10th International Conference on Circulating Fluidized Beds and Fluidization Technology - CFB-10

Refereed Proceedings

Spring 5-2-2011

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Recommended Citation

Hairui Yang, Xuan Yao, Tao Wang, Hai Zhang, Qing Liu, Junfu lv, and Guangxi Yue, "Investigation on The Hydrodynamic Properties in The External Loop of Circulating Fluidized Bed With a Loop Seal" in "10th International Conference on Circulating Fluidized Beds and Fluidization Technology - CFB-10", T. Knowlton, PSRI Eds, ECI Symposium Series, (2013). http://dc.engconfintl.org/cfb10/4

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INVESTIGATION ON THE HYDRODYNAMIC PROPERTIES IN THE EXTERNAL LOOP OF CIRCULATING FLUIDIZED BED WITH A LOOP SEAL

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ABSTRACT

The pressure balance and mass balance are influenced by the characteristics of different components in the loop of a circulating fluidized bed (CFB). Experiments were conducted in a 4.3 m high cold laboratory CFB test rig with a loop seal. With a fixed bed inventory and superficial gas velocity, the pressure drop of the loop seal decreased with increasing aeration, thus causing an increase in the solid circulation flux (Gs). Correspondingly, the pressure drop in the riser became higher with increasing Gs; the pressure drop of the cyclone had a non-linear relationship with Gs, and the transition point was determined in the experiment. Using the laser fiber and gas tracer method, hydrodynamic characteristics in the standpipe were directly measured. It was found that the pressure gradient, voidage, and solid height in the standpipe were affected by the pressure balance in the whole loop. By adjusting the gas flow rate and direction in the standpipe, the gas-solid slip velocity and pressure gradient changed correspondingly. Therefore, the standpipe could maintain the pressure balance and realize self-equilibrium of the loop by absorbing the pressure drop variations of other parts in the system.

INTRODUCTION

Circulating fluidized bed (CFB)normally consists of the riser, cyclone, standpipe and solid recycling valve. The standpipe and recycling valve can overcome the high pressure difference and recycle particles collected by cyclone to the bottom of the riser. The standpipe often has the function to prevent gas bypassing. Non-mechanical valves, such as loop seal, L valve, are commonly used in industrial CFB boilers as they can work under the harsh conditions of high temperature and pressure. The solid circulating flux is commonly controlled by changing the aeration rate in the valves.

Though a number of studies have been conducted on gas-solid flow in the riser and cyclone [1-5], there are few studies on the hydrodynamic properties in the external loop of CFB system, especially for the influence of riser operation conditions on the performance of the recycle valve and standpipe. Basu [1] built a model to describe the CFB external loop pressure drop and analyzed the influence of aeration rate, riser velocity and Gs on the standpipe pressure gradient. However, the gas flow direction and vodiage in the standpipe were not measured directly. Monazam[2] studied the influence of bed inventory, riser velocity and aeration rate on G_S and confirmed that the performance of the loop seal and standpipe can't be studied ignoring the influence of other components in the whole system.

Standpipe is a special part of the CFB system. It has the function to absorb the pressure variation of other components in the system and the gas bypassing can be prevented by designing the standpipe correctly. However, there is very little literatures on the performance of the standpipe in the CFB system. The flow state in the standpipe is still in controversy and there is little evidence to validate the different viewpoints [1,6].

In this paper, experiments was conduced in a 4.5 m high CFB test rig with a loop seal to study the influence of operating conditions on the performance of hydrodynamic properties in the external loop, including the loop seal and standpipe. Laser fiber and gas tracer methods were applied to measure the flow behavior in the standpipe directly, including the voidage and gas flow direction.

EXPERIMENTAL

Experimental test rig

Experiments were conducted in a CFB cold test rig as shown in Fig.1. The rig consisted of a distributor, a riser, a cyclone, a standpipe and a loop seal. The riser had a cross-section area of 0.1x0.1 m^2 and a height of 4.5m. The cyclone was of high separation efficiency. The standpipe had a height of 3.0m and a diameter of 0.08m and connected the riser with a loop seal [7]. The dimension of the loop seal was shown in Fig.2. 20 pressure taps were installed at different heights along the solid circulation loop to measure the pressure drop online. The fluidizing gas rate and loop seal aeration rate, Q, were measured by gas flow meters. Two methods were used to measure the solids circulation flux, G_S. One was based on the time for the recirculating solids to accumulate to a certain height in the standpipe after a sudden close of a butterfly valve installed in the standpipe. The other method used a self-designed measuring device placed under the

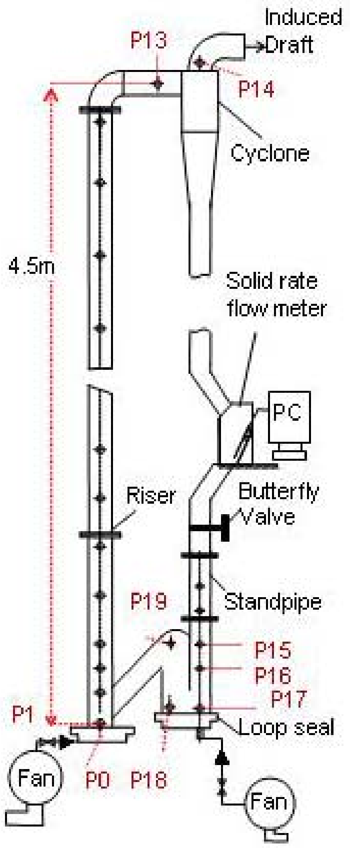

Fig. 1 Schematic diagram of experimental test rig

cyclone. All experiments were carried out at ambient temperature and atmospheric pressure. The bed material was quartz sand, its physical properties are listed in Table 1.

Table 1 Physical properties of the bed material

Real density	Bulk voidage	Minimum voidage	Minimum fluidization velocity	Size range	Sauter diameter
2625 kg/m^3	0.50	0.58	0.09 m/s	200-500 μ m	360 μ m

Flow behavior measurement in the standpipe and loop seal

To study the gas flow behavior in the standpipe, high purity CO_2 gas was used as the tracer. As shown in Fig. 2, CO_2 was injected into the system at Point A, and CO_2 concentration at Tap 1, 2 and 3 were simultaneously measured by a CO_2 detecting system with 3 channels, each equipped with a sampling probe, a CO_2 sensor (GSS-C20) and a vacuum pump. A laser fiber was used to measure the solid volumetric fraction at Taps 2 and 3. Signals from the CO_2 sensors and laser fiber were recorded online through a data acquisition system.

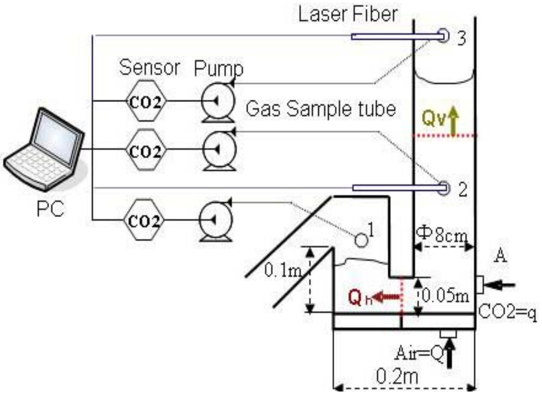

Fig. 2 Measurement system of flow behavior in loop seal and standpipe

In the first test, it found that CO_2 concentrations at different locations in the same cross section were nearly the same, so the gas and solids in the standpipe were regarded as well mixed horizontally. Shown in Fig.2, in the control volume enclosed by the dot lines and solid walls, the gas balance can be expressed as following equations when CO_2 is injected with a certain volumetric flow rate q at Point A. According to Eqn.1and 2, Q_V and Q_H can be calculated with known Q, q, C_1 and C_3.

$$Q_V + Q_H = Q + q \tag{1}$$

$$Q_V \times C_3 + Q_H \times C_1 = q \tag{2}$$

DISCUSSION

Riser pressure drop

The solid circulation flux G_S of the system has significant influence on the mass balance in the CFB reactor, and directly determines the performance of the system. As shown in Fig. 3, G_S increases with the aeration rate, Q, in the loop seal. After Q increases to a critical value, G_S no long changes with aeration rate and maintains at the maximum rate about 45kg/m^{2}s.

G_S can be estimated by the particle suspension density in the upper region of the riser. $G_S = \rho_s(1-\varepsilon)(u_{riser} - u_t)$ .Therefore, G_S can be used characterize the suspension density in the upper riser. Fig. 4 shows the solids hold up distribution in the riser at U_{riser}=5.0 m/s. With increasing G_s, particles hold up in the riser becomes denser. Former studies have shown that, with increasing G_s at a certain riser fluidizing velocity, the flow in the riser will transition from dilute phase pneumatic conveying to the fast fluidization state [8]. In the fast fluidized bed, the voidage in the dense zone and upper dilute zone are held stably, while the height of dense zone ascends gradually and the voidage in the transition zone increases.

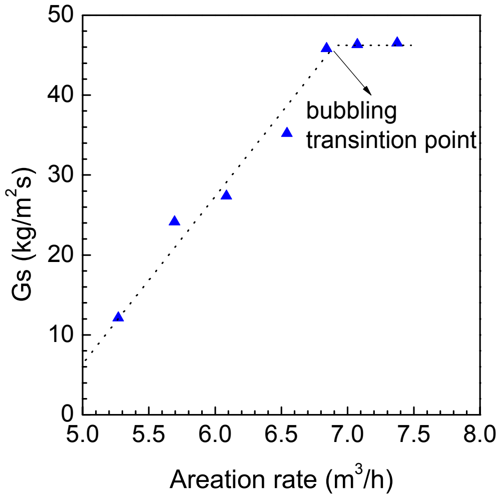

Fig. 3 Variation of G_S with Q of loop seal

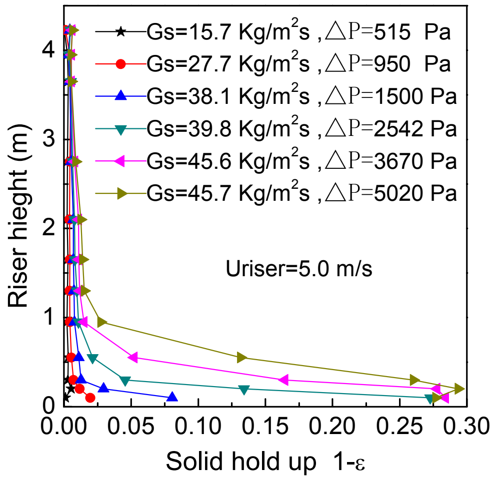

Fig. 4 solid hold up distribution in riser

The pressure drop of the riser $\triangle P_r$ is approximately equal to solids gravity pressure drop, which is determined by solids inventory in the riser. Fig. 5 shows the relationship of $\triangle P_r$ and G_s. $\triangle P_r$ and G_s represent proportional relationship, but after the $\triangle P_r$ is larger than 3.0KPa, G_s maintains at about 45kg/m^{3}s. According to Figs 4 and 5, when Gs reaches the critical value 45kg/m^{2}s, solid hold up of upper and bottom region of the riser remains unchanged. The increase of solids inventory in the riser only causes height of dense phase zone increase. Overall solids hold up distribution fit the S type curve of fast fluidization, and the saturated carrying rate under 5.0m/s in the paper is about 45 kg./m^{2}s.

Cyclone characteristic

The pressure drop or resistance of the cyclone $\triangle P_{cyc}$ has a square relationship with the entering gas velocity. However, $\triangle P_{cyc}$ is also influenced by solids concentration C_S. C_S is defined as the solids mass in one cubic meter of fluidizing gas. It can be calculated with G_S by $C_S = G_S A_S / (Ar\ u_{riser})$.

In this paper, besides the traditional steady method, a transient method is used to study the characteristic of the cyclone pressure drop. At a specific $U_{riser,}$ after a steady state with a large Gs was maintained for a few minutes, the loop seal aeration was suddenly cut off, the bed inventory was then elutriated out of the riser and accumulated in the standpipe. The flow regimes in the riser changed from fast fluidization to dilute convey regime with decreasing G_s, until the riser was empty of particles. This method is simple and has better reproducibility than traditional steady method.

Fig. 6 shows the characteristic of the cyclone at different $U_{riser.}$ The comparison between the steady method and transient method further verifies the reliability of the transient method.

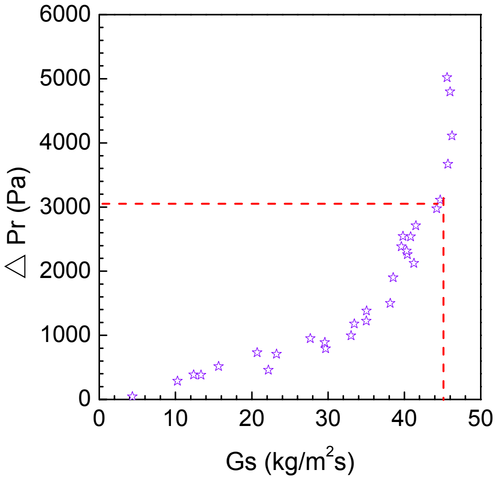

Fig. 5 Variations of △Pr with Gs

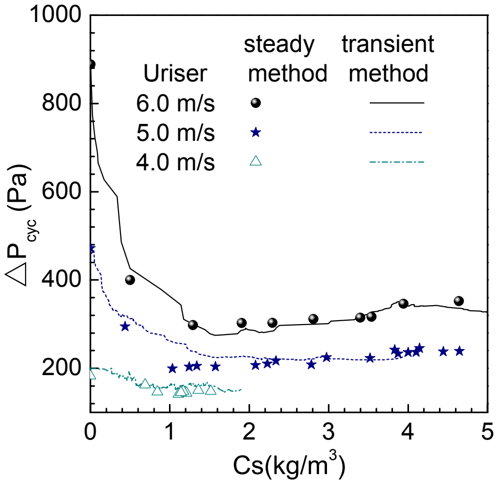

Fig. 6 character of cyclone △Pcyc

Flow behavior of loop seal and standpipe

It's generally believed that all the aeration gas passes through the loop seal into the riser. However, industrial operation has verified that the gas-bypassing phenomenon in standpipe can't be ignored. As shown in Fig. 7, the actual gas flow rate across the loop seal is not equal to the aeration rate. With a small aeration rate,Q, Q_H through the loop seal is close to the aeration rate, account for more than 95% percent of Q. However, with increasing Q, more gas goes up through the standpipe, Q_H/Q rapidly decreases.

A loop seal can be divided into a horizontal part and a vertical part based on its physical structure, as shown in Fig.2. The gas-solid flow in the horizontal part belongs to the transport state, the resistance of which is mainly caused by the friction among particles and the wall. With increasing aeration rate, the pressure drop of the horizontal section (P17-P18) increases due to higher G_S. The flow in the vertical section is in the bubbling bed regime. With higher aeration rate, as Q_H/Q decrease, the ejecting height of particle decreases rapidly due to less $Q_{H.}$ This results in the reduction of $\triangle P_{lsl}$, as shown in Fig. 7.

Therefore, the loop seal characteristics are closely related to the flow state in the standpipe, which affects the actual gas passing through the loop seal. In this paper, the pressure drop gradient, voidage and gas flow were directly measured.

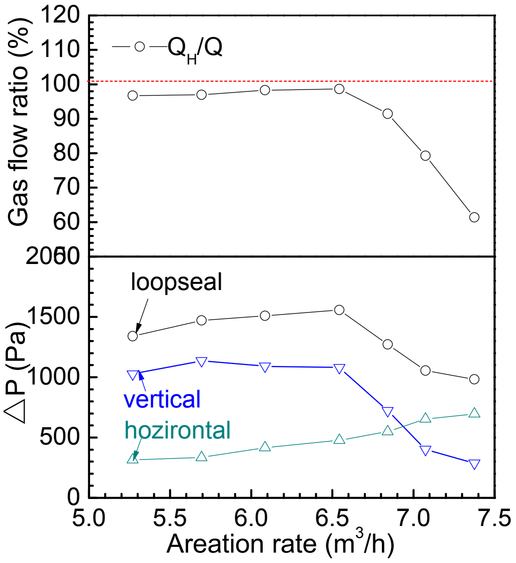

Fig. 7 the performance of loop seal (U_{riser}=5.0 m/s)

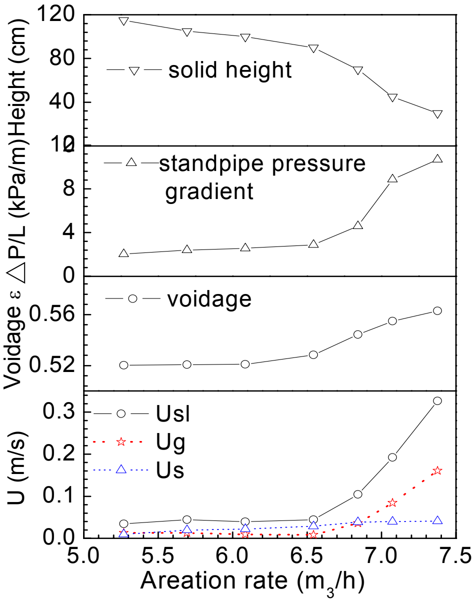

Fig. 8 flow behavior of standpipe (U_{riser}=5.0 m/s)

As shown in Fig. 8, when Gs increases with increasing aeration rate, Q, at fixed U_{riser} and bed inventory, I_V, the mass of solid and thereby solid height in the standpipe decrease because more solids accumulate in the riser. At the same time, the pressure gradient in the standpipe increases. This is a special feature of transient packed bed flow [9], which is related to the pressure gradient and gas-solid slip velocity $U_{Sl.}$ According to the experimental measurement of voidage by laser fiber and gas flow rate measured by gas tracer, the slip velocity U_{Sl} can be calculated by the equation $U_{Sl}=G_S/\rho_p(1-\varepsilon)+U_g/\varepsilon$[9]. With increasing aeration rate, particle velocity, $U_{S,}$ increases due to higher G_S. At the same time, the upward gas flow rate in the standpipe, $Q_{V,}$ also increases. Therefore, the slip velocity will increase with increasing aeration rate. Although the solid height decreases, the solid seal can provide a pressure head because of the increasing pressure gradient and slip velocity U_{Sl}. With increasing aeration rate, the upward gas flow, $Q_{V,}$ keeps on increasing and the voidage gradually approaches to the minimum fluidization voidage. With very high aeration rates, upward flowing bubbles can be visually observed and the flow reaches the bubbling state.

Pressure balance of the CFB external loop

As shown in Fig. 9, at fixed riser fluidizing velocity, more bed material accumulates in the riser with increasing aeration rate. As a result, $\triangle P_r$ increases. At the same time, both the pressure drop gradient and total pressure drop, $\triangle P_{sp}$, in the standpipe increase. Under stable operation condition, the pressure balance of the CFB system can be expressed as $\triangle P_r + \triangle P_{lsl} + \triangle P_{cyc} = \triangle P_{sp}$. Whenever pressure drop of any other parts changes, the pressure gradient $\triangle P/L$ and U_{sl} in the standpipe change correspondingly to rebalance the system. Therefore, the standpipe has the ability to keep pressure balance in the CFB by adjusting inner flow behavior. Its characteristic is greatly affected by the operation conditions of the riser and other parts, and should be studied in the external loop of CFB system [10].

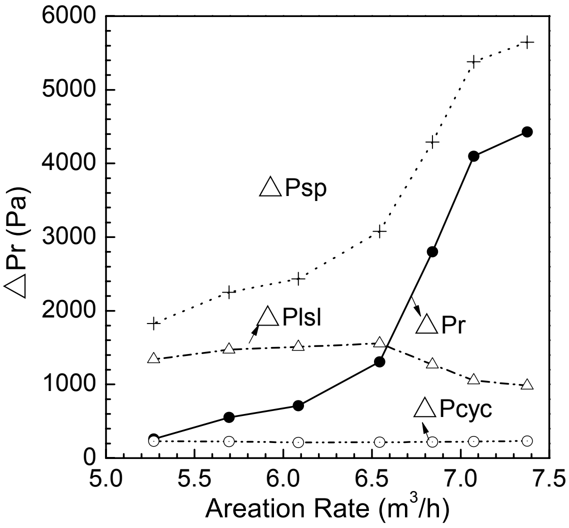

Fig. 9 Variations of pressure drops around the CFB loop

CONCLUSION

The flow behavior of a CFB external loop, including loop seal and standpipe is schematically studied in this paper. It found that with a fixed bed inventory and fluidizing velocity, the pressure drop of the riser increases with solid circulation flux because more particles accumulate in the riser. When Gs reach a critical value, solids suspension distribution can be described by the S type curve of the fast fluidization. The pressure drop of a cyclone depends on the riser gas velocity and solids concentration. The cyclone pressure drop first decreases and then increases with suspension solid concentration. The actual gas flow ratio Q_H/Q through the loop seal decreases with increasing aeration rate, while the upward flow gas rate in the standpipe increases.

Voidage in the standpipe increases and the flow state gradually transitions to the minimum fluidizing state from packed bed flow. The flow behavior in the standpipe adjusts to conditions in the whole CFB system. The standpipe maintains the pressure balance by changing the slip velocity and pressure gradient to provide the required pressure head with lower solids height.

Because the CFB system used in this paper is an inventory constrained system, the results, especially for the transition points, may be different under different bed inventories. At same time, the solids properties also have an influence on the results. These factors will be studied in the future studies.

ACKNOWLEDGMENT

Financial support of this work by High Technology R&D (863) (2009AA05Z302) is acknowledged.

NOTATION

Ar	section area of riser, m^2	As	section area of standpipe, m^2
C_S	solids concentration, kg/m^3	G_S	solid circulation flux, kg/m^2s
I_V	system bed inventory, kg	Q	loop seal aeration, m^3/h
Q_H	gas flow cross loop seal, m^3/h	Q_V	gas flow cross standpipe, m^3/h
q	gas tracer($CO_{2)}$ flow rate,m^3/h	U_g	superficial gas velocity m/s
U_{riser}	riser fluidizing velocity, m/s	U_{Sl}	gas –solid slip velocity m/s
U_S	actual particle velocity m/s	U_t	actual solid velocity m/s
ρ_s	particle density kg/m^3	ε	voidage
P0~P19	Number of pressure taps	$\triangle P_{cyc}$	pressure drop of cyclone, P13-P14, Pa
$\triangle P_{lsl}$	pressure drop of loop seal, P17-P19 Pa	$\triangle P_r$	pressure drop of riser,P0-P13, Pa
$\triangle P_{sp}$	pressure drop of standpipe, P17-P14,Pa	$\triangle P_{sp}/L$	pressure drop gradient, (P16-P15)/0.1, Pa /m

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