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Pressure drop and pressure fluctuations in spouted beds with binary mixtures of particles

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ABSTRACT

When handling fine particles in spouted beds, addition of coarse particles has shown improved spouting stability than single particle systems. However, segregation may still occur because of insufficient mixing in binary mixtures, which will adversely influence the process performance. Therefore, in this study, analysis of pressure drop and its fluctuation signals were for the first time used to understand mechanisms of flow regime transitions in spouted beds with binary mixtures. The results showed that the typical varying sequence of pressure drop can be observed for spouted bed with binary mixtures and the peak pressure drop is related to the mixing degree of particles, which is mainly influenced by the inter-particle forces between fine particles and their counterpart coarse ones. The statistic characteristics of pressure drop time series, i.e., average value, standard deviation and probability distributions, were found to vary for different flow regimes. Therefore, they could be used for the characterization of these flow regimes. The spouting stability of binary mixtures can be reflected by power spectrum analysis; the influences of particles size and density difference on spouting stability were discussed through power spectral analysis.

1. Introduction

Spouted beds, as an alternative to fluidized beds for handling coarse particles larger than 1 mm in diameter (typically Group D particles according to the Geldart classification) have been widely employed in various physical operations such as drying, coating and granulation [1]. Spouted beds also possess some unique structural and flow characteristics of great potential applications as chemical reactors [2–10]. However, the main factor impeding their wider use as chemical reactors is the limited interfacial area because of use of relatively large particles, leading to lower conversions [11]. In particular, they are not suitable for being used in a mass transfer limited process where only the external catalyst surface is effective [5]. Therefore, operating the spouted bed with relatively smaller particles (such as Group B particles according to the Geldart classification) is considered to be a remedy to increase interfacial areas and enhance conversions while the desirable spouting characteristics remain intact.

Spouted beds operated with Group B particles have larger gas solid contact areas, thus leading to increased conversions. In the literature, it has been reported that the spouting of Group B particles is significantly different from that of Group D particles and a stable spouting can only be achieved under strict conditions [12–15]. It has been shown that adding coarse particles can effectively improve the stability of spouted beds with fine particles [16–19]. In spouted beds, as noted by Huilin et al. [20], the solid–solid drag force is caused by particle collisions. The internal friction for mono-sized particles is considered to be related to the granular temperature, which takes both the particle velocity fluctuations and particle collisions into account according to a kinetic theory of granular flow (KTGF) [21]. When adding coarse particles, this stress can be greatly decreased as can be explained by KTGF. However, excessive addition of coarse particles to the spouted bed is no longer beneficial and particle segregation is observed, thereby giving rise to a decrease in the spouting stability. Therefore, an advanced understanding of spouting formation, mixing behavior and flow regime transition mechanisms is still lacking. In the literature, a few diagnostic tools have been employed to analyze flow regime transitions. In general, they can be classified into three categories: direct measurement (visual observation or advanced instrumentation such as PIV, LDV etc.), probe measurement (pressure probes or optical fiber probes, etc.) and X-ray measurement. Among those tools, pressure measurement is the most commonly adopted one due to its robustness, ease in use, and economic advantages.

The analysis of pressure fluctuations, mainly related to motions within the bed, has been widely used for decades for identifying flow regimes in fluidized beds. Various analysis methods have been described in detail in published comprehensive reviews [22–25]. In general, there exist three methods for analyzing pressure signals, which are

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time domain method, frequency domain method, and state space method. The time domain method is typically the first step in the data analysis, where either the standard deviation or the average absolute deviation is often used to identify a flow regime change [26–30]. The statistical analysis in time domain is the simplest and the most commonly employed; it is also very fast and easily applicable. The most commonly used method in time domain is to study the amplitude of signals, expressed as a standard deviation (viz., square root of second-order statistical moment). The change in amplitude with operating conditions has been of interest to many fluidization researchers for identification of transitions between regimes. For instance, for a circulating fluidized bed, the gas velocity corresponding to the peak of the variation is typically defined as the onset of the transition to turbulent regimes, while that corresponding to the point where the variation levels off is defined as the onset of the turbulent regime [31]. However, as pointed out by Dhodapkar and Klinzing [32], the amplitude of pressure fluctuations alone is not sufficient to elucidate the composition of the fluctuating signals and thus spectral analysis via Fast Fourier Transform (FFT) has been applied on time series of pressure data in fluidized beds (e.g. [26,33]). Frequency domain analysis includes the estimation of power spectral density functions that contain information regarding the frequency distribution in the pressure time series. Power spectral density functions are obtained via Fourier transformation of signals. Analysis of frequency distribution has been widely applied in time series analysis of fluidized beds for the characterization of flow regimes (e.g. [34,35]) and for verification of scale-up relationships for fluidized beds (e.g. [36]). Dhodapkar and Klinzing [37] concluded that the nature of the static wall pressure fluctuations in fluidized beds depends on the particle size, particle density, bed height, column diameter, location of the pressure taps and the gas velocity. Frequency analyses of pressure fluctuations on both a conventional spouted bed [38] and a slot-rectangular spouted bed [39] have demonstrated promising results on flow regime identification. The disadvantage of power spectral density function is that deciding which peak in the power spectrum is treated as a dominant frequency sometimes can be subjective [40]. Therefore, a combination of different analysis methods is needed to gain a better view of hydrodynamic behavior in fluidized beds. Therefore, the present work utilized both statistical analysis and frequency domain analysis to identify flow regime transitions of spouted beds of binary mixtures.

More recently, the pressure fluctuation analysis also has been used to characterize the flow behavior in spouted beds [41–45]. However, the above analysis was predominantly carried out with pressure fluctuation signals collected from spouted bed with mono-sized particles. The pressure fluctuations obtained from a binary system could be quite different. In the literature, this difference was noted in a fluidized bed by Chen et al. [46] due to the presence of particle mixing and segregation in binary particle systems. However, to the best of our knowledge, such an analysis for spouted beds with binary mixtures is not reported in the literature. Recognition and characterization of flow regimes are critical for designing and operating spouted beds, in particular, when operated with binary mixtures. In view of this knowledge gap, the objectives of this study were to investigate pressure drop in a spouted bed with binary mixtures and to identify the flow regime transition and particle mixing/segregation by means of pressure signal analysis.

2. Experimental setup

A schematic diagram of the experimental set-up is shown in Fig. 1. In this work, a plexi-glass spouted bed, with 80 mm in diameter, 4–10 mm of nozzle diameters and 60° of conical base angle was adopted. The experiments were carried out at ambient conditions. The gas flowrate was controlled by a pressure regulator and measured by several flowmeters with different measuring ranges (1.6–16 m^3/h and 6–60 m^3/h). After the particles were charged into the spouted bed, the air flowrate was adjusted for different bed heights to achieve flow regime transitions. The pressure drops and pressure fluctuations were measured by pressure transducers (Omega, PX164-010D5V) installed by an interval of 16.7 mm along bed wall and the pressure data were recorded by a PC after A/D conversion. The bottom pressure trap was installed on the wall just above the nozzle. Pressure fluctuations were collected at three bed levels, i.e., total bed, lower section and upper section of bed, through plastic tubes installed on the column wall. The particles used were composed by Al_2O_3 particles and silica gel particles with a volume ratio of 4:1.

The properties of the particles used are presented in Table 1, including narrowly-distributed silica gel, Al_2O_3 and glass beads. The densities and voidages at loosely packing state of the particles were measured by a water displacement method for glass beads and wax was used for silica gel and Al_2O_3 particles. The volume ratio refers to the bulk volume

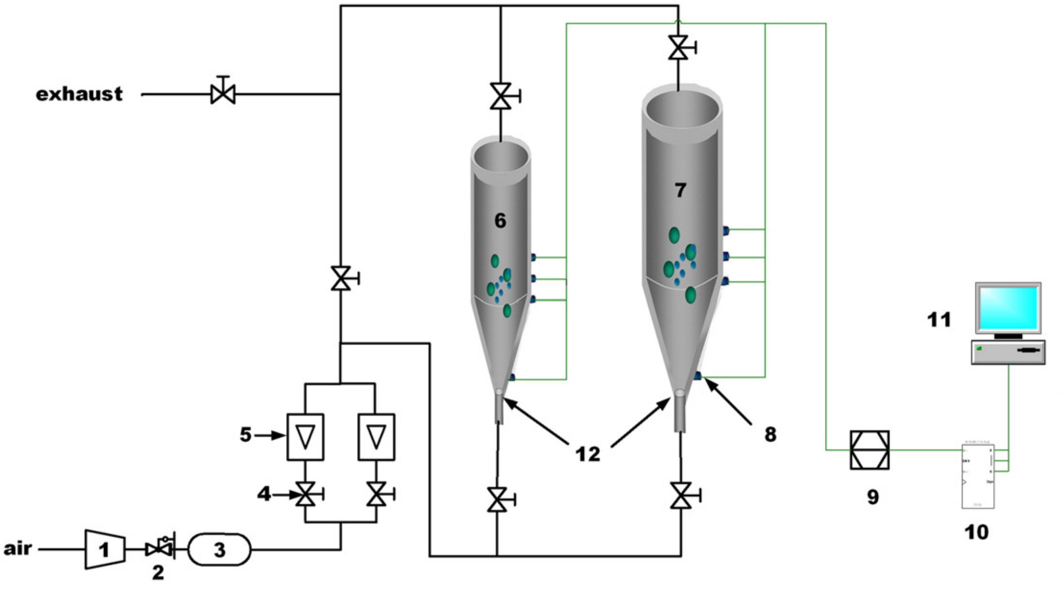

Fig. 1. Schematic diagram of the experimental apparatus. 1. Compressor; 2. Pressure regulator; 3. Buffer tank; 4. Gate valve; 5. Mass flow controller; 6. Spouted bed 80 mm; 7. Spouted bed 150 mm; 8. Pressure taps; 9. pressure transducer; 10. A/D converter; and 11. PC.