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Gas–solid flow behavior and contact efficiency in a circulating-turbulent fluidized bed

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ABSTRACT

Circulating-turbulent fluidized bed (C-TFB) was characterized by high solid holdup, homogenous axial and radial flow structure, no net downflow of solids and high contact efficiency in this study. These flow dynamic properties were mainly represented by solid holdup profiles, the identification of flow regime and cluster dynamics in a riser, 100–150 mm in diameter and 10.06 m in height. To quantify the effect of novel diameter-expanding structure on flow dynamics, a parameter (contact efficiency) was introduced firstly. The effects of gas–solid interaction on flow performance were investigated by a fiber-optic probe to detect solid holdup. CO_2 tracer injection and sampling system were used to characterize the flow structure and define the contact efficiency. The experimental results showed that flow regime in C-TFB is belonging to dense riser upflow (DRU) or dense-suspension upflow (DSU) regimes and transient region disappears in axial position. Flow structure is different from previous studies about traditional circulation fluidized bed (CFB) due to the effect of expanding structure and ring-feeder internal. A flow model based on the profiles of solid holdup and CO_2 tracer concentration was proposed to account for the gas–solid contact efficiency in the reactor. The contact efficiency in C-TFB is much higher than that of high-density circulating fluidized bed (HDCFB), which means C-TFB reactor would exhibit better performance to optimize the product distribution under the same operating conditions.

1. Introduction

Circulating fluidized bed reactors have been utilized extensively in industrial processes such as coal combustion, FCC and gasification of biomass [1,2]. However, CFB is characterized by intensive back mixing and non-uniformity flow patterns where there are still considerable radial gradients in particle density, with higher solid holdup near the wall than in the interior of the riser, which results in low contact efficiency. For catalytic gas-phase reaction processes, the gas phase is the reacted product so that gas back mixing is not desirable. This would require a relatively high gas velocity in the riser to promote plug flow and short contact time between gas and solid catalyst [3]. The difference between industrial and experimental operating conditions constrains the reference value of experimental studies to practical industrial production. Solids fluxes can reach up to 200 $kg/m^2/s$ in industrial operating condition, which is much higher than that of the experimental study. High-density circulating fluidized bed (HDCFB) proposed by Grace can achieve it as there is no net downflow of particles at the wall, relatively short and uniform residence times of catalyst particles and favorable bed-to-surface heat transfer with higher particle concentrations and higher solids fluxes [4]. Another reactor can counterbalance some drawbacks of CFB reactor. Turbulent fluidized bed (TFB) plays a good performance in mixing and mass transfer due to vigorous interaction between particles and voids, high solid holdup and much more uniform radial distributions [5]. Zhu [6] has proposed a novel circulating turbulent fluidized bed (C-TFB), which combines the advantages of HDCFB and TFB such as high solid holdup and solids flux, homogenous axial and radial flow structure, no net downflow of solids and high contact efficiency from large amount of experimental studies.

Previous studies associated with C-TFB are restricted to solid holdup profiles. There is a lack of further research in the literature regarding a detailed experimental and theoretical analysis of the flow regime and contact efficiency. Understanding of the flow regimes in fluidized system is important because different flow regimes provide vastly different gas–solid mixing and thus different chemical reaction rate. Since C-TFB was proposed in recent years, there were no reports on introducing its flow regime specially. However, numerous studies on flow regimes in CFB riser are available in the literatures summarized in Table 1 [7–14], in which the identification of different flow regimes through U_{sf} and G_s is adopted widely for its simplicity, precision and operability. In addition, the very method is utilized in this work to identify flow regime in C-TFB and relevant correction or modification factor is supposed to be added in order to be applied to this novel diameter-enlarged structure.

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Table 1
Identification and characteristics of different flow regimes in a CFB.

Reference	Flow regime identification	Flow regime classification	Flow regime influence factors
Kwauk and Li [7]	(1) Powder per unit mass of solids, suspension and transport portion N_{st}; (2) Saturation carrying capacity K^*	(1) Particle dominating flow regime; (2) Fluid particle-compromising flow regime; (3) Fluid-dominating	(1) Operating variables; (2) Physical properties of particles
Molodtsof [8]	An asymptotic approach to general multiphase flow equations	(1) The similar profiles regime; (2) The transition regime; (3) Dense phase flow regime	(1) Solid concentration; (2) Gas–solid interaction force; (3) G_s and U_{sf}
Xu and Gao [9]	U_{sf} and G_s	(1) Fully dense flow regime; (2) Axially nonuniform flow regime; (3) Dilute suspension flow regime	(1) Solid flow control valve; (2) Riser height and gas velocity; (3) Particle properties
Monazam and Shadle [10]	Transport velocity	(1) Dense phase turbulent regime; (2) Fast fluidization regime; (3) Dilute-phase flow regime	(1) Saturated carrying capacity; (2) Transport velocities
Rabinovich and Kalman [11]	Relationship between the Archimedes and Reynolds number modified by solid flow rate	Fluidized flow, bubby flow, slug flow, turbulent fluidization, fast fluidization, plug flow	(1) Particle and gas properties; (2) Pipe diameter; (3) Particle concentration
Hu et al. [12]	The short-term average energy; Mel frequency Cepstrum coefficient; Cepstrum	(1) Annular flow; (2) Roping flow; (3) Stratified flow	Fluctuation signals of three gas/solid flow regime
Shaul et al. [13]	Correlations for the Reynolds number versus the Archimedes number	(1) Bubbling flow regime; (2) Slugging flow regime; (3) Dilute transport flow regime	(1) Particle groups type; (2) Height to bed diameter ratio; (3) Transition velocity
Mahmoudi et al. [14]	Positron emission particle tracking	Dilute, dense, core-annulus and combined flow regime	Superficial gas velocity and solids circulation flux

Although researchers have recognized the factors which affect gas–solid contact efficiency in CFB-riser reactor, there is no one effective way proposed to quantitatively examine the effect of various factors, and thus it is limited to understand the essential characteristics of the gas–solid contact process. Previous researchers conducted a preliminary exploration of gas–solid contact efficiency. Heat pulse methods, which were interpreted in terms of the degree to which gas and solid come into intimate contact, were used by Dry et al. [1] and Contractor et al. [15]. However, the heat loss and stability control on 'pulse' affect the accuracy of measurement in spite of that this measurement was compensated for by the calibration procedure to some extent. Zhang et al. [16] established a reliable dyeing measurement system to understand the nature of liquid–solid contact in feed stack zone of a downer. In the system, saturated alcohol with rhodamine B as dyeing indicator was used to replace the liquid feed contacted with catalysts. A novel parameter can be defined as catalyst/oil ratio multiplied by dying ratio to quantitatively describe the contact efficiency. With in-depth study on steady-state and transient kinetics such as reaction order, reaction ratio constant on metal oxide catalysts, the ozone decomposition reaction as significant research tools devoted to hydrodynamic and reaction studies can supply direct information on reactor performance in the CFB riser reactors and downer reactor [17–21]. Relative concentration (C/C_0) is an important parameter employed by many researchers. It is a common and effective method for analyzing the influence of operating conditions on contact efficiency. However, it is necessary that a certain amount of standard should be made to depict the maximum contact efficiency for a specified operating condition. It is important to define parameters to depict contact efficiency between gas and solids in CFB reactor, and then find the ways to improve the gas–solid contact efficiency.

In this paper, diagrams including U_{sf}, G_s and solid holdup information were employed for flow regime distinction between HDCFB and C-TFB. Flow structure especially uniformity and cluster dynamics in radial position was discussed. A parameter (contact efficiency) was defined for further discussion of flow dynamics and gas–solid contact effect.

2. Experiment

2.1. Cold C-TFB apparatus

Experiments were conducted in a riser with a 0.1-m diameter (expanding part was 0.2 m) and the height of 10.06 m (expanding part was 1.8 m) made out of Plexiglas, as shown in Fig. 1. In order to simulate gas–solid flow of the stratified injection, upper feed and lower feed units were set up at the height of 0.8 m and 3.6 m, respectively, above the bottom of the riser. In addition, the lower feed style applied ring-feeder internal to improve the gas–solid interaction. The ring-feeder internal was designed with 12 nozzles at 90° angles to the interval beneath them. The hopper with an inner diameter of 0.48 m and a height of 7 m was designed and solids inventory in the hopper was about 650 kg. The height of solids inventory L could be modified through adding or removing solids in the hopper. Solids used were spent FCC catalyst particles with a mean diameter d_p of 80 μm and particle density ρ_p of 1780 kg/m^3. Size distribution of FCC particles measured by BT-9300ST laser particle size analyzer was a normal distribution shown in Fig. 2. Compressed air was injected into the riser through pressure stabilization valve (remaining 0.18 MPa) and rotameter. Solids were transported upward in the riser and returned to the hopper after being separated by cyclone. A method was used to measure the solids circulating rate G_s based on the accumulating time of solids to a certain height in the measuring tank after a sudden close to a flapper valve.

The solid holdup information was obtained by PV-56 D optical fiber probes developed by the Institute of Processing Engineering, Chinese Academy of Sciences. When sampling, the probe emitted a light to the particles and then received the light reflected by the particles. After that, the optical signals were converted into voltage signals by a photo-multiplier. Finally, the voltage signals were fed to the PC and converted to the solid holdup fluctuation signals by corresponding calibration curve. More details about the measurement mechanism can be referenced by Zhu [5].

Operating system was started up in the high superficial velocity and high flux conditions. The superficial gas velocities ranged from 8 to 12 m/s and solids fluxes ranged from 200 to 400 kg/m^2/s, respectively, in C-TFB and HDCFB. The volume flow ratio of pre-lifting part, expanding part and traditional part was kept constant and the corresponding superficial velocity of expanding part ranged from 1.2 to 1.8 m/s. More specific operating conditions can be referenced by previous work of our research team [22]. Typical operating conditions of circulating-turbulent fluidization have been studied by Qi et al.[23]. The solids fluxes ranged from 50 to 500 kg/m^2/s, and the typical superficial velocity in expanding part varied from 1 to 3 m/s. Operating conditions in this paper are within this range, which means all experiments carried out are supposed to active C-TFB. Local solid holdup in