Powder Technology 307 (2017) 175–183

Contents lists available at ScienceDirect

Powder Technology

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

Experimental investigation on gas-solid hydrodynamics of coarse particles in a two-dimensional spouted bed

He Zhang, Malin Liu, Tianjin Li *, Zhiyong Huang, Xinming Sun, Hanliang Bo, Yujie Dong

Key Laboratory for Advanced Reactor Engineering and Safety of Ministry of Education, Institute of Nuclear and New Energy Technology, Collaborative Innovation Center for Advanced Nuclear Energy Technology, Tsinghua University, Beijing 100084, China

ARTICLE INFO

Article history:
Received 15 September 2016
Received in revised form 5 November 2016
Accepted 15 November 2016
Available online 30 November 2016

Keywords:
Flow pattern
Particle velocity
Spout diameter
Coarse particle
Two-dimensional spouted bed
CFD-DEM coupling

ABSTRACT

The gas-solid hydrodynamics of coarse particles in a two-dimensional spouted bed (2DSB) are measured using 6 mm glass beads to obtain quantitative experimental results. A one-dimensional mathematical model based on gas-solid mass and momentum balance is used to characterize the spout-annulus interaction and to further interpret the experimental results. The superficial velocity and static bed height are in the range of 2.58 to 4.39 m/s and 8.0 to 13.3 cm, respectively. Pressure fluctuation periodicity of the bed pressure drop is characterized by power spectral density (PSD) analysis. The whole-field particle velocity profiles in 2DSB are obtained by high speed CCD camera and PIV technique. The results show that particle motion in the spout in the present 2DSB experiments is dominated by the balance of drag force, solid stress and gravitation. The existence of obvious solid stress from particle impaction and friction leads to energy dissipation, which limits the increase of vertical particle velocity along the spout axis (v_{yc}) in the spout and results in a flat stage of v_{yc} with slight fluctuation near the bottom of the fountain. The solid stress also contributes to the nearly flat peak of lateral profile of downward particle velocity in the annulus. These detailed results are helpful for understanding the gas hydrodynamics and particle motion behavior of coarse particles in 2DSB, and for verification of the extended CFD-DEM coupling method for particle size approaching fluid cell size.

1. Introduction

Spouted beds have been studied for handling coarse particles in many areas, such as drying, granulation, particle coating, gasification, pyrolysis and combustion [1]. The development of draft tube spouted beds also provides a new kind of non-mechanical solids feeder, i.e. the spouted bed feeder [2–4], for vertical pneumatic conveying of coarse particles. A novel non-mechanical solids feeding device, called draft tube type feeder (DTF) which is based on the combination of draft tube technique and local fluidization principle, has been developed by our group [5,6] for application in absorber sphere pneumatic conveying in pebble bed High Temperature Gas-Cooled Reactor (HTGR or HTR).

HTGR is the Generation IV advanced nuclear reactor, which has the advantages of inherent safety, high efficiency and multiple purpose application potential [7–9]. Absorber sphere conveying in pebble bed HTGR is a special application of pneumatic conveying technique in nuclear engineering [10,11]. Our group has studied absorber sphere pneumatic conveying for many years [6,12]. The main features of absorber sphere pneumatic conveying are as follows: (a) coarse particles (e.g. particle diameter $d_p = 6$ mm), (b) small ratio of riser internal diameter to particle diameter (D_t/d_p) in the range of 6 to 10, (c) high pressure helium gas used as conveying gas, and (d) high temperature environment for feeder operation (about 250 °C, requires non-mechanical feeder for high reliability). Although the draft tube type feeder developed in our previous work meets the need of project requirements, there are still strong demands on interpretation the mechanism of coarse particle entrainment and vertical conveying for the design optimization of the feeder and conveying process. The accurate prediction of particle motion behavior and gas flow hydrodynamics is important for the system design and process optimization for the absorber spheres conveying in pebble bed HTGR.

CFD-DEM coupling simulation is an effective method at particle scale for understanding the relationship between macroscopic behavior and microscopic properties of gas-solid flow system [13–19]. The **common** CFD-DEM coupling is based on the momentum exchange in each discretized fluid flow cell, in which the particle-induced force on the fluid flow is treated as a body force. This method fails when particle size approach (including larger than) the fluid cell size. The absorber spheres conveying through the draft tube type feeder and riser pipe (featured with $d_p = 6$ mm and D_t/d_p of about 8) in pebble bed HTGR is such an example in engineering practice. The demand from the engineering practice promotes the research of CFD-DEM coupling simulation for particle size approaching fluid cell size.

* Corresponding author at: Institute of Nuclear and New Energy Technology, Tsinghua University, 30 Shuangqing Rd, Haidian, Beijing 100084, China.
E-mail address: tjli@tsinghua.edu.cn (T. J. Li).

http://dx.doi.org/10.1016/j.powtec.2016.11.024
0032-5910/

There are two types of strategy reported in literature to deal with the problem of particle size approaching fluid cell size in CFD-DEM coupling simulation. One strategy is to decrease flow field resolution by using rough fluid cell size to meet the requirement of common CFD-DEM method. This strategy is used by Yang et al. [20] in the simulation study of gas-solid flow of soybeans in spouted bed with draft tube (equivalent $d_p = 6$ mm, draft tube diameter of 35 mm). The other strategy is to develop **extended** CFD-DEM method by modifying the interphase coupling calculation method.

Several kinds of concept have been proposed in developing the extended CFD-DEM method, e.g. the local averaging concept [21], porous media concept [22,23], two-grid concept [24–28], distribution function concept [29], diffusion-based concept [30,31] and particle meshing method concept [32]. The verification of prediction accuracy of these extended CFD-DEM method for gas-solid flow is insufficient, since the choice of proper parameters remains an open question (e.g., the distribution width in distribution function, which strongly affects the distribution of the force of a particle on the fluid to an appropriate volume of the fluid) [31]. The particle diameter and Reynolds number are two important factors for choosing the proper distribution parameters [31].

There are only a few open publications on quantitative experimental study on particle motion behavior of coarse particles ($d_p > 4$ mm) in gas-solid flow system. These publications are mainly in the study of pneumatic conveying and spouted beds. Vasquez et al. [33] measured the plug velocity and plug length of four types of coarse particles in horizontal plug conveying (d_p in the range of 4 to 5.41 mm, $D_t \sim 50$ mm). Neto et al. [34] reported experiments of soybeans (equivalent $d_p = 6$ mm) in a 3-Dimensional (3D) spouted bed with draft tube (inner diameter 35 mm), in which only pressure drop was measured. Neuwirth et al. [35] reported the particle motion behavior of spherical polymer particles with a mean diameter of 6 mm in a 3D rotor granulator with the Magnetic Particle Tracking technique. Chen et al. [36] investigated distribution of particle velocity of corn (equivalent volume diameter 6.6 mm) in a 3D conical cylindrical spouted bed with the slightly-invasive optical fiber endoscope measurement. Olazar et al. [37] reported the particle motion behavior of $d_p = 4$ and 5 mm coarse particle in 3D spouted beds with the slightly-invasive optical fiber probes measurement. The measurement results might be unrealistic because of the improper application of the optical fiber probes [38]. The two-dimensional spouted bed (2DSB) have the advantage in obtain whole-field detailed information of particle motion behavior with the non-invasive PIV techniques [39–41]. However, the particle diameter are all no >2.5 mm in the reported conical 2DSB [42] and the flat bottomed 2DSB experiments [22,38].

The main purpose of this study is to make a better understanding of gas-solid hydrodynamics of coarse particles in a 2DSB, and to obtain detailed whole-field experimental results of particle motion behavior of coarse particle for verification of the extended CFD-DEM method. Section 2 describes the experimental setup and procedure. In Section 3, we describe the flow pattern and measure the velocity profiles of the coarse particles in the 2DSB. Furthermore, a one-dimensional mathematical model based on gas-solid mass and momentum balance is used to characterize the spout-annulus interaction and to further interpret the experimental results.

2. Experimental setup

2.1. Apparatus

The experimental system (shown in Fig. 1) is mainly composed of a 2DSB, air compressor, pressurizer, rotameter, PIV measuring system and high frequency pressure acquisition system. Geometric parameters of the 2DSB and particle properties are summarized in Table 1. To ensure the bed operates at a ‘two-dimensional’ not a ‘slot-rectangular’ mode, the ratio of column thickness to column width (L_z/L_c) used in this study is small enough to eliminate the third-dimensional effects along bed thickness [43]. The ratio of column thickness to particle diameter (L_z/d_p) is larger than the critical value of 5 to reduce the wall friction effects [44]. 2DSB is made of plexiglass to observe and film particle movement. Spherical glass beads of $d_p = 6$ mm and particle density $\rho_p = 2518$ kg/m^3 are used in the experiments.

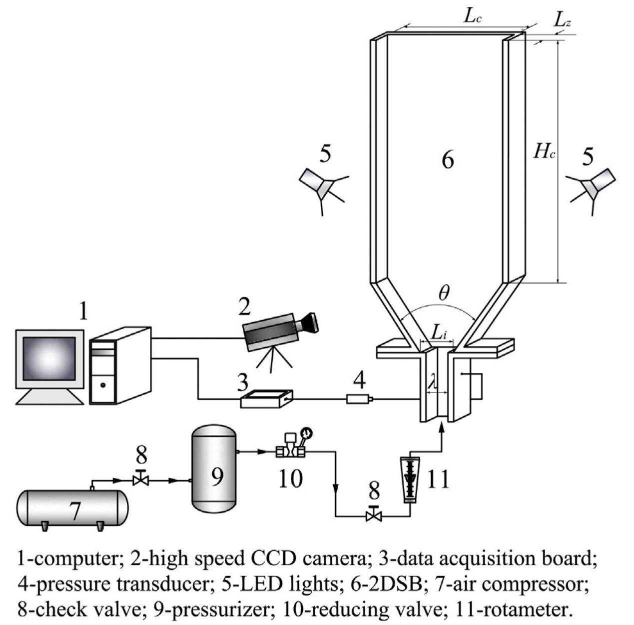

Fig. 1. Schematic diagram of the two-dimensional spouted bed experimental system.

Glass beads are loaded into 2DSB at a low gas velocity to inhibit particles falling into the gas inlet slot. Six different mass loadings of 400, 500, 600, 700, 800 and 900 g are considered, which approximately correspond to the static bed height (H_b) of 8.0, 9.2, 10.4, 11.4, 12.4 and 13.3 cm in the wedge section of the bed, respectively. Ambient air is used as the source gas. Gas inlet flow rate (Q_0) is controlled and measured by the rotameter, which is increased slowly to the value of operating condition. Superficial gas velocity U_g with respect to the bed column cross section of 210 × 36 mm is in the range of 2.58 to 4.39 m/s. The experimental condition of $U_g = 4.39$ m/s and different static bed height of 12.4, 10.4 and 8.0 cm are referred as case 1, 2 and 3, respectively, for convenience.

Images of particle movement are recorded by a high speed CCD camera during stable spouting. The camera provides 670 pixel × 900 pixel resolution at 1000 fps (frames per second) and can continuously record for several seconds for these parameters. The flow field of the recorded section is illuminated by two identical 150 W LED lights symmetrically placed beside the bed at an angle smaller than 45° to avoid undesirable reflections [22,23].

2.2. Pressure measurement

The pressure measurement point is at the side wall of gas inlet slot and 30 mm below the bed bottom. The sampling time is 10 s with a

Table 1
Geometric parameters of the 2DSB and particle properties.

Items	Unit	Values
Column width, L_c	mm	210
Included angle, θ	°	60
Column thickness, L_z	mm	36
Slot width, λ	mm	30
Bottom width, L_i	mm	45
Column height, H_c	m	1.2
Particle diameter, d_p	mm	6
Particle density, ρ_p	kg/m^3	2518