Powder Technology 269 (2015) 207–218

Contents lists available at ScienceDirect

Powder Technology

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

Length scales of solid clusters in a two-dimensional circulating fluidized bed of Geldart B particles

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ARTICLE INFO

Article history:
Received 27 April 2014
Received in revised form 5 August 2014
Accepted 14 August 2014
Available online 4 September 2014

Keywords:
Circulating fluidized bed
Cluster dimensions
Length scale
Image analysis

ABSTRACT

The flow pattern in a circulating fluidized bed (CFB) is characterized by clusters of particles. The length-scale distribution of solid clusters was analyzed both horizontally and vertically from a number of experiments carried out with Geldart B particles in a two-dimensional circulating fluidized bed. Cluster dimensions were found to be dependent on solid loading, superficial gas velocity and location in the bed. Large length scales were found to be typical for the bottom region, above which more narrow dense clusters are common. The majority of clusters in the upper part of the riser have a width less than 20 mm, which means that in CFD simulations of circulating fluidized beds the mesh resolution should be finer than 5 mm to accurately reproduce the clusters. However, a significant fraction, of the order of 10–15% of the measured cluster widths, was below 2 mm. This is about ten times the particle diameter which is the mesh spacing recommended in the literature for CFD simulation of CFBs. The findings of the study on the width and height distributions of the clusters may also be used as a point of comparison with corresponding measures observed in simulated systems, by which a quantitative validation of CFD results could be made.

1. Introduction

The flow pattern in a circulating fluidized bed (CFB) is characterized by a complicated structure with continuously forming and vanishing clusters of particles. According to Davidson [1] the clusters are particle groups having larger height than width, retaining the primitive structure for a substantial time travel through the CFB riser. For Geldart B particles the shapes of the clusters are obscure and long narrow strands of particles are typical, while Geldart A particles additionally form small, more tightly packed clusters (Cocco et al. [2]).

Computational fluid dynamics (CFD) simulations have become an important tool in the development of CFB processes. To accurately describe the flow patterns, transient simulations should be carried out in a fine computational mesh. In practice, however, computational resources limit the feasible mesh size [3]. Thus it becomes important to understand what length scales of the flow field can be resolved by the simulation and what scales should be covered by sub-grid scale equation closures (see, e.g., Igci et al. [4]). Typically, the thinnest clusters are narrower than the mesh spacing, but their importance is not clear; the share of solids collected in such narrow clusters is not well known.

In case of Geldart A particles, the size of a cluster formed due to cohesive forces can sometimes be easy to measure. For Geldart B particles it is not as easy to define a cluster size, although such attempts have been made [5,6]. Measurements with optical probes can be applied to determine cluster length scales, typically the vertical ones [7,8]. Instead of defining a cluster size the widths and lengths of the particle strands and other regions with high solid content can be analyzed. Many researchers have already observed that the dimensions of clusters vary at different bed locations along with their duration of appearance [9]. It has been noted that clusters at the wall region sustain longer than clusters of the central region. Studies have also shown that in two-dimensional CFBs the solid particle clusters form into streaks [10]. Solid hold-up plays a major role for the cluster shapes. Bai et al. [11] found that higher solid hold-up in solid particle clusters gives rise to a U-shaped form but if the particle density becomes low the particles instead form stands. Furthermore, the dynamic behavior of clusters is very specific to the position and bed properties. Image analysis and evaluation of physical properties of clusters have been undertaken by Rhodes et al. [12] and Lim et al. [13], who inferred that the clusters become elliptical or arched-shaped in vertical front view. Based on experimental evaluations in a pilot-scale CFB, Chew et al. [14,15] stated that for Geldart B particles the local riser position has a very dominant influence on cluster characteristics. These authors also suggested that the physical properties of clusters be dependent on the bed conditions and this influence is more dominant in the upper region of the CFB riser. Their investigations furthermore revealed that higher bed inventory (solid loading) produces U-shaped clusters while lower bed inventory produces more inverted U-shaped structures.

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http://dx.doi.org/10.1016/j.powtec.2014.08.031
0032-5910/

Cluster dimensions are important in the study of cluster hydrodynamics. In the present study cluster dimensions, both in the vertical and horizontal directions, are studied in a preudo-2D cold CFB rig. Efforts were made to analyze the cluster dimensions at different riser locations to gain an understanding of the influence of specific regions for given bed conditions. Both dilute and dense phase flow structures were studied with appropriate cluster definitions. On the basis of the results, conclusions are finally drawn on the appearance of different-sized clusters in the parts of the bed, on the effect of fluidization conditions and bed loading, as well as on the selection of a suitable mesh resolution in CFD simulation of a circulating fluidized bed.

2. Experimental

In the present work, a cold CFB unit at Åbo Akademi University, Åbo, Finland (Guldén, [16]) was used to study length scales of variations in solid volume fractions (Fig. 1). The height of the riser is 3 m and the width is 0.4 m. The distance between the riser walls is 0.015 m which renders the unit fairly two-dimensional. The air distributor consists of 8 equally spaced air nozzles. The front and back walls are made of polycarbonate plates allowing visual observation and image analysis. In the experiments the bed is illuminated from behind for video recording. The bed material consisted of spherical glass particles with a material density of 2480 kg/m^3. Before the tests, the bed material was sieved to a narrow size range with a Sauter mean diameter of 0.255 mm. The total mass of the bed material was varied between $m = 2.0$ kg and 4.0 kg.

Superficial gas velocities studied were $u = 1.25$ m/s, 1.75 m/s, 2.25 m/s and 2.75 m/s. At the lowest gas velocities solid circulation was minimal and the character of the flow behavior could be classified as turbulent fluidization. However, especially at the highest velocity of 2.75 m/s significant amounts of solids exited the riser and returned to the riser bottom through the solid circulation loop. For the cases with bed masses of 2 kg and 3.3 kg, the measured solid circulation rates per riser cross-sectional area were 24 kg/m^2 s and 47 kg/m^2 s, respectively. A core-annular flow pattern prevailed in these cases along the entire riser height. According to [17] the transport velocity above which fast fluidization state is reached would be for the present case 2.8 m/s, i.e. slightly above the highest velocity used in our study. The measured high circulation rates, the observed core-annular flow structure and the fact that clusters formed below 1.0–1.5 m height were commonly transported up to the riser exit indicate, however, that the flow conditions in our 2D riser were close enough to the conditions in the fast fluidization regime to allow for drawing conclusions on length scales in CFB conditions. Short tests at higher velocities were carried out to visually confirm this but due to the difficulties related to operation of the loop seal and the increased static electricity at higher gas velocities, no long enough videos at higher velocities were recorded for the present analysis.

Fig. 1 illustrates the flow structure at three heights at a superficial gas velocity of 2.75 m/s. The images show long narrow clusters and strands in the upper part of the riser and denser complicated structures further down. At the walls in the bed bottom region wide dense sections occur. The behavior of the CFB at the bed bottom up to 0.73 m, in the middle from 0.73 m to 1.37 m and at the top from 1.37 m to 1.95 m was video recorded in all the experiments. From every test a 3-minute video was analyzed in detail by image processing. To verify that the

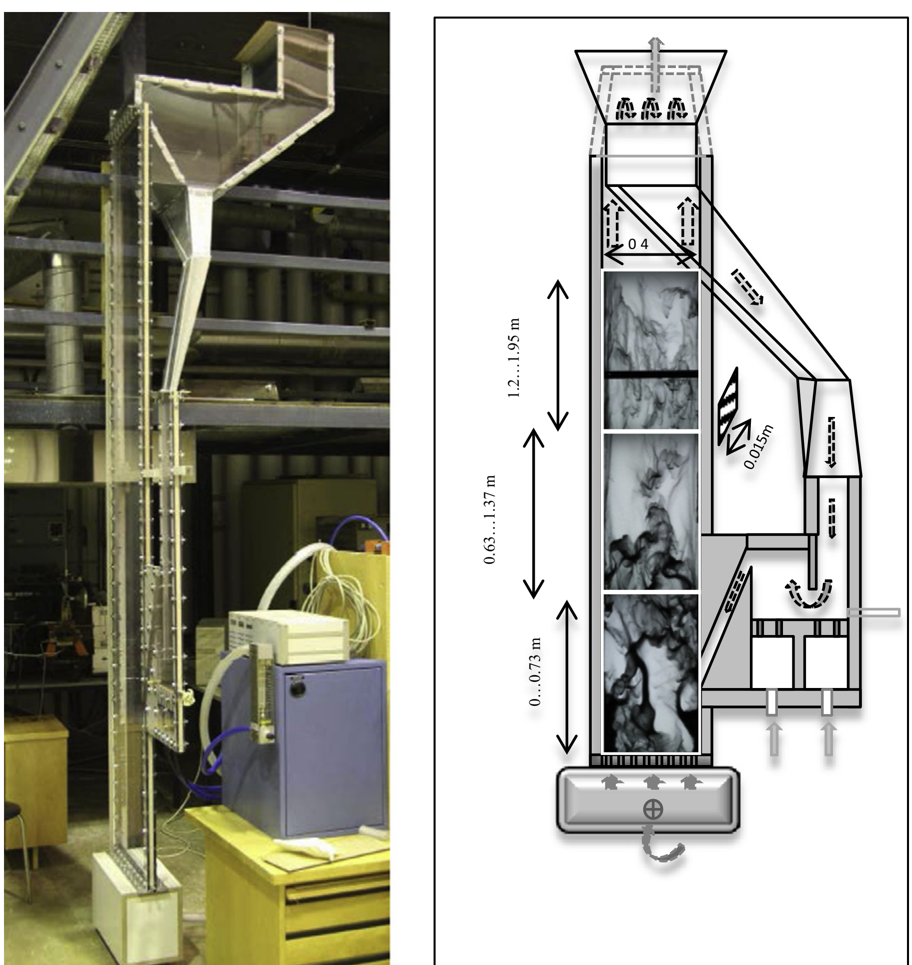

Fig. 1. Left: Photograph of the lab-scale CFB. Right: Functional diagram of the CFB along with experimental images from heights $z = 0.00…0.73$ m, 0.63…1.40 m and 1.40…2.20 m.