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HEAT TRANSFER PEERFORMANCE RESEARCH OF HONEYCOMB CERAMIC THERMAL ENERGY STORAGE

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Abstract

Thermal energy storage (TES) is core advantage for the concentrated solar power (CSP) technologies. A packed bed of rocks or other ceramic is especially suitable when gas is used as the heat transfer fluid. The heat transfer performance of thermal energy storage (TES) device which use the air as the heat transfer fluid and the honeycomb ceramic as the storage material was researched by experimental in this paper. The results showed that the temperature distribution was obvious thermocline distribution when charging and discharging process. The charging efficiency of the TES device was higher than 75%, and the discharging efficiency was higher than 85%.

Key words: *thermal energy storage; honeycomb ceramic thermal storage; heat transfer performance*

1 Introduction

Thermal energy storage (TES) is core advantage for the concentrated solar power (CSP) technologies. TES appears to be an important solution to correcting the mismatch between the thermal energy availability and demand of energy. Sensible heat storage is the most simply and inexpensive way of energy storage system although there are few advantage of phase change energy storage over sensible heat storage, but the technological and economical aspects make sensible heat storage superior[Sigh et al, 2010]. For CSP plants operating with air as the heat transfer fluid [Bader et al, 2011, Wang et al, 2015], TES using a packed bed of rocks has been shown to offer a simple and efficient technical solution for overcoming the intermittency of solar radiation [Zanganeh et al, 2012, Meier et al, 1991, Hänchen et al, 2011, Gross et al, 1980]. A packed bed of rocks or other ceramic is especially suitable when a gas is used as the heat transfer fluid [Sigh et al, 2010, Hanchen et al, 2011, Coutier and Faber, 1982, Hasnain 1998]. The numerical and experimental results show that the porous structure which maximize heat transfer between fluid and storage media and minimize heat transport inside the storage media [Xu et al, 2013, Zavatoni et al, 2014, Zanganeh et al, 2012]. The heat storage performance of two tanks TES and single TES had been researched by EPRI [Palo, 2010], the results showed that the cost of a single TES using fluid and solid material as the thermal storage media can reduce 33%. TES using a packed bed of sensible-latent material has been shown that a PCM volume of 1.33% of the total storage volume was sufficient to achieve stabilization of the outflow air temperature around the PCM's melting point [Zanganeh et al, 2014].

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Nomenclature

L	TES storage length
$\dot{m}$	Mass flow rate, kg/h
T	Temperature, ℃
z	Axial position
η	Efficiency
t	Time, s
c_p	Heat capacity, kJ/kg.K

Subscripts/Superscripts

i	The test section number of honeycomb ceramic of TES device
j	The thermocouple number in each test section
air	Heat Transfer fluid-air
$area$	The position of test section of TES
s	Honeycomb ceramic material
in	inlet
out	outlet
c	Charging process
d	Discharging process

In this paper, the solid thermal storage system which use the air as the heat transfer fluid and the honeycomb ceramic as the storage material was built-up and the heat transfer performance under different condition were investigated.

2 A honeycomb ceramic TES system

2.1 A honeycomb ceramic TES device

Fig.1 shows the schematic of the honeycomb ceramic TES device. The honeycomb ceramic TES device is a box which is consisted of inlet pipe, outlet pipe, cover plates and the TES materials. The size of the TES device is 1512×1412×1584mm. The air was used as the heat transfer fluid during the charging and discharging process. Honeycomb ceramics were used as the TES materials, and 4000 pieces of honeycomb ceramic were inserted into the TES device. Fig.2 is the photo of honeycomb ceramic material. The size of the honeycomb ceramic is 34.3×34.3×100mm. The property of honeycomb ceramic was shown in Table1.

Fig.1. The schematic of packed-bed TES device

Fig.2. The photo of honeycomb ceramic

Table 1 Property of honeycomb ceramic material

Aperture ratio (%)	Porosity (%)	Cell density (cell/cm^2)	Heat storage capacity (MJ/m^3)	Conductivity (W/m.k)
74	42	45	197	10.7

2.2 A honeycomb ceramic TES system

In order to analyze the heat transfer performance of the packed-bed thermal storage, an experimental system of thermal storage was built up. Fig.3 is the layout of the packed-bed thermal storage system using honeycomb ceramic as the thermal storage material.

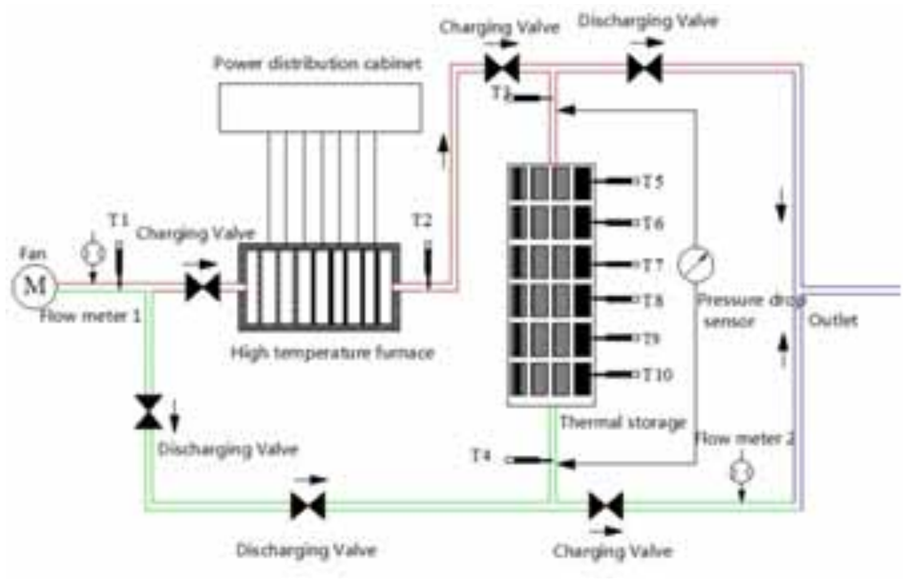


Fig.3. Schematic of packed-bed TES system

The thermal storage system is consisted of fan, high temperature air furnace, a honeycomb ceramic TES device, pressure drop sensor, thermocouple and flow meter. In the system, the fan transported air from the environment to the furnace or pipes. The high temperature furnace is the heating apparatus to heat the air.

The pressure drop when air flows through the thermal storage device were measured by the pressure drop sensor. The air temperature, honeycomb ceramic temperature and the surface temperature of the thermal storage were measured by several thermocouples. Fig.4 is the photo of the packed-bed thermal storage system.

Fig.4 The photo of the thermal storage system

In order to analyze the performance of the thermal storage device and the heat transfer between air and honeycomb ceramic, air volumetric flux, temperatures of air, honeycomb ceramic and the surface of the thermal storage device, the pressure drop of the thermal storage device were measured. The inlet air flow rate was measured by a volumetric flow meter with the range from 15 to 300m^3/h and the error is ±0.5%. The outlet air flow rate was measured by a vortex flow meter with the range from 80 to 800m^3/h and the error is ±0.5%. The pressure drop of the thermal storage was measured by the pressure drop sensor which the error is ±0.5%.

The temperatures of air, honeycomb ceramic and the surface of the thermal storage device were measured by thirty eight K-type or S-type thermocouples, which all error is ±0.1℃. The positions of the thermocouple inserted into the thermal storage device are shown in Fig.5.

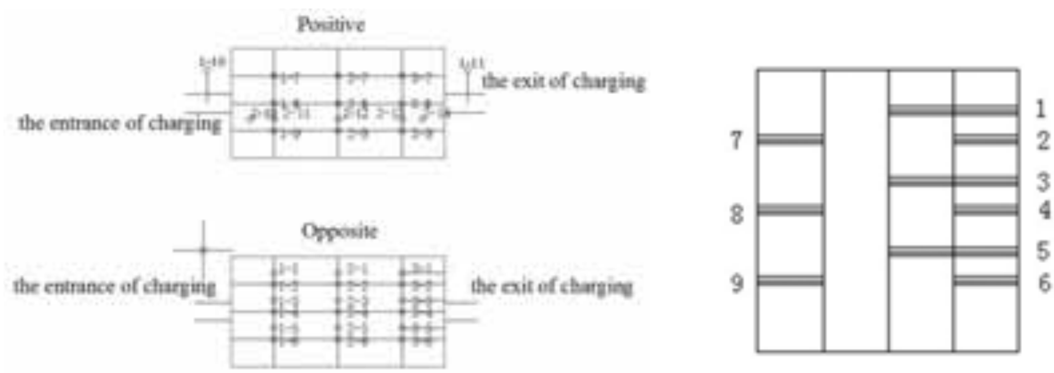


Fig.5 The position of the thermocouple in the packed bed thermal storage device

The thermocouples of 1-10 and 1-11 were measured the air inlet temperature and the air outlet temperature.

In order to measure the temperatures of honeycomb ceramic, 27 thermocouples were inserted into the thermal storage device and attached to the honeycomb ceramic surface. The thermal storage device is divided into three blocks along the length by thermocouples. The thermocouples of 1-1 to 1-9, 2-1 to 2-9 and 3-1 to 3-9 which were measured the honeycomb ceramic temperatures of the first block, the second block and the third block. The thermocouples of 2-10 to 2-14 were measured the surface temperature of the thermal storage device.

3 Experimental data analysis method

As shown in Fig.5, the arithmetic average temperature of each section is calculated as Equation (1):

$$T_{i,area} = \frac{\sum_{j=1}^{j=9} T_{i,j}}{9} \quad (i=1,2,3;\ j=1,2,...9) \qquad \text{(eq. 1)}$$

The average temperature of all the honeycomb ceramic in TES device is calculated as Equation (2):

$$T_s = \frac{\sum_{i=1}^{i=3} T_{i,area}}{3} \quad (i=1,2,3) \qquad \text{(eq. 2)}$$

The efficiency of the charging process is defined as the ratio of the net heat stored by thermal energy storage material and the total heat released by the hot air in the charging process, which can be expressed as the following equation:

$$\eta_c = \frac{M_S c_S [T_S(t_c) - T_S(0)]}{\int_0^{t_c} [T_{air,in} - T_{air,out}] c_{p_{air}} \dot{m}_{air}\, dt} \times 100\ \% \qquad \text{(eq. 3)}$$

The efficiency of the discharging process is defined as the ratio of the net heat which removed by the cold air and the total heat released by the thermal energy storage material during the whole discharging process, which can be expressed as the following equation:

$$\eta_d = \frac{\int_0^{t_d} [T_{air,out} - T_{air,in}] c_{p_{air}} \dot{m}_{air}\, dt}{M_S c_S [T_S(0) - T_S(t_d)]} \times 100\ \% \qquad \text{(eq. 4)}$$

4 Results and discussion

Several experiments under different thermal storage temperatures and air flow rates have been carried out and the thermal performance of the TES device was analyzed.

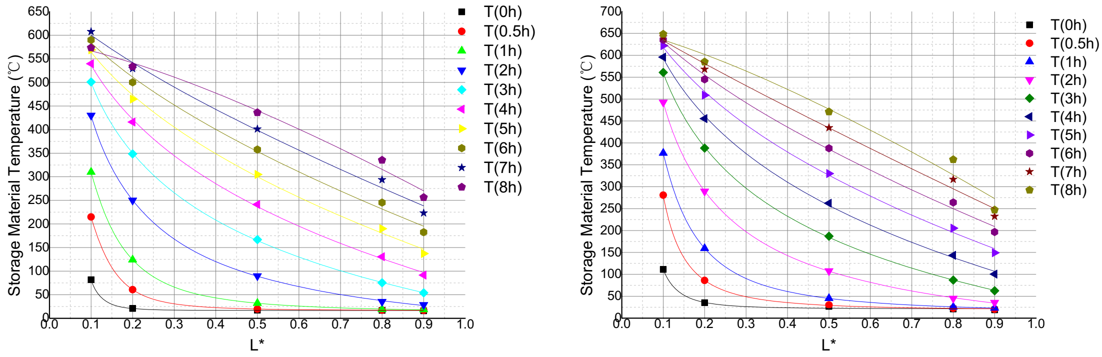
4.1 Temperature distribution

Fig.6 shows the temperature distribution in TES device during the charging process. To better compare the charging behaviour among TES, the temperature results of storage materials are reported using dimensionlesss coefficiencies for axial length, which was defined by equation (5). In this way, the L* can assume value between 0 and 1.

$$L^* = \frac{z}{L} \qquad \text{(eq. 5)}$$

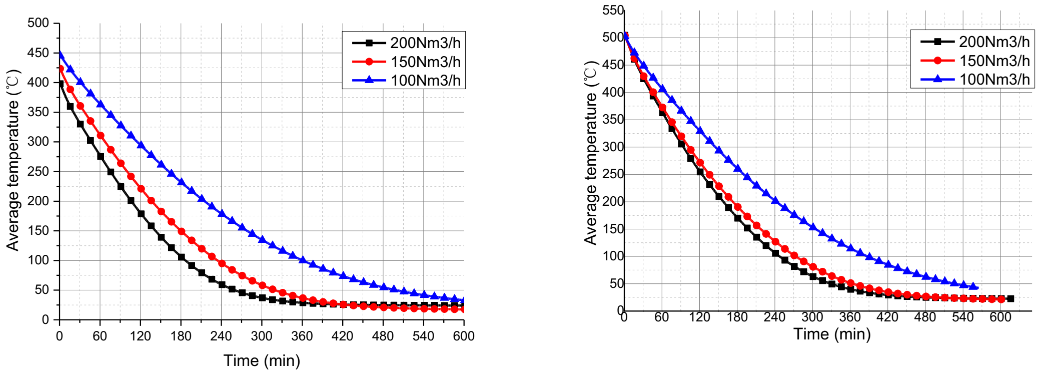
As shown in Figure.6, from the inlet to the outlet, the temperature distribution is obvious thermocline distribution. At the beginning, the temperature gradient is very steep, but the temperature gradient is more and more gently during charging process. When the charging temperature is higher, the temperature difference of thermocline is greater.

Fig.7 shows the average temperature distribution of storage material under different flow rates respectively at the initial temperature of 400℃ and 500℃during discharging.



（a）400℃　　　　　　（b）500℃

Fig.6 Storage material temperature distribution of charging process

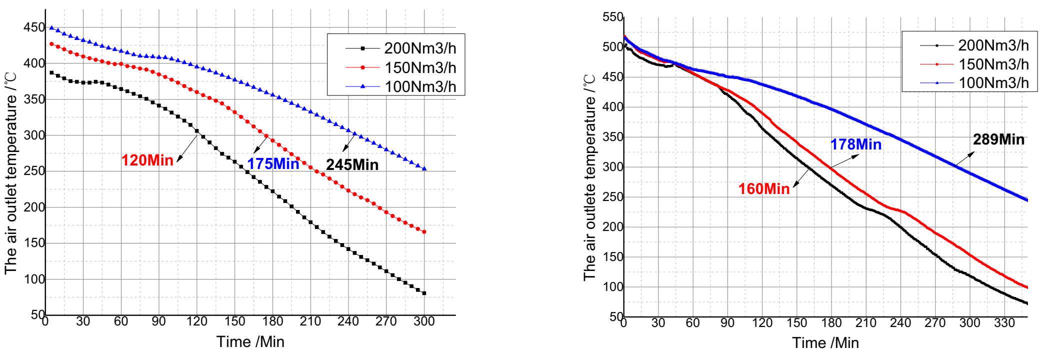


（a）400℃　　　　　　（b）500℃

Fig.7. Average temperature distribution of discharging process

From the figures, the average temperature drop of honeycomb ceramic material increases with the increasing air flow rates. The rate of temperature drop at the beginning discharging in TES device is significantly greater than the late stage of discharging. This is because the heat transfer rate between the air and the honeycomb ceramic material increases with the temperature differences increase.

Fig.8 shows the air outlet temperature variations under different air flow rates during discharging.



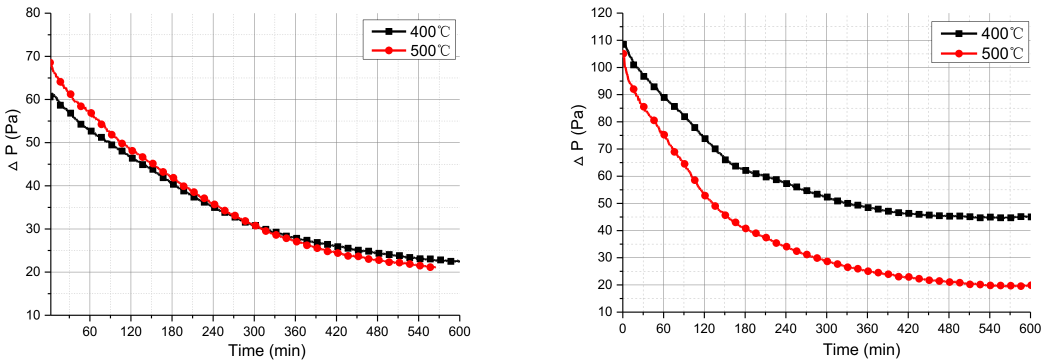
（a）400℃　　　　　　（b）500℃

Fig.8. Air outlet temperature variations of discharging process

Fig.8 indicated that the discharging time can be extended with the air flow rate decreased. The numbers in the figure mean the time that the air outlet temperature decreases from the initial temperature to 300℃. It can be seen that the time for the air outlet temperature declining to a specified value increases with the air flow rates decreases. The outlet temperature of air is higher when the temperature of honeycomb ceramic is higher at the begging of discharging.

4.2 Pressure Drop distribution

Fig.9 shows the pressure drop distribution in the TES device under different air flow rates.



(a) 100Nm³/h (b) 150Nm³/h

Fig.9 Pressure drop distribution with time

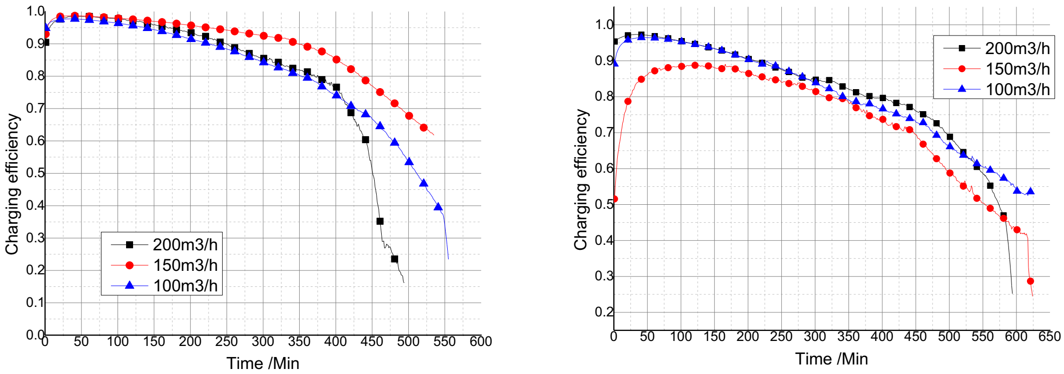
The pressure drop when air flowing through the TES device was kept below 110Pa under different discharging temperature. The pressure drop increases with the increasing air flow rate, and decreases with the decreasing air outlet temperature. From the pressure drop results it can be seen that porous structure material as the thermal storage material and air as the heat transfer fluid is feasible.

4.3 The thermal storage efficiency

In order to analyze heat transfer performance of the solid thermal storage system, the charging efficiency and the discharging efficiency under different flow rates and temperature have calculated using the equation (3) and equation (4).

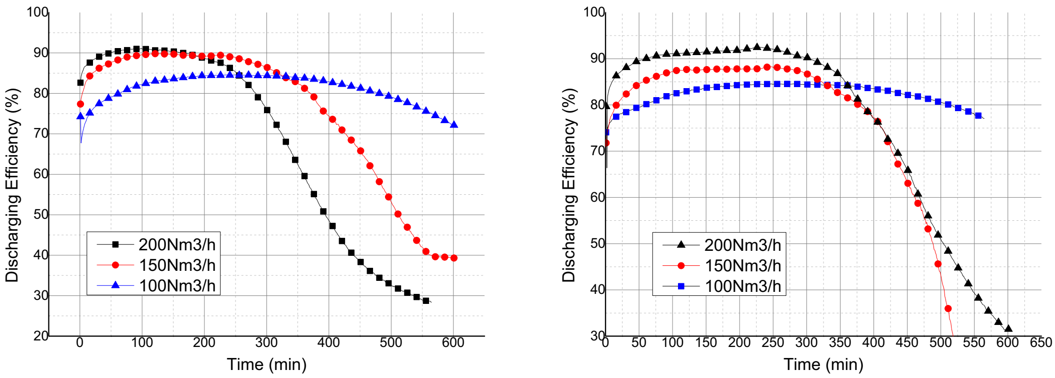
Fig.10 shows the charging efficiency with time of the TES device under different air flow rate. Under different flow rate the highest charging efficiency have reached about 90%, and there was a maximum efficiency within 30Min, then the charging efficiency decreased with time. The reason is that convection and conduction between air and honeycomb ceramic are weakened with the temperature difference decreased. More and more heat can be exchanged to the honeycomb ceramic.

Fig.11 shows the discharging efficiency with time of the TES under different air flow rate and initial discharging temperature. As shown in Fig.11, the discharging efficiencies of the TES are higher than 85% under different air flow rate in 300 minutes. Under the same air flow rate, even though with the different initial discharging temperature, the discharging efficiencies of the TES are nearly same in 3 hours. It clearly indicates that the honeycomb ceramic material has a good thermal stability and high heat transfer performance. Besides, the greater the air flow rate in discharging process, the higher the heat efficiency of the TES. The heat transfer rate between the air and storage material increased with the air flow rate.



（a）400℃ （b）500℃

Fig.10 Charging efficiency under different air flow rate



（a）400℃ （b）500℃

Fig.11 Discharging efficiency under different air flow rate

5 Conclusions

In this paper, the heat transfer characteristic of charging and discharging were researched by experimentally.

(1) A single tank TES of packed bed using air as heat transfer fluid and honeycomb ceramic as storage material is feasible. The temperature distribution is obvious thermocline in TES when charging and discharging processes. The discharging time can be extended with the air flow rate decreased.

(2) The charging efficiency of the developed TES device was higher than 75%, and the discharging efficiency was higher than 85%.

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