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Clustering behavior of solid particles in two-dimensional liquid–solid fluidized-beds

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Abstract

In this paper, the clustering behavior of solid particles in a two-dimensional (2D) liquid–solid fluidized-bed was studied by using the charge coupled devices (CCD) imaging measuring and processing technique and was characterized by fractal analysis. CCD images show that the distribution of solid particles in the 2D liquid–solid fluidised-bed is not uniform and self-organization behavior of solid particles was observed under the present experimental conditions. The solid particles move up in the 2D fluidized-bed in groups or clusters whose configurations are often in the form of horizontal strands. The box fractal dimension of the cluster images in the 2D liquid–solid fluidized-bed increases with the rising of solid holdup and reduces with the increment of solid particle diameter and superficial liquid velocity. At given solid holdup and solid particle size, the lighter particles show smaller fractal dimensions.

Keywords: CCD; Liquid–solid fluidized-bed; Fractal dimension; Cluster; Self-organization structure

1. Introduction

Liquid–solid fluidized-beds are widely used in chemical, biochemical, environmental and food industries because of their unique advantages such as efficient liquid–solid contact and high heat and mass transfer rates. However, the fundamental understanding of liquid–solid fluidization system is still limited on account of the existence of the complex flow structures resulting from the interactions between the liquid and solid phases.

Generally, the liquid–solid fluidization system is considered “particulate”, in which solid particles are uniformly distributed in space and time (Couderc, 1985). However, flow non-uniformity has also been noticed in liquid–solid fluidized-beds. Wilhelm and Kwauk (1948) reported that liquid–solid fluidized-beds could exhibit “aggregative” or bubbling behavior in case of heavy solid particles such as lead shot or copper beads. Water-glass-beads beds are generally considered homogeneous, while non-homogeneous behavior for the heavier particles often took place. Hassett (1961) reported the appearance of horizontal bands or low density or completely void mushroom-shaped bubbles traveling upward in the bed. Kmiec (1978) reported irregular movements of solid particle clusters near the wall at low liquid flow rates. Chen, Jang, Cai, & Fan (1991) and Fan, Kang, Yashima, & Neogi (1995) observed clustering and irregular movements of solid particles in fluidized-beds with naked eyes and concluded that the irregular circulation of particle clusters resulted in the non-uniform distribution of solid holdups in the fluidized-beds. The solid particle clusters and the bubbles in fluidized-beds are also named coherent structure or self-organization structure by Van den Akker (1998). Such flow structure has a close relationship with the rate of heat and mass transfer occurring in the fluidized-beds. However, it is difficult to describe such phenomena. A few years ago, fractal method was introduced into the gas–liquid–solid fluidization system and the fractal analysis of flow image was employed to characterize the gas bubble cluster behavior and flow regime transition in three-phase fluidization system (Duan, 1993). The fractal dimension of the flow images was found to be a good quantifier of the three-phase fluidization system, and fractal reconstruction was carried out to rebuild the clustering behavior of gas bubbles.

In this paper, in order to better understand the complex fluid hydrodynamics, especially the self-organization structure of

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Nomenclature

Ar	Archimedes number, $Ar = (gd_p^3(\rho_s - \rho_l)\rho_l)/\mu_l$ dimensionless
D	box fractal dimension
Dn	discrimination number, $Dn = (Ar/Re_{mf})((\rho_s - \rho_l)/\rho_l)$ dimensionless
d_p	particle diameter (m)
H_0	initial bed height (m)
$N_{(\delta)}$	number of boxes
Re	Reynolds number, $Re = u_l d_p/\nu_l$ dimensionless
u_l	superficial liquid velocity (m/s)
u_{mf}	minimum fluidization velocity (m/s)
u_t	terminal velocity of a single particle (m/s)

Greek letters

δ	box size
ε_s	solid holdup
ν_l	kinematic viscosity of liquid (m/s^2)
ρ_s	density of particles (kg/m^3)

solid particles in the liquid–solid fluidized-beds and to develop proper physical and mathematical models, experiments were carried out in a two dimensional (2D) liquid–solid fluidized-bed by using the developed charge coupled devices (CCD) image measuring and processing technique and fractal analysis is used to character the clustering behavior of solid particles in the fluidized-bed.

2. Experiments and estimating method of fractal dimension

2.1. Experiments

Fig. 1 is the schematic diagram of the experimental system used in this study. The 2D liquid–solid fluidized-bed was 1 m high with a cross-section of 0.1 m × 0.006 m. A steel screen at the bottom of the fluidized-bed was used to support the solid particles. A fixed-bed of 0.003 m glass beads with a height of 0.15 m located at the bottom of the screen support served as the liquid distributor.

Tap water was used as the liquid phase. The physical properties of the solid particles used are listed in Table 1. All experiments were carried out at ambient temperature. Liquid pumped from the liquid reservoir, measured by a liquid flowmeter, entered the liquid distributor. Liquid and solid particles moved upward in the 2D fluidized-bed, and then the liquid returned back from the outlet at the top of the fluidized-bed to the liquid reservoir.

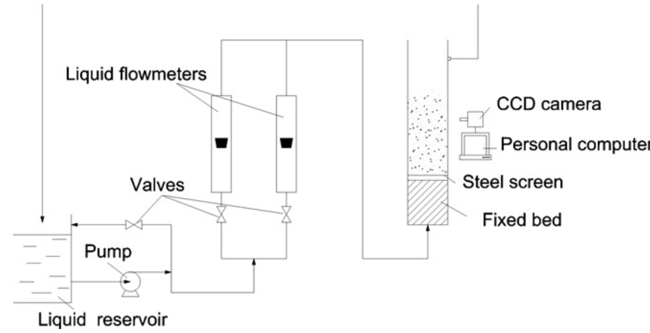

Fig. 1. Schematic diagram of the experimental installation.

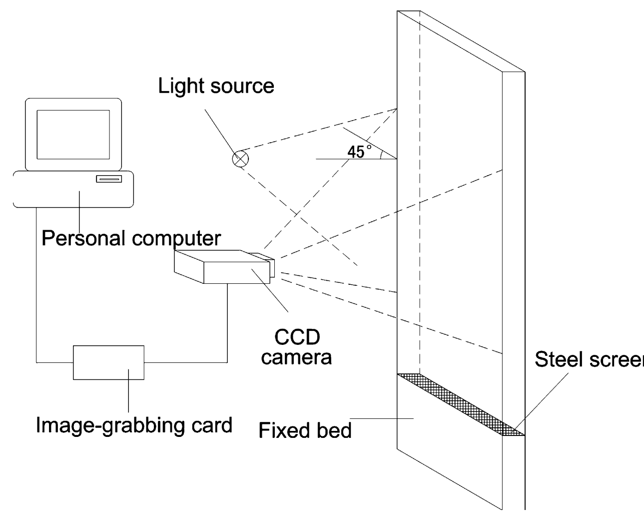

Fig. 2. The CCD measuring system.

When steady movement of the solid particles in the bed was achieved, the flow images of solid particles were taken by using the CCD image measuring system for different operating conditions. During image recording, the CCD camera was set at a perpendicular distance of about 0.5 m from the fluidized-bed. As shown in Fig. 2, the measuring system consists of a CCD camera, a black–white image-grabbing card, a personal computer and a 60 W light source. The image acquisition rate was 50 Hz. Snapshots of the moving particles were recorded with a CCD camera and the time interval between two consecutive frames was 0.02 s.

Note that the Reynolds number is $Re = d_p u_l/\nu_l$, where d_p is the diameter of the particles, ν_l the kinematic viscosity and u_l

Table 1
Physical properties of the solid particles

Solid particles	d_p (m)	ρ_s (kg/m^3)	u_{mf} (m/s)	u_t (m/s)	$Dn \times 10^{-4}$ (Liu, Kwauk, & Li, 1996)
Poly-formaldehyde	0.0040	1420	0.0399	0.2233	0.2125
Ceramic	0.0018	2670	0.0321	0.2986	0.3396
	0.0028	2670	0.0778	0.3724	0.9945
	0.0038	2670	0.1432	0.4339	2.3296
	0.0040	2670	0.1469	0.4523	2.5057