Chemical Engineering Science 66 (2011) 4212–4220

Contents lists available at ScienceDirect

Chemical Engineering Science

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

Flow behaviors in the downer of a large-scale triple-bed combined circulating fluidized bed system with high solids mass fluxes

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ARTICLE INFO

Article history:
Received 20 December 2010
Received in revised form
7 March 2011
Accepted 2 June 2011
Available online 12 June 2011

Keywords:
Triple-bed combined circulating fluidized bed
Downer
Riser
Bubbling fluidized bed
Gas seal
Pressure balance
High density

ABSTRACT

The flow behaviors in the downer of a large-scale triple-bed circulating fluidized bed (TBCFB) gasifier cold model, which is composed of a downer (Φ 0.1 m × 6.5 m), a bubbling fluidized bed (BFB, 0.75 × 0.27 × 3.4 m^3), a riser (Φ 0.1 m × 16.6 m) and a gas-sealing bed (GSB, Φ 0.158 m × 5 m), were investigated. Sand particles with a density of 2600 kg/m^3 and an average particle size of 128 μm were used as bed materials. Solids mass fluxes were in the range 113–524 kg/m^2 s. Average solids holdup in the developed region of the downer increased with increasing solids mass flux. The gas seal between the riser and the downer had a large effect on the solids holdup distribution in the downer. Compared with the solids holdup in the riser, a relatively low solids holdup was formed in the downer even at high solids loadings. A pressure balance model was set up to predict the solids mass flux for this TBCFB system. It was found that the static bed height in the GSB had a great effect on the solids mass flux. The possibilities of achieving a high density solids holdup in a downer were discussed.

1. Introduction

The circulating fluidized bed (CFB) has been widely studied in the past several decades since it has many advantages in industrial processes such as coal combustion, fluid catalytic cracking (FCC) and the Fischer–Tropsch process. Recently, many new applications in the energy and raw materials industries have been developed (Bi and Liu, 2010; Corella et al., 2007; Guan et al., 2010a, 2010b; Hayashi et al., 2006; Hosokai et al., 2008; Liu et al., 2008; Kuramoto et al., 2009; Matsuoka et al., 2008; Tsutsumi, 2004, Xu et al., 2005; 2006a; 2006b). In particular, high density circulating fluidized beds (HDCFB), in which solids mass flux (G_s) > 200 kg/m^2 s and solids holdup (ε_s) > 0.1 are expected, have attracted the attention of many researchers (Aitani et al., 2000; Arena et al., 1991; Bai et al., 1997; Bi and Zhu, 1993; Bi and Liu, 2010; Contractor et al., 1994; Grace et al., 1999; Guan et al., 2010a, 2010b; Issangya et al., 1999, 2000; Kim et al., 2004; Liu et al., 2008; Pärssinen and Zhu, 2001a; 2001b; Wang et al., 2008; Wei et al., 1997,1998; Bi and Zhu, 1993). For example, autothermal dual fluidized bed steam gasification systems require rapid heat transfer from the exothermal fluidized bed combustor to the endothermal fluidized bed pyrolyzer/gasifier (Bi and Liu, 2010; Corella et al., 2007; Hayashi et al., 2006). In this case, a higher G_s as well as a higher ε_s can enhance the heat transfer between the two beds, and simplify the control of this system. However, in this two-bed circulating fluidization system, pyrolysis and gasification are carried out in the same bed. It was found that the tar, light hydrocarbon gases and inorganic gases produced at the initial stage of pyrolysis could severely hinder the gasification of the char (Bayarsaikhan et al., 2006; Hayashi et al., 2006; Huang et al., 2010; Lussier et al., 1998). Thus, in order to maintain the catalyst activity and/or to enhance the efficiency of char gasification, the volatiles produced during pyrolysis should be separated from the remaining char. To solve this problem, we have proposed a triple-bed combined circulating fluidized bed (TBCFB) system, which is composed of a downer (for rapid pyrolysis of coal/biomass), a bubbling fluidized bed (BFB, for slow steam gasification of char) and a riser (for combustion of unreacted char), for the steam

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0009-2509/$ - see front matter © 2011 Elsevier Ltd. All rights reserved.
doi:10.1016/j.ces.2011.06.006

gasification of coal/biomass (Fushimi et al., 2011; Guan et al., 2010a, 2010b, 2010c). In this system, combustion of unreacted char in the riser can be used to provide the heat needed for the pyrolysis of coal/biomass in the downer. For this purpose, the heat can be carried by inert solid medium such as sand circulating in the system. In order to utilize the heat effectively in the downer for the pyrolysis of coal/biomass, a dense solids holdup is also preferable. On the other hand, mixing of the gases produced in the different reactors should be avoided in an industrial scale system. Therefore, gas seals between the reactors, which allow solid particles to move between the reactors while preventing direct flow of gases from one bed to the other, should be considered one of the most crucial components of this type of coal/biomass gasifier system.

The downer reactor, in which gas and solids move downward in a co-current fashion, has attracted the attention of many researchers in the past two decades due to its unique features such as shorter residence time, narrow residence time distribution, little or no solids backmixing and lower pressure drops since gravity acts in the same direction as the flow of gas compared to the fast gas–solids upflow riser (Cheng et al., 2008; Zhu et al., 1995). These features of a downer reactor can potentially lead to its application for carrying out ultra rapid reactions such as the highly selective and fast catalytic conversion of heavy oil or other hydrocarbons (Bassi et al., 1994; Berg et al., 1989; Fujiyama, 2005; Shaikh et al., 2008) and the pyrolysis of coal and biomass (Fushimi et al., 2011; Guan et al., 2010a, 2010b, 2010c; Kim et al., 2001; Wang et al., 2005). To date, a large amount of studies has been conducted on the multiphase flow behavior in a downer system. However, due to gravitational acceleration of particles in a downer, the solids holdups achieved in the fully developed region of a downer are generally much lower (typically below 0.01) than those of risers (0.01–0.05) even in a circulating fluidized bed (CFB) system with a high solids mass flux. It is well known that a low solids holdup usually leads to low heat transfer rates and low reaction efficiencies in the downer (Kim et al., 1999; Ma and Zhu, 1999). Bolkan-Kenny et al. (1994) found that gas–oil conversion could be increased by approximately 4% when the catalyst/oil ratio increased from 8 to 10 in the fluid catalytic cracking process. However, only a few studies have been reported in the literature (as shown in Table 1) on the hydrodynamics of a downer with a dense solids holdup. Liu et al. designed a 5 m tall, 0.025 m i.d. downer system with a special fluidized feeder (Liu et al., 2001). A solids holdup as high as 0.07–0.2 with a solids mass flux of up to 280–1500 kg/m^2 s were achieved in the fully developed region. The solids holdup decreased with increasing gas superficial velocity but increased linearly with increasing solids mass flux. Chen and Li (2004) designed a special circulating fluidized bed with a 5.6 m tall, 0.08 m i.d. downer. A maximal solids mass flux of 600 kg/m^2 s and a maximal solids holdup of 0.14 in the downer were obtained. They found that the radial solids distribution gradually became more uniform with increasing axial distance along the downer and with an increasing solids mass flux. Song et al. (2005) also designed a special solids feeding system for a 3.2 m tall, 0.078 m i.d. downer, and a cross-sectional average solids holdup of 0.165 was achieved at the axial position of 3.0 m below the air injection point under the operating condition of solids mass flux of 1400 kg/m^2 s. In their downer system, as the superficial gas velocity was increased from 0 to 6 m/s with a fixed solids mass flux of approximately 400 kg/m^2 s, the solids holdup distribution became less uniform (denser near the wall and more dilute at the center), which were quite different from the results found at lower solids mass fluxes.

In the present study, the flow behaviors in the downer of a large-scale TBCFB gasifier cold model with gas seal structures were investigated. The objectives of this work are to characterize the hydrodynamics of the downer with high solids mass fluxes and to explore possibilities of obtaining a high density solids holdup in the downer.

2. Experimental

Fig. 1 shows the schematic diagram of the large-scale TBCFB cold model, which is composed of a riser (0.1 m-I.D. × 16.6 m-high), a multi-tube solid distributor for the downer, a downer

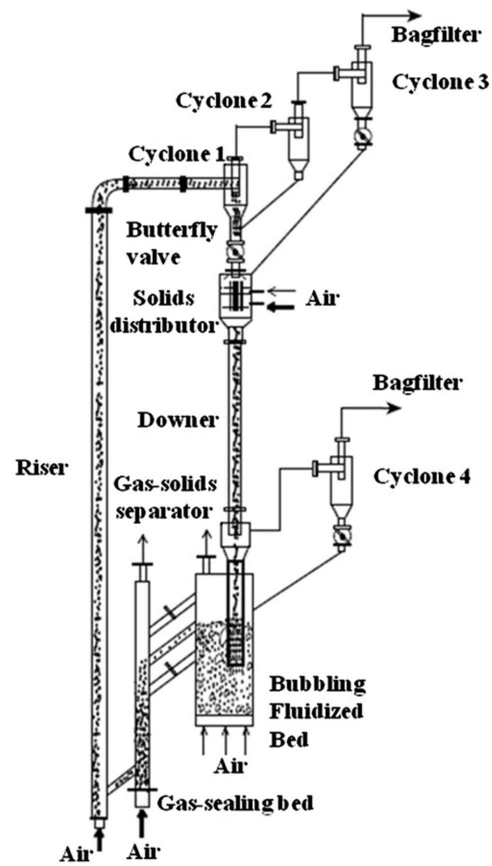

Fig. 1. Schematic diagram of the large-scale TBCFB cold model.

Table 1
Experimental conditions for high density downers in the literature.

H_d (m)	D_d (m)	d_p (μm)	ρ_p (kg/m^3)	U_{gd} (m/s)	G_s (kg/m^{2}s)	ε^*_{ds}	Reference
5	0.025	70	1300	0–5.44	280–1500	0.07–0.2	Liu et al. (2001)
		123	2500				
		332	2500				
5.6	0.08	82	992	0.8–1.65	200–552	0.07–0.13	Chen and Li (2004)
		131	2480				
		128	750				
		572	750				
3.2	0.078	133	1600	0–3.0	430–1400	0.07–0.27	Song et al. (2005)