Experimental Investigation on Solid Particle Flow Characteristics in Particle Curtain Heat Exchanger

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Abstract. The particle curtain heat exchange, which is based on the rapid heat equilibrium theory of gas-solid two-phases, has attracted more and more attentions of researchers due to its flexible system arrangement, excellent heat transfer performance and real-time adjustable heating surface etc. In order to provide data for optimal design and operational control of the curtain exchanger, experiments were conducted to investigate flow characteristics of sand particles and geometry of the curtain under different conditions such as air velocity at the inlet, initial thickness of particle curtain, diameter of sand particle and mass flow rate of particles etc.

Key words. Particle curtain heat exchanger; solid particle; flow characteristic; experimental investigation

1. Introduction
Based on the principle of gas-solid two-phase rapid thermal equilibrium, the particle curtain heat exchanger is attracting more and more attentions due to its flexible system arrangement, outstanding heat transfer capacity, and real-time adjustable heat-transfer capacity. With the micron size of silica sand as its heat carrier, the heat exchanger passes flue gas surplus heat to the heat carrier. Then by passing heat from the heat carrier to combustion air to realize the maximized recycle of the application of flue-gas heat in preheating combustion air [1-5].

The research of the gas-solid two-phase flow theory is relatively mature at home and abroad, but little researches on the flow characteristics of falling particles in horizontal airflow, mostly concentrated on the experiment. But most of the experiments are limited to a single inlet velocity, single particle diameter or single mass flow rate in the horizontal airflow [6-13]. The content and depth of the research is rather simple, the gas-particle two phase flow and heat transfer characteristics and fouling performances in a particle curtain heat exchanger still need to be further deepened. At the same time, the gas-particle two-phase flow and the heat transfer process in the particle curtain heat exchanger are very complicated.
2. The experimental equipment’s and method

2.1. The Experimental Equipment’s
The experimental equipment’s of the flow property of solid particle curtain in a particle curtain heat exchanger is shown in Figure 1. The device consists of the heat-exchanger itself, particle feeding system, particle collecting system, gas reducing uniform distribution, the heat exchanger itself is a channel of 2000mm long, 800mm wide and 1000mm high.

2.2. The Geometric Feature Parameters of the Particle Curtain
As shown in Figure 2, in order to quantitatively analyze the structural characteristics of the falling particle curtain, we defines the following geometric feature parameters related to it as follow: the left entrance of measuring pocket is taken as the origin, the horizontal direction of heat transfer exit as x-axis, the vertical direction of heat transfer as y-axis:

(1) Front/back boundary of particle curtain: the last /first boundary that airflow contacts with the particle curtain;
(2) The longitudinal thickness of the particle curtain $x_b$: the distance between the front and back boundary of particle curtain at the location of the same height in heat transfer channel;
(3) The vertical distance from the top of heat exchange chamber $h$;
(4) Particle curtain’s horizontal offset of the back edge $x_1$: the distance between the particle curtain’s back boundary after falling and before falling at the location of the same height in heat transfer channel;
(5) The horizontal offset of falling point $x_2$: the distance between the particle curtain’s center lines of droppoint after falling and before falling at the location of the same height in heat transfer channel;

![Fig.1 Schematic diagram of the particle curtain heat exchanger based on the single-stage unit.](image1)

![Fig.2 Schematic diagram of geometric feature parameters of the particle curtain](image2)
2.3. The experimental factors and design

2.3.1. The experimental factors. By adopting orthogonal design, this experiment is mainly researched the influence rules of four factors, i.e., inlet velocity $v_0$, the initial thickness of particle curtain $b_0$ and particle diameter $d_p$ to particle curtain’s horizontal offset of the back edge $x_1$, the horizontal offset of falling point $x_2$ and airflow velocity of particle curtain’s back $V_g$ edge, etc.

2.3.2. The experimental design. In order to prevent the out entrainment of small particles from the heat exchange chamber (this phenomenon is called elutriation), the maximum velocity $v_{\text{max}}$ is generally less than 2m/s, so the ranges of inlet velocity takes $1.0 \sim 2.0$ m/s; the initial thickness of particle curtain takes $60 \sim 180$ mm; when the solid particle size $< 200 \mu m$, particles enter the flue gas or air can reach thermal equilibrium instantly ($\sim 10^{-1}$s), heat transfer efficiency is high, therefore, the ranges of particle takes $120 \sim 300 \mu m$.

2.4. The experimental method

Five measurement holes with a diameter of 25mm were installed at equal intervals on the straight line that 250mm from the entrance of the heat exchange chamber and 850mm from the exit, the distance between every measurement hole is 166mm. To get the particle curtain’s front and back flow velocity distribution, the hot wire anemometer with precision of $\pm 0.05$m/s of VT110 model is used to measure and record air velocity values of measuring point 1-5. The intelligent anemometer of XY-5000PA model and standard pitot tube are used to measure and record air velocity of measuring point 6-10. In the heat exchange chamber, transparent lattice thin films were glued on the front wall of it, and using color pens to record particle curtain’s front and back boundary point in every measuring point, the distance between the front and back boundary point of particle curtain is particle curtain’s thickness in its location; the distance between particle curtain’s back boundary after falling and before falling is particle curtain’s horizontal offset of the back edge; after the falling of all particles, measuring the distance between the particle curtain’s center line of droppoint after falling and before falling, we can get the horizontal offset of falling point. At the same time, in order to guarantee the accuracy and credibility of experimental data, the high-speed digital camera of 1076 frames/s was used to capture the image of falling particles. Under this experimental condition, the thickness value of particle curtain, particle curtain’s horizontal offset of the back edge and particle curtain’s horizontal offset of falling point were gained through a weighted average of these data extracted from the photo and the measured values.

3. Experimental results and analysis

3.1. The impact of inlet velocity on the flow property of solid particle

3.1.1. The longitudinal thickness of the particle curtain and the horizontal offset of the back edge. Air velocity in this experiment is adjusted by controlling the forming complete sets of ventilator’s rotation rate through frequency convertor. Particle curtain’s longitudinal thickness and horizontal offset of the back edge under different inlet velocity are shown in Figure 3 and 4 respectively. As you can see in the two figures, when the inlet velocity increased from 1.45m/s to 1.88m/s, the longitudinal thickness of the particle curtain at the location of the same height decreases, while the horizontal offset of the back edge is of the opposite, the largest increase reached 25.61% and appeared on the point that with a vertical distance of 832mm from the top of the heat exchange chamber. This is because the gas-particle inter-phase momentum interaction degree increases with the increase of initial airflow speed, with it the particle’s horizontal movement speed will also
become bigger, therefore, the horizontal offset of the back edge increases with the increase of inlet velocity.

![Graph](image1.png)

**Fig. 3** The longitudinal thickness of particle curtain under different air velocity

![Graph](image2.png)

**Fig. 4** The trailing edge horizontal offset of particle curtain under different air velocity

![Graph](image3.png)

**Fig. 5** The placement horizontal particle curtain under different air velocity

3.1.2. *Particle curtain’s horizontal offset of falling point.* Particle curtain’s horizontal offset of falling point under different inlet velocity is shown in Figure 5. As you can see in the figure, the horizontal offset of falling point increases with the increase of inlet velocity. The reason is that when the particle curtain falling inside the heat exchange chamber, the contact of gas and solid particles is a process of exchange of momentum. When the horizontal movement speed becomes bigger, the
greater the gas-particle inter-phase momentum interaction degree is, the bigger the particles horizontal velocity component will be, and the bigger the particle’s horizontal displacement at the location of the same height will be.

3.2. Effect of the initial thickness of particle curtain on the flow property of solid particle

3.2.1. The longitudinal thickness of the particle curtain and the horizontal offset of the back edge. The initial thickness of particle curtain is defined as the thickness when the heat exchange particles just entered the heat exchange.

**Fig.6** The longitudinal thickness of particle curtain under different initial thickness of particle curtain

**Fig.7** The trailing edge horizontal offset of particle curtain under different initial thickness of particle curtain

**Fig.8** The placement horizontal particle curtain under different initial thickness of particle curtain
Channels. In this experiment, the initial thickness of particle curtain is changed by changing falling width of effective particles on the bottom floor screen cloth in the unfirming device of particles. The longitudinal thickness of the particle curtain and the horizontal offset of the back edge in different initial thickness of particle curtain are shown in Figure 6 and 7 respectively. As you can see in the two figures, when the initial thickness of particle curtain increased from 60mm to 140mm, the longitudinal thickness and horizontal offset of the back edge increases with it, the largest increase are 63.03% and 76% respectively, and these all appeared on the point that with a vertical distance of 832mm from the top of the heat exchange chamber. This is because when the falling particles’ mass flow rate remain the same, the smaller the initial thickness of particle curtain is, the more compact the distribution of particles will be. The greater the degree of interaction among falling particles when they move horizontally is, the smaller the particle curtain’s moving forward distance will be, therefore, the horizontal offset of particle curtain decreases with the decrease of the thickness of particle curtain.

3.2.2. Particle curtain’s horizontal offset of falling point. Particle curtain’s horizontal offset of falling point in different initial thickness of particle curtain is shown in Figure 8. As you can see in the figure, with the increase of the initial thickness of particle curtain, the particle curtain’s horizontal offset of falling point gradually decreased. The reason is that when the initial thickness of particle curtain increases, under a certain amount of particle mass flow rate, the sparse degree among particles will become bigger, the air drag force on particles will become smaller, consequently, the particles’ horizontal movement velocity components decreases, causing the decrease of particles’ horizontal displacement.

3.3. Effect of particle diameter on the flow property of solid particle

3.3.1. The longitudinal thickness of the particle curtain and the horizontal offset of the back edge. In this experiment, silica sand particles of different average particle diameter \(d_p\) were obtained by filtering with different aperture of screen cloth. The longitudinal thickness of the particle curtain and the horizontal offset of the back edge with different particle diameters are shown in Figure 9 and 10 respectively. As you can see in the two figures, when particle diameter \(d_p\) increases from 215\(\mu\)m to 310\(\mu\)m, the longitudinal thickness and horizontal offset of the back edge have a decrease tendency, the largest decrease are 20.78% and 24.48% respectively, and these all appeared on the point that with a vertical distance of 832mm from the top of the heat exchange chamber. The reason is that the smaller the particle diameter is, the larger the particles’ specific surface will be, it will make interaction area of gas-particles two-phase become bigger. That is to say, the greater the gas-particle inter-phase momentum interaction degree is, the bigger the particle’s horizontal velocity component will be, then the larger the particle curtain’s horizontal offset of the back edge will be. The horizontal velocity also increases the complex speed of the particles, leading to a gradual increase of the particle concentration in the cross section of the particles. When the airflow passes through the particle curtain, the particles will spread out, therefore, the smaller the particle diameter is, the larger the longitudinal thickness of the particle curtain will be.
3.3.2. Particle curtain’s horizontal offset of falling point. Particle curtain’s horizontal offset of falling point at different particle diameters $d_p$ is shown in Figure 11. It can be seen from the figure that with the increase of particle diameter, particle curtains horizontal offset of falling point decreases gradually. The reason is that when the particle diameter increases, the specific surface area of the particle decreases, which makes the area of momentum exchange between the airflow and the particle decreases. The concrete manifestations are: the force of airflow on the particles in the horizontal direction decreases, resulting in a decrease of particles’ velocity component in the horizontal direction and the reduction of speed in the horizontal direction eventually reduces the Horizontal offset.
4. Conclusion

Based on the above experimental results, the following conclusions can be drawn from the experimental study on the flow property of solid particle in the particle curtain heat exchanger:

1. The longitudinal thickness of the particle curtain increases with the initial thickness of particle curtain, and decreases with the increase of inlet velocity, particle diameter and particle mass flow rate.
2. Particle curtain’s horizontal offset of the back edge increases with the increase of inlet velocity and the initial thickness of particle curtain, and decreases with the increase of particle diameter and particle mass flow rate.
3. Under different inlet velocity, different initial thickness of particle curtain, different particle diameter and different particle mass flow rate, the longitudinal thickness of the particle curtain and particle curtain’s horizontal offset of the back edge all increase with the increase of particle curtain’s falling height.
4. Particle curtain’s horizontal offset of falling point increases with the increase of inlet velocity, and decreases with the increase of initial thickness of particle curtain, the particle diameter and particle mass flow rate.

Acknowledgments

I would like to express my gratitude to all those who helped me during the writing of this thesis. I gratefully acknowledge the help of my supervisor, Mr. Chen, who has offered me valuable suggestions in the academic studies. In the preparation of the thesis, he has spent much time reading through each draft and provided me with inspiring advice. Without his patient instruction, insightful criticism and expert guidance, the completion of this thesis would not have been possible.

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