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ORIGINAL RESEARCH ARTICLE

Experiment and characterization of dynamic thermal storage characteristics of porous media thermal storage system

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ABSTRACT

The aim is to understand the thermal storage characteristics of porous media thermal storage materials under thermal dynamic conditions, and obtain the dynamic thermal storage characteristics parameters of thermal storage materials. In the 120 kW thermal dynamic thermal storage system of porous media, we studied the dynamic thermal storage characteristics of honeycomb porous ceramic thermal storage materials with different pore diameters (2.9, 4, 5.5 mm) and lengths (100–400 mm) under different hot flue gas conditions include thermal storage rate, thermal storage efficiency and storage. The results show that the relationship between the heat storage rate and time is parabolic, and the heat storage efficiency gradually decreases with the heat storage time. At the same time, the regenerative rate and unit regenerative resistance loss increase with the increase of specific surface area or the decrease of pore diameter of regenerator, and the regenerative efficiency increases with the increase of regenerator length. According to the experimental research and analysis, the dynamic heat storage characteristics of porous regenerator can be characterized by heat storage rate, heat storage efficiency and unit heat storage resistance loss.

Keywords: Porous Media; Thermodynamics; Dynamic; Heat Storage; Heat Storage Rate; Heat Storage Efficiency; Heat Storage Resistance

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1. Introduction

High-temperature air combustion technology can recover waste heat from flue gas and preheat combustion air efficiently, which has the dual advantages of greatly saving energy and reducing emission of NO and other pollutants in flue gas[1-4]. Porous media, including honeycomb ceramic regenerator, is widely used in air combustion technology under high temperature because of its excellent thermophysical properties, chemical properties, economic properties, mechanical properties and thermal shock resistance. Its internal heat exchange performance and resistance characteristics determine the overall performance of waste heat recovery system and affect the design of heat storage system[5-6].

Gas-solid heat transfer characteristics in regenerator are important thermal properties of regenerator. Yuan *et al.*[7-9] and Srikanth *et al.*[10-14] analyzed and summarized the gas-solid heat transfer characteristics inside the regenerator, and pointed out that the heat flow rate, heat transfer area and structure of high-temperature air flow are all important parameters that affect the heat storage performance. The experimental conclusion shows that the average convective heat transfer coefficient of porous honeycomb regenerator increases with the increase of high-temperature gas flow rate and the decrease of pore size. Some researchers also use temperature efficiency (the ratio of actual flue gas heat release to theoretical maximum heat release)[15-17] and heat recovery rate (the ratio of actual flue gas heat absorbed by heat storage system to theoretical maximum flue gas heat absorbed)[18-19] to characterize heat storage. The study shows that both of the efficiencies increase with the increase of the length of the regenerator. Other researchers[20-23] defined the ratio of heat stored by the regenerator to resistance loss as the thermal performance index, which represents the heat stored by the regenerator under the condition of unit resistance loss.

In the above experimental study, the gas-solid convective heat transfer coefficient and heat storage efficiency in the regenerator are taken as the parameters to measure the heat storage performance, and the average heat storage of the regenerator in a period of time is studied. Whether these parameters can fully represent the thermal storage characteristics in the design and operation of large thermal storage system, and how the related parameters change dynamically with time, all these problems need further study.

In this paper, the dynamic thermal storage test of porous media honeycomb ceramics with different structures is carried out in the thermal storage test system of 120 kW power, and the dynamic thermal storage characteristics of the regenerator are studied. The thermal storage rate, thermal storage efficiency and specific thermal storage resistance loss are defined as the thermal storage characteristic parameters, which can provide guidance for the industrial design and operation of the porous media thermal storage system.

2. Experiment and method

As shown in **Figure 1**, the porous medium dynamic heat storage test system mainly consists of a combustion engine, a high-temperature flue gas mixing chamber, a porous medium heat storage test chamber, an induced draft fan, a water cooling system and a test system.

The high-temperature flue gas of porous medium dynamic thermal storage system is provided by diesel combustion engine, and the designed thermal power is 120 kW. In order to stabilize the flow rate of high-temperature flue gas entering the porous medium thermal storage test device, a high-temperature flue gas mixing chamber is set in front of the thermal storage test device, which is made of Castable. Three K-type thermocouples are arranged in the mixing chamber along the central axis to measure the temperature distribution in the furnace. In order to observe the combustion flame conveniently, two Shi Ying glass observation windows are set in the middle of the side of the mixing chamber.

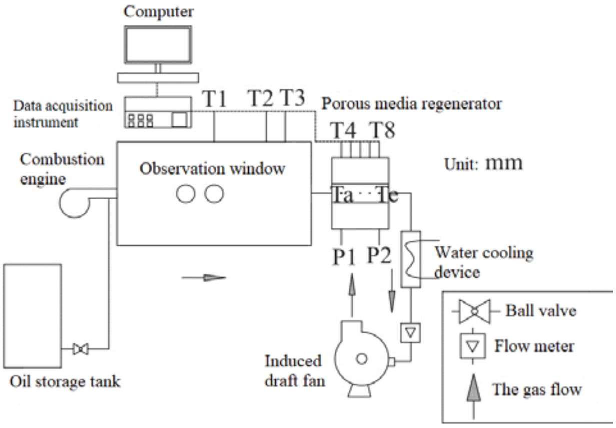


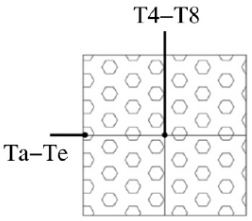
Figure 1. Schematic diagram of dynamic thermal storage test system for porous media.

The heat storage material is placed in the porous medium heat storage test room, and its front view and side view are shown in **Figure 2**.

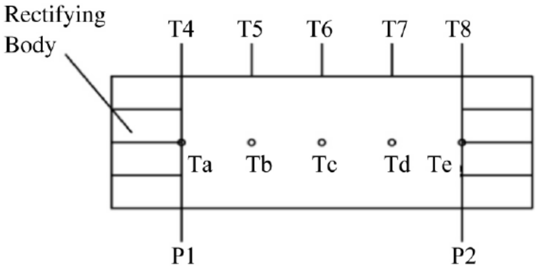
Porous medium regenerator is made of Castable, and thick silicic acid insulation cotton is laid outside to reduce heat dissipation. The regenerative chamber is 600 mm in length and 200 mm × 200 mm in cross section, and each cross section can discharge 4 pieces of porous medium honeycomb ceramic regenerative bodies of 100 mm × 100 mm × 100 mm (see **Figure 2**).

A total of 10 K-type thermocouples are arranged in the regenerator, in which Ta-Te thermocouples extend into the regenerator wall to measure the temperature of the regenerator wall. T4-T8 thermocouples extend into the center of the section of the regenerative chamber, and measure the temperature at the center of the regenerator, with each thermocouple spaced 100 mm apart.

During the test, eight heat accumulators at the inlet and outlet of the heat accumulator chamber were kept unchanged, which were used as rectifying heat accumulators to study the heat storage characteristics of the middle heat accumulator. Adjust the axial length of the regenerator by changing the number of discharge blocks of the regenerator.



(a) Main view of regenerative chamber



(b) Side view of regenerative chamber

Figure 2. Main drawing of regenerative chamber.

Pressure measuring points are set at the inlet and outlet of the regenerator, and the resistance loss in the regenerator is measured by connecting a differential pressure transmitter with a hose. All thermocouple signals and pressure signals in the test are connected with the computer through the data acquisition instrument, and the data are automatically collected every 5 s and displayed and stored in real time. Flue gas flow is measured by vortex flowmeter. Before each test, the regenerator is at room temperature.

The combustion of medium and diesel oil burners produces high-temperature flue gas, which enters the heat storage test device after being stabilized in the mixing chamber, and heats and stores heat in the porous medium honeycomb ceramic heat storage device. The experimental power of the burner is 60 kW, 72 kW and 84 kW respectively, and the corresponding flue gas mass flow rates are 89 kg/h, 107 kg/h and 125 kg/h, respectively. Three kinds of porous honeycomb ceramic regenerators with the same material and different geometric structures were used in the test, all of which have hexagonal pass, with structural parameters as shown in **Table 1** and test conditions as shown in **Table 2**.

Table 1. Structural parameters of honeycomb ceramic regenerator

Accumulator number	No.1	No.2	No.3
Pass	Hexagonal	Hexagonal	Hexagonal
Material	mullite	mullite	mullite
Wall thickness/mm	1.4	0.9	0.8
Aperture/mm	5.5	4	2.9
Specific surface area/m^2·m^{-3}	462	666	847
Void ratio (ε)	0.63	0.66	0.61
Density/kg·m^{-3}	1,169.2	1,074.4	1,232.4

Table 2. Test conditions

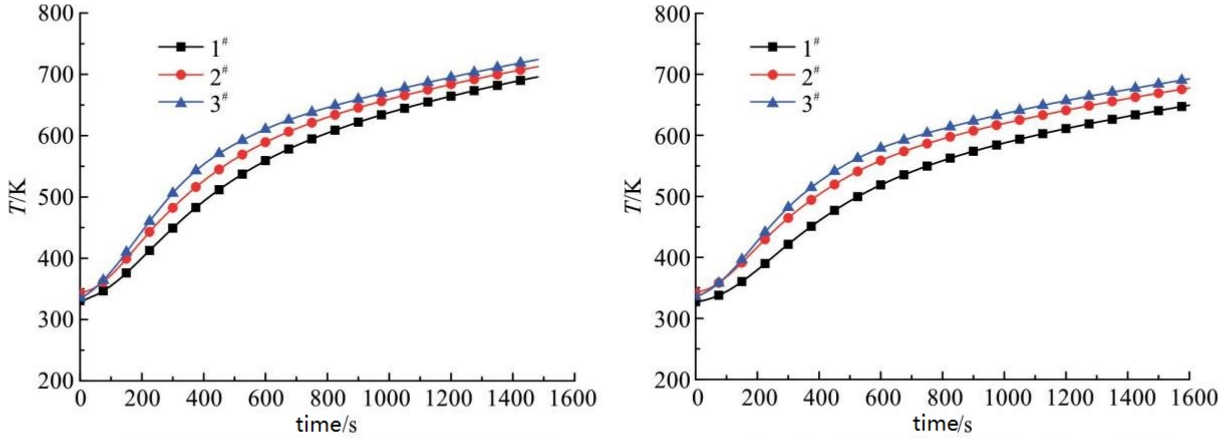
Flue gas flow/kg·h^{-1}	Heat accumulator	Heat accumulator length/mm
89	No.1	400
	No.2	400
	No.3	400
107	No.1	400
	No.2	400
	No.3	400
125	No.1	400
	No.2	400
	No.3	400
107	No.1	300
107	No.1	200
107	No.1	100

3. Experimental results and discussion

3.1 Dynamic temperature distribution of porous regenerator

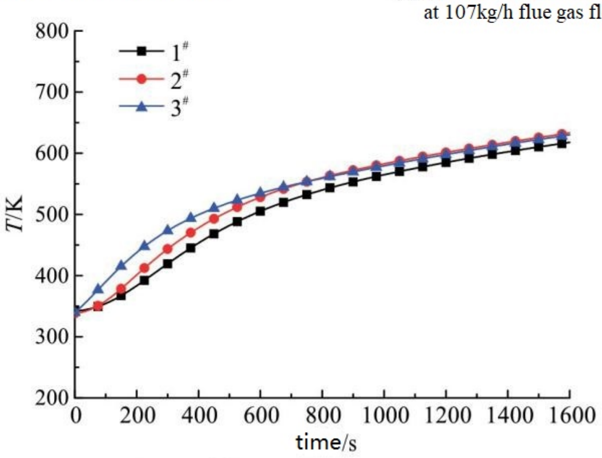
Figure 3 shows the dynamic distribution of the average temperature of the regenerator in the process of heat storage under different working conditions. Is the weighted average temperature of each temperature point in the temperature regenerator.

As can be seen from **Figure 3**, with the progress of the heat storage process, the internal temperature of the regenerator rises and gradually stabilizes. When the mass flow rate of flue gas is constant, the temperature difference of regenerator with different structures is not significant. When the flue gas flow rate is 125 kg/h, the regenerator temperature reaches 600 K in about 600 s, and when the flue gas flow rate is 107 kg/h, the regenerator temperature reaches about 800 s at 600 K and 89 kg/h, it reaches this temperature around 1200 s. The larger the flue gas flow rate, the shorter the time it takes for the regenerator to reach the same temperature, which is consistent with the research results of Srikanth and Assunta *et al*.[10,24]. The reason is that the larger the gas heat flow rate, the larger the flow velocity in the flue gas hole, the more intense the convective heat transfer between gas and solid, the better the heat transfer effect, and the shorter the time for solid to approach the temperature of gas flow.



(a) Dynamic temperature distribution of regenerator at 125kg/h flue gas flow

(b) Dynamic temperature distribution of regenerator at 107kg/h flue gas flow



(c) Dynamic temperature distribution of regenerator at 89kg/h flue gas flow

Figure 3. Dynamic temperature distribution of heat accumulator under different working conditions.

3.2 Dynamic flow characteristics of flue gas in porous regenerator

In the process of heating the regenerator with high temperature flue gas, the velocity of flue gas flowing through the regenerator changes dynamically due to the dynamic change of the regenerator temperature. The velocity in the high temperature flue gas hole can be calculated by formula (1).

$$v = \frac{q_v}{A_\Sigma} \tag{1}$$

Where: q_v is the gas flow rate, measured by the flowmeter in real time, m^3/s; A is the cross-sectional area of the regenerator, which is 0.04 m^2 in this paper; ε is the porosity of the regenerator.

Figure 4 shows the relationship between the velocity of flue gas in the hole and time under different working conditions. In the initial stage of heat storage, the increase of the temperature inside the regenerator causes the volume expansion of flue gas flowing through it, which in turn increases the flow velocity in the hole, and then the temperature of the regenerator gradually stabilizes and the flow velocity in the hole gradually fluctuates at a certain value. With the increase of high temperature flue gas mass flow rate, the velocity in flue gas hole increases; With the decrease of the void ratio of the regenerator, the flow area of the regenerator per unit section decreases, and the flow velocity in the hole increases when the flue gas flow rate is constant.

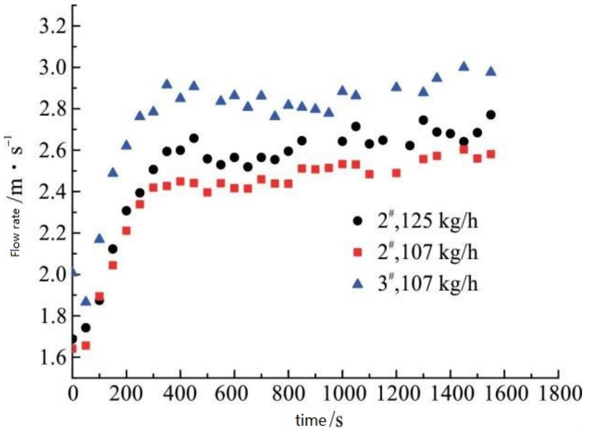


Figure 4. Variation of flow velocity in flue gas hole at inlet with time.

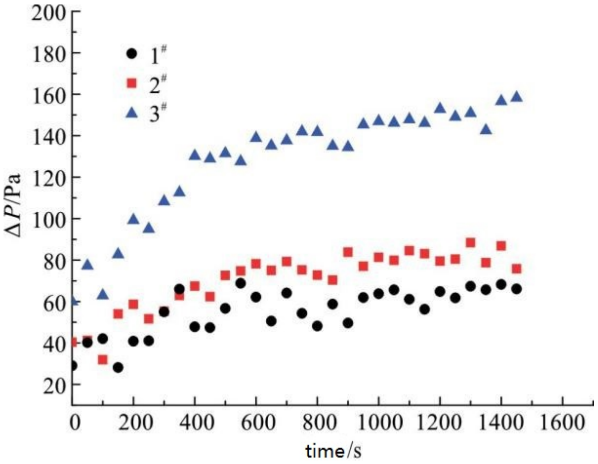


Figure 5. Variation of pressure drop of regenerator with time under 125 kg/h flue gas flow rate.

Figure 5 shows the resistance loss of regenerator with different structures under the flue gas flow rate of 125 kg/h. It can be seen from the figure that the flow rate in the hole and the temperature of the regenerator rapidly increase (see **Figure 3** and **Figure 4**) during the start time of heat storage. It results in an increase in resistance loss, and then the temperature of the regenerator and the flow rate in the hole gradually stabilize, and the resistance loss also gradually stabilizes. Resistance loss under the same flue gas flow rate: No.3 regenerator > No.2 regenerator > No.1 regenerator. The smaller the diameter of the regenerator is, the greater the velocity in the hole and the greater the resistance loss along the path. The increase of specific surface area of regenerator means that the contact area between airflow and regenerator increases, which leads to the increase of friction between airflow and regenerator and the increase of resistance loss. Therefore, the resistance loss of regenerator increases with the decrease of pore size and the increase of specific surface area. This conclusion is consistent with the research results of Yuan and others[25-30].

3.3 Characterization parameters of thermal storage characteristics of porous thermal storage materials

3.3.1 Heat storage rate

In **Figure 3**, there is little difference in dynamic temperature distribution curves of regenerators with different structures. In order to more clearly study and compare the temperature change speed of porous regenerators with different structures in the process of heat storage, the "heat storage rate" is used here to characterize, which is defined as the heat storage capacity per unit mass of regenerators in a certain period of time. According to the definition of "heat storage rate", it can be used to express the degree of heat storage of porous heat storage materials:

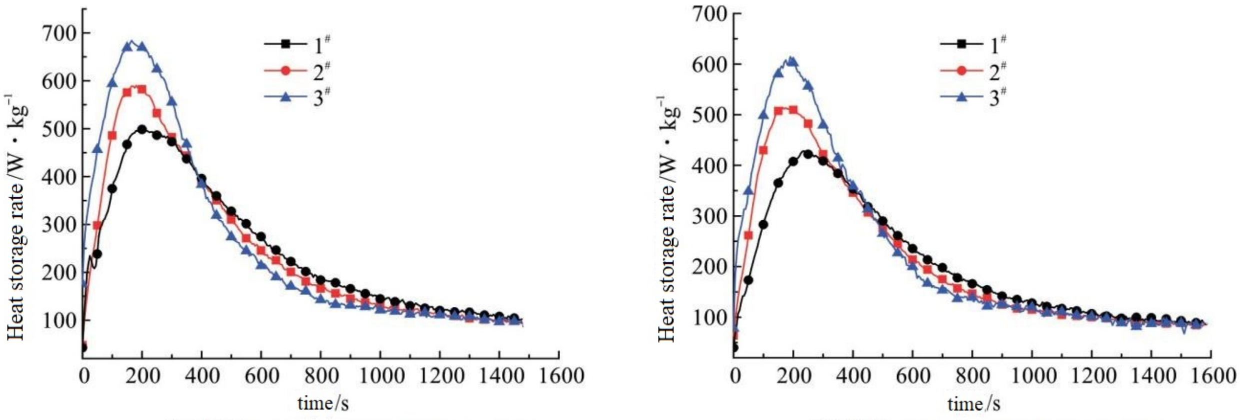
$$Q_v = \frac{\int_{T_1}^{T_2} C_p dT}{\Delta t} \tag{2}$$

Where: T_1 and T_2 are the average temperatures before and after each acquisition by the data collector; Setting value of C_p.

Figure 6 shows the relationship between heat storage rate and time under different working conditions under the above definition of heat storage rate.

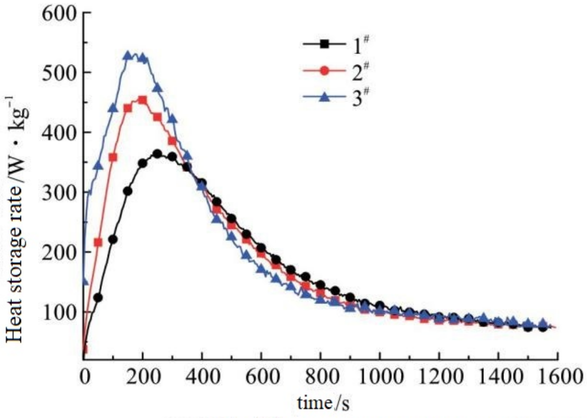
It can be seen from **Figure 6** that the change trend of heat storage rate under different working conditions is similar, and the peak time is around 200 s. The area before the peak is called the heat storage front section, and the area after the peak is called the heat storage rear section. If the radiant heat transfer between flue gas and regenerator is not considered, the heat storage rate depends on the intensity of gas-solid convection heat transfer. In the front stage of heat storage, the temperature difference between gas and solid in the regenerator is large, and at this time, the flow velocity in the hole is rapidly increasing (see **Figure 4**), the convection heat transfer intensity of the gas-solid is intense, and the heat storage rate is almost linearly increasing. In the later stage of heat storage, the temperature difference between gas and solid gradually decreases, the flow velocity in the hole gradually stabilizes, and the heat storage rate gradually decreases, and there is little difference between the heat storage rates of different regenerators in the later stage of heat storage.

It can be seen from **Figure 6** that for the same regenerator, the greater the flue gas heat flow, the greater the heat storage rate. Under the same flue gas heat flow rate, the regenerative rate of No.3 regenerator is higher than that of No.1 and No.2. The wall thickness and porosity of the three kinds of regenerators are similar, and the third regenerator has the smallest aperture and the largest specific surface area. Yuan[7] and others pointed out that the smaller the pore size, the better the thermal performance of the regenerator. Meng[9], Wen[11] and others pointed out that the larger the specific surface area, the larger the gas-solid heat transfer area, and the more heat transfer under the same conditions, the better the thermal performance of the regenerator.



(a)Heat storage rate at 125 kg/h flue gas flow

(b)Heat storage rate at 107 kg/h flue gas flow



(c)Heat storage rate at heat storage rate at 89 kg/h flue gas flow

Figure 6. Heat storage rate of heat accumulator under different working conditions.

The two views seem unrelated, but in fact they are mutual verification. Because the specific surface area of the regenerator is determined by the pore size and wall thickness. When the wall thickness of the regenerator is similar, the smaller the pore diameter, the larger the specific surface area. **Figure 6** verifies the viewpoint of the above researchers. Therefore, when other conditions are the same or close in this case, the smaller the pore size of the regenerator, the larger the specific surface area, the larger the gas-solid heat exchange area, the faster the heat storage, and the better the heat storage effect.

The gas-solid convective heat transfer coefficient of the regenerator proposed by previous scholars can reflect the gas-solid heat transfer inside the regenerator, while the heat storage rate proposed in this paper reflects the direct result of gas-solid heat transfer, that is, the speed of heat storage. Compared with the gas-solid convective heat transfer coefficient, the heat storage rate is more intuitive to characterize the heat storage characteristics, and it is more efficient to select the regenerator suitable for the heat storage system than the size of the heat storage rate. Therefore, the heat storage rate proposed in this paper has more reference value than the gas-solid convective heat transfer coefficient proposed by previous scholars.

3.3.2 Heat storage efficiency

The speed of heat storage of porous media regenerator is characterized by heat storage rate. Except that, in the process of dynamic heat storage, the ability of regenerator to store the total heat carried by high-temperature flue gas is also an important feature of heat storage material, which reflects the ability of regenerator to utilize the heat passing through it, that is, the degree of utilization of flue gas waste heat. "Heat storage efficiency" can be defined to characterize:

$$\eta = \frac{T_{in} - T_{out}}{T_{in} - T_0} \tag{3}$$

Where, T_{in} is the high temperature flue gas temperature at the entrance of the regenerative body; T_{out} for storage Flue gas temperature at hot body outlet; T_0 is the initial temperature of the heat accumulator Degrees.

Heat storage efficiency means the ratio of the actual heat release of high-temperature flue gas to the theoretical maximum heat release, which is basically the same as the definitions of temperature efficiency and heat recovery rate mentioned earlier, and both reflect the utilization degree of heat carried by the regenerator on flue gas. The higher the heat storage efficiency, the more fully the heat carried by flue gas is utilized. Hong *et al*.[17] pointed out that the length of the regenerator is the main factor affecting the temperature efficiency, but the void ratio has little effect on it, so this paper focuses on the study of the heat storage efficiency of different length regenerators.

Figure 7 shows the dynamic heat storage efficiency of No.1 regenerator at different lengths when the flue gas flow rate is 107 kg/h. With the increase of heat storage time, the temperature difference between inlet and outlet of flue gas becomes smaller and smaller, and the heat storage efficiency also decreases gradually. Therefore, at the beginning of heat storage, the heat storage efficiency is the highest, at this time, the flue gas waste heat of the regenerator is fully utilized, and the heat storage efficiency has dropped below 0.3 when the heat storage reaches 1,000 s. At any moment, the longer the length of the regenerator, the greater the heat storage efficiency. Because this dynamic regenerative efficiency can be used to reflect the utilization degree of flue gas waste heat by the regenerator at a certain moment.

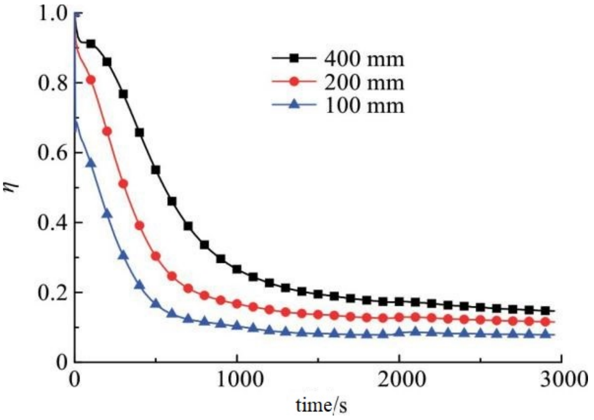


Figure 7. Dynamic heat storage efficiency of No.1 regenerator under 107 kg/h flue.

3.3.3 Unit heat storage resistance loss

According to the experimental results, it is found that when the diameter or specific surface area of the regenerator changes, the influence on the regenerative rate and the resistance loss of the regenerator is the same, that is, the resistance loss will also increase with the increase of the regenerative rate. Therefore, the resistance that the regenerator needs to overcome to store the unit heat is also an important index of the design and operation of the regenerator system, which reflects the loss of the unit heat stored by the regenerator.

Based on the experimental research and analysis, the characteristic parameter “resistance loss per unit heat storage” is defined as the resistance loss that the regenerator needs to overcome to store the unit heat, which is a dimensionless number and can be calculated by formula (4):

$$I^{'} = \frac{\mathit{\Delta} P \bullet q_v}{Q_v \bullet m} \tag{4}$$

Where: $\mathit{\Delta} P$ is the pressure drop of the regenerator; q_v is flue gas flow; Q_v is the heat storage rate; *m* is the total mass of the regenerator.

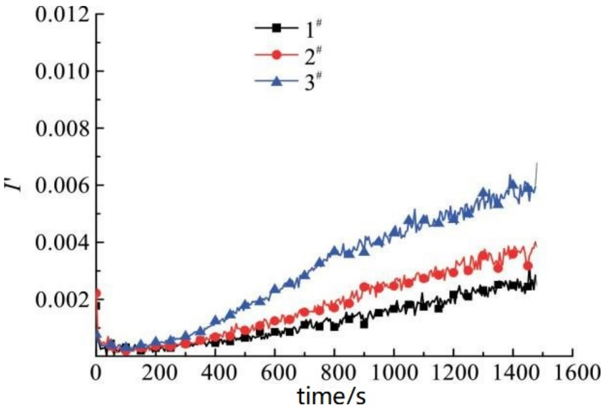


Figure 8. Unit heat storage resistance loss at 125 kg/h flue.

Figure 8 shows the change with time of the unit regenerative resistance loss of three kinds of regenerators calculated by formula (4). As can be seen from the figure, when the flue gas flow rate is 125 kg/h, with the heat storage time, the unit heat storage resistance loss gradually increases linearly. Because the heat storage rate gradually decreases (see **Figure 6**) and the resistance loss gradually increases (see **Figure 5**). With the decrease of pore size or the increase of specific surface area, the resistance loss of unit heat storage increases, because when the pore size decreases, the resistance loss increases more than that of heat storage. The magnitude of the rate increase. Compared with the thermal performance index put forward by Lu[20], the resistance loss per unit heat storage can more intuitively reflect the resistance loss that different regenerators need to overcome to store unit heat. In the industrial heat storage system, not only the aforementioned parameters such as heat storage rate and heat storage efficiency should be considered, but also the unit heat storage resistance loss, because the resistance characteristics will also affect the design of the heat storage system.

4. Conclusion

(1) The heat storage rate is defined. The relationship between heat storage rate and time is parabola, and its size is mainly related to the structure of the regenerator and the heat flow. The greater the heat flow, the faster the heat storage; the smaller the pore size of the regenerator or the larger the specific surface area, the greater the heat storage rate.

(2) The heat storage efficiency and the heat storage efficiency at the beginning of heat storage are defined.

The rate is the highest and then decreases gradually with the heat storage. The longer the length of the regenerator, the higher the heat storage efficiency, which indicates that the regenerator makes full use of the waste heat of flue gas.

The unit regenerative resistance loss is defined, which increases with the decrease of regenerator aperture or the increase of specific surface area.

Therefore, the regenerator with small pore size or large specific surface area can realize rapid heat storage, but at the same time, the resistance loss of the regenerator will also increase. Increasing the regenerator properly can improve the heat storage efficiency.

Conflict of interest

The authors declared no conflict of interest.

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