdot m^{-3}$, belonging to group A of the Geldart powder classification. Particles were fluidized with air at atmospheric pressure. The flow regime diagram of gas–solid reactors covers the operation of fixed and moving beds, conventional fluidized beds, circulating beds, spouted beds, and pneumatically conveyed suspensions. Reh proposed the fluidized bed regime diagram between groups A and B and between groups B and D of the Geldart powder classification scheme [24]. In our study, the velocity range of spouted beds is from 0.031 to 0.1869 $m \cdot s^{-1}$ in the phase diagram.

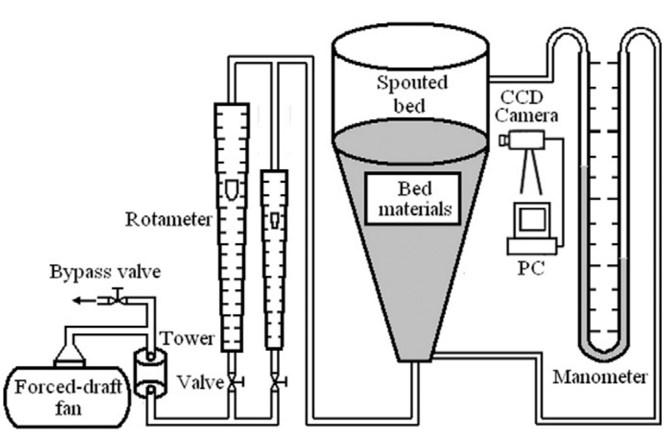

Fig. 1. Experimental set-up of spouted bed.

3. CFD Model for Spouted Beds

The two-fluid model (TFM) is applied to simulate the complex gas–solid flow in conical spouted beds. By the TFM approach, the gas and solid phases are treated mathematically as continuous and mutually interpenetrating. For simplicity, it is further assumed that flow is isothermal without reactions, the gas phase is incompressible, and particles are spherical and monosized.

The Eulerian approach is used for both gas and particle phases within the spouted bed, taking into account all possible intra- and inter-phase interactions. In this work, the governing equations for the conservation of mass and momentum for each phase and the constitutive relations are given in Table 1. The mass balance equation of the gas phase is expressed by Eq. (T-1). In the gas phase momentum equation Eq. (T-3), the gas-phase stress tensor is calculated according to Newton's expression of Eq. (T-6). For simplicity, the constant viscosity of the gas phase is used in the present simulations.

The continuity equation of the particles is Eq. (T-2). The momentum equation of particles is Eq. (T-4), where the second term on the right-hand side (RHS) is the solid pressure which includes the collisional part $p_{s,k}$ and frictional part $p_{s,f}$. The third term represents the solid stresses. The remaining terms on the RHS represent the influence of the forces acting on particles. As for the conical base, the momentum equation of mixture of particles and gas is expressed by Eq. (T-5) at the steady state, where the last term on the RHS is the stress frictions originated from the wall of conical base by the gas phase and particles. D_t in Eq. (T-5) is the equivalent diameter, defined as $D_t = D_0 - D_1$, where D_0 is the top diameter of the conical base, and D_1 is the bottom diameter. In addition to the mass and momentum conservation equations for the solid phase, a fluctuation kinetic energy equation, Eq. (T-6), is also solved to account for the conservation of the fluctuation energy of the particle phase, through the implementation of the kinetic theory of granular flow (KTGF) [10]. In principle, KTGF derived from the kinetic theory of dense gas, where the thermodynamic temperature is replaced by the granular temperature, defined as $\theta = \langle \boldsymbol{c}^2 \rangle /3$, where $\boldsymbol{c}$ is the particle fluctuating velocity. The granular temperature expresses the macroscopic kinetic energy of random particle motion. A more complete discussion of the implemented kinetic theory model can be found in Gidaspow [10].

At high concentrations of particles, individual particles interact with multiple neighbors through sustained contact. Under such conditions, the normal forces and the associated tangential frictional forces of sliding contact are the major contributions to the particle stresses. Following Savage [25], the particulate stress tensor, τ_s, is simply the sum of the kinetic stress tensor and the frictional stress tensor. Therefore, an additional frictional solid pressure $p_{s,f}$ and viscosity $\mu_{s,f}$ are added to the solid pressure and solid viscosity [24]. For the frictional pressure of particles, the semi-empirical model proposed by Johnson & Jackson [26] is used, as given in Eq. (T-10), where *F*, *n* and *p* are empirical material constants. The values of empirical parameters of $\varepsilon_{s,min}$, *F*, *n* and *p* are taken to be 0.5, 0.05, 2.0 and 5.0 for glass beads, respectively [26].

The frictional viscosity is related to frictional solid pressure in an expression proposed by Schaeffer [27], as given in Eq. (T-12), where ψ is