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Cluster size distribution in the freeboard of a gas–solid fluidized bed

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ABSTRACT

Size distribution of clusters was determined in the freeboard of a 0.05 m diameter fluidized bed using a fiber optic probe at various axial and radial positions and different superficial velocities. The experimental results showed that the cluster size distribution is wider at lower axial positions due to the existence of larger clusters. Size of clusters decreases in the vicinity of the wall owing to wall effects and high rate of contacts between ascending and descending clusters. Studying the cluster size distribution at three superficial gas velocities showed that the size of clusters increases and their distribution becomes wider by increasing the superficial gas velocity. Effect of particle size on the cluster size distribution was examined which indicated that larger clusters are formed in a bed of larger particles.

1. Introduction

Circulating fluidized bed (CFB) is used in many chemical processes such as fluid catalytic cracking, coal combustion and coal gasification. At the bottom part of the riser of a CFB and above the dense bed, the particles are accelerated to a constant upward velocity. Above this region, in the fully developed zone, the flow characteristics become invariant against height. Then, the velocity of solid particles decreases due to the exit geometry. The height of these zones depends on various parameters such as gas superficial velocity, mass flux, properties of solids and solid circulating rate [1]. In spite of their extensive applications, some hydrodynamic aspects of CFBs have not been well understood yet mainly due to difficulties in determining the hydrodynamic properties of fluid and solids in these systems [1]. The knowledge of gas–solid behavior is essential to predict heat and mass transfer rates in the riser of a circulating fluidized bed [2].

Clusters are characterized by high concentration of particles. It is important to detect clusters in the fluidized bed in order to evaluate their considerable impact on the hydrodynamics of the bed [3]. Many experiments have been conducted to study the properties of clusters in fluidized beds. Soong et al. [4] identified clusters with capacitance probes. Zhou et al. [5] detected clusters by micrographs using a video camera. Many researchers widely used optical fiber probe as an effective tool for studying clusters in the fluidized bed [6–8]. To analyze the data series achieved from the fiber optic probe, several methods, such as chaos theory, fractal analysis and wavelet analysis, have been used. Among these methods, wavelet analysis has been proven to be the most effective one in recognizing different phenomena involved in a specific time series [3]. Time series data were decomposed into micro-scale (particle size, noises), meso-scale (small bubbles) and macro-scale (large bubbles, plugs) by using wavelet analysis [9,10]. Guenther and Breault [11] studied clusters in a CFB and indicated that the clusters length may vary by an order of magnitude under certain operating conditions which can be detected by multi-resolution capability of wavelets.

In contrast to the turbulent fluidized bed, where numerous investigations have been conducted [12], there are only a few studies on the cluster behavior in the freeboard of a fluidized bed. In several studies, the acceleration zone was neglected. This can cause inaccuracy and considerable error especially in short risers [13]. Therefore, identifying hydrodynamics of the acceleration zone is important for accurate modeling of riser and freeboard due to a drastic change of parameters such as bed void and pressure gradient in this zone. In this study, a comprehensive set of experiments was conducted to determine cluster diameter and their distributions in the acceleration zone of a freeboard at various operating conditions using an optical fiber probe and the wavelet approach.

2. Experiments

The experiments were conducted in a column with an inside diameter of 50 mm and the height of 1 m which was made of glass (Fig. 1). To minimize the electrostatic effects, the outer wall of the column was grounded by wires. Air entered the column through the distributor at room temperature and its flow was controlled by a mass flow controller. A cyclone was located at the column exit which separated the entrained solids and returned them back to the column.

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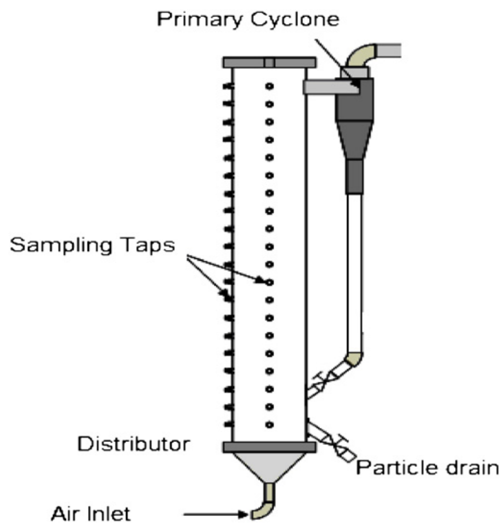

Fig. 1. Schematic of the experimental set-up.

In order to determine the acceleration zone, pressure drop along the riser of the bed was measured using a monometer. There were 20 sampling taps along the column wall, 5 cm apart from each other. The experiments were carried out at various gas velocities and a constant solid circulation rate. Two sizes of sand particles were used in the experiments. The initial height of solids in the bed was 1.5 times the column diameter in all experiments. Operating conditions and properties of the sands used in the experiments are reported in Table 1.

A reflecting optical fiber probe was used to detect clusters and determine their size in the acceleration zone. Details of the fiber optic probe are illustrated in Fig. 2. Both light-emitting and light-receiving fibers were located in a special order in the probe. When the particles reached the probe tip, the reflection of the emitted light was received by the receiving fibers. Then, a photo-multiplier amplified the received light and converted it into voltage. Data acquisition was repeated five times in each point and operating condition to assess reproducibility of the experiments. Based on the recommendation of Herbert et al. [16], the data were collected at a frequency of 300 kHz in order to detect all the phenomena in a fluidized bed. In each point, 4,500,000 data points were achieved for each fiber in 15 s.

The experiments were conducted along the freeboard of the fluidized bed at various axial distances above the distributor (17.5, 27.5, 37.5 and 42.5 cm). Also, data were acquired at three radial positions ($r/R = 0$, 0.5 and 1) at 27.5 cm above the distributor to obtain radial distribution of cluster size in the acceleration zone. In order to operate in the fast fluidization regime, gas superficial velocity was adjusted above the terminal velocity. In all experiments, solid circulation rate was constant at special values of 72 and 62 kg/m^{2}s for 150 μm and 300 μm solids, respectively.

3. Data analysis

For each receiving fiber, a time series signal was generated. The time delay between the signals was calculated by the cross-correlation method. Using this delay time and knowing the distance between two sequent fibers, velocity of clusters was determined.

Table 1
Operating conditions of experiments and properties of the sands used in the experiments.

d_p (μm)	ρ_p (kg/m^3)	U_{mf} (m/s) [14]	U_{tr} (m/s) [15]	G_s (kg/m^{2}s)	r/R	U (m/s)
150	2640	0.042	2.75	72	0, 0.5, 1	3, 3.25, 3.5
300	2640	0.158	3.89	62	0, 0.5, 1	4, 4.2, 4.4

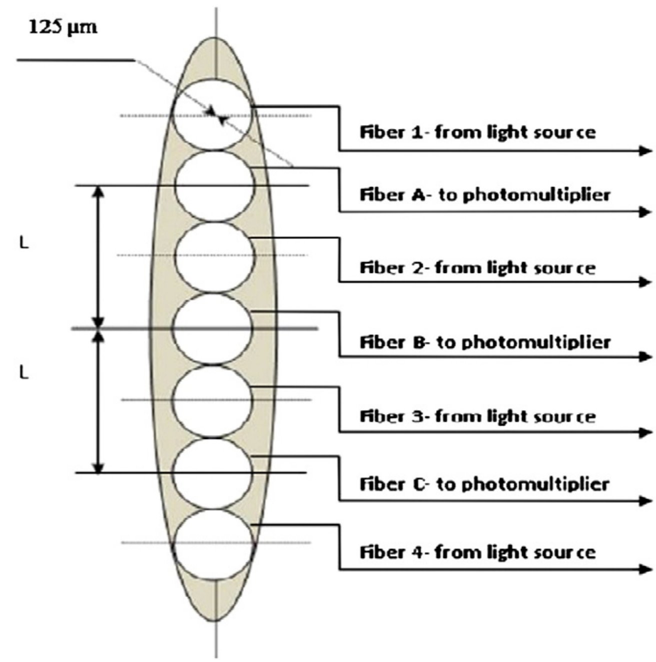

Fig. 2. Schematic of the tip of fiber optic probe.

Then, the size distribution of the clusters was evaluated at every point using cluster velocity.

3.1. Processing of signals

Wavelet has been successfully used to extract information from pressure fluctuations in a bubbling bed [8] and studying clusters in a downer [5]. In these investigations, wavelets were used to decompose data containing different scales into corresponding low and high frequency components. Moreover, wavelets were used to characterize clusters in the riser of a circulating fluidized bed by considering both high and low frequency components of the pressure fluctuation signal [11]. In all these investigations, the time series were reconstructed by adding the particular detail coefficient levels (high frequency) to approximation levels (low frequency) where both of them were generated by wavelet decomposition process. Since the wavelet was used as a low pass filter in the signal analysis [3,11], it was very important to use efficient level of the detailed coefficient due to identify all clusters.

In the present study, the smallest cluster was considered to be 1 mm in the center of the bed with a maximum velocity of 10 m/s. For such a cluster, when passing in front of the probe tip, Δt was calculated by:

$$\Delta t = (L + D)/V \tag{1}$$

where fiber bundle and length of cluster are denoted by L and D, respectively. Therefore, the frequency of passing such a cluster was estimated to be about 9500 Hz. By applying the Nyquist limit, used by several researchers [3,11], the frequency needed to accurately resolve the signal should be 19,000 Hz. Therefore, in the wavelet decomposition, by excluding d_1 and d_2 and considering other detail signals, the high frequency noise was removed from the signal. In this paper, level three approximation ($s = a_3 + d_3$), which caused smaller residuals than other levels, was used to reconstruct the original signal(s).

3.2. Cluster size

The signals obtained from the fiber optic probe represent the reflection of the light from the particles. High value of the voltage in