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Radial solids flow structure in high flux gas-solids circulating fluidized bed downers

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ABSTRACT

High flux gas-solids circulating fluidized bed downer reactors have unique characteristics especially suitable for very fast reactions. Detailed hydrodynamics of such reactors are experimentally studied using FCC particles at various superficial gas velocities (1–7 m/s) under high flux conditions up to 700 kg/m^2 s for the first time. Results show that although the radial distribution of solids holdup is somewhat less uniform under very high flux conditions in the downers, it is still much more uniform compared to riser reactors. Radial profiles of solids holdup, particle velocity and solids flux are significantly affected by the operating conditions. Particle velocity distribution is characterized by a relatively flat core and an annulus, where the particle velocity slightly increases towards the wall under low flux. In very high flux downer reactors, the shape of the local particle velocity becomes parabolic. It is also found that relationships between local solids holdup and particle velocity are different in the downers compared to the risers due to their different flow characteristics. Compared to the riser reactor, downer has a self-adjusting mechanism to perform with the nearly "ideal" plug flow nature.

1. Introduction

Circulating fluidized bed (CFB) reactors have found very important applications in the field of chemical, petrochemical, environmental and energy industries [1,2]. Gas-solids CFBs can mainly be operated in two modes: concurrent upflow CFB (riser) wherein the gas and solids flow upward and concurrent downflow CFB (downer) which involves downflow of both gas and solids. Compared to the conventional fluidized bed (bubbling and turbulent bed) reactors, CFB risers have such advantages as high contact efficiency, high gas and solids throughput, and high turndown ratios [2,3]. The unique characteristics of riser reactors have resulted in them being used in a number of chemical processes such as fluid-catalytic cracking and CFB combustion [4]. However, CFB riser is far from what may be considered optimal from a reaction engineering perspective [5], as it still suffers from non-uniform flow structure such as core-annulus flow structure, severe solids backmixing as well as radial segregation of gas and solids [2,3]. These disadvantages of the risers may result from the flow against gravity inside of the reactors. Thus, concurrent downflow CFB reactor (downer) has been proposed as an alternative.

In the past two decades, downer has drawn much attention [1,3,6–19]. Wang et al. [20] reported the axial flow structure by measuring axial pressure gradients distributions and found that the downer could be divided into three zones: the first acceleration zone, the second acceleration zone, and the constant velocity zone. Wei and Zhu [6] systematically studied the axial solids mixing behavior and compared the similarities and differences between the downer and riser. Zhang et al. [10,11] comprehensively investigated the hydrodynamics in a 100 mm downer with 9.3 m high using FCC particles. Ma and Zhu [8] measured heat transfer inside the downer, which was the same as Zhang's. Luo et al. [14] conducted the experiments on the characteristics of mass transfer with the adsorption of CO_2 tracer by activated charcoal particles. Li et al. [21] used a hot model reaction (ozone decomposition) to study downer reactor performance. Recent studies of hydrodynamics on downer reactors can be found in the review papers by Zhu [2] and Cheng et al. [16].

Based on those previous studies, it is common to recognize that both gas and solids distributions become much more uniform axially and radially than those in the risers. In spite of its significant advantages, downer suffers a serious shortcoming: very low volumetric solids holdup (mostly < 1%) which results in limited reaction intensities, especially when high solids/gas ratio is required [1,7,22]. Although many studies on the downer reactors had been carried out, only a few researches focused on the high density/flux CFB downer. In a special effort to achieve high solids holdup, Liu et al. [23] designed a special high-density downer where a 0.66 m tall with 250 mm diameter funnel was placed at the top of a 25 mm and 5 m tall downer to pre-accelerate the particles, so that particles can be fed into the downer at their terminal velocity so as to facilitate high solids flux. With this particular apparatus, an average solids holdup as high as 0.07–0.09 was achieved with solids

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circulation rate (G_s) of over 400 kg/m^2 s using FCC particles. They also obtained a solids holdup of 0.2 when G_s equaled 1500 kg/m^2 s with glass beads. Chen and Li [24] showed that using FCC particles, solids holdup was 0.14 with the maximal solids flux of 200 kg/m^2 s at very low superficial gas velocities ($U_g = 0.8$ m/s). Song et al. [25] presented that using coke particles, mean solids holdup of 0.165 was achieved at $G_s = 1400$ kg/m^2 s and $U_g = 2.0$ m/s in a very short downer (only 3.2 m high) operated under a batch mode. Guan et al. [26] proposed a triple-bed system including a CFB downer and the solids holdup was up to 0.03 in the fully developed region with $G_s = 439$ kg/m^2 s. However, most of these experiments were concentrated on the axial solids distributions mainly inferred from the axial pressure profiles for inadequate operating conditions. So far, there have been limited attempts to study local solids flow including local solids holdup, particle velocity and solids flux in high density/flux downers. Therefore, more studies are needed on high flux CFB downer to obtain a more detailed and clear understanding of the local flow structures in downer reactors. For this purpose, a comprehensive study is conducted on radial distributions of solids holdup, particle velocity and local solids flux in the CFB downers operating at wide operating conditions with in particular, very high solids circulating rate up to 700 kg/m^2 s in this paper.

2. Experimental details

2.1. CFB experimental setup

Fig. 1 shows the overall experimental apparatus includes three fluidized beds. The fluidized bed on the left of Fig. 1 serves as a high flux riser (76 mm i.d. and 10 m high). The fluidized beds on the right hand contain two circulating fluidized bed downers (concurrent downflow circulating fluidized beds) of different diameters (76 mm i.d. and 5.8 m high (3″ downer) and 50 mm i.d. and 4.9 m high (2″ downer), respectively). A downcomer with an inner diameter of 203 mm for solids return during riser operating and at its bottom a solids storage tank with an inner diameter up to 457 mm are used as general solids storage for the entire system. The entire fluidized bed system uses aluminum as the main construction material with small portions made of Plexiglas for visual observation. In order to minimize possible electrostatic charges formed in the columns during the experiments, the whole fluidized bed system is electrically grounded.

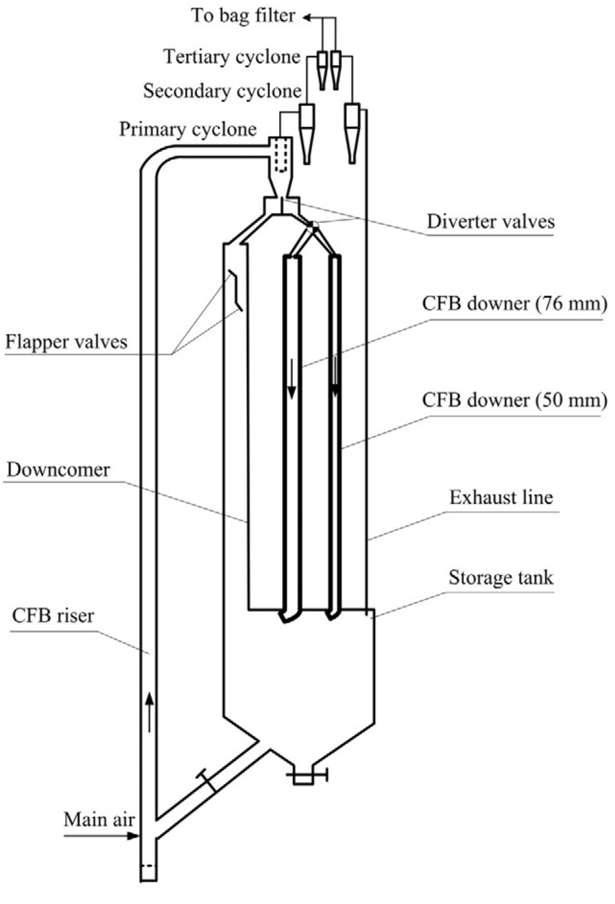

Fig. 1. Schematic diagram of the CFB system.

When the system is under downer operating mode, particles from the solids storage tank are first lifted to the top through the riser, separated by the primary cyclone fixed at the top of the downcomer and then fed into the downers by a diverter valve switched to the downer side. A second diverter valve below directs the particles to the appropriate downer for experiments. At the top of either downer there is a gas-solids distributor, which will be explained in the next paragraph, where the particles are uniformly distributed along with the downer air to flow downward concurrently. At the bottom of either downer, gas and solids are separated by gravity. Most of the particles are first separated and fall down into the storage tank. Fine particles with downer gas flow upwards along the exhaust pipe. These remained particles captured by two cyclones installed in series at the top of the exhaust pipe and the common bag filter are retained in the storage tank through the downcomer as illustrated in Fig. 1. To eliminate the effects of solids inventory and other possible influencing parameters on the solids flow in the downers, the whole experimental work in this study was carried out with a constant particle mass of 280 kg loaded in the storage tank.

The fluidization gas used in this study is supplied by a large compressor capable of delivering up to 283 Nm^3/min at 241 kPa. Equilibrium FCC catalyst particles are used as the bed material with mean diameter and the particle density of 76 μm and 1780 kg/m^3 respectively. Most of the experimental work in this study was carried out in the 76 mm downer under a wide range of operating conditions with solids circulation ranging from 100–500 kg/m^2 s. In order to obtain high solids flux and high density in the downer, some experiments with the highest solids flux of 700 kg/m^2 s were conducted in the 50 mm downer with special designed solids distributor shown in the next paragraphs.

Details of the distributors are shown in Fig. 2. The image on the left shows the solids distributor of the 3″ downer (76 mm i. d. downer). The distributor shell is a 102 mm diameter pipe connecting with the downer column through a conical flanged section. Inside the shell, there are several internals including main air distributor, seal plate and aeration (auxiliary) air grid. Above the gird, a small fluidized bed operated under minimum fluidization by the aeration air is used to obtain a stable solids feeding. Solids flow into the downer through nineteen brass tubes with 17.5 mm diameter which are arranged in an equilateral pitch centered at the downer centerline. Main gas is distributed through a perforated plate mounted at the top of the downer.

The picture on the right of Fig. 2 schematically shows the solids distributor of the 2″ downer (50 mm i. d. downer) which is specially designed for high density operation. To ensure the particles enter the downer at a relatively high velocity so as to obtain a high solids flux, the distributor system consists of three subsystems from top to bottom: the fluidized bed, the solids feeding tubes and the feeding funnel. The upper section is a fluidized bed with 152 mm inner diameter and 183 mm height maintained at the minimum fluidization state by two sets of auxiliary air. Solids from the upper fluidized bed are introduced through eight brass tubes with larger diameter of 25 mm, which are evenly distributed in the circumference of the auxiliary gas distributor grid. The lower portion is a feeding funnel (203 mm high), within which particles are pre-accelerated by gravitational force. The downer main gas is introduced just below the feeding funnel. The main air distributor is configured with 112 holes of 6.3 mm diameter evenly distributed around the circumference of the column. Gas jets with high velocity allow the intimate mixing of gas and solids in the entrance of