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# Flow regime transition and hydrodynamics of spouted beds with binary mixtures

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ABSTRACT

The spouting of fine particles is significantly different from that of coarse particles and a stable spouting can only be obtained under very constrained operating conditions. However, the stability of a spouted bed with fine particles can be effectively improved by addition of coarse particles. In this work, the flow regime transition and hydrodynamics of spouted beds with binary mixtures were experimentally investigated under a broad range of operating parameters. Effects of particle size, density, mixing ratio, gas velocity and nozzle diameter on flow regime transition and minimum spouting velocity in spouted beds were explored. The results show that a moderate increase in the mean particle diameter and density due to addition of coarse particles is beneficial to spouting stability. However, segregation is also observed when adding excess amount of coarse particles, thus leading to decreased spouting stability.



## 1. Introduction

Spouted beds, as an alternative to fluidized beds for handling coarse particles larger than 1 mm in diameter, are now widely applied in various physical operations, such as drying, coating, and granulation [1]. Spouted beds also possess unique structural and flow characteristics of potential applications in chemical processes [2–9]. The present research group [10] has shown that spouted beds can be operated under much broader conditions than circulating fluidized beds (CFBs) when employed as reactors for catalytic partial oxidation of methane (CPOM) processes. Higher reaction rates and better C/H product ratio can be achieved. However, spouted beds have been recognized with some disadvantages, among which using relatively larger particles may weigh against their wider use as chemical reactors. As for a fast catalytic reaction achieving complete conversion within a few milliseconds, the whole process is generally mass transfer limited and thus only the external catalyst surface is effectively utilized in the chemical process [11]. This is consistent with that demonstrated by Mathur and Epstein [12], spouted beds, in comparison with fluidized beds, always yielded lower conversions. Therefore, one promising method to increase the conversion in a conventional spouted bed is to operate it with relatively smaller particles without significantly changing the desirable spouting characteristics. Spouted beds operated with fine particles, which have higher gas solid contact efficiency leading to the enhanced conversions, recently have attracted increasing interests. Grace [13] pointed out that the spouting of the Geldart Bparticles is significantly different from that of coarse particles and a stable spouting can only be obtained under more restricted conditions. Similarly, a few other studies [14–21] showed that the fine particle spouting was more restricting and unstable compared to coarse particle spouting. In general, it has been found that hydrodynamic behaviors, such as the spoutability, spouting stability, and flow regime transitions were different between fine and coarse particles in spouted beds.

In the aforementioned studies, research efforts were mainly placed on improving spouting stability for fine particle systems toward applications as chemical reactors. And one feasible approach is addition of coarse particles to spouted beds of fine particles. Olazar et al. [22]-investigated multi-particle mixing in a gas–solid spouted bed with different sized particles, and the results show that the binary mixture can effectively improve the spouting stability for fine particle systems. Zhang et al. [23–25] investigated the effects of mixing index, particle size and particle density on spouting in a flat-bottom spouted bed. Huang et al. [26] studied the particle mixing in the annular of a spouted bed and found that the static bed height has a significant impact on the uniformity of the final mixture and addition of small particles increases the mixing speed. Ren et al. [27] studied the mixing behavior in spouted beds and found that the mixing process for binary mixtures has three phases: macro-mixing, micro-mixing, and stable mixing phases.

As seen from these studies, despite of improved spouting stability for binary particle systems in spouted beds, hydrodynamics in such systems is complex and mixing and segregation still may occur during

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the operation. Therefore, applications of spouted beds with binary mixtures to large scale industrial processes will encounter many challenges due to a lack of comprehensive understanding in the flow regime transition where the segregation could happen [28–30], as well as hydrodynamic characteristics, such as minimum spouting velocity ($U_{ms}$), and maximum spouting bed height ($H_m$), which are quite different from these in the single sized particle system [22]. Thus, in this study, the mechanism of flow regime transition of spouted beds with binary mixtures was systematically investigated and flow regime maps of different binary systems were experimentally developed. Hydrodynamics of spouted beds with binary mixtures was investigated. The main objective of this work was to provide new information for designing and operating spouted beds with fine particles toward broadened applications as chemical reactors.

## 2. Experimental

### 2.1. Experimental set-up

A schematic diagram of the experimental set up is shown in Fig. 1. In this work, experiments were performed in a plexi-glass spouted bed, with 80 mm inner diameter, 4–10 mm of nozzle diameters and a conical base angle of 60°. The experiments were carried out at ambient temperature and atmospheric pressure. The gas flow rate was controlled by mass flow controllers and measured by several flow meters with different measuring ranges. After the particles were charged into the cylindrical vessel, the air flow rate was adjusted for different bed heights to achieve a desired flow regime transition.

### 2.2. Measurements

The bed height and the fountain height were measured from recorded videos. For a spouted bed operated under stable conditions, the deviations of the measured fountain heights were within $\pm 5$ mm. $H_m$ was achieved by first obtaining stable spouting, and then increasing the bed height gradually until the fountain disappeared by varying the gas flow rate. $U_{ms}$ was measured from a descending approach in which the gas flow rate was gradually decreased to a point where stable spouting collapsed as a commonly adopted method [31].

### 2.3. Properties of particles

Particles used in this research were first sieved to obtain a narrow distribution range. Then the weight of a certain number (more than 600) of particles was measured, and the mean diameter can be calculated by $\overline{d_\rho} = \sqrt[3]{\frac{6m}{\pi \rho_b g n}}$. In this study, $Al_2O_3$ particles with diameters of 0.20 mm, 0.39 mm and 0.79 mm (Geldart B particles), were used as fine particles. And coarse particles (Geldart D particles) were silica gel particles of 1.05 mm and 1.75 mm and glass beads of 1.76 mm in diameter. Their respective physical properties are listed in Table 1. The densities of the particles were measured by a water (for glass beads) or wax (for silica gel and $Al_2O_3$ particles) displacement method. The volume ratio used in this study refers to the bulk volume ratio.

## 3. Flow regime transition

Spouting only occurs over a definite range of gas velocity for a given combination of gas, solid, vessel geometry, and configuration. The flow regime transition can be represented by flow regime maps, where the transition from a static bed to a spouted bed, and hence often to a bubbling bed and a slugging bed is clearly shown as a function of the superficial gas velocity. These transitions can be quantitatively presented by plots of the bed depth $H$ versus the superficial gas velocity $U$. From the flow maps, it can be seen that the spouting area of fine particle spouted beds is less than that of the coarse particle beds.

### 3.1. Spouting of single sized particle systems

The flow regime transitions of the single sized particle system were first investigated as a baseline. As observed in the experiments, for A1 particles, the finest particle used in this work, the stable spouting cannot be established with the nozzle of 7.6 mm in diameter ($d_i/d_p = 38$). For A2 particles ($d_i/d_p = 19.5$), a poor or restricted spouting is obtained, and a bubbling phenomenon appears when increasing the static bed height to 130 mm. For larger and heavier A3 particles ($d_i/d_p = 9.6$), a much better spouting is observed and the stable operational range is apparently larger than those for A1 and A2 particles. However, an unstable spouting is still observed when the bed height reaches 160 mm. When spouting coarse particles, the spouting stability ncreases with increasing the particle size and density. As noted by previous studies, the flow regime transitions for fine particles and coarse particles are quite different in terms of spout shapes and flow patterns in the bed. Becker [32], Pallai and Nemeth [33], and Mathur and Epstein [12] showed that the flow pattern in a spouted bed could more easily change from spouting to slugging with decreasing the particle size. Some researchers [34–36] have pointed out that fine particles are prone to formation of aggregates, leading to unstable

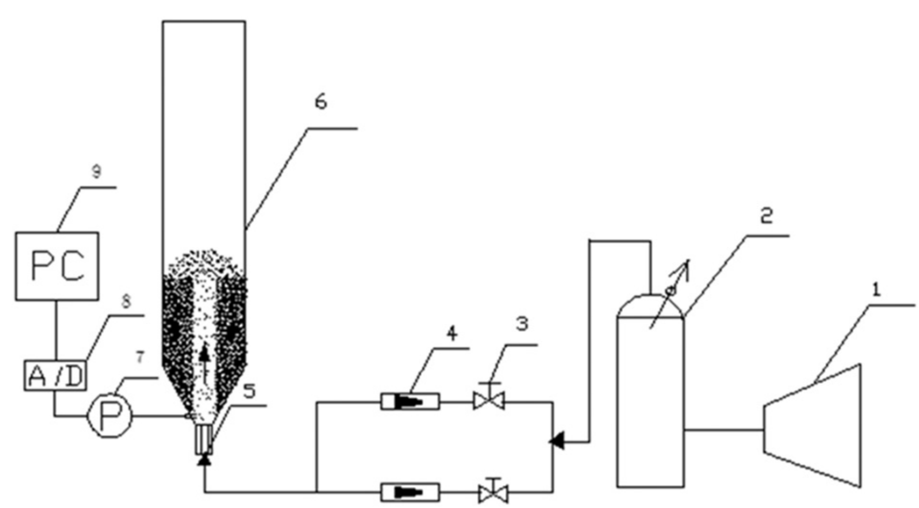


**Fig. 1.** Schematic diagram of the overall experimental apparatus. (1)compressor; (2)buffer tank; (3)gate valve; (4)mass flow controller; (5)nozzle; (6)spouted bed reactor; (7)pressure transducer; (8)A/D convertor; (9)PC.