Powder Technology 254 (2014) 407–415

Contents lists available at ScienceDirect

Powder Technology

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

A novel method based on image processing to visualize clusters in a rectangular circulating fluidized bed riser

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ARTICLE INFO

Article history:
Received 12 October 2013
Received in revised form 4 January 2014
Accepted 6 January 2014
Available online 13 January 2014

Keywords:
Clusters
Rectangular circulating fluidized bed
Image processing
High-speed video camera

ABSTRACT

A new image processing method based on image calibration has been developed to visualize clusters in a Plexiglas rectangular circulating fluidized bed (CFB) riser at the fully developed region. A high speed video camera is adopted with FCC particles of 67 μm used as the bed material. In order to make sure day-to-day shooting images reliable and comparable under the same light illumination during the whole shooting period, a reference plate is made first to verify the light illumination consistency. After the verification, the relationship between solids holdup and image grayscale is calibrated in the same riser with both calibration curve and equation obtained. With given solids holdup thresholds increasing from 0.01 to 0.1, cluster size clearly decreases while cluster solids holdup increases by transforming gray images into binary ones. The variation of cluster profiles with different thresholds also reveals that there is a solids holdup gradient inside the cluster with a lower value at the surface and a higher one in the core. The change in dense phase holdup or cluster population with operating conditions is indicated by the variation of the black area under given solids holdup thresholds, which compare well with the well-known fact reported by many previous studies: higher G_s and lower U_g are beneficial for clusters with higher solids holdup to form, while lower G_s and higher U_g induce clusters to breakup. This consistency proves that the image processing method developed in the present study is effective and very useful.

1. Introduction

In gas–solid circulating fluidized beds (CFBs), the phenomenon that particles tend to aggregate together to form groups which have a relatively high particle concentration than the mean solids concentration, have been reported by many earlier researchers [1–5]. Particle groups, first referred to as "clusters" in the so called "fast fluidization" realized in CFBs in the 1970s [2,3], have been studied comprehensively, starting from finding the evidence of their existence to attempting to observe their formations and movements. Later on, further studies have revealed that there are different types of clusters with different shapes and sizes in the CFB riser.

Takeuchi et al. [6–8] noted that both relatively small and large chaotic dense packets existed and moved rapidly at two vertical heights along the riser. Besides, strands with parabolic shape pointing upward were relatively often observed. Li et al. [9] visualized that cluster shapes are in general irregular but appear strand-like in the core region and spherical near the wall. Cluster sizes are also found highly variable. Rhodes et al. [10] identified three flow forms: dilute, dense and swarm flow. The dense flow form was found least stable, agglomerating to produce swarm flow. Moreover, typical arch-shaped particle swarms with downward velocity were observed and size of vertical particle strands are often longer than 0.1 m. Bi et al. [11] identified four possible particle aggregation forms and illustrated their evolution and transformation through observation made in a two-dimensional circulating fluidized bed. With "internal" and "external" picturing systems, Kuroki and Horio [12,13] were able to obtain "internal and external" images of clusters with G_s in the ranges of 0.2–16.5 and 0.016–0.60 kg/m^{2}s respectively. The cluster shape changed frequently but its typical shape from the observation was a paraboloid heading downward and having a long skirt upward. In the dilute phase, particles from clusters were shed to the dilute phase continuously and were absorbed again by other clusters. The cluster sizes were rather uniform under a given operating condition but decreased with increased solid mass flux. The high-speed video observations from Matsuda et al. [14] indicated that most particle swarms in the central region of the CFB riser are descending ones and the packing density of particle swarms was as high as that of a fixed bed. Van den Moortel et al. [15,16] first used particle aggregates and void regions to characterize gas–solid flow structure and then reported that up-flowing particle clusters exhibited horseshoe shapes heading upward with thin downward tails, while the downward-moving cluster also exhibited a horseshoe shape but heading downward with thin tails upward. The tails were formed by the motion of gas pockets on both sides. Shi et al. [17] captured visual images and the micro-structure of various clusters. According to the distance between particles and the shape and appearance position, clusters are classified into four categories.

As mentioned above, the understanding of clusters has been progressing. However, due to the complication of microscopic gas–

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http://dx.doi.org/10.1016/j.powtec.2014.01.015

solid two phase flow in CFB, more studies are required before further insights about the characteristics and hydrodynamics of clusters obtained. As there have been few common understandings on the definition and classification of clusters so far, to avoid confusion, the 'clusters' used in this paper are a generalized conception, which refers to all forms of particle agglomeration.

Generally speaking, published experimental measurement techniques that were used to study the characteristics and structure of clusters in gas–solid systems can be mainly divided into two categories: intrusive probes [18,19] (also including some 'inside bed imaging' systems such as a high-speed video camera attached with a bore scope [6–8] and a video camera connected with an optic fiber micrograph probe [9,20]) and non-intrusive visualization systems [10,17]. The former is advantageous for using in dense regions and determining local flow properties such as solids holdup and particle velocity. The latter, however, are preferable due to their little disturbance to the flow. Visualization techniques were first devised as a method only providing qualitative indications and mapping the overall flow structures under dilute solids holdup conditions. However, with the development and improvement of modern video cameras and application of imaging process and analysis methods, those limitations are in the process of being overcome [20–25]. Compared to complicated calibration procedures and undesirable physical flow disturbances of intrusive probes, visualization techniques are attracting more researchers in recent years. Visualization measurement techniques using video cameras to study clusters are listed in Table 1.

To summarize the previous cluster studies with video cameras, it is worthwhile to note that, firstly, most frame rates of the video camera setups were lower than 1000 fps with longer shutter times. In order to study the behavior and properties of clusters comprehensively, higher frame rates are required. Thus, the frame rate of 2000 fps was set in the current study. Secondly, almost all of the studies were conducted under lower solids circulation rates (<80 kg/m^{2}s) and superficial gas velocities (<8.0 m/s). Taking into account the industrial applications of fluidized beds, cluster and flow structure visualization under higher G_s and U_g deserves further study. The present visualization technique with image processing method in this study has proved to be effective under high solids concentrations where G_s is at least up to 150 kg/m^{2}s. Lastly, there was no discussion about relationships to correlate the image information (shown as various degrees of grayscale) and characteristics of clusters in the former image-based studies. However, in order to "extract" and process useful information from obtained images for a quantitative analysis, it is very necessary to build such a relationship before image processing methods are applied. As a result, an image processing method was introduced for the first time in the present paper.

As an image-based research work, the aim of the present study is to develop a systematic and integrative method to view clusters with certain solids holdups formed inside the rectangular CFB riser and to build a basis for deriving a comprehensive understanding of the micro-flow structure by processing and analyzing the images of clusters in the following studies.

2. Experiment

2.1. Circulating fluidized bed and operating conditions

The experiments were conducted in a cold-model rectangular CFB system that consists of a 7.6 m high riser with a rectangular cross section of 19 mm × 114 mm, a 3.85 m height of 38 mm × 203 mm downcomer with a 1.85 m cylindrical storage column of 203 mm i.d. on the top, two cyclones, a bag house filter, two flapper valves in the cylindrical storage section for solids circulation rate measurement and a gas distributor at the bottom of the riser (Fig. 1). A flip valve is used to control the solids flow rate. Air enters into the bottom of riser through the distributor, mixes with the particles fed from the downer and carries

Table 1
Clusters studies with visualization techniques in gas–solid flow.

Author	Measurement technique	Video camera setup		Particles	Particle properties		Operating conditions	
		Frame rate (fps)	Shutter time (μs)		dp (μm)	ρ_p (kg/m^3)	G_s (kg/m^{2}s)	U_g (m/s)
Takeuchi and Hirama [6]	High speed video system	400	200	FCC	57	930	45.6	2.03, 2.42
Li et al. [9]	Video camera with optical fiber micrograph probe	n/a	n/a	FCC	54	929.5	7.32–64.65	1.31–3.49
Rhodes et al. [10]	High speed video camera	1000	n/a	Alumina particles	74.9	2456	2–80	3–5
Kuroki and Horio [12]	Laser sheet & TV camera	n/a	4000	FCC	61.3	1780	0.2–16.5	0.6–1.3
Horio and Kuroki [13]	Laser sheet & TV camera	60	10000	FCC	61.3	1780	0.016–0.60	0.15–0.60
Zou et al. [20]	Video camera with optical fiber micrograph probe	n/a	n/a	FCC	54	929.5	9.3–64.7	1.3–3.5
Takeuchi et al. [7]	High speed video system	1000, 2000	100	FCC	57	930	45.6	2.03, 2.42
Matsuda et al. [14]	High speed video system	2000, 3000	n/a	Glass beads	400	n/a	10–35	3–6
Lim et al. [21]	Video camera	n/a	4000	Sand	213	2640	10–60	4.5–8
Van den Moortel and Tadrist [15]	Laser sheet & video camera	25	n/a	Glass beads	120	2400	0.077, 0.25	0.9, 1
Van den Moortel et al. [16]	Laser sheet & video camera	25	n/a	Glass beads	60, 120, 230	2400	0.002–0.16	0.3–1.5
Takeuchi et al. [8]	High-speed video system	1000	100	FCC	57	930	45.6	2.03, 2.42
Lackermeier et al. [22]	High-speed video techniqe and laser sheet	1000	100	Sand	140	n/a	6	3
Shi et al. [17]	PIV	n/a	n/a	Glass beads	250, 333, 420	2379, 2478, 2514	4.35, 10.5, 45	5.2, 5.47
Cocoo et al. [23]	High-speed video camera	3000–6000	20	Polyethylene FCC	70, 76	400, 1500	n/a	0.61

n/a: data not given in the paper.