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Hydrodynamic characteristics of a large-scale triple-bed combined circulating fluidized bed

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ABSTRACT

A novel large-scale triple-bed combined circulating fluidized bed (TBCFB), consisting of a riser (16.6 m in height, 0.10 m inner diameter), a downer (6.5 m in height, 0.10 m inner diameter) and a bubbling fluidized bed (BFB; $0.27\times0.75\times3.4$ m^3), was constructed as a cold model for a gasifier. The purpose of the new reactor design was to achieve a high solids mass flux which is required for exergy recuperative steam gasification of coal/biomass. In the TBCFB, a gas-sealing bed (GSB; 5.0 m in height, 0.158 m inner diameter) was installed between the BFB and the riser bottom to increase the pressure head to transport solids to the riser. The hydrodynamic behavior of silica sand particles (arithmetic mean diameter is 128 μm) was investigated by independently controlling the flow rates of air in the riser, downer, BFB and GSB, and varying the bed heights of the BFB (H_{BFB}) and GSB (H_{GSB}) under ambient conditions. When the GSB gas velocity (U_{gg}) was 0.10 m/s, the solids mass flux (G_s: kg/(m^2 s)) substantially increased with increase in riser gas velocity (U_{gr}). The maximum G_s obtained was 546 kg/(m^2 s) at $U_{gr}=12$ m/s and $H_{GSB}=4.6$ m. This is due to the fact that the pressure head for transport of solids to the riser bottom increased sufficiently by increase in the GSB height. From the solids holdup (ε_s) obtained from the apparent pressure difference, a dense phase (solids holdups: 0.070–0.095) was found to be formed at the bottom part of the riser ($H_r\leq5$ m). The flow in the downer was developed in 1.5 m. The solids holdup in the developed area of the downer decreased from 0.0212 to 0.0128 as the downer gas velocity (U_{gd}) increased from 0 to 1 m/s when G_s was 406 kg/(m^{2}s).

1. Introduction

Coal is the world's biggest energy resource for electricity generation and its utilization is expected to substantially increase in Asian countries, especially in China and India [1]. However, the combustion of coal is a major contributor to anthropogenic emission of carbon dioxide (CO_2) and pollutants such as nitrogen oxides and sulfur oxides. Consequently clean coal technology (CCT) has been developed in many countries. In the last decade, Integrated coal Gasification Combined Cycle (IGCC) and Integrated coal Gasification Fuel-cell Combined cycle (IGFC) processes have been developed to drastically reduce CO_2 emission from coal-fired power plants. The thermal efficiencies of the IGCC and IGFC under development are estimated to be 48% and 55%, respectively, on the higher heating value (HHV) basis [2].

Because steam gasification is a highly endothermic reaction, heat is required for the reaction. In the conventional IGCC/IGFC system the heat is provided by combustion or partial oxidation of coal. The combustion of coal inevitably causes a large amount of exergy loss due to conversion of chemical to thermal energy, which results in low cold gas efficiency of gasification reactions [2–5]. To further increase power generation efficiency, we have proposed the exergy recuperation concept [2,6–11], which utilizes the exhaust heat of a gas turbine or solid oxide fuel cells (SOFCs) as a heat source for endothermic gasification reactions. It was estimated that such exergy recuperation can improve the thermal efficiency (HHV basis) up to 57% in the advanced-IGCC (A-IGCC) process and by 65–70% in the advanced-IGFC (A-IGFC) process [2,10,11].

In the A-IGCC and A-IGFC processes, the gasification of coal should take place at low temperatures (700–900 °C) using pure steam or large steam-to-oxygen ratios, to efficiently recuperate the exhaust heat of gas turbine and/or SOFCs [2,10–12]. This low-temperature gasification technology is also promising for utilization of low-rank coals such as lignite and sub-bituminous coal, and biomass [10,11]. However, such low temperatures are unsuitable for the conventional entrained flow bed gasifier operating at high temperatures (1100–1500 °C) using oxygen [2,10–12].

For the gasifier of the A-IGCC/IGFC system, a dual-bed circulating fluidized bed (DBCFB) is considered to be a suitable reactor because of

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its high efficiency for coal/biomass steam gasification [13–22]. In the DBCFB, pyrolysis and gasification (endothermic reactions) of coal/biomass occur in one bed and the combustion of unreacted char (exothermic reactions) occurs in the other bed. The heat from the combustion of char is transferred for pyrolysis/gasification by solids circulation between the two beds. Xu et al. [16] demonstrated the combinations of reactors for combustion and pyrolysis/gasification, and reported the combination of fuel gasification in a dense low-velocity fluidized bed and char combustion in a high-velocity pneumatic riser gives higher gasification efficiency and lower tar production.

However, it has been reported that when pyrolysis and gasification take place in the same bed, the volatiles produced including tar, light hydrocarbon gases and hydrogen, greatly inhibit gasification of the char [10,23–25]. Thus to avoid reduction in char reactivity and/or enhance conversion of char to gas, the volatiles produced in pyrolysis should be separated from the remaining char. To that end we have proposed and developed a triple-bed combined circulating fluidized bed (TBCFB) gasifier, which is composed of a downer (pyrolyzer), a bubbling fluidized bed (BFB, gasifier), and a riser (combustor) [11,26,27]. Because pyrolysis is a very rapid reaction, a downer reactor is considered to be suitable for its characteristically short residence time, narrow residence time distribution due to insignificant back mixing, and relatively uniform gas-solid flow [28–34]. The coal/biomass is first fed into the downer pyrolyzer and rapidly pyrolyzed, then the volatiles (gas and tar) produced are separated from the char using a quick gas–solid separator. The char together with inert fluidizing material enters the BFB gasifier to be gasified with steam, which recovers exhaust heat from gas turbines and/or SOFCs, in a relatively long residence time. The unreacted char flows into the riser combustor to be partially or completely oxidized with oxygen or air. The heat generated in the riser is carried by inert solids and transported into the downer pyrolyzer and the BFB gasifier to provide the heat required for pyrolysis and gasification. Consequently, the TBCFB gasifier is expected to give higher overall gasification efficiency than the DBCFB gasifier.

For realization of a gasifier for the A-IGCC/IGFC system, from the energy and mass balance analyses between the pyrolyzer/gasifier (endothermic reaction side) and the combustor (exothermic reaction side), it was found that a high density and high solids flux (G_s>500–1000 kg/(m^2 s)) CFB is necessary when pure steam or a large steam to oxygen ratio is used for gasification [2,12,35,36]. To date many studies [35–57] have been conducted on conventional CFBs under high solids mass flux conditions since Bi and Zhu [58] proposed the concept of the high density circulating fluidized bed (HDCFB), for which the solids mass fluxes (G_s) are greater than 200 kg/(m^2 s) and solid holdups (ε_s) are over 0.1. From the viewpoint of heat transfer media between the combustor and pyrolyzer/gasifier, sand particles, whose density is much larger than that of fluid catalytic cracking (FCC) particles are considered to be better than FCC particles. However, many studies have used FCC particles as bed materials [37,40–54], and only a few results have been reported on high solids mass flux systems using other particles as bed materials [35–39].

Liu et al. [35,36] designed a novel CFB by installing a moving bed in the bottom section of the riser, to increase the solids mass flux. They reported that the maximum G_s was 370 kg/(m^2 s) when using sand particles as bed materials. Wang et al. [38] developed a high solids flux CFB (riser: 0.06 m i.d. and 5 m height), for which the maximum G_s reached 395 kg/(m^2 s) utilizing sand particles with density 2700 kg/m^3 and average particle size 140 μm as bed materials. Pugsley et al. [39] developed a unique solids feeding system with an aerated annular bed of solids and a radial gas distributor surrounding the base of the riser. Sand particles enter the riser through orifices at the riser base. By using this system solids mass fluxes up to 700 kg/(m^2 s) for sand were achieved in a 0.05 m diameter, 5 m tall riser at superficial gas velocities between 5.5 and 8.5 m/s. Arena et al. [57] reported solids mass fluxes in the range 5–600 kg/(m^2 s) using glass beads and a CFB whose column height and inner diameter were 6.40 and 0.041 m, respectively. These results suggest that HDCFB is achievable even when solid particles other than FCC particles are used as bed materials in the CFB.

In the TBCFB system, we previously investigated [26,27] the flow behavior of a small-size cold model (riser: 0.05 m i.d.×6 m high, downer: 0.05 m i.d.×1.3 m high, and BFB: 0.37×0.08×1.5 m^3) using silica sand with average particle size 83 μm as bed material. The solids mass flux ranged from 80 to 336 kg/(m^2 s) for superficial riser gas velocities in the range of 3 to 8 m/s. By correlation of solids mass flux (G_s), solids bed height, and solids holdup (ε_s), it was found that a dense solids holdup (ε_s>0.1) could be obtained if the solids bed height in the BFB was sufficient. However, the height of the downer in the small-size TBCFB was only 1.3 m and a very deep BFB, which is not suitable for stable operation, is needed to increase G_s and solids holdups in this configuration [27]. Based on the calculation of pressure balance between a riser and a downcomer as reported by Bi and Liu [12], the riser height and the equivalent diameter of the open area of the control valve between the downcomer and the riser should be larger to obtain higher solids mass fluxes. However, in the small-size cold model, the G_s could not exceed 350 kg/(m^2 s) [26,27], which was insufficient for the realization of A-IGCC. Hence in the present study a large-scale TBCFB cold model was set up to increase G_s and ε_s, and the flow characteristics of sand particles in the TBCFB at high solids circulation rate were investigated.

2. Materials and methods

2.1. Apparatus and bed materials

A schematic image of the large-scale TBCFB experimental system is shown in Fig. 1. The TBCFB system comprised a riser (0.10 m i.d. and 16.6 m high), a downer (0.10 m i.d. and 6.5 m high), and a BFB (0.75×0.27×3.4 m^3). A gas-sealing bed (GSB: 0.158 m i.d. and 5.0 m high) was installed between the outlet of the BFB and the bottom of the riser to i) prevent backflow from the riser to the BFB, and ii) increase the pressure head for solids transport to the riser [35,36]. The BFB, GSB and the lower part of the riser (H_r≤7 m) were made of stainless steel; the top part of the riser was also stainless steel to avoid attrition. The downer, gas–solids separator and the middle part of the riser were made of acrylics. Silica sand particles with particle density (ρ_p) 2600 kg/m^3 (bulk density (ρ_b): 1400 kg/m^3) and arithmetic mean particle size (d_p) 128 μm (minimum fluidization velocity (U_{mf}) = 0.0074 m/s) were used as bed material.

Forty seven differential pressure sensors (Keyence Corp., AP48) were installed in pressure taps along the riser, downer, BFB and GSB. The output signals from the differential pressure sensors were acquired at sampling frequency 100 Hz for 90 s with a data acquisition system (CONTEC CO., LTD., AIO-163202FX-USB) and a laptop computer.

2.2. Procedure

Solids were fed to the BFB and fluidized by air. Solids that overflowed from the BFB were accumulated in the GSB, then transferred to the riser bottom with the assistance of air. The solids were transported by air in the riser. At the top of the riser, the solids passed through an elbow with smooth shape to increase solids circulation rate [42,59,60], and into three cyclones to separate solids from air. Solids separated in the first and second cyclones were merged and went to a dipleg for solids mass flux (G_s) measurement. G_s was measured using a butterfly valve as the time to accumulate particles for given amount, and determined from the mean value of ten replicated measurements at steady state. The solids then went to a solids distributor for the downer, which was installed below the