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Flow pattern and transition in gas–liquid–solid three phase spouted bed

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ABSTRACT

The flow patterns and transitions in a gas–liquid–solid three phase spouted bed were investigated. Experiments were carried out in a cylindrical and a semi-cylindrical spouted bed with conical base. Glass beads and water were used as the solid phase and liquid phase, respectively. The changes in pressure drop and photographs were used to determine the flow patterns. Five distinct flow patterns were identified and described, i.e. fix bed (FB), grain spouting (GS), cluster spouting with slugging (CS-S), solid fixed with gas–liquid bubbling (SF-GLB), and slurry agitated bed (SA). Flow pattern maps of a three phase spouted bed ($d = 2.6$ mm, $H_0/D_t = 1.86$) under different liquid saturations were plotted. It was found that the flow pattern transition with the spouting gas velocity increasing at different liquid saturations (S) could be divided into three stages, i.e. transition from FB to GS when $S < 0.2$, transition from FB to CS-S when $0.2 < S < 0.5$, and transition from SF-GLB to SA when $S > 0.5$. Increase in liquid saturation (S) always leads to increasing of the amplitude of pressure fluctuations. Besides, in stage I (GS), the minimum spouting velocity increases initially and then decreases apparently with increasing S. The range of stage I region becomes wider with lower initial bed height and particle diameter.

1. Introduction

Gas–liquid–solid three phase spouted bed reactors, whose major advantages are the excellent heat transfer and ease of addition and removal of solid, can be used extensively in petro-chemical [1], bio-oil refining [2,3], drying of solutions [4], granulation [5], particle coating [6] and environmental protecting [7,8]. Compared with three phase fluidized bed, three phase spouted bed reactors are proven to be of great potential to react due to their ability to deal with particles with larger sizes and to provide good particle circulation.

The optimized design of a three phase spouted bed is a difficult task and understanding its hydrodynamics is critical to successful scale up from lab to commercial scale. Compared with gas–solid spouted bed, the hydrodynamic characteristics of three phase spouted beds inevitably are considerably different and more complicated.

Several works reported in the literature have investigated the hydrodynamic characteristics of wet particles spouted bed. Í. Vukov et al. [9] studied the hydrodynamic characteristics of a three phase spouted bed contactor which contains the pressure drop, bed expansion and liquid holdup in the bed. M. Passos et al. [10] modeled the capillary force components arising from liquid bridges, relating them to stress tensor applied to the solid phase assembly in the spouted bed. W. Oliveira et al. [11] studied the degree of instability depending on the system configuration and operating parameters, such as liquid-to-spouting gas flow rate ratio, as well as the physical and chemical properties of the liquid in a wet spouted bed. Y. Nagahashi et al. [12] studied the spouting enhancement by addition of small quantities of liquid to gas-spouted beds. M. Bacelos et al. [13] investigated air–solid flow behavior in conical spouted beds composed of glass bead mixtures coated by glycerol. They found that gas–solid flow characteristics were changed due to the growth of interparticle forces, and the trends of these changes were also affected by the glass bead mixture type. T. Schneider et al. [14] studied the effect of liquid injection on spouting characteristics. They found that the key factors were the liquid content and the presence of cohesive forces between particles. P.S. Neto et al. [15] found three types of paste behaved differently in terms of the variation of the spouting pressure drop and the minimum spouting velocity.

The spouted-bed reactors which are applied to handle the sticky solids also belong to the three phase bed and involve similar problems. Actually, the sticky nature of the particles is due to appearance of a sticky liquid. In order to avoid defluidization in bubbling fluidized beds, a spouted bed was used for pyrolysis of plastics by R. Aguado et al. [16,17]. They found that the conical spouted bed reactor is especially suitable for avoiding agglomeration problems and the critical thickness of the plastic layer for the spouted bed is higher than that for the fluidized bed. D.P. McCullough et al. [18] investigated the mechanisms of agglomeration and defluidization during the gasification of an Australian low-rank coal in a spouted bed. They found that a torus shaped agglomerated mass collected around the wall in some cases

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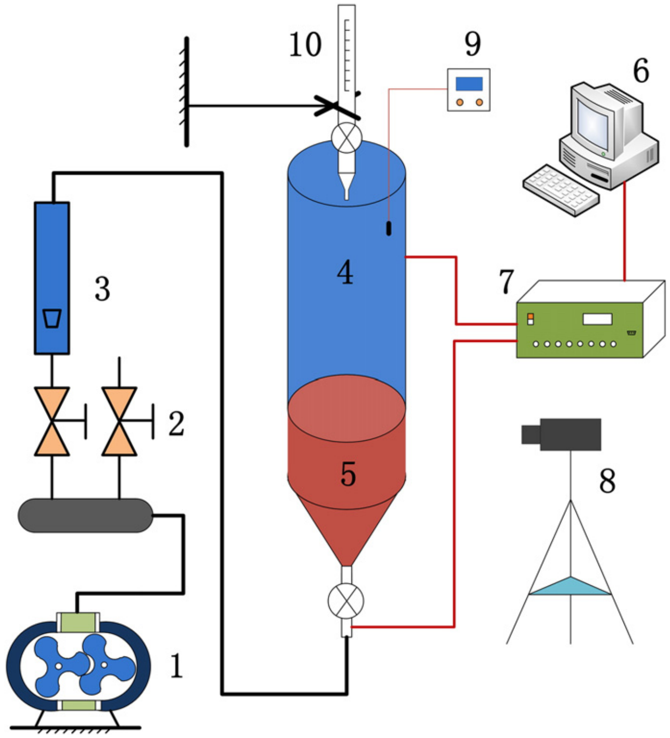

Fig. 1. Schematic of diagram of experimental setup: (1) roots blower; (2) control valve; (3) rotameter; (4) spouted bed; (5) glass beads; (6) computer; (7) differential pressure sensor; (8) digital CCD; (9) thermo hygrometer; (10) burette.

and sluggish particle movement at the walls appeared to create conditions favorable for agglomerate formation. In these studies, most of experiments were carried out under very low liquid content conditions.

Generally, research on the hydrodynamics of three phase spouted bed is still very limited. Many essential issues are still unknown. For example, how do the flow patterns convert as the liquid contents change? What spouting characteristic does the liquid-particles mixture present in the high liquid contents spouted bed? How do the particle diameter and bed height affect the flow pattern transition? This knowledge could be very useful in spouted bed drying, coating, chemical reacting and biological treating.

In this article, the spouting of spherical particles in a spouted bed was experimentally investigated. Glass beads are adopted as solid phase. The characteristics of flow patterns and pressure drop of the three phase spouted bed are involved in experiments to reveal the effects of liquid contents on the spouting behaviors. In addition, influences of the particle diameter and bed height on the flow pattern transition are also discussed.

2. Experiments

2.1. Description of equipment apparatus

The spouted bed experimental system is schematically shown in Fig. 1, including a conical–cylindrical Plexiglas column, a gas supply system, a water adding system, an imaging system and a multi-channel differential pressure signal sampling system. The internal diameter of the cylindrical column is 140 mm and the height is 1000 mm. The conical base of internal angle 60° and height 85 mm is located at the bottom of cylindrical column. The spouting gas, supplied by a Roots blower, was introduced into the column through the inlet orifice of diameter 20 mm and was adjusted by a valve. The flow rates of spouting gas were measured by rotor flow meter that offers ±1.5% full-scale accuracy for the range of 10–100 m^3/h.

Pressure fluctuations in the bed were obtained by a multichannel differential pressure signal sampling system. The pressure drops were measured and then converted into voltage signals by a multichannel differential pressure signal transmitter with a scale of 0–50 kPa. The pressure sensor offers ±0.2% full-scale accuracy. The voltage signals were finally sent to a computer through an A/D converter. The pressure sensor has two ports, with one connected to the pressure-measuring hole in the column wall at height of 800 mm above the bottom of cylindrical column, and the other connected to the pressure-measuring hole in the spout nozzle. A high speed digital camera (Nikon Coolpix L200) set in front of the spouted bed was used to record the spouting process.

Because the full cylindrical bed prevents observation of the spout, the semi-cylindrical bed has been used for observation of the spout region by many researchers [19]. In our experiments, a semi conical–cylindrical spouted bed, whose feature size is same as the integrated bed, was used to preliminarily investigate the internal structure of three phase spouting process. The thickness of the semi cylindrical spouted bed is 70 mm.

2.2. Experimental procedure

Water was used as the liquid phase in three phase spouted bed. Two kinds of nearly spherical particles were used in the experiments. Table 1 presents the physical properties of the tested particle. A ball valve was fixed in the spout nozzle to support the solid particles.

In the experimental process, the static particles bed height H_0 was a maintained constant. Different volumes of water were measured by metering tank and then added to the bed to set up different experimental conditions until the liquid content in the bed was saturated. Spouting was carried out about 5 minutes before measuring to assure a uniform concentration of water, and then the gas flow descending process was chosen to execute the experiment. The gas flow rate decreased from 80 m^3/h to10 m^3/h gradually. The average liquid saturation (S) [13] was used to illustrate the state of liquid–solid mixture in the initial packed bed. The liquid saturation (S) is the ratio of void volume occupied by the liquid to the total void volume (gas and liquid) of a bulk [20].

$$S = \frac{V_l}{V_{\mathrm{void}}} = \frac{1-\varepsilon}{\varepsilon} \cdot \frac{V_l}{V_p} \tag{1}$$

where ε is packing void fraction, V_l is volume of liquid, and V_p is volume of particles. Some topic experimental conditions for glass bead A (d = 2.6 mm) are shown in Table 2.

A significant amount of the liquid will be carried out by spouting gas when the three phase spouted bed is operating. Thus, a graduated burette was used to compensate the loss of water into the spouted bed. The loss of water was measured by the digital thermo hygrometer via

Table 1
Properties of particles.

Particle	d (mm)	δ (%)	ρ_p (kg/m^3)	ε
Red glass bead A	2.6	5.4	2600	0.37
Red glass bead B	1.9	6.5	2600	0.39

Table 2
Topic experimental conditions for glass bead A (d = 2.6 mm).

Case number	H_0/mm	S	V_l/V_p	α_p	α_l	α_g
1	260	0	0	0.63	0	0.37
2	260	0.1	0.06	0.63	0.04	0.33
3	260	0.4	0.24	0.63	0.15	0.22
4	260	0.8	0.47	0.63	0.3	0.07
5	260	1	0.59	0.63	0.37	0