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Experimental research on solid circulation in a twin fluidized bed system

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Abstract

A twin fluidized bed solid circulation system, in which two adjacent fluidized beds exchange solids, was developed for coal gasification to produce middle heating value gas. The effects of bed material, operation velocity, and bed structure on the solid circulating rate were tested at a small-scale test facility. Experimental results showed that the solid circulation rate of the system could be adjusted by changing gas velocities of two beds and could attain 30–40 times of the fuel feed rate, which would meet the demands of heat supply to an endothermic process of a gasifier. On the basis of experiments, reasonable operation and design parameters were put forward, which can be used to as a reference for the commercial gasifier design. A mathematical model was erected to calculate the solid circulation rate of the system, and it could predict well the solid flow rate through a horizontal orifice by comparison with experimental data.

Keywords: Coal gasification; Twin fluidized beds; Solid circulation; Mathematical model

1. Background

Multi-fluidized bed solid circulation systems are widely used in the process of catalyst regeneration, coal gasification, coking, thermal cracking, drying and incineration of waste [1–11]. The two main types of solid circulation systems are the external circulation system and the internal circulation system. In the external circulation system, two fluidized beds are collected by two circulation pipes (riser and downcomer), and particles flow in pipes, controlled by means of valving and aeration rates [1]. In the internal circulation system, one vessel is divided into several chambers or compartments by internal walls. There are orifices on the walls and solid can flow through orifices between different chambers. Compared with the external circulation system, this type of the system has a simple structure, low energy consumption and low investment. Rudolph and Judd [2] put forward a vessel with a draft tube for coal gasification process. Snieders et al. [3] made a research on a four-compartment interconnected fluidized bed system, and Chong et al. [4] introduced an adjacent fluidized bed with no gas mixing for char production process.

Presently, most of the small-scale industry gasifiers operate with air/steam aeration and can only produce low heating value gas. The gasifier which produces the middle heating value gas usually operates at high temperature and high pressure with oxygen aeration such as Texaco, U-gas gasification process, and need very high investment and are difficult to be accepted by small-scale enterprises. A new type of gasifier which produced middle heating value gas with air and steam blown, was developed by Zhejiang University, by means of a twin fluidized bed system.

A sketch of the twin fluidized bed system is shown in Fig. 1. The reactor consists of two adjacent fluidized beds, divided by a vertical wall with two orifices at a certain distance. The two fluidized beds operate at different gas velocities and form so-called the fast bed (fluidized vigorously) and the slow bed (aerated slowly). Fig. 2 shows a typical pressure distribution along the bed height of two beds. Due to differences in height and void of two dense beds, pressure gradients are established at the lower and upper orifices. Driven by the pressure gradient, solid particles in the slow bed flow into the fast bed through the lower orifice, moving upward in the fast bed and recycling back into the slow bed through the upper orifice. In this way, solid circulation between the two fluidized beds is formed.

In the process of coal gasification, the slow bed acts as a gasifier and the fast bed acts as a combustor. The gasifier

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Nomenclature

A_o	cross section area of orifice (m^2)
b	orifice width (m)
B	fuel feed rate (kg/s)
C_0, C_1	constants in Eq. (12)
C_D	discharge coefficient
d_b	bubble diameter (m)
d_p	mean particle diameter (mm)
f_b	bubble frequency
g	gravity constant
Gs	solid circulation rate (kg/s)
Δh_j	height of the j zone (m)
H	fluidized bed height (m)
ΔH	distance between two orifices (m)
H_1	bed height at the top of the lower orifice (m)
ΔH_1	height of the lower orifice (m)
$\Delta H'_1$	particle flow height at the lower orifice (m)
ΔH_2	height of the upper orifice (m)
m	constant in Eq. (11)
n_1, n_2	constants in Eq. (12)
Δp	pressure gradient at the orifice (Pa)
Δp_1	pressure gradient at the top of the lower orifice (Pa)
R	solid circulation ratio
u	particle flow velocity (m/s)
u_0	particle flow velocity at the top of the orifice (m/s)
u_{sj}	particle velocity at j zone of the lower orifice (m/s)
U	fluidized gas velocity (m/s)
y	height at a orifice (m)

Greek letters

δ_b	bubble fraction
ε	void fraction
ρ_p	particle density (kg/m^3)
ϕ	shape factor

Subscripts

f	fluidized condition
h	fast bed
l	slow bed
mf	minimum fluidized condition

operates at the temperature of 800–850 °C with steam aeration, while the combustor operates at 900–950 °C with air aeration. Coal is first fed into the gasifier, heated and pyrolysed, and char reacts with steam. The absorption heat of gasification process is provided by high temperature circulating solids from the combustor. The semi-coke from the gasifier recycles into the combustor with circulating solids and burnt out there. The heat produced in the combustor is used for heating-up the circulating solids and steam generation. The raw gas from the gasifier is cooled and purified to be a clean gas in which the main composition is H_2, CO and CH_4 and used for middle heating value gas supply.

The key technology of the scheme is how to maintain large enough and stable solid circulation rate between the two beds to supply enough heat for endothermic process of the gasifier. A series of experiments on the solid circulation rate was carried out at a small-scale test facility. This paper introduced main experimental results.

2. Experiments

A two-dimensional test facility of the twin fluidized bed system is shown in Fig. 3. The reactor was 2 m high and the section of the slow bed was 280 mm × 40 mm while the fast bed was 280 mm × 40 mm. There were two orifices allocated on an internal divided wall at a certain distance with the width of 40 mm. The height and distance of the two orifices can be adjusted by changing the vertical wall. The front and back walls of the reactor used transparent glass, which was used to observe and measure particle flow through the orifice. Two other sides used steel plates, on which 20 small pressure pipes with jam-prevention air aeration devices were allocated along the bed height for pressure measurement. Each of two beds had its own wind-box and air supply.

There are many methods to measure the particles flow rate, such as the light fiber velocity detector [5], radiotracer residence time method [6], heat response measurement [7], and the high-speed video recorder [8]. Here we used a high-speed digital video recorder to record particle flow in the lower orifice through the transparent glass wall of the reactor. Combined with a computer correlation analysis method, particle flow velocity could be determined by replaying video tapes slowly. The experiments showed that particle velocities varied along the height of the orifice and fluctuated with time (see Fig. 8). So the orifice was divided into several zones along the height. Particle velocities at different times were measured and time mean velocities were obtained. The total solid flow rate can be calculated according to the following equation:

$$\mathrm{Gs} = \rho_p(1-\varepsilon_{mf})b\sum_{j=1}^{k}u_{sj}\,\Delta h_j \qquad (1)$$

where ρ_p is the particle density (kg/m^3), ε_{mf} the void fraction at the minimum fluidized velocity, b the orifice width (m), u_{sj} the particle time mean velocity at the j zone (m/s), and Δh_j the height of the j zone (m).

The bed materials experiments used were plastic balls with narrow size distribution and industry fluidized bed ash with broad size distribution. The properties were shown in Table 1.

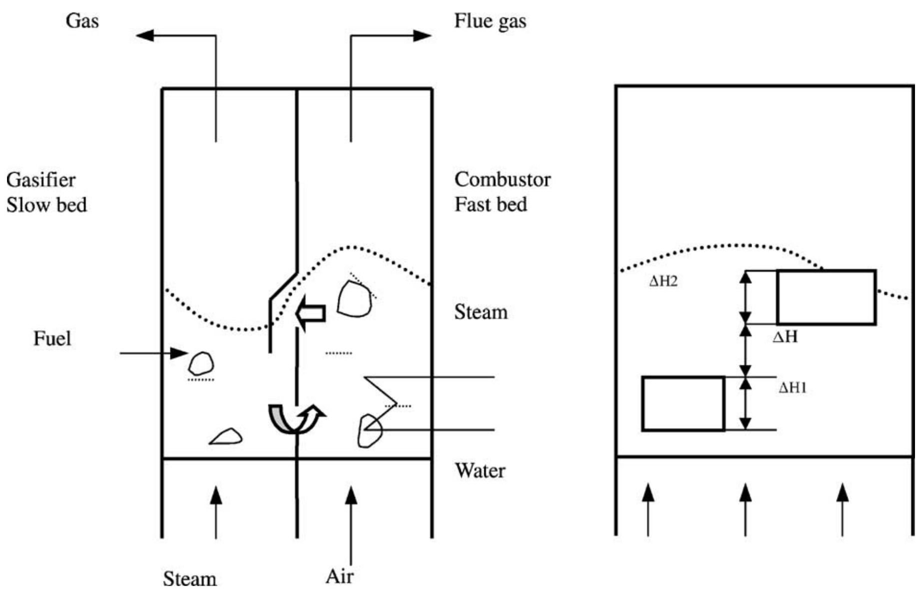

Fig. 1. Scheme of the dual fluidized bed system.

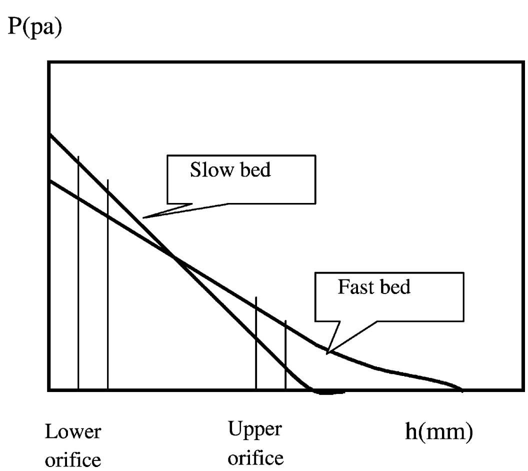

Fig. 2. Pressure distribution of the two beds.

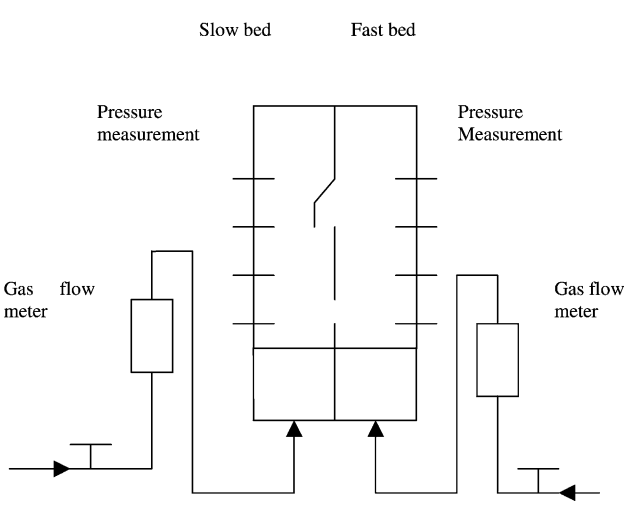

Fig. 3. A small-scale test facility.

Table 1
The properties of bed materials

Bed material	Size range (mm)	ϕ	d_p (mm)	ρ_p (kg/m^3)	U_{mf} (m/s)	ε_{mf}
Plastic balls	3–5	1	4	997	1.05	0.571
Fluidized bed ash	0–8	0.7	2.26	2433	0.71	0.45

3. Results and discussion

The main factors, which affect the solid circulation rate in the twin fluidized bed system, are bed material properties, fluidization velocities of the fast bed and the slow bed U_h and U_l, the size and distance of the orifices.

3.1. Effect of the bed material

Bed material properties such as particle density, diameter, and fluidization characteristics have an obvious effect on solid circulation. Fig. 4 shows the solid flow rate variation with the gas velocity by using plastic balls and fluidized bed ash as a bed material separately. The circulation rate of fluidized bed ash was much higher than that of plastic balls at the same gas velocity and bed structure, because fluidized bed ash has a higher density and thus a higher pressure gradient to drive particle flow at the orifice than plastic balls.

3.2. Effect of gas velocities

The gas velocities of the two beds have a great effect on the solid circulation rate. Experiments showed that the beds had some dead zones or obvious segregation when gas velocity U/U_{mf} was less than 1.2 for plastic balls and

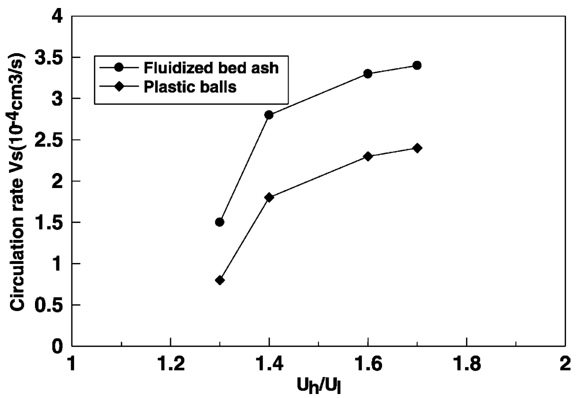

Fig. 4. Effect of the bed material on the solid circulation rate ($H_{mf} = 390$ mm, $\Delta H = 170$ mm, $\Delta H_1 = 100$ mm, $\Delta H_2 = 100$ mm, $U_h/U_{mf} = 2.2$).

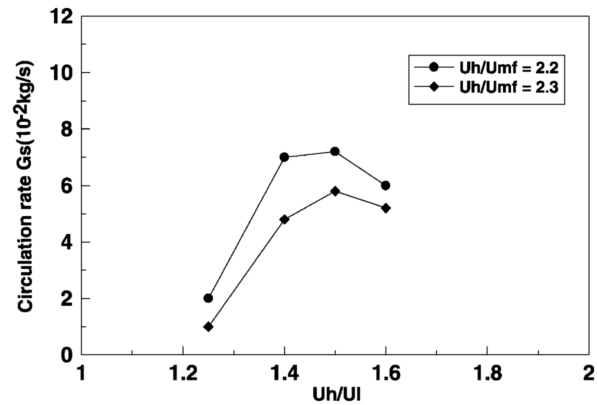

Fig. 6. Effect of the velocity of the slow bed on the solid circulation rate (plastic balls) ($H_{mf} = 380$ mm, $\Delta H = 170$ mm, $\Delta H_1 = 50$ mm, $\Delta H_2 = 100$ mm).

2 for fluidized bed ash separately. This means fluidization velocities of the two beds must be larger than a certain value.

Fig. 5 shows the effect of the gas velocity of the fast bed U_h on the solid circulation rate, while the gas velocity of the slow bed kept constant. The solid circulation rate increased with U_h sharply and then slowly when U_h attained a certain value. This was due to two opposition influences on the solid circulation rate by U_h. In one aspect, with increase of U_h, the dilute density of the fast bed decreased and the pressure gradient at the orifice increased, and led to the solid flow rate increasing. In another aspect, too high U_h enhanced bubbling near the lower orifice and hindered the solid flow into the fast bed.

Fig. 6 shows the effect of the gas velocity of the slow bed U_l on the solid circulation rate, while U_h was kept constant. When U_l decreased, i.e. U_h/U_l increased, the solid circulation rate increased firstly, and then decreased slowly. This is because the decrease of U_l caused the increase of pressure gradient at the orifice, but has a negative influence on bed material fluidization.

The experiments showed that the gas velocity ratio of the two beds U_h/U_l should be kept in the range of 1.5–1.7 to attain high solid circulation rate.

3.3. Effect of orifice allocation and size

The location of the two orifices had a distinct effect on the solid circulation rate. When the lower orifice was nearer the distribution plate of the bed, the pressure gradient at the orifice became higher and the solid circulation rate increased. Similarly, when the upper orifice was nearer the surface of the dense bed, the pressure gradient and the particle flow rate increased. In this case, the upper orifice is usually allocated near but lower than the static bed height. Fig. 7 shows that the solid circulation rate increased with the vertical distance of two orifices ΔH as predicted before.

The horizontal distance of the two orifices would affect residence time of circulation solid in the two beds. In order to keep enough heating time for solids in the combustor (the fast bed), the two orifices must keep a certain distance in the vertical and horizontal direction.

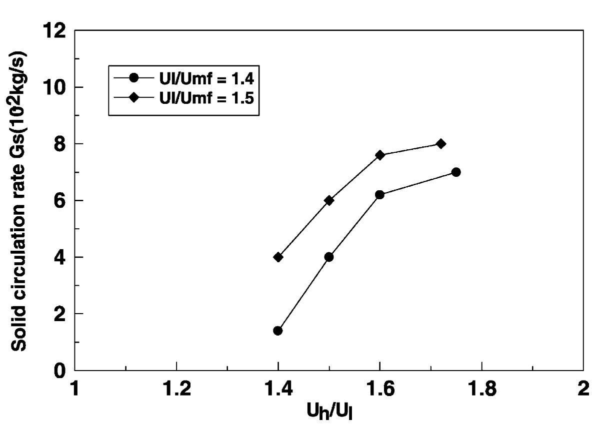

Fig. 5. Effect of the velocity of the fast bed on the solid circulation rate (plastic balls) ($H_{mf} = 380$ mm, $\Delta H = 170$ mm, $\Delta H_1 = 50$ mm, $\Delta H_2 = 100$ mm).

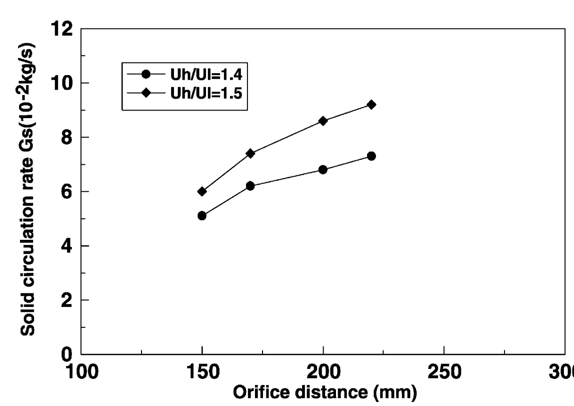

Fig. 7. Effect of the vertical distance of two orifices on the solid circulation rate (plastic balls) ($H_{mf} = 400$ mm, $U_l/U_{mf} = 1.4$, $\Delta H_1 = 50$ mm, $\Delta H_2 = 150$ mm).

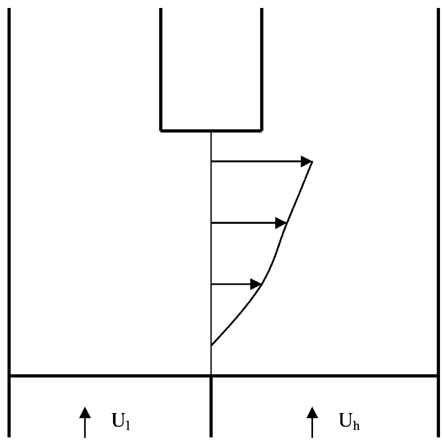

Fig. 8. Particle velocity distribution along the height of the orifice.

The size of the orifice is an important parameter for design. For a rectangular orifice, the bigger the orifice width, the higher the solid circulation rate. Experiments showed that particle velocity profile through the orifice formed a similar shape of parabola, which attained the maximum at the top of the orifice and decreased to zero at the bottom of the orifice as shown in Fig. 8. Surprisingly, particle flow height was usually less than or equal to the orifice height. So the solid circulation rate first increased with the height of the lower orifice, attained the largest when the orifice height was kept at a certain value, and then decreased as shown in Fig. 9. Fig. 10 shows the effect of the height of the upper orifice on the solid circulation rate. Different from the lower orifice, the solid circulation rate increased with the upper orifice height. This is because solid flow at the upper orifice was more likely to overflow from the low bed to the fast bed.

3.4. Gas leakage rate between the two beds

In the coal gasification process, gas leakage rate is expected to be zero or a little and too much gas leakage will affect the quality of the product gas. Experiments were made to measure the gas leakage rate between the two beds by means of a hydrogen trace method. Hydrogen gas was injected into the slow bed and the fast bed separately. Hydrogen concentrations along the height of the two beds were measured by a gas detector, and hydrogen leakage ratio through the lower and upper orifice were calculated. The gas leakage ratio of the lower orifice was higher than the upper orifice as shown in Fig. 11.

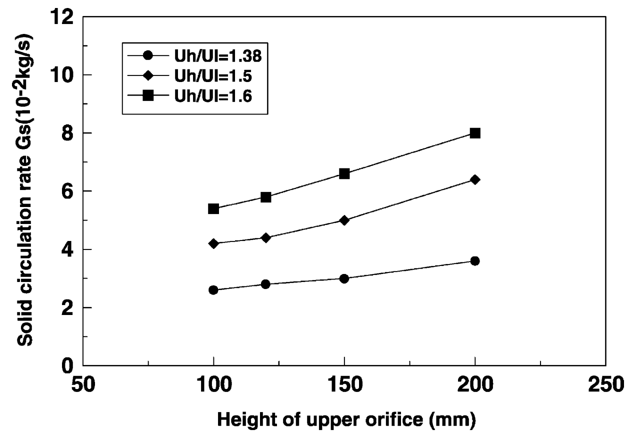

Fig. 10. Effect of the height of the upper orifice on the solid circulation rate (plastic balls) ($H_{mf} = 400$ mm, $U_l/U_{mf} = 1.4$, $\Delta H_1 = 95$ mm, $\Delta H = 170$ mm).

3.5. Reasonable design and operation parameters

Experiments showed that the solid circulation rate could be controlled by changing the two bed velocities and the orifice structure. To keep a large solid circulation rate, the reasonable orifice sizes and gas velocities of the system were put forward on the basis of experiments.

1. The lower orifice should be near the bed bottom and the upper orifice near but under the bed static height. The

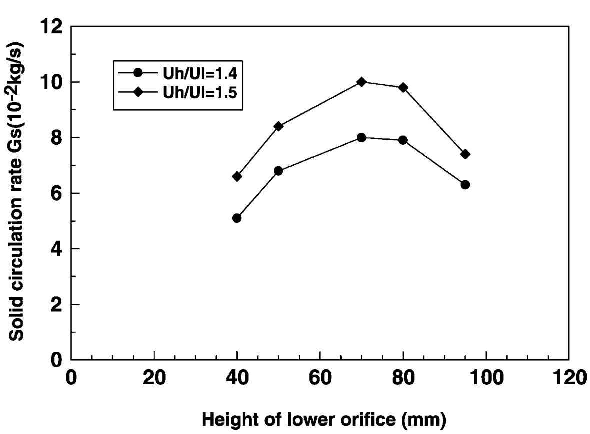

Fig. 9. Effect of the height of the lower orifice on the solid circulation rate (plastic balls) ($H_{mf} = 400$ mm, $U_l/U_{mf} = 1.4$, $\Delta H_2 = 150$ mm, $\Delta H = 170$ mm).

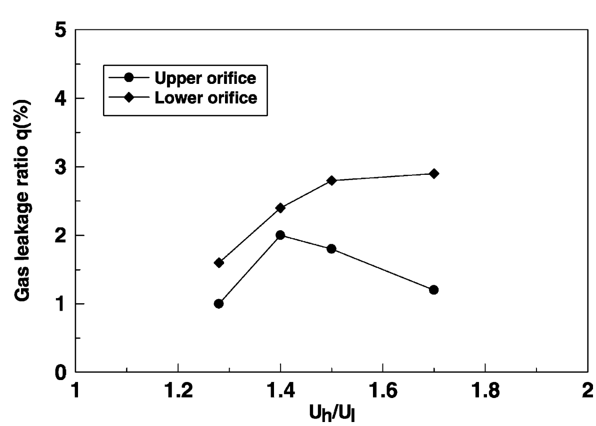

Fig. 11. Gas leakage ratio through the orifice changes with gas velocities (plastic balls) ($H_{mf} = 400$ mm, $U_l/U_{mf} = 1.4$, $\Delta H_1 = 95$ mm, $\Delta H_2 = 150$ mm, $\Delta H = 170$ mm).

horizontal and vertical distance were determined by the particle heating time and the residence time.

2. The height of the lower orifice ΔH_1 and the height of the upper orifice ΔH_2 should be kept in the range of 0.15–0.3H_{mf} and 1–1.5 ΔH_1 separately. The width of the two orifices could be determined according to Eq. (1).
3. The gas velocities of the two beds should be controlled in the following ranges:
   - for plastic balls with narrow size distribution: $U_{\mathrm{l}}/U_{\mathrm{mf}} \geq 1.4$;
   - for fluidized bed ash with broad size distribution: $U_{\mathrm{l}}/U_{\mathrm{mf}} \geq 2.2$;
   - $U_{\mathrm{h}}/U_{\mathrm{l}} = 1.4$–$1.8$.

Experiments showed that the solid circulation rate could attain 1000 kg/h for the fluidized bed ash given the small-scale test facility. To compare with a circulation fluidized bed, a concept of the solid circulation ratio R is introduced here:

$$R = \frac{\mathrm{Gs}}{B} \tag{2}$$

where Gs is the solid circulation rate (kg/s), and B the fuel feed rate (kg/s).

According to the calculation, the solid circulation ratio in the system could attain 30–40, which is enough for the heat supply to an endothermic process of a gasifier.

4. Solid circulation rate calculation

Most of the literature [10] on the flow of a particulate material through an orifice is using the well-known relation for the discharge of a liquid through an orifice, derived from the Bernoulli equation:

$$\mathrm{Gs} = C_{\mathrm{D}} A_{\mathrm{o}} [2\rho_{\mathrm{p}}(1-\varepsilon_{\mathrm{f}})\,\Delta p]^{1/2} \tag{3}$$

where the mass flow through an orifice Gs has been plotted against the pressure gradient of the orifice Δp and other influence factors sum up to the discharge coefficient C_{D} [2,3,10]. Snieders et al. [3] predicted that Gs increasing with the square-root Δp is not reflected by the experiment data and put forward the following equation:

$$\mathrm{Gs} = C_{\mathrm{D}} A_{\mathrm{o}}\,(\Delta p)^{1.64} \tag{4}$$

According to our experiments, the solid flow is different from the liquid flow. Despite of the influence of the bed pressure, the gas velocity and the bed material also affect the solid flow through the orifice. So a mathematical model to calculate the solid circulation rate in a twin fluidized bed system was erected here on the basis of experiments.

4.1. Pressure difference at the orifice

Experiments showed that there existed a narrow gas channel on the top of the lower orifice, where, driven by the pressure gradient, gases flew quickly and carried particles to move layer by layer under the effect of the friction force, which forms a particle velocity distribution as shown in Fig. 8. So, here the pressure gradient at the top of the lower orifice Δp_1 is a very important parameter, which directly controls the particle flow through the orifice. The Δp_1 can be calculated according to Eq. (5):

$$\Delta p_1 = p_{\mathrm{l}} - p_{\mathrm{h}} = ((1-\varepsilon_{\mathrm{fl}})(H_{\mathrm{fl}} - H_1)\rho_{\mathrm{p}} g) - ((1-\varepsilon_{\mathrm{fh}})(H_{\mathrm{fh}} - H_1)\rho_{\mathrm{p}} g) \tag{5}$$

where $\varepsilon_{\mathrm{fl}}$ and $\varepsilon_{\mathrm{fh}}$ are the void fractions of the slow bed and the fast bed in the dense zone, H_{fl} and H_{fh} the dense bed height of the slow bed and the fast bed, and H_1 the height from the top of the lower orifice to the bed distributor.

According to the ‘two-phase theory’, the dense bed consists of two phases, a bubble phase and an emulsion phase at incipient fluidized condition. Thus, void fraction ε_{f} can be obtained by the following equations:

$$\varepsilon_{\mathrm{f}} = \delta_{\mathrm{b}} + (1-\delta_{\mathrm{b}})\varepsilon_{\mathrm{mf}} \tag{6}$$

$$\delta_{\mathrm{b}} = 0.3 f_{\mathrm{b}} d_{\mathrm{b}}^{0.5} \tag{7}$$

where δ_{b} is the bubble fraction in the dense bed, f_{b} the bubble frequency, and d_{b} the bubble diameter. For coal fired fluidized bed, f_{b} and d_{b} can be calculated according to the following empirical equations [11]:

$$f_{\mathrm{b}} = 1.74(U - U_{\mathrm{mf}})^{0.725} H_{\mathrm{f}}^{-0.434} \tag{8}$$

$$d_{\mathrm{b}} + 0.9 U_{\mathrm{mf}} d_{\mathrm{b}}^{0.5} - 0.862(U - U_{\mathrm{mf}})^{0.275} H_{\mathrm{f}}^{0.434} = 0 \tag{9}$$

The height of the dense bed H_{f} can be got from operation data:

$$\Delta p_{\mathrm{f}} = (1-\varepsilon_{\mathrm{f}})\rho_{\mathrm{p}} g H_{\mathrm{f}} \tag{10}$$

where Δp_{f} is the pressure drop of the dense bed.

4.2. Particle flow model

As mentioned earlier, the particle velocity profile through the orifice formed a shape of parabola, which attained the maximum at the top of the orifice and decreased to zero at the bottom of the orifice. So the particle velocity profile can be described by the following equation:

$$\frac{u}{u_0} = \left(\frac{y}{\Delta H_1'}\right)^m \tag{11}$$

where u_0 is the particle flow velocity at the top of the orifice, and $\Delta H_1'$ the particle flow height at the lower orifice. According to the experiment, when $\Delta H_1/H_{\mathrm{mf}} = 0.4$, $\Delta H_1' = H_1$ and when $\Delta H_1/H_{\mathrm{mf}} > 0.4$, $\Delta H_1' = 0.4 H_{\mathrm{mf}}$. A fit to the experimental data resulted in $m = 0.55$ with a correlation coefficient, r^2 of 0.966 as shown in Fig. 12. The u_0 mainly related with the bed material, the fluidization velocity, and

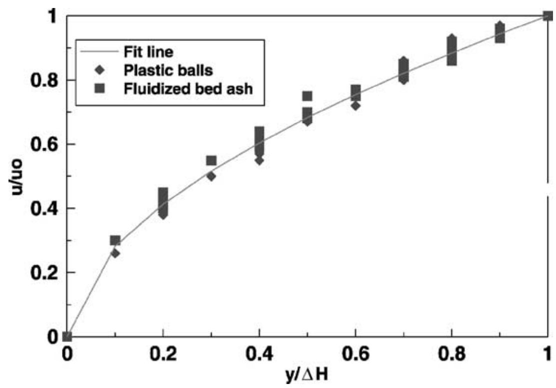

Fig. 12. Particle velocity profile through the orifice.

the pressure gradient. So here u_0 was correlated with Δp_1 and U_l using the following equation:

$$u_0 = C_0 \left(\frac{U_l}{U_{mf}} - C_1\right)^{n_1} \Delta p_1^{n_2} \tag{12}$$

where C_0 is a factor related to bed material property, and C_1 the minimum fluidization number from the experiment. By fitting with data, u_0 was obtained by the following equations as shown in Figs. 13 and 14. For plastic balls with narrow size distribution:

$$u_0 = 1.604 \times 10^{-6} \left(\frac{U_l}{U_{mf}} - 1.2\right)^{1.256} \Delta p_1^{1.78} \tag{13}$$

For fluidized bed ash with broad size distribution:

$$u_0 = 3.312 \times 10^{-6} \left(\frac{U_l}{U_{mf}} - 2\right)^{1.256} \Delta p_1^{1.78} \tag{14}$$

So particle flow rate Gs:

$$\mathrm{Gs} = (1-\varepsilon_f)\rho_p b \int_0^{\Delta H_1'} u_0 \left(\frac{y}{\Delta H_1'}\right)^m \mathrm{d}y = (1-\varepsilon_f)\rho_p b u_0 \frac{\Delta H_1'}{m+1} \tag{15}$$

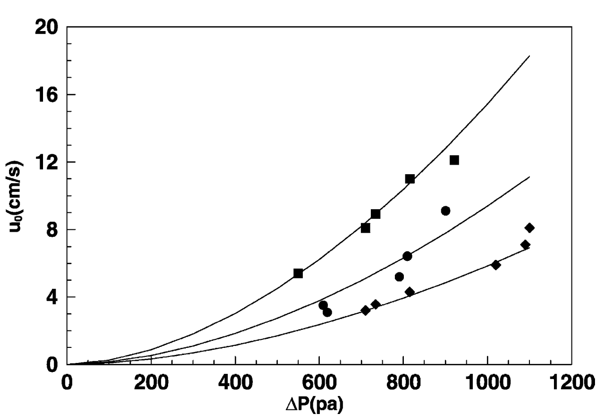

Fig. 13. Plot of solid flow rate vs. pressure gradient (plastic balls) ((■) $U_l/U_{mf} = 1.72$, (●) $U_l/U_{mf} = 1.55$, (◆) $U_l/U_{mf} = 1.44$).

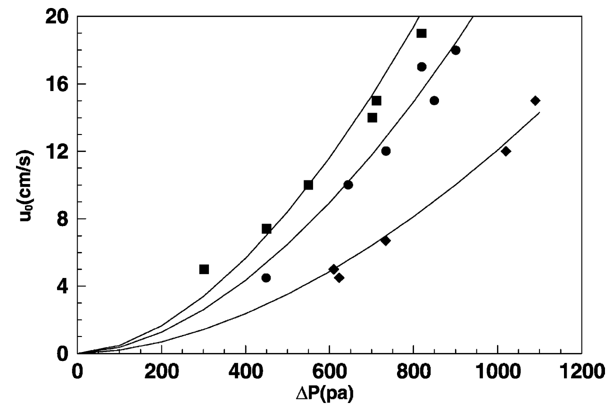

Fig. 14. Plot of solid flow rate vs. pressure gradient (fluidized bed ash) ((■) $U_l/U_{mf} = 2.48$, (●) $U_l/U_{mf} = 2.39$, (◆) $U_l/U_{mf} = 2.28$).

Using Eq. (12):

$$\mathrm{Gs} = \frac{C_0}{m+1}(1-\varepsilon_f)\rho_p b\, \Delta H_1' \left(\frac{U_l}{U_{mf}} - C_1\right)^{n_1} \Delta p_1^{n_2} \tag{16}$$

For plastic balls:

$$\mathrm{Gs} = 1.035 \times 10^{-6}(1-\varepsilon_f)\rho_p b \times \Delta H_1' \left(\frac{U_l}{U_{mf}} - 1.2\right)^{1.256} \Delta p_1^{1.78} \tag{17}$$

For fluidized bed ash:

$$\mathrm{Gs} = 2.136 \times 10^{-6}(1-\varepsilon_f)\rho_p b \times \Delta H_1' \left(\frac{U_l}{U_{mf}} - 2\right)^{1.256} \Delta p_1^{1.78} \tag{18}$$

Fig. 15 shows the comparison of calculation results using the given Eqs. (3)–(18) and experimental data and the relative deviation between calculation results and experimental data is less than 15%. So this model can predict solid flow through a horizontal orifice well.

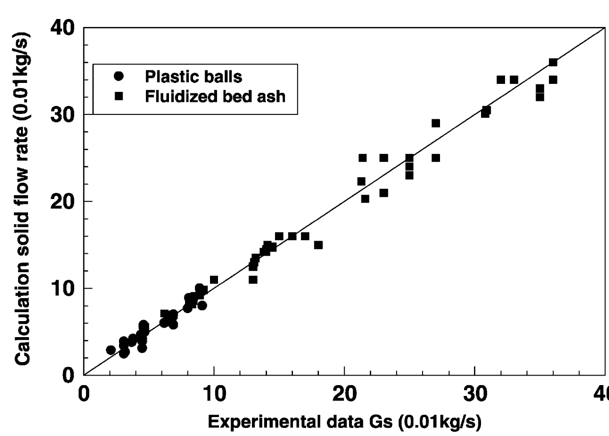

Fig. 15. Comparison of calculation results and experimental data.

5. Conclusions

A twin fluidized bed solid circulation system, in which two adjacent fluidized beds operated in different gas atmospheres and exchanged solids but not gases, was developed to be utilized in coal gasification to produce middle heating value gas. Experiments on a small-scale test facility showed that the main factors, which affected the solid circulation rate, were bed material property, gas velocities of the two beds, orifice size and distance. The solid circulation rate for the fluidized bed ash could attain 1000 kg/h, given the small-scale test facility. On the basis of experiments, the reasonable gas velocity and size of orifice structure were put forward, which could be used as a reference for the coal gasifier design. A mathematical model was erected to calculate particle flow rate through the orifice in the system, which considered the effects of bed material, pressure gradient and gas velocity. The relative deviation between calculation results of the model and experimental data is less than 15%.

Acknowledgements

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