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Flow structures in the downer circulating fluidized bed

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Abstract

The flow structures in downers have been investigated by a micro-video and by analysis of local voidage signals in this work. The experiments of micro-video action shot were performed in a downer with an internal diameter of 0.09 m. The local voidage signals were collected in a downer with an internal diameter of 0.285 m. The micro-video action shot showed that there were particle-clustering phenomena in the downer and the clusters existed mainly in the form of floc and stick. Through wavelet analysis of local voidage signals, the cluster size and frequency were obtained. However, the probability density distributions of local voidage signals confirmed that the clusters in the downer were unstable and could not form a stable phase.

Keywords: Downer; Flow structure; Cluster

1. Introduction

The complex structures and its dynamic variation are the common characteristics of a complex multiphase system, causing the difficulties for the study and quantitatively description and project of the system. A downer reaction system belongs to this class of multiphase systems. Besides the common structures of the flow, the different phases (gas and solids) in a downer can aggregate to form also meso-scale structures. There are a dilute phase (more dispersed) and a cluster phase (more dense). These meso-scale structures can be affected by the system boundaries and by its own interactions forming complex macro-structures characterized by mean radial and axial solids distributions. Therefore, the study of these transient flow structures in downers can elucidate which mechanisms are important for the control of flow behaviors, and for the downer design, scale-up and overall control.

Many investigations have been performed to study the flow structures in downers. Yang et al. [1] showed that in a downer, the particle concentration was uniform in the radial direction except for the position near the wall, where a dense phase zone ($r/R = 0.86$–0.95) existed and the particle density was 2–3 times higher than that of bed center. Krol et al. [2] studied the cluster formation in down flow reactors by using a new optical sensor, the CREC-GS-Optic probe. They found that the solid evolved as strings of particles and the average cluster size was ranged from 2 to $6d_p$ with most probable string size of $3.5d_p$. Zhang et al. [3] presented that there existed particle clusters in the downer, but a stable cluster phase with solids fraction of $1\text{-}\varepsilon_{mf}$ was not observed. However, presently, the opinions on the existence of cluster in a downer are rather divergent. A definition of “cluster” in a detectable way is of great importance as well. Sharma [4] has proposed a criterion for detecting the starting and ending time of a cluster once it has been detected by the $2\sigma_{\underline{s}}$ criterion of Soong et al. [5].

Nowadays, there are numerous studies on flow structures and clusters in risers [6–16]. Li et al. [9] first observed the clusters in the riser of CFB by using the micro-camera. Horio et al. [10–11] used the multiple laser-sheet techniques to observe the three-dimensional flow structures of dilute suspensions in the circulating fluidized bed. The cluster size and their velocity distributions were determined from the video image analysis. Using the high-speed video technique in combination with the laser sheet technique, Lackermeier et al. [12] visualized the local flow structure inside upper dilute zone of CFB and successfully obtained shapes and

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Nomenclature

d_p	particle diameter (m)
D_{cluster}	cluster size (m)
$\bar{D}_{\text{cluster}}$	average cluster size (m)
f	cluster frequency at a certain point (1/s)
g	acceleration of gravity (m/s^2)
G_s	mass flow rate (kg/m^2 s)
i	ith cluster
l	bed length from the solids entrance (m)
n	cluster number
r	radial interval (m)
R	bed radial (m)
Re	Reynolds number
$t_{\text{c,after}}$	back peak time around cluster position in wavelet resolution signal (s)
$t_{\text{c,before}}$	former peak time around cluster position in wavelet resolution signal (s)
$t_{\text{c,end}}$	end time of cluster through an optical fiber (s)
$t_{\text{c,start}}$	start time of cluster through an optical fiber (s)
Δt_{cf}	time of cluster through a certain point (s)
$\Delta \bar{t}_{\text{cf}}$	average cluster falling time (s)
Δt_{whole}	whole time of time series (s)
Δt_1	cluster falling time through the point of an optical fiber (s)
Δt_2	cluster falling time from wavelet analysis (s)
U_{g}	gas velocity (m/s)
U_{t}	terminal velocity of particle (m/s)
U_{solid}	solid velocity (m/s)
V	output signal voltage of optical probe (V)

Greek letters

ε	voidage
ε_{mf}	voidage at minimum fluidization
$\bar{\varepsilon}_{\text{s}}$	mean solids holdup
μ	gas viscosity (Pa s)
ρ_{g}	gas density (kg/m^3)
ρ_{p}	particle density (kg/m^3)
σ_{s}	standard deviation of solid volume fraction

velocities of the flow structures. According to the heterogeneous structure consisting of a solid-rich dense phase (Cluster) and a gas-rich dilute phase, Li et al. [13] developed a comprehensive model of the energy-minimization multi-scale (EMMS) approach. Horio et al. [14] predicted the cluster size in circulating fluidized beds. Harris et al. [15] developed the correlations for predicting the properties of clusters of particles traveling near the riser wall such as cluster mean solid concentration, cluster size, cluster velocity, cluster shape, and time fraction of cluster appearance at the wall. Sharma et al. [16] studied the cluster characteristics, as determined by capacitance probe measurements of instantaneous local solid concentrations, and the results indicates the clusters can strongly affect operational characteristics, and the particle size, superficial gas velocity affects the duration time, occurrence frequency, time-fraction of existence and solid concentration in clusters. However, with gas–solids flow behaviors in downers researched further, the studies on the flow structure in a downer, especially with respect to clusters are attracting the researchers in the world [2–3,17]. This paper also focuses on experimentally studying the flow structures in a downer, attempting to explain the flow behavior from the viewpoint of the so-called “multi-scale approach” [18–20], which can be used to explain the “structure/interface” in a complex system.

2. Experimental

The experiments on flow structures in the downer were performed in two setups with different scales, shown schematically in Fig. 1. The voidage time series experiment was carried out in a large-scale downer. The micro-video action shot experiment was carried out in the smaller scale downer. The large scale indicates the larger diameter of downer tube and high solids circulation, and the small scale indicates the small diameter of downer tube and low solids circulation.

The large-scale downer system includes an elevator, a bag filter, a hopper, a screw, a fluidized bed feeder, a gas–solid diffuser and a tubular downer. The total height of the downer is 3.5 m with an inner diameter of 0.285 m, as shown in Fig. 1(a). The solid materials used in the experiment were glass beads with an average diameter of 57.6 μm and a density of 2500 kg/m^3. The smaller scale downer with an inner diameter of 0.09 m and a height of 8.2 m is shown in Fig. 1(b). The FCC particles with a density of 1350 kg/m^3 and an average diameter of 76 μm were used as the bed materials.

In a downer, the local gas–solids slip velocity is normally much higher than the terminal velocity of a single particle [21], which indicates that the particle clustering phenomena may exist. However, it is difficult to directly observe the individual cluster. In order to observe the micro scale gas–solids flow structures on line in the downers, the micro-video camera developed by the Institute of Process Engineering was used in the experiment. The measuring unit couples a microscopic lens with a new type CCD micro-camera. The optical glass rod and the compound lens sleeve can be inserted into the bed. When the compound lens is focused on a desired position in the downer, the shoot starts and the video of the local micro flow structure at the position can be logged in a computer. The schematic diagram of the video system is illustrated in Fig. 2.

If the cluster size is assumed to be the length of a cluster in the falling direction, Eq. (1) can be employed to estimate the cluster size

$$D_{\text{cluster}} = U_{\text{solids}} \Delta t_{\text{cf}} \tag{1}$$