Korean J. Chem. Eng., 39(2), 241-250 (2022)
DOI: 10.1007/s11814-021-0951-9

pISSN: 0256-1115
eISSN: 1975-7220

REVIEW PAPER

Experimental study on particle circulation characteristics of external circulating fluidized bed evaporator

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(*Received 20 April 2021 • Revised 21 August 2021 • Accepted 5 September 2021*)

Abstract−In order to solve the particle circulation problem of external circulation fluidized bed evaporator, a new particle circulation device was developed, and a cold experiment device was set up for reference to the principle of gas-solid circulating fluidized bed U-loop seal valve. The adjustment characteristics of the particle circulation device were studied experimentally. The effects of different flow combinations on pressure drop, particle circulation rate and particle volume fraction of heat exchange tube were investigated when the main flow and any auxiliary flow of the sealing valve were combined. It was found that when the main flow rate is constant, the pressure drop of the heat exchange tube increases with the increase of the auxiliary flow rate, and the pressure drop trend is stable when the main flow and loose flow are combined. The flow rate of particle circulation can be adjusted by adjusting the flow rate of any auxiliary flow alone, and fluidized flow has the strongest ability to regulate the particle circulation rate. The amplitude of the power spectral density of the pressure differential fluctuation signal is related to the particle circulation rate and volume fraction, so the flow state in the pipe can be studied by this method.

Keywords: Circulating Fluidized Bed, Particle Circulation Device, Seal Valve, Evaporator

INTRODUCTION

The evaporation process is one of the key steps in the utilization of saline wastewater. Since wastewater contains a great amount of salt and impurities, the scale formation of evaporation equipment is especially serious; the scale on the surface will not only cause the decrease of heat transfer efficiency and the increase of energy consumption, but also the corrosion of equipment and shorter service life. The circulating fluidized bed (CFB) heat exchanger was developed to overcome the problem of poor heat transfer performance and scale formation of the traditional heat exchanger. The principle is to transform a traditional heat exchanger into a multiphase fluidized bed heat exchanger system by adding inert solid particles into the heat exchanger system. While moving about, the solid particles destroyed the boundary layer of the flow, and the number of vaporization nucleus was increased. At the same time, the addition of solid particles increased the shear force of the fluid on the surface and destroys the distribution of temperature and concentration in the boundary layer. While achieving good anti-fouling and descaling effects, it also enhances the heat transfer process.

Currently, the research on circulating fluidized bed heat exchanger mainly focuses on two aspects: particle movement and pressure drop. Wen et al. [1], Wang et al. [2], Liu et al. [3], Pronk et al. [4] and Donghyun et al. [5] mainly studied the influence of the structure of the distribution plate, installation method, operating parameters and other factors on the particle distribution and pressure drop inside the heat exchange tube when the particle distribution device is installed in the tube box of the shell and tube heat exchanger. However, due to the limitation of technical confidentiality and production application of the distribution board design, the progress is still relatively slow even though a great deal of research has been down. There are still many improvements needing to be made. Liang and Zhang [6], Natarajan et al. [7], Jiang et al. [8], Liu and Sun [9], Shaikh and Razzak [10], and others have studied the influence of the measurement methods of solid holdup, particle parameters and operating conditions on the particle distribution in the tube/pipe. The correlations of average solid holdup in heat exchanger tubes under different conditions were studied, but correlations with universal significance were not obtained. In the aspect of pressure drop, Ritesh and Shilapuram [11], Wen and Jia [12], Grieco and Marmo [13] and Siyao et al. [14] investigated the effects of riser diameter, fluid medium characteristics, particle characteristics and heat flux on pressure drop of riser, the empirical formula of pressure drop under the experimental condition was obtained. Researchers have made systematic studies on the particle distribution and pressure drop of CFB heat exchangers. However, these studies have been carried out based on the normal circulation of particles in the heat exchanger. When the circulating fluidized bed heat exchanger is applied to the evaporating equipment, since the external circulation evaporator includes two ways of natural circulation and forced circulation, the circulation of particles can be realized if the evaporation process of natural circulation satisfies the initial fluidization velocity of particles, there is no requirement on external power supply. Most of the existing research is carried out under this circumstance. In the forced circulation evaporation process, the circulation of the fluid requires the use of the forced circulation pump to provide power, and the forced circulation pump

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usually does not allow the medium with particles through, so the forced circulation evaporation requires an independent particle circulation path. In terms of the particle circulation characteristics, Schmidtke and Genthner [15] proposed the forced external circulation evaporator. On the basis, Maddahi et al. [16] improved the traditional evaporator that is easy to scale and achieved on-line anti-scaling and descaling by controlling particle circulation. Klaren et al. [17], Hashemi et al. [18] and others conducted experiments to verify this equipment, and concluded such improvement is feasible. Wei [19] installed the nozzle as the particle circulation control device at the tee section between the external circulation fluidized bed and the horizontal conveying pipe. Experimental results indicate that the nozzle can achieve particle circulation well, but the energy consumption is high. At the current stage, there are insufficient studies on particle circulation in forced evaporators with external circulation.

To solve the problem of particle circulation in forced circulation evaporator, a particle circulation device is proposed in this paper. The key structure of the device is based on the design principle of U-Loop sealing valve in gas-solid circulating fluidized bed and applying it to the particle circulation device of the forced external circulation multi-phase flow evaporator, so the particle circulation device has a good ability of regulating and controlling the solid circulation quantity and ensure that the external circulation fluidized bed evaporator can operate within a larger load range. The flow seal valve is widely used in the gas-solid circulating fluidized bed reclaimer. Both domestic and foreign scholars have done considerable research on the operating characteristics of the flow seal valve [20-25]. These researches examine the effect of operating parameters and structural parameters on the operating characteristics of the flow sealing valve. Bandara et al. [25], Wang et al. [26], Basu and Cheng [27], Chinsuwan and Somjun [28] carried out a detailed study on the characteristics and flow model of the U-type return valve, and revealed the operating characteristics of the return valve to certain extent. However, because of the complexity of the structure of the flow seal valve and the combination of operating conditions, there is no general formula for the design of the return valve. At the same time, because the density difference between liquid and solid phase is much smaller than that between gas and solid phase, and the viscosity of liquid is much larger than that of gas, and the applications of gas-solid circulating fluidized bed and liquid-solid circulating fluidized bed are very different, it is necessary to do further research on the particle circulation characteristics of external circulating fluidized bed.

In this paper, a new type of external circulation fluidized bed evaporator particle circulation device is developed with a cold state experimental platform of external circulation fluidized bed evaporator. The structure parameters, auxiliary flow position and inlet mode, material characteristics, downcomer pipe diameter and operation conditions will affect the transmission of solid particles. The pressure drop can reflect the flow and power consumption in the heat exchanger directly and indirectly, and the movement of particles in the circulating fluidized bed heat exchanger directly affects the stable operation of the fluidized bed, the flow of the working fluid, the heat transfer effect, etc. Through an experimental study of the liquid-solid circulating fluidized bed of the new structure, we studied the impact of operating conditions on pressure drop, circulating flow rate and particle volume fraction of heat exchange tube under the circumstance with the same structural parameters and material characteristics of the particle circulation system, but different combinations of main water flow and auxiliary water flow. The study would provide technical support for further in-depth study.

EXPERIMENTAL APPARATUS AND METHODS

According to the process of a typical external circulating fluidized bed evaporator, the cold state experimental device for the external circulating fluidized bed evaporator was set up as shown in Fig. 1 and Fig. 2, including heat exchange pipe (0.02 m i.d.×1.25 m high), particle circulating devices, water tank, pump sets and measurement systems. The particle circulating device is composed of a liquid-solid separator (0.3 m i.d.), downcomer (0.06 m i.d.×0.85 m high), seal valve (0.955 m×0.2 m×0.955 m) and inclined tube (0.016 m i.d.×0.55 m high). Liquid-solid separator is used to separate liquid and solid. Most of the liquid through the overflow tube back to the storage tank, and a small portion of liquid with particles will flow into the downcomer. The downcomer is used to maintain the steady of solid particles flow and form enough pressure drop to overcome the liquid breakover problem between the seal valve and the liquid-solid separator. The function of the seal valve is to transport and regulate the circulation of solid particles. The right side is the delivery room and the left side is the feed chamber. The purpose of the inclined tube is to allow the particles from the delivery room to overflow into the main flow and to prevent the liquid breakover problem between the main flow and the seal valve. Due

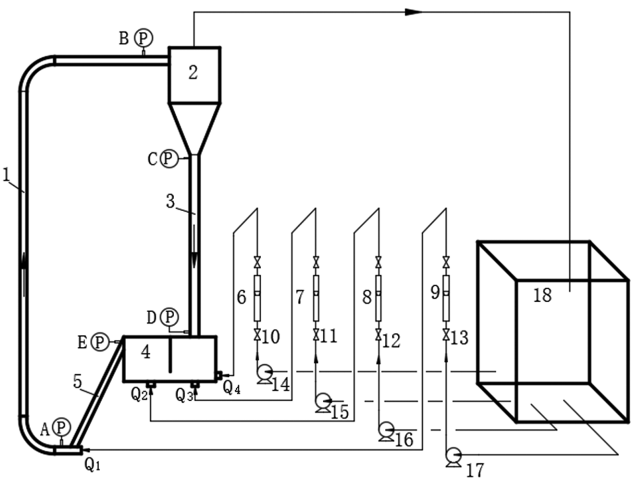

Fig. 1. Schematic diagram of cold experiment device of external circulating fluidized bed evaporator.

1 Heat exchanger tube
2. Liquid-solid separator
3. Downcomer
4. Seal valve
5. Inclined tube
6,7,8,9. Rotameter
10,11,12,13. Control valve
14. Side flow pump
15. Loose pump
16. Fluidization pump
17. Main flow pump
18. Water tank
Q_1. Main flow
Q_2. Fluidization flow
Q_3. Loose flow
Q_4. Side flow

Fig. 2. Physical drawing of the test system.

to the different regulating functions of auxiliary flows, each flow is controlled separately in this experiment. To observe the flow state of liquid and solid phases in each part of the process, the device is made of transparent Plexiglas.

According to the existing literature [3,9,19,29,30], the diameter of the heat exchange tube and the diameter of the downcomer of the liquid-solid separator are determined to be 20 mm and 16 mm, b respectively. The structural design of the sealing valve is related to the size of the downcomer, and the structural size of the seal valve is obtained as shown in Fig. 3.

The test was carried out in a liquid-solid system composed of water-particles at room temperature. The liquid medium was tap water, the solid particles of mean diameter and density which was 2.32 mm and 2,350 $kg\cdot m^{-3}$, respectively, were alumina. Initial particle mass in the system was 4.0 kg.

Pressure monitoring points were implemented at A, B, C, D and E as illustrated in Fig. 1. The pressure signals of each measuring point adopt CGYL-202 type pressure sensors. Because of the different pressure of installation positions, the measure ranges of different pressure measurement points are 0-20 kPa at A, 0-30 kPa at B and C, and 0-50 kPa at D and E, respectively, and the accuracy grade is 0.2%, which is determined by the sensor manufacturer. To avoid the disturbance of local flow field, wall-mount measurement was adopted. The pressure signal is collected by CGCJ-800 multi-function data collecting box, the collecting frequency is set to 100 Hz, the collecting time is 60 s-250 s.

The pressure drop of each key component is calculated from the pressure of each point, the particle circulating device reaches a pressure equilibrium at the steady state operation. Those can be written as,

$$\Delta P_{AB}+\Delta P_{BC}+\Delta P_{CD}+\Delta P_{DE}+\Delta P_{EA}=0$$

where the pressure drops at the liquid-solid separator (ΔP_{BC}), downcomer (ΔP_{CD}), seal valve (ΔP_{DE}) and inclined tube (ΔP_{EA}).

Main flow and auxiliary flow are measured by LZS glass rotameter with a measuring range of 600 $L\cdot h^{-1}$-800 $L\cdot h^{-1}$ and an accuracy of 20 $mLmin^{-1}$. The movement of particles was captured by high-speed camera (PCO1200 hs).

The circulating flow rate of solid particles in the heat exchange tube was measured by particle displacement tracking (PDT) method. A high-speed camera was used to capture the image of the particle movement in the heat exchange tube, and the pixel size was calibrated in pixels. In the processing software Adobe Photoshop, the actual size of the pixel was calibrated through the size of the pipe diameter, and Δh and punched Δt were calculated according to the pixel bits moved by the specific particles in the adjacent exposure photos. Under the condition of stable operation, by measuring the time required for the characteristic particles to rise to specific height in the heat exchange tube, the calculation formula

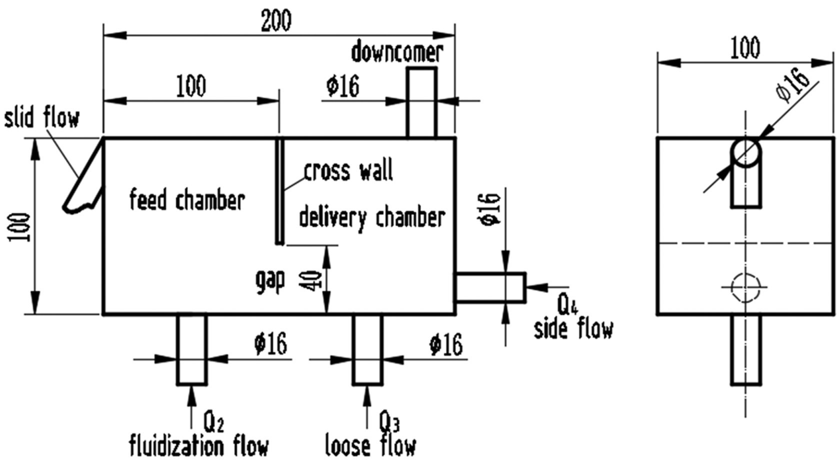

Fig. 3. Schematic diagram of seal valve.

of circulating flow rate is:

$$G_s = \frac{\rho_s \Delta h}{\Delta t}$$

To comprehensively investigate the impact of different operating conditions on the pressure drop, circulating flow rate and particle volume fraction of the heat exchange tube when the main flow is combined with different auxiliary flows, a total of 72 groups of experiments were carried out by single factor experimental method, the test scenario is shown in Table 1.

RESULTS AND ANALYSIS

To investigate the effect of different flow combinations on the pressure drop of the heat exchange tube, particle circulation flow rate, and particle volume fraction when the main flow is combined with any auxiliary flow, the main flow rate Q_1 is fixed and the fluidization flow rate Q_2, loose flow rate Q_3 and side flow rate Q_4 are changed separately. When the main flow rate is constant, the influence of the auxiliary flow rate change on the pressure drop of the heat exchange tube, the particle circulation flow rate, and the par-

Table 1. Combined test scheme of main flow and any auxiliary flow

The main flow+fluidization flow		The main flow+loose flow		The main flow+side flow	
Main flow Q_1 ($L \cdot h^{-1}$)	fluidization flow Q_2 ($L \cdot h^{-1}$)	Main flow Q_1 ($L \cdot h^{-1}$)	Loose flow Q_3 ($L \cdot h^{-1}$)	Main flow Q_1 ($L \cdot h^{-1}$)	Side flow Q_4 ($L \cdot h^{-1}$)
200	100-600	200	100-600	200	100-600
300	100-600	300	100-600	300	100-600
400	100-600	400	100-600	400	100-600
500	100-600	500	100-600	500	100-600

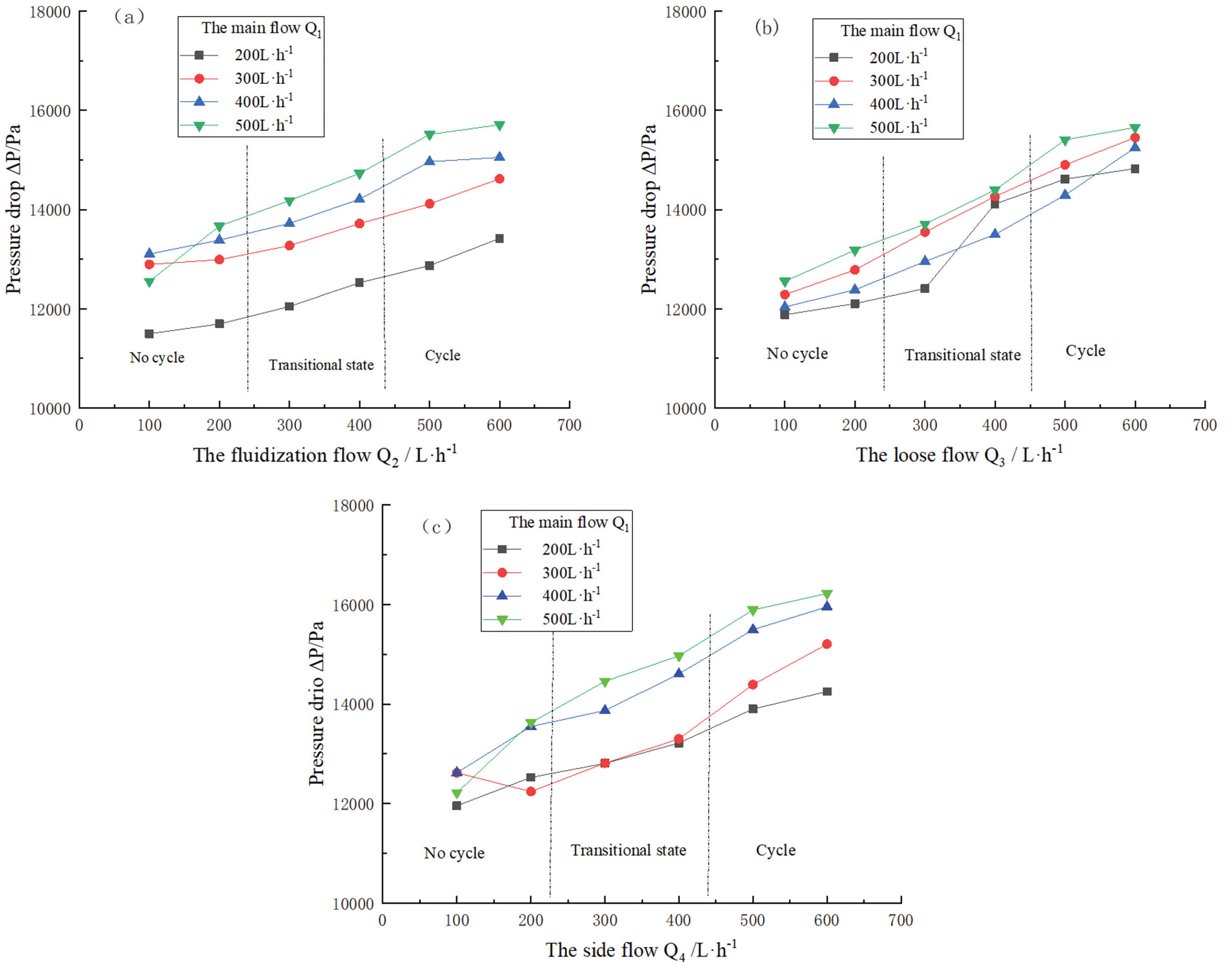

Fig. 4. The relationship between the auxiliary flow rate and the pressure drop of the heat exchanger tube when the main flow rate is constant.

ticle volume fraction are obtained.

1. Influence on Pressure Drop when the Main Flow Combined with Any Auxiliary Flow

The pressure drop along the tube side of the external circulating fluidized bed heat exchanger affects the distribution of particle void ratio and the entrainment of particles, and is closely related to the content and distribution of particles in the bed. At the same time, it provides a basis for the selection of power equipment. When the main flow rate is constant, the influence of the auxiliary flow rate on the pressure drop is shown in Fig. 4.

It can be seen from Fig. 4 that when the main flow is constant, the pressure drop of the heat exchange tube increases with the increase of the auxiliary flow. Therefore, regardless of the flow state in the tube, the pressure drop of the heat exchange tube is still positively correlated with the medium flow rate. In addition, from the perspective of experimental phenomena, the liquid-solid flow in the heat exchange tube can be divided into three states: particle no cycle, transitional state and cycle. As can be seen from Fig. 4(a), when the main flow rate is $200\,L\cdot h^{-1}$, the pressure drop changes abruptly with the fluidization flow, and the flow state in the corresponding pipe is also very unstable. This is because fluidization flow has a great influence on the flow of solid particles in the seal valve. When the auxiliary flow is constant, the pressure drop does not increase with the increase of the main flow rate, indicating that the pressure that the fluidization flow provides to the delivery room in the seal valve is also different for different main flow rate. This is because the amount of fluidization flow required to prevent the main flow from flowing backward along the inclined tube into the seal valve is also different. From Fig. 4(b), the pressure drop changes relatively smoothly with the loose flow rate. However, when the loose flow rate is constant, the change of pressure drop with the main flow rate is larger than the other two combinations. From Fig. 4(c), the influence of side flow on the pressure drop of the heat exchange tube is less regular since the side flow first enters the feed chamber of the seal valve and provides a driving force for the particles to pass through the gap of the seal valve. However, the structure of the feed chamber is complicated and the resulting flow state is unstable, resulting in an unstable pressure drop in the heat ex-

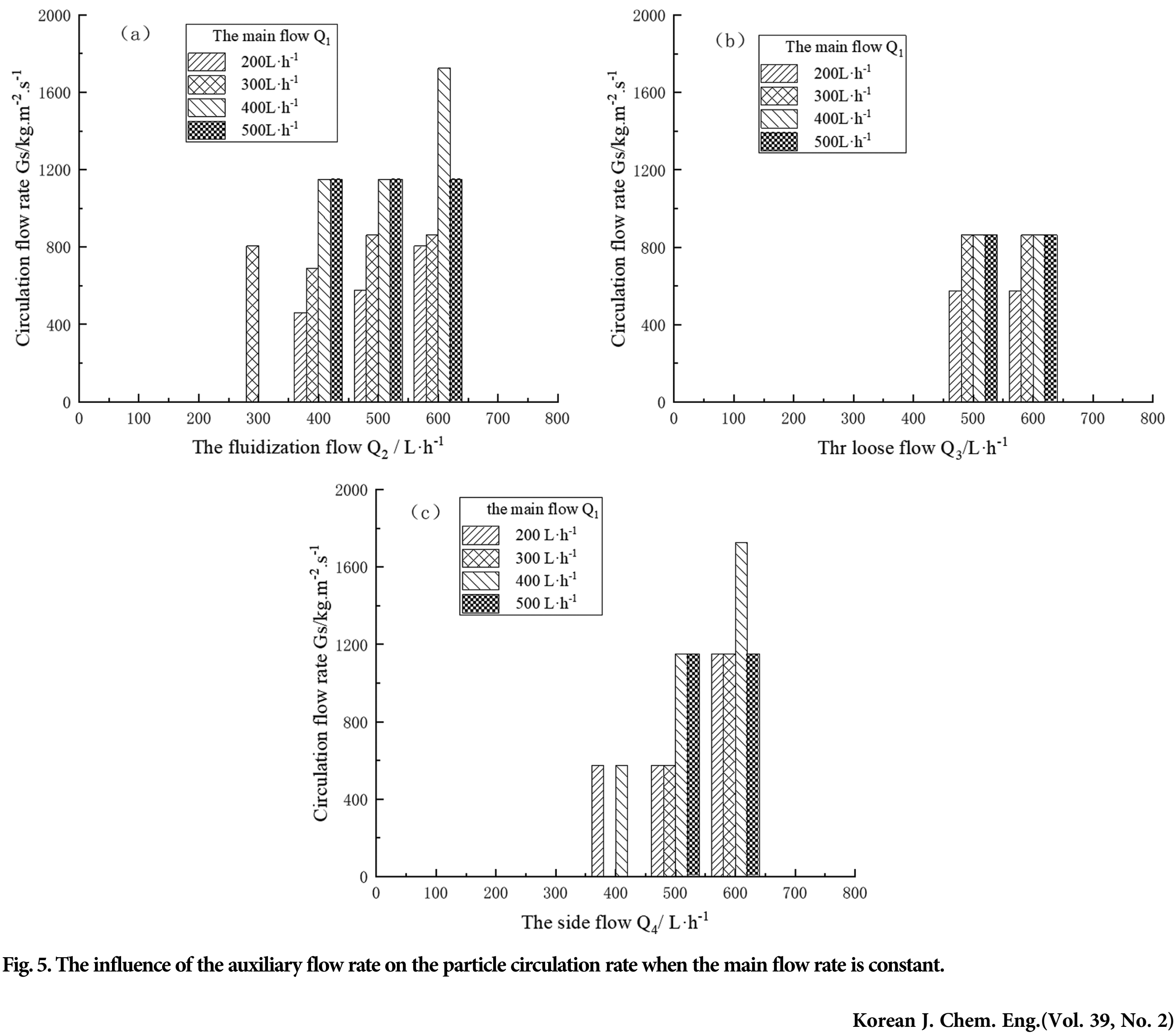

Fig. 5. The influence of the auxiliary flow rate on the particle circulation rate when the main flow rate is constant.

change tube. In conclusion, even if the rate of the main flow is the same as any auxiliary flow, the fluid velocity of the heat exchange tube is also different, which makes the particle flow state and pressure drop in the tube different. However, when the main flow and the loose flow are combined, the changing trend of pressure drop of heat exchange tube is relatively stable.

2. The Influence of the Combination of the Main Flow and Any Auxiliary Flow on the Particle Circulation Rate

In a circulating fluidized bed, the movement characteristics of the particles are of great significance to the overall performance of the evaporator. The study shows that as the circulating flow rate increases, the effect of descaling increases, but the wear rate on the inner wall of the tube also increases. Therefore, the particle motion in the heat exchange tube can be deeply understood by the particle circulation rate. When the main flow rate is constant, the effect of the auxiliary flow rate on the particle circulation rate is shown in Fig. 5.

As can be seen from Fig. 5, when the auxiliary flow rate is less than 300 $L{\cdot}h^{-1}$, there is no particle circulation in the heat exchange tube corresponding to any main flow rate under the experimental conditions; that is, the particle flow only begins in the heat exchange tube when the auxiliary flow rate increase to a certain value. The flow at this time is generally called the minimum auxiliary flow Q_{min}. When the auxiliary flow rate is less than Q_{min}, the particles in the downcomer and the seal valve are stationary or tend to move in the delivery room, and the circulating rate of the particles in the heat exchange tube is zero. The minimum auxiliary flow corresponding to different main flow is different.

From Fig. 5(a), when the fluidization flow rate is 300 $L{\cdot}h^{-1}$, there is particle circulation in the heat exchange tube with a particle circulation rate of 805 $kg{\cdot}m^{-2}{\cdot}s^{-1}$ only when the main flow rate is 300 $L{\cdot}h^{-1}$. When the fluidization flow rate is greater than 300 $L{\cdot}h^{-1}$ and the main flow rate is constant, the circulating flow rate varies with the increase of the fluidization flow rate. When the main flow rate is 200 $L{\cdot}h^{-1}$, the circulating flow rate increases with the increase of the fluidization flow rate. When the main flow rate is 300 $L{\cdot}h^{-1}$, the circulating flow rate first increases with the flow rate of the fluidization flow and then remains constant. When the main flow rate is 400 $L{\cdot}h^{-1}$, the circulating flow rate first remains constant with the flow rate of the fluidization water and then increases again. When the main flow rate is 500 $L{\cdot}h^{-1}$, the circulating flow rate does not change with the flow rate but remains a constant. It can be seen that when the main flow rate is constant, initial auxiliary fluidization flow rate is required to make the particles circulating in the heat exchange tube, and as the fluidization flow rate increases, the circulating flow rate can only be increased to a certain extent. This phenomenon is due to when the main flow is constant, a certain amount of fluidization flow is required to ensure no fluid will flow into seal valve from the main flow pipeline. In the experiment, the maximum particle circulation rate is 1,725 $kg{\cdot}m^{-2}{\cdot}s^{-1}$ when the main flow rate is 400 $L{\cdot}h^{-1}$ and the fluidization flow rate is 600 $L{\cdot}h^{-1}$.

From Fig. 5(b), when the loose flow rate is greater than 400 $L{\cdot}h^{-1}$, there is particle circulation in the heat exchange tube. When the loose flow rate is 500 $L{\cdot}h^{-1}$ and the main flow rate is 200 $L{\cdot}h^{-1}$, the particle circulation rate is 575 $kg{\cdot}m^{-2}{\cdot}s^{-1}$. When the loose flow is 600 $L{\cdot}h^{-1}$ and the main flow is 300 $L{\cdot}h^{-1}$, 400 $L{\cdot}h^{-1}$ and 500 $L{\cdot}h^{-1}$, the particle circulation rate is 862.5 $kg{\cdot}m^{-2}{\cdot}s^{-1}$. Therefore, when the main flow is constant, a higher loose flow is required to realize particle circulation in the heat exchange tube, and the particle circulation flow rate does not change much. It indicates the loose flow has a limited ability to adjust the particle circulation rate.

From Fig. 5(c), under the condition that the flow rate of side flow is 400 $L{\cdot}h^{-1}$, when the main flow rate is 200 $L{\cdot}h^{-1}$ and 400 $L{\cdot}h^{-1}$, there is particle circulation in the heat exchange tube, and the particle circulation rate is 575 $kg{\cdot}m^{-2}{\cdot}s^{-1}$. When the flow rate of side flow is 500 $L{\cdot}h^{-1}$ and 600 $L{\cdot}h^{-1}$, the circulating flow rate increases with the increase of the flow rate of side flow. In the experiment, the main flow rate is 400 $L{\cdot}h^{-1}$ and the flow rate of fluidization flow is 600 $L{\cdot}h^{-1}$, the maximum particle circulation rate is 1,725 $kg{\cdot}m^{-2}{\cdot}s^{-1}$, with the same results as the main flow rate and the fluidization flow rate.

It can be seen from Fig. 5 that the particle circulation rate can be adjusted by changing the rate of any auxiliary flow individually when the main flow rate is fixed, but the regulating effect is quite different. Compared with the experimental results, it is found that the fluidization flow has the best regulating ability because a certain amount of fluidization flow can restrain the reverse flow in the inclined pipe and help to make the particles in the delivery room form spouting flow, which is easier for particles moving along the inclined pipe to the main flow pipeline. The adjustment ability of the side flow is weaker, and the effect of the loose flow is the worst. Both flows influence the particle movement in the feed chamber. However, due to the difference of direction of the two flows, for the particle flow through the gap, side flow is better than loose flow.

3. Relationship between Power Spectral Density and Particle Circulation Flow Rate and Particle Volume Fraction

The Welch method was used to calculate the power spectral density of the pressure drop fluctuation signal in the manuscript. The power spectral density (PSD) provided by the MATLAB signal processing toolbox function automatically realizes the Welch method estimation, PSD is programmed by MATLAB to process the fluctuation signal of pressure drop. Power spectral density (PSD) is the signal description of the original time domain into a frequency domain, which reflects the probability distribution of the statistical parameters of the stochastic process in each frequency domain. It is a simple and effective method to describe the characteristics of wave signal in frequency domain. According to the amplitude distribution and energy distribution of each frequency component of the power spectral density of the pressure drop fluctuation signal, the relationship between the power spectral density and the circulating flow rate of particles in the heat exchange tube is studied. To examine the relationship between the PSD and the particle circulation flow rate and the particle volume fraction, this section only discusses the condition which the particle circulation is in the tube, i.e., the normal particle circulation in Fig. 4.

3-1. Combination of Main Flow and Fluidization Flow

Fig. 6 shows the relationship between the pressure drop signal of the heat exchange tube and the circulation flow rate and the volume fraction under different flow conditions due to the combination of the main flow and the fluidization flow.

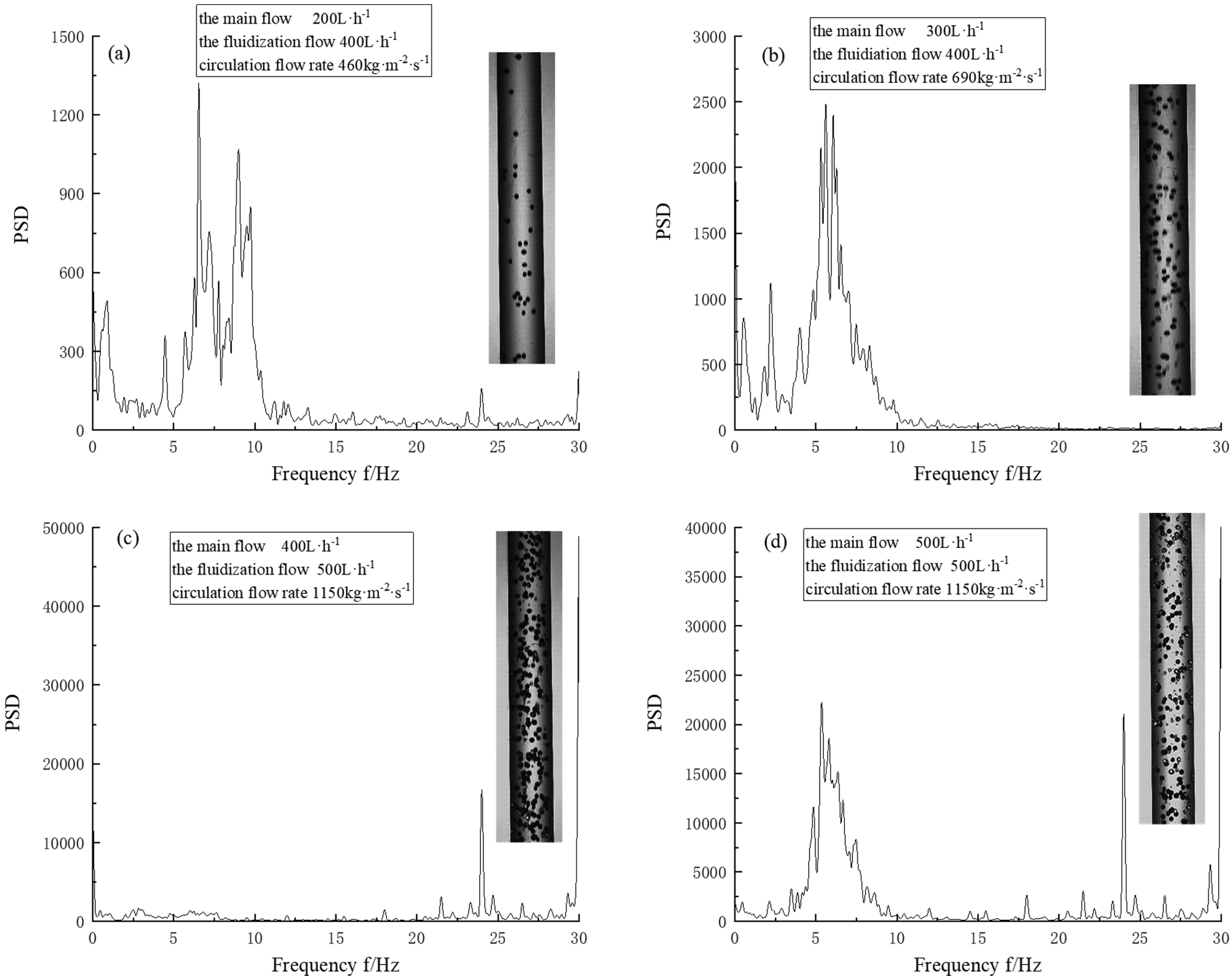

Fig. 6. The relationship between PSD and particle circulation flow rate and volume fraction when the main flow and fluidization flow are combined.

As can be seen from Fig. 6, with the increase of the sum of the two flows, both the circulation flow rate and the particle volume fraction in the tube increase, since the sum of the two flows, the liquid velocity in the tube and the energy driving the particle circulation increase, and the amplitude of the PSD increases. From Fig. 6(a) and Fig. 6(b), the particle volume fraction is not great, the particle distribution in the Fig. 6(b) is more homogeneous than that in the Fig. 6(a). And there is a clear peak in the PSD. The frequency of the highest peak is called the main frequency of the signal, the inverse of the signal main period. From Fig. 6(c) and Fig. 6(d), with the increase of the particle volume fraction in the tube, in addition to the main peak in the PSD, there is also a broad-band high-frequency signal, especially Fig. 6(d). The main reason is that when the volume fraction of particles is large, the collision among particles and the collision between particles and tube wall are more intense, and the disturbance of particle motion to flow field is also intensified. Fig. 6(a) and Fig. 6(b) indicates that there is an energy concentration on the PSD between 5 and 10 Hz when the particle volume fraction is low. As the volume fraction increases, as shown in Fig. 6(c), the PSD is concentrated at 25 Hz. In Fig. 6(d), the particle volume fraction decreases as compared to the Fig. 6(c), and the PSD is concentrated at between 5 and 10 Hz and around 25 Hz. A quantitative analysis cannot be given in the manuscript because the flow rate of the liquid in the heat exchange tube was not measured in the experiment.

3-2. Combination of Main Flow and Loose Flow

Fig. 7 shows the relationship between the pressure drop signal of the heating tube and the circulation flow rate and the volume fraction under different flow rates due to the combination of the main flow and the loose flow.

Comparing Fig. 6 and Fig. 7, the particle volume fraction in the tube is generally small when the main flow and the loose flow are combined. The loose flow from the storage tank through the pump 15 enters the feed chamber of the sealing valve, and loose flow needs to flow the solid particles from the sealing valve feed chamber to the delivery room. During the process, the flow needs to overcome the flow resistance between the feed chamber and the delivery room. In addition, the liquid-solid flow of the down-

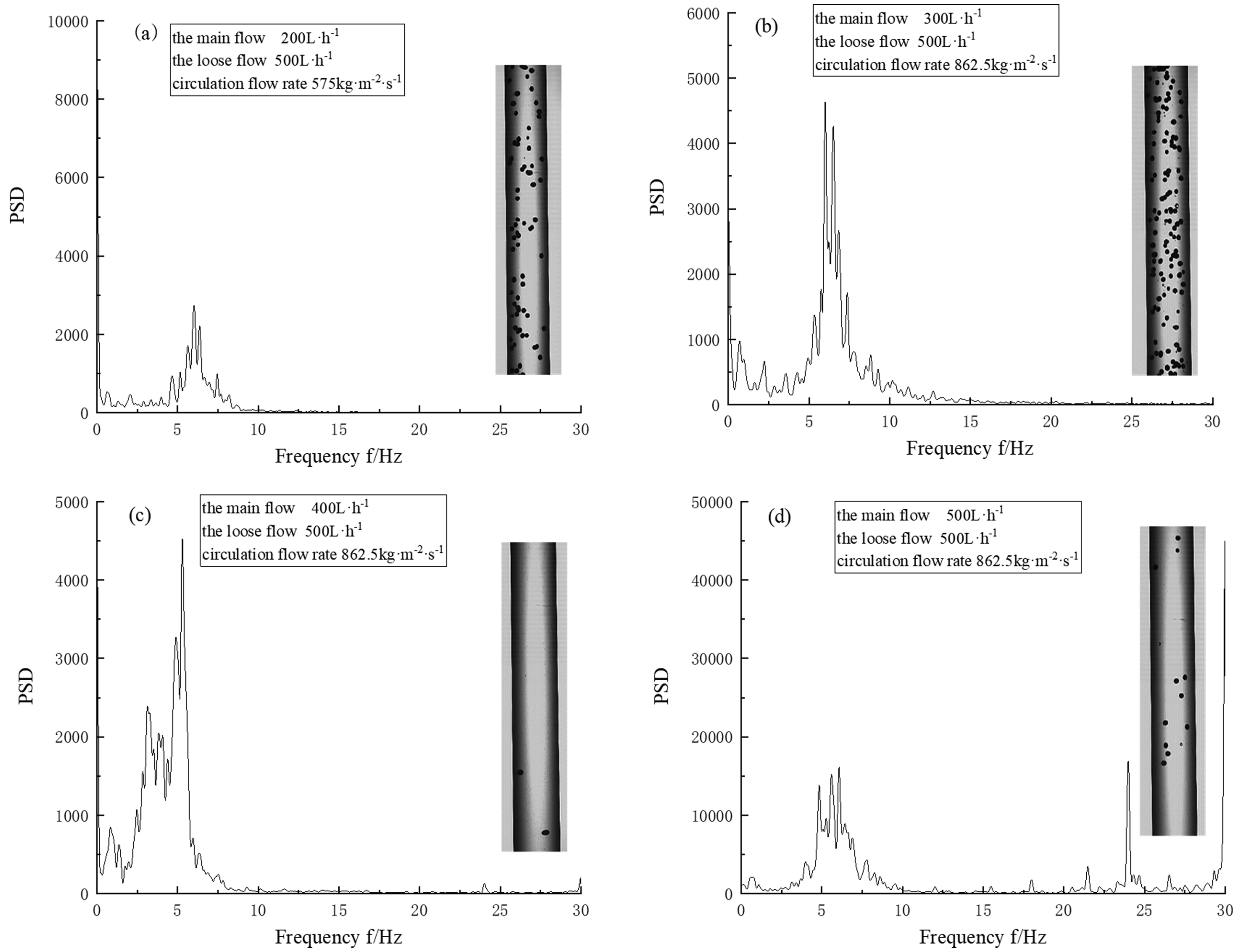

Fig. 7. The relationship between PSD and particle circulation flow rate and volume fraction when main flow and loose flow are combined.

comer is also related to the loose flow. From Fig. 7 and the experimental phenomena, the increase of the combined water flow is not conducive to the circulation of particles in the heat exchange tube. It is caused by the seal valve being required to prevent the increase of the pressure of the liquid in the inclined tube and the increase of the loose flow when the main flow increases. It also increases the friction resistance between the particles and the wall and between the particles in the downcomer, which makes it difficult for the particles to enter the feed chamber from the downcomer. As can be seen from Fig. 7(a) and Fig. 7(b), the energy distribution of the PSD is consistent when the particle volume fraction is similar to that of Fig. 6(a) and Fig. 6(b). According to Fig. 7(c), there is the approximate single-phase flow within the tube, and the PSD only reflects the condition of single-phase flow. There are few differences with the distribution of the PSD in Fig. 6(a), which requires the further identification of the cycle and non-cycle of particles. From Fig. 7(d), due to the relatively complex movement of particles in the seal valve, the flow rate in the heat exchange tube is very unstable, resulting the particle circulation unstable. The situation should be avoided in the actual production process. When the velocity of liquid in the heat exchange tube fluctuates greatly, it will cause the vibration of the heat exchange tube and the changing of evaporation volume will disrupt the normal process of evaporation. In conclusion, many factors should be considered in determining the discharge of the loose flow.

3-3. Combination of Main Flow and Side Flow

Fig. 8 shows the relationship between the PSD of the fluctuation signal of the pressure drop of the heat exchange tube and the circulation flow rate and volume fraction with different flow rates of the combination of main flow and side flow.

From Fig. 8(a) and 8(b), it can be seen that the circulation rate is 575 $kg\cdot m^{-2}\cdot s^{-1}$ under different flow rates, but the particle volume fraction increases with the total flow rate. Power spectral density also changes from the presence of the main peak to a relatively wide distribution. From Fig. 8(c) and Fig. 8(d), under different combined flow rates, the circulation flow rate in the tube is 1,150 $kg\cdot m^{-2}\cdot s^{-1}$, and the PSD has a main peak, but the corresponding frequency changes from 0-8 Hz to 3-10 Hz, and the amplitude changes from 4,000 to 8,000. It indicates that the side flow can adjust the particle volume fraction in the heat exchange tube, and it also provides the main driving force to overcome the flow resistance in the gap. The amplitude of the pressure drop fluctuation

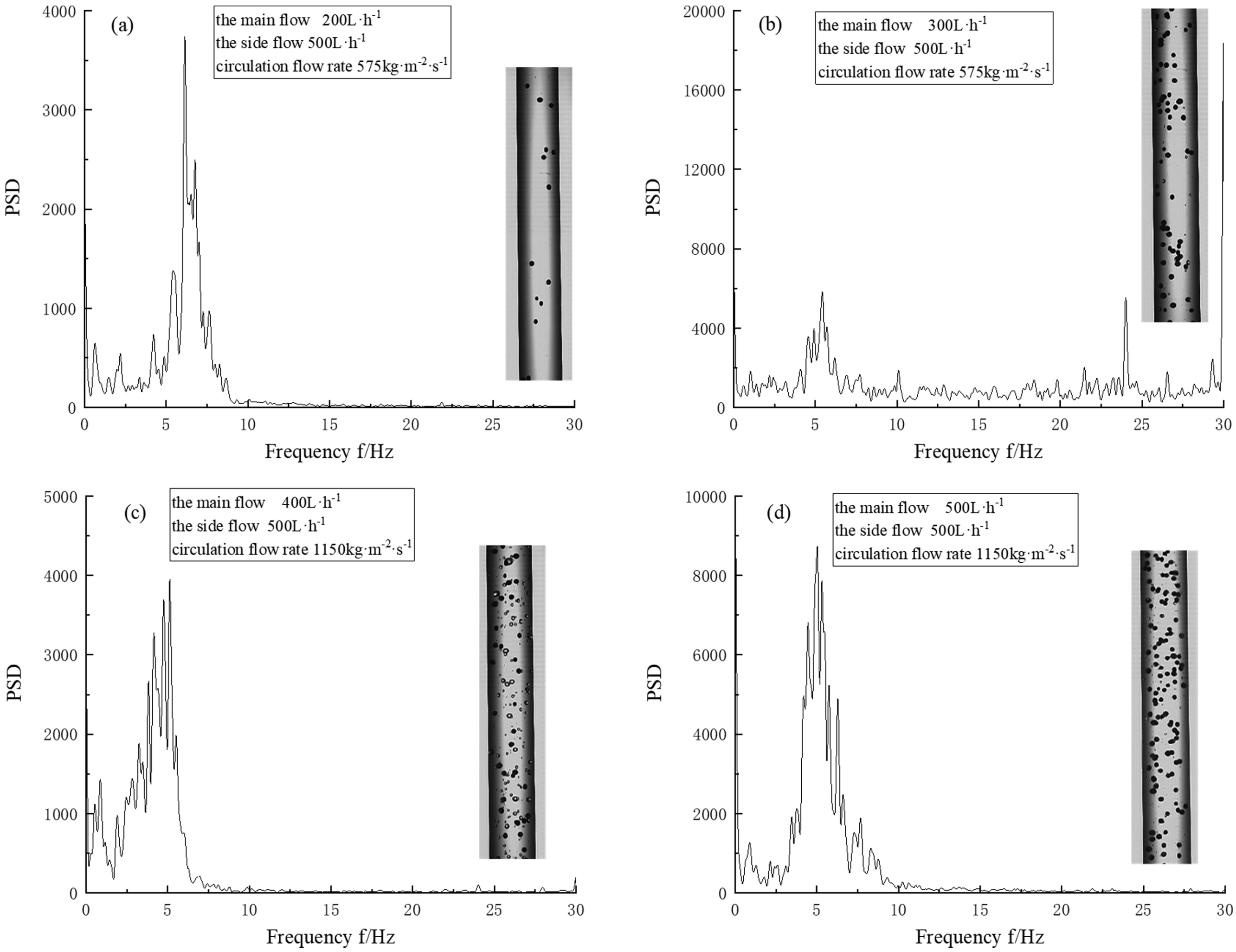

Fig. 8. The relationship between PSD and particle circulation flow rate and volume fraction when the main flow and side flow are combined.

signal can be used to study the flow state in the tube, and the relationship between the amplitude and the particle circulation flow rate and the volume fraction shows that the amplitude increases with the increase of the circulation flow rate. This method can be used to monitor the change of the flow state in the heat exchange tube, but it is necessary to study the relationship between the cyclic flow rate and the amplitude in detail on the basis of this study to obtain a general conclusion. In addition, during the experiment, it was found that the solid holdup in the tube changes with the flow rate of the liquid, and the fluctuation of the liquid velocity in the operation would lead to the fluctuation of the solid holdup in the tube and the change of the pressure drop in the tube; in severe cases, it may destabilize the entire circulatory system. Therefore, to avoid the unstable operation of the whole system, the relative stability of the flow in all structures needs to be ensured.

CONCLUSIONS

A cold experimental device for the external circulating fluidized bed evaporator was set up, Under the combined working conditions of main flow and fluidization flow, loose flow and side flow respectively, the change rules of pressure drop, circulating flow rate and particle volume fraction in the heat exchange tube with operating conditions were investigated. The conclusions are as follows:

When the main flow is constant, the pressure drop of the heat exchange tube increases with the increase of the auxiliary flow. When the main flow and the loose flow are combined, the pressure drop of the heat exchanger is stable.

When the main flow rate is constant, the particle circulation rate can be adjusted by adjusting any auxiliary flow rate. The fluidization flow rate has the greatest ability to adjust the particle circulation flow rate.

In the case of particle circulation, the amplitude of the spectral density of the pressure signal has a corresponding relationship with the particle circulation rate and the volume fraction, and the flow state in the tube can be characterized by the amplitude change.

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