Powder Technology 328 (2018) 397–405

Contents lists available at ScienceDirect

Powder Technology

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

Experimental investigation of a triplet ash valve for circulating fluidized bed

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ARTICLE INFO

Article history:
Received 26 September 2017
Received in revised form 19 January 2018
Accepted 22 January 2018
Available online 31 January 2018

Keywords:
Ash valve
Circulating fluidized bed
Solids flow rate
Loop seal

ABSTRACT

In a circulating fluidized bed (CFB), the ash discharge process is challenging due to poor reliability of the solid or mechanical valve at high temperatures and pressures, particularly for a CFB gasifier. This work proposed a novel triplet ash valve for solids discharge in CFB. It resembles a loop seal. The ash valve is comprised of three supply chambers and one discharge chamber. The hydrodynamics and operation characteristics of the ash valve were investigated using Geldart B particles in a cold flow model. The effects of chamber aeration, pressure drop of the standpipe and back pressure on the performance of the ash valve were analyzed. A wide linear operation range of solids flow rate can be achieved by adjusting the aeration of the three supply chambers and the discharge chamber. The specific feasible operation scheme of the ash valve was discussed. An increase of pressure drop in the standpipe promoted the solids flow rate of the ash valve, whereas a higher back pressure of the ash valve decreased the solids flow rate. Finally, a correlation was presented to predict the solids flow rate of the ash valve.

1. Introduction

Gasification can convert coal to syngas in an environment-friendly way. The coal gasification process is commonly achieved in a gasifier. There are three gasification technologies: moving bed [1], fluidized bed [2], and entrained flow bed [3]. Fluidized bed offers high flexibility and reliability for coal gasification due to good gas-solid contact [4–6]. The solids back-mixing within the bed generate a uniform temperature distribution in the gasifier, thus reducing slag formation and heat loss [7,8]. It can also handle high grade coal and biomass with high conversion efficiency [9–11]. In a circulating fluidized bed (CFB), ash discharge is necessarily required to regulate the solids concentration and solids circulation rate within the bed [12,13]. Currently, the ash discharge process is typically accomplished by a conveyor in CFB boilers or a mechanical valve in CFB gasifiers. In CFB boilers, the conveyor and secondary pneumatic system are well established and technologically proven. In CFB gasifiers, mechanical valves are applied due to more stringent requirement of sealing. Typical mechanical valves include water-cooling screw, rotary valves with moving parts for actuation. These valves usually suffer failure under high temperature and pressure conditions due to sealing, erosion and mechanical problems. The reliability of ash valve in long-term operation is still the main challenge of CFB gasifier. The ash valve is therefore crucial for the safe and stable operation of CFB gasifier.

For application to high temperature and pressure condition, non-mechanical valves are commonly employed. The non-mechanical valves include L-valve [14–16], V-valve [17], J-valve [18] and loop seal [19–21]. The non-mechanical valve can control the solids flow rate merely by aeration [22,23]. Loop seals are commonly employed in CFB systems to convey particles from a low-pressure region to a high-pressure region [22,23]. A loop seal is typically composed of five parts, i.e., a standpipe, a supply chamber, a slit opening, a recycle chamber and a recycle pipe [24]. It is robust, inexpensive and easy to construct. In the loop seal, solids exhibit a liquid-like behavior due to fluidization as aeration is implemented. The solids flow through the valve when the drag of aeration air exceeds the resistance holding the solids together. The loop seal can also regulate the solids flow rate by adjusting aeration; the loop seal principle can therefore be extended for ash discharge [25].

There are many investigations on the principle of loop seal operation in CFBs [26–28]. Basu et al. [27,29] carried out an extensive experimental study on factors that influence the solids flow rate of a loop seal, such as air velocity, bed inventory, particle size, standpipe size and slit size. They analyzed the twin exit loop seal configuration [30] on the solids flow rate and found that the total solids circulation rate does not increase proportionately with the rise in loop seal discharge area. Kim et al. investigated the solids flow characteristics in loop seal [22,23,31]. In their loop seal configuration, a vertical aeration was deployed in the standpipe and the maximum solids flow rate could be achieved at H/D = 2.5. They found that the solids flow rate was affected by particle properties, and the pressure drop along standpipe and loop seal increased linearly with increasing solids inventory in the bed. Monazam et al. [28] investigated the impact of the circulating fluidized bed riser on the performance of the loop seal. It was found the gas-solid flow was significantly affected by the superficial gas velocity and solids inventory in the riser. Yazdanpanah et al. [20] used different solid

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https://doi.org/10.1016/j.powtec.2018.01.059
0032-5910/

particles, and analyzed the pressure drop in different elements of the loop seal as a function of gas and solid flow rate. The minimization of gas leakage was also investigated. In a loop seal, the slit opening was a stratified flow driven by static pressure and fluid resistance [32,33]. The long distance of the slit opening can lead to high resistance to solids flow, resulting in a larger decrease in pressure in the slit opening [34]. Thus, Yang et al. [35] proposed a new loop seal called an N-type loop seal, which had a slope passage connecting the supply and recycle chambers. The N-type loop seal required lower aeration rate than common loop seals to acquire the same solids flow rate. They also revealed that the pressure drop across the loop seal was directly proportional to solids flux while inversely proportional to aeration rate [25].

The design of the ash valve of a CFB has interestingly received little attention in literatures, but a large number of CFB gasifiers operating around the world face the problem of ash valve failure, leading to complete or immediate shutdown of the entire plant. This paper proposes a novel triplet ash valve. The ash valve derives from the looping seal. It features three supply chambers and one discharge chamber. The solids in CFBs could be continuously removed through the ash valve by chamber aeration. This direct gas-solid transportation in the chamber eliminates any moving parts in the valve. The high-temperature solids can be cooled by aeration gas as well, and so higher reliability and accuracy are expected for this valve. The difference of the proposed ash valve and a conventional loop seal is that the ash valve applies three supply chambers to achieve a linear solids flow rate in a wide range. The superposition of three supply chamber increases the linear manipulation range if a suitable discharge aeration rate is adopted. This is a key feature of the triplet ash valve. Empirical correlations of the solid flow rate have been presented in previous researches [36,37], but the practical operation of different CFBs is complex, and the accuracy and general applicability of the equations cannot be verified and extended to such a new type of valve. The objective of this study is to investigate the characteristics of the ash valve incorporating a CFB cold flow model, the operation region is identified and the operation scheme is discussed, a correlation that predicts the solids flow rate as a function of variables is proposed as well.

2. Experimental setup and methods

2.1. Cold flow prototype

Fig. 1 shows the CFB cold flow model. It is composed of a riser (0.05 m i.d. × 4.5 m height), two standpipes (0.05 m i.d. × 2.7 m height and 0.02 m i.d. × 1.2 m height), two loop seals, and two cyclones (separation efficiency up to 95%). For the primary loop seal, the supply chamber is 85 mm long, and the recycle chamber is 40 mm long with 70 mm wide. The prototype is constructed using transparent Plexiglas, which permits visual observation and facilitates modifications if required. The outlet of the riser is located 0.2 m below the top to alleviate the back mixing of solid particles and decrease the resistance to the cyclone. The solids flow rate within the CFB is controlled by changing the aeration rate of the loop seal. The ash valve is connected to the bottom of the primary standpipe.

The sketch of the triplet ash valve is shown in Fig. 2. It consists of three supply chambers (1#, 2# and 3#) and one discharge chamber. A slit opening connects the supply and discharge chambers. The supply chambers convey the solids to the discharge chamber. The three supply chambers are aerated individually. The thickness of walls to separate the three supply chambers are 2 mm. The discharge chamber is aerated to transport the solids into a collection hopper (0.2 m i.d. × 60° tapered) through an overflow weir. The air box is arranged at the bottom of the chamber. The three supply chambers have different cross-sections to allow an accurate control of the solids flow rate. The size of supply chambers are shown in Table 1. Each slit opening is relatively small to increase the resistance and limit the solids flow to the target rate. A drainage pipe connects the inlet of ash valve with the standpipe of CFB. The standpipe height of the junction point with the drainage ash pipe is 0.54 m. The drainage pipe is rectangular with an internal size of 28 × 12 mm. The drainage pipe is connected with the ash valve at the center of supply chamber 2#, as shown in Fig. 2. The ash falls into the three chambers without any special structure. The separation of ash to the three chambers is achieved by chamber inner walls. A portion of solids in the standpipe is shunted to the ash valve via the drainage pipe as the ash valve is aerated.

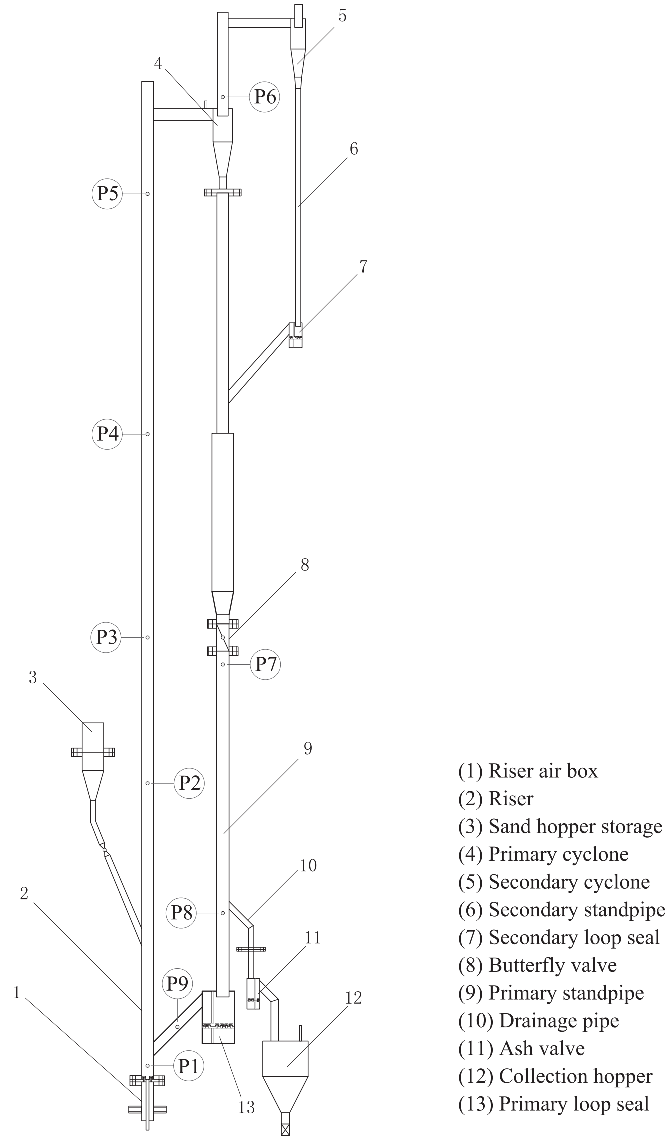

Fig. 1. Schematic diagram of the experimental cold CFB.

2.2. Gas repartition

In the test, the components within the CFB systems were aerated by air from a blower. The air flow was measured by rotameters. There were nine pressure taps located along the riser and the standpipe, as shown in Fig. 1. The pressures were measured by pressure transducers and registered to a data acquisition system.

CO_2 tracing is an effective way to investigate the gas distribution in the ash valve. CO_2 was supplied from a CO_2 cylinder with a purity of 99.9%. CO_2 flow rate was regulated by means of a rotameter after depressurization. A static gas mixer was used in the air injection tube to ensure fully mixing of CO_2 and air. The CO_2 molar fraction was as low as 5 vol% to ensure the trace gas does not change the air properties