Conference Proceedings

Solar World Congress 2015
Daegu, Korea, 08 – 12 November 2015

Experimental investigation of the heat performance using a packed bed of ceramic balls for high temperature thermal energy storage unit

Bei Yang[1], Yan Wang[1], Fengwu Bai[1]

[1] Key Laboratory of Solar Thermal Energy and Photovoltaic System,

Institute of Electrical Engineering, Chinese Academy of Sciences, Beijing 100190, China

Abstract

A thermal energy storage (TES) system was designed based on a packed bed of ceramic balls as storage material and air as heat transfer fluid (HTF). A series of contrast experiments were carried out under specified working conditions to analyze the heat performance of TES unit. The results showed that temperature distribution in axial direction of the packed bed and thickness of thermal stratification can be manually controlled by adjusting the air flow rate or the heating power during charging to achieve a better discharging performance. The packed bed has a good temperature uniformity along the radial direction which means a less exergy loss and smaller convective mixing radially. It was also shown that the TES unit has a highest discharging heat power of 16.5 kW, and discharging efficiency of 90%, indicating that the TES unit can achieve to store and release heat effectively.

Keywords: *Packed bed, Thermal storage, Sensible heat, Air, Ceramic balls*

1. Introduction

TES is vital for the solar thermal electricity technologies due to the random solar irradiations. The form of sensible heat storage in packed-bed of solid material is especially suitable for the system whose heat transfer fluid is air, and the cost of fabrication of tank and the heat storage material is significantly lower than other methods (Markus Hanchen et.al 2011). A wide body of publications describes numerical models for sensible heat storage in packed-beds (Antoni Gil et al., 2010; G. Zanganeh et al., 2012, 2015; Jon T. et al. , 2011; Opitz and Treffinger, 2014), but only a few include experimental investigation. The numerical results show that the porous structure maximizes heat transfer between fluid and storage media and minimizes heat transport inside the storage media.

In this paper, the design, fabrication, test of a packed-bed TES unit were described. And indicators including thermal stratification, radial temperature difference, discharge outflow temperature, discharging power output and thermal efficiency were analyzed to evaluate the heat performance.

2. Pilot-scale TES design and experimental setup

2.1. A packed-bed TES device

The packed-bed TES unit is shown schematically in Fig.1, which consists of one cylindrical shell and two conical shells. The two conical shells are arranged on the top and the bottom of the tank respectively, used to be connected with the pipes and form a raletively uniform air flow. The tank has a circular cross section with a inner diameter of 0.7 m, and a total height of 4 m. The circular tank wall is made of refractory bricks, with a thick of 100 mm. The refractory brick has a a small coefficient of thermal expansion and a raletively high strength, which can help to reduce the effect of thermal ratcheting caused by thermal expansion of the storing material; In addition, the low thermal conductivity of the refractory brick can help to reduce the heat loss as

doi:10.18086/swc.2015.02.04 Available at http://proceedings.ises.org

well. Outside the refractory bricks is a 100-mm layer of asbestos insulation, while outside which covered a 6-mm layer of stainless steel shell.

The tank is filled to the height of 2.3 m with high alumina ceramic balls with an equivalent sphere diameter of 25mm, shown as Fig.2. The physical parameters of the ceramic balls are shown in table 1. A porous metal perforated strainer is installed inside the bottom of the tank, supporting the weight of the storage materials, and avoiding the ceramic balls and debris dropping and blocking the following pipes at the same time.

Fig.1 Photo of packed-bed TES unit

Fig.2 Photo of ceramic balls

Table1. Physical parameters of ceramic ball and packed bed

Al_2O_3(%)	Packed-bed Porosity*	Density (kg m^{-3})	Specific Heat Capacity (kJ $kg^{-1}K^{-1}$)
65	0.463	2200	1.0

*Remarks: porosity is calculated as the ratio between the volume of solid material and the tank capacity in packed height.

2.2. A packed-bed TES testing system

Fig.3 shows the layout of the packed-bed TES testing system. The testing system consists of a blower, an air heating furnace, a packed-bed TES unit using ceramic balls as TES material, and regulating valves. The ambient air pumped from the blower can be heated to 600-900℃ by the 60 kW electric heating furnace, and then the hot air enters through the inlet pipe from the top, flows through the packed bed to charge the ceramic balls. Charging from the top allows the exploitation of the buoyancy effect to create and maintain thermal stratification inside the packed bed, keeping the hottest region being at the top. During discharging, the direction of the flow is reversed as cold air is circulated through the tank from the bottom.

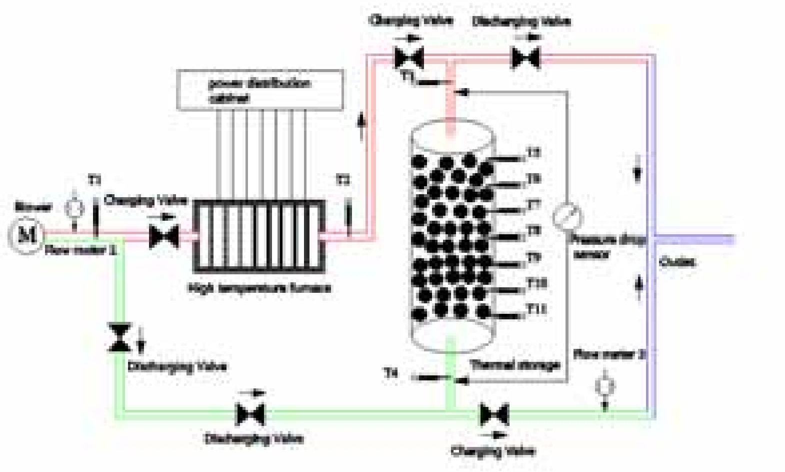
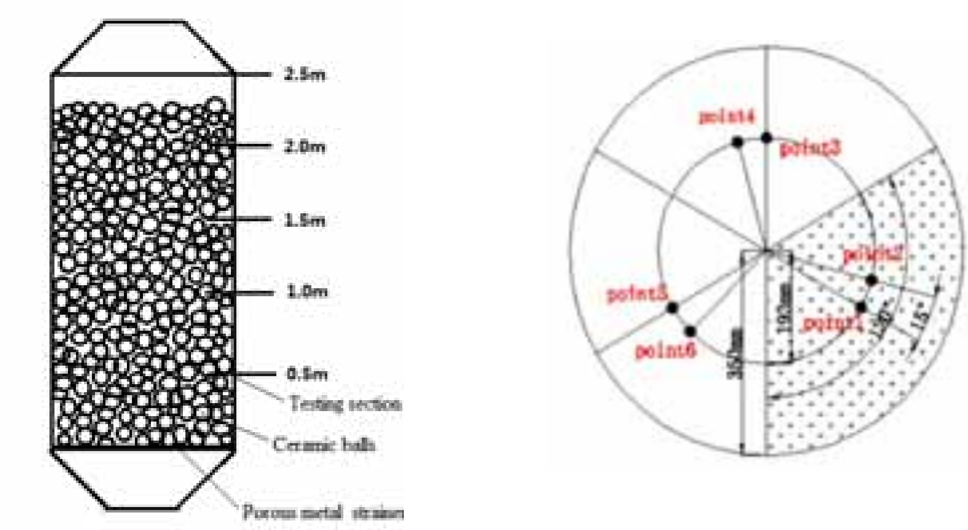


Fig.3. Schematic of packed-bed TES system

During the charging and discharging processes, the temperature is recorded by 43 K-type or S-type thermocouples throughout the system, of which 30 thermocouples are located inside the packed bed at different vertical positions. Along the height of packed bed, 5 measurement sections are arranged in every 0.5-m high, and 6 thermocouples are arranged in each section, shown as figure 4, notably that the thermocouples at the height of 2.5 m are not covered with ceramic balls; 2 thermocouples measure the temperature just above the packed bed on the tank axis and 2 in the bottom outlet pipe. In addition, other measurements include: ambient air temperature, the air flow rates at the inlet and outlet of TES system, and pressure drop when the air flowing through the packed bed. The thermocouples have an accuracy of ±0.5%. The flow meters installed at the inlet of system is a volumetric flowmeter with a measuring range of 15~300m^3/h and outlet a vortex-shedding flowmeter with range of 80~800m3/h, both of which share a common accuracy of ±0.5%.



(a) (b)

Fig.4. Distribution of testing sections in packed bed (a) and testing points in each section (b)

3. Results and Discussion

In order to analyze the charging and discharging performance of the packed-bed TES system, several experiments were carried out under different working conditions with an initial discharging temperature of solid storage material about 500℃ and a discharging air flow rate of 50 Nm³/h, 100 Nm³/h, 150 Nm³/h respectively.

3.1. Temperature distribution

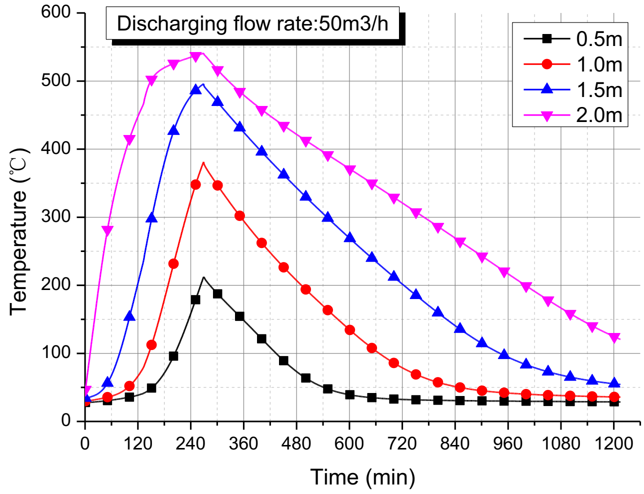
During the charging and discharging processes, the transient temperatures of ceramic balls were recorded by the thermocouples arranged at different heights of the packed bed. 6 thermocouples were adopted in each measuring section to ensure measurement accuracy. Thus, the average temperature at each section can be calculated as equation (1):

$$T_i = \frac{\sum_{j=1}^{j=6} T_{i,j}}{6} (\mathrm{i} = 1, 2, 3, 4) \quad \text{(eq.1)}$$

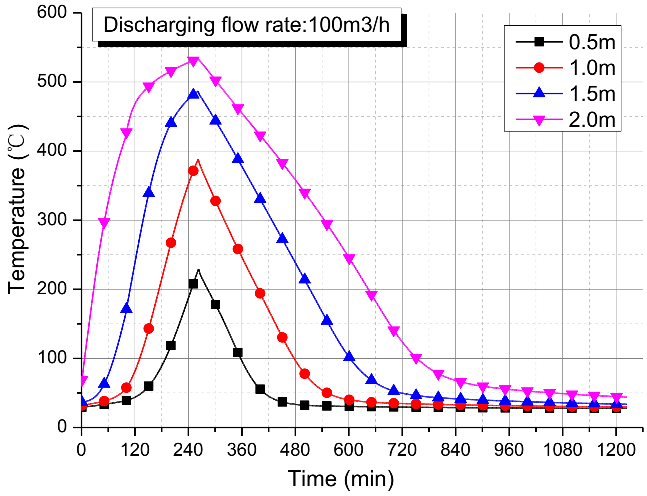
Where, i=1,2,3,4 refers to the temperature testing section at the height of 0.5m, 1.0m, 1.5m, 2.0m respectively.

3.1.1 Transient temperature distribution of the ceramic balls

(a)



(b)



(c)

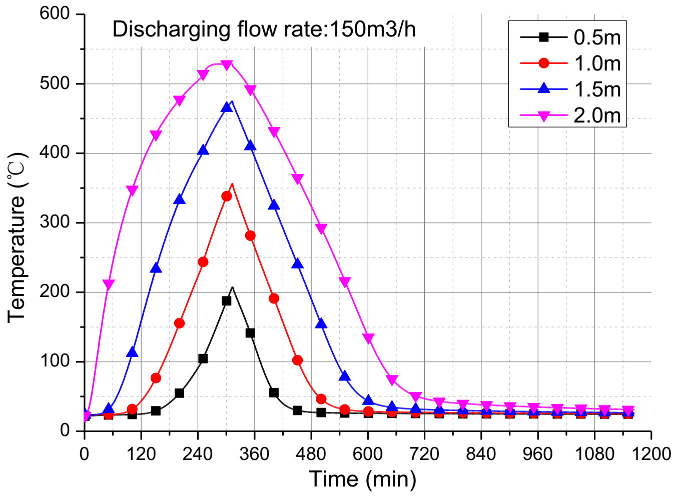


Fig.5. Transient changes of temperature distribution of ceramic balls under various conditions

(a.50 Nm³/h b. 100 Nm³/h c.150Nm³/h)

Figure 5 show the temperature distribution of ceramic balls under three different conditions. The charging conditions were not strictly controlled but manually adjusted to ensure a similar initial discharging temperature distribution of the packed bed at the end of charging. Seen from the figures, at the end of charging temperature of ceramic balls at the height of 2.0 m is up to around 530 ℃, while at the height of 0.5 m around 210 ℃, which means the temperature difference between the top and the bottom is over 300℃. The reason for this obvious thermal stratification inside the packed bed is mainly that the air buoyancy effect was fully exploited by charging from the top and discharging reversed which keeping the hottest region being at the top and the coldest at the bottom. The experimental experience indicated that temperature distribution of packed bed and thickness of thermal stratification could be manually controlled by adjusting the air flow rate or the heating power during charging.

While during discharging the air flow rate was strictly controlled to be 50 Nm^3/h, 100Nm^3/h, 150Nm^3/h respectively. Seen from figure 5, temperature drops of the ceramic balls increase obviously with the increasing air discharging flow rate, since the convective heat transfer between air and solid material is distinctly enhanced with a higher air velocity. After cold air enters the packed bed from the bottom, it exchanges heat with the ceramic balls from bottom to top, and the temperature of air is gradually raised while the heat energy is extracted for its further use.

It's worth noting that the air temperature rising during discharging is directly related to the thermal stratification of packed bed at the end of charging. Therefore, it is possible to match the air temperature rising and the thermal stratification of packed bed by the means of charging process control and air preheating before discharging etc., which can minimize the heat transfer temperature difference between air and solid materials, namely minimize the irreversible energy loss, and maximize the exergy efficiency of the TES system eventually.

3.1.2 Transient discharging outflow temperature

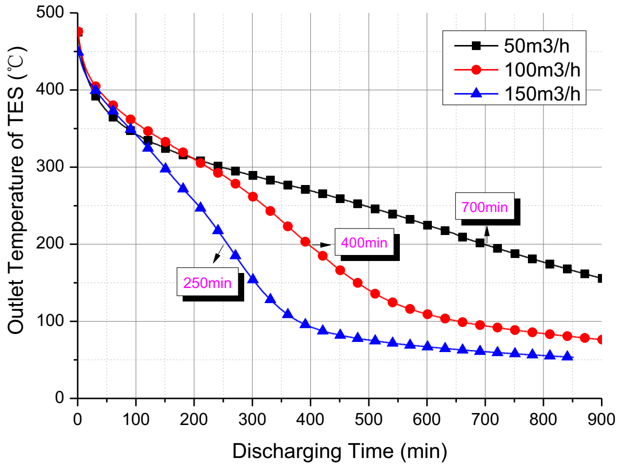


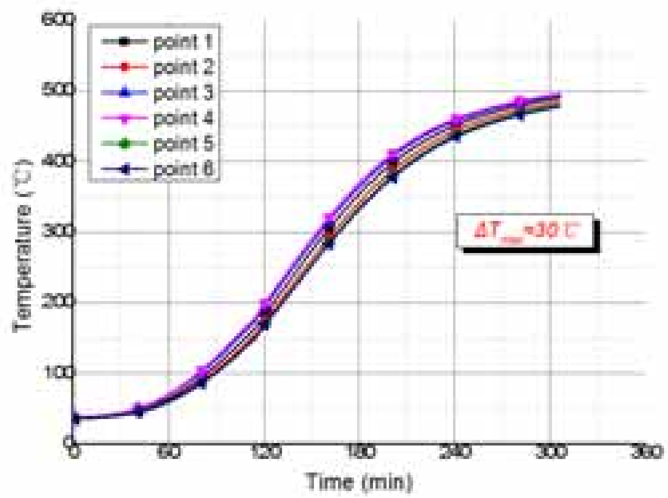
Fig.6. Transient changes of dischaging outflow temperature under different flow rates

Figure 6 shows the variation of outlet air temperature under different air discharging flow rates. Seen from it, the highest air outlet temperature is up to about 480 ℃, and it takes a period of 250min, 400min, and 700min for the outflow temperature decreasing from 480℃ to 200℃under the discharging flow rate of 50 Nm^3/h, 100 Nm^3/h, 150 Nm^3/h respectively when the initial discharging temperature distributions are roughly the same. The results indicated that certain air outlet temperature and certain quantity of heat extracted can be obtained by controlling the discharging air flow rates, which leads the discharging process to last for various period of time, and then meets demand of various thermal storage applications.

3.1.2 Radial temperature difference in top testing section

Figure 7 shows the transient changes of radial temperature difference in the top testing section, which reflects uniformity of radial temperature distribution in the packed bed. As can be seen from the figure, the radial teperature difference is respectively about 30 ℃ and 10 ℃ during charging and discharging process when the discharging air flow rate is 100Nm³/h, showing that the packed bed has a good uniformity along the radial direction. The main reason for this phenomenon is that the packed bed has a raletively high porosity of 0.463, which makes it possible for air to flow evenly in packed bed and maximizes heat transfer between air and ceramic balls.

(a)



(b)

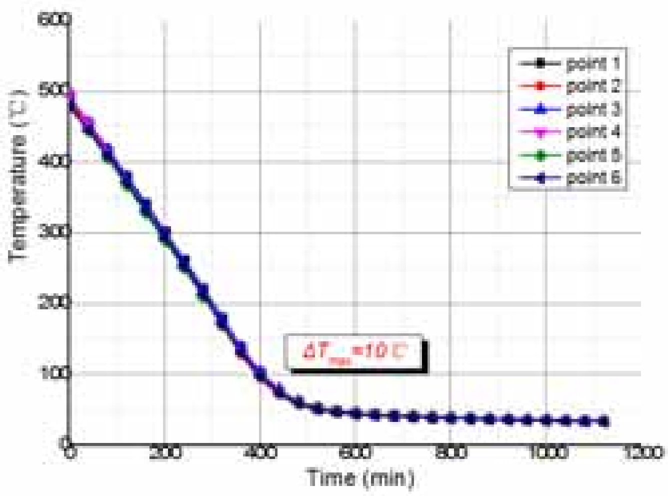


Figure 7. Radial temperature difference in top testing section
(a. Charing; b. Discharging; Discharging flow rate: 100Nm³/h)

This uniformity has advantages that exergy loss is reduced caused by heat exchanges within certain temperature ranges and radial convective mixing of air is lightened as well, resulting in a great improvement for exergy efficiency of the TES unit.

3.2 Net discharging power output

Net discharging power is defined as the heat extracted from solid materials by air in unit discharging time, which can be calculated as equation (2):

$$P_d = c\dot{m}\Delta T = c\dot{m}(T_{ao} - T_{ai}) \qquad \text{(eq.2)}$$

The temperature-dependent thermal properties of air are considered in the calculation, and density of air is determined by empirical correlation (3):

$$\rho = 0.72447e^{(-T/532)} + 0.39845e^{(-T/125.93)} + 0.16623 \qquad \text{(eq.3)}$$

Figure 8 shows variation of net discharging power under various air flow rates. As can be seen from it, the highest power can be up to 16.5 kW with a flow rate of 150 Nm³/h; and the lower the air flow rate is, the more fully heat transfer between air and ceramic balls developed, and the more stable the net discharging power output. The power curve under a certain flow rate declines slightly at the beginning of discharging, then increases to the highest value, and then continues to slowly drop eventually. The reason for this trend is that the pipe at the top of packed bed remains hot at the end of charging, while during discharging the top pipe will be cooled down at first and then heated by the discharging air, and it takes a while for the temperature difference between air outlet and inlet to reach a consistent variation.

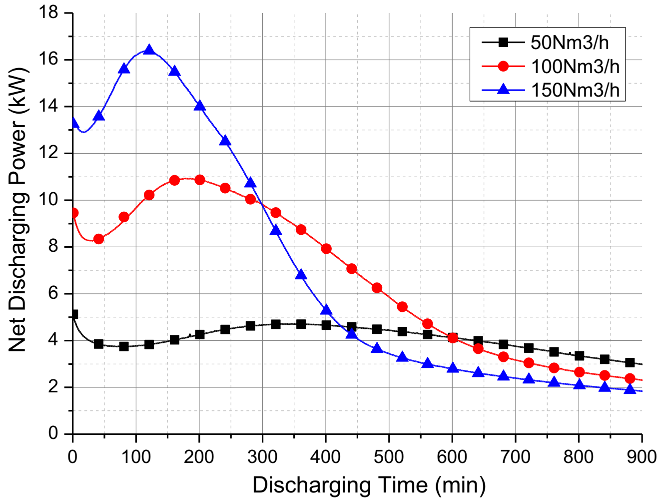


Figure 8. Transient changes of net discharging power under various air flow rates

Area between the single curve and abscissa represents the quantity of heat ectracted by air, and the results shows that the higher the air flow rate is, the larger quantity heat extracted in the first part of discharging. Therefore, it's critical to control appropriate discharging flow rate to adapt for different energy needs.

3.3 Thermal efficiency of TES unit

The heat performance of TES unit can be evaluated by the value of its thermal efficiency, including the charging and discharging efficiency. Charging efficiency is defined as the ratio of the net heat stored by solid material and the total heat released by the hot air during the charging process, which can be expressed as equation (3):

$$\eta_c = \frac{A(1-\varepsilon)\rho c_s \int_0^H [T(t_c, h) - T(t_0, h)]dh}{\int_0^{t_c} [T_{ai} - T_{ao}] c_a \dot{m}_a \, dt} \times 100\% \qquad \text{(eq.4)}$$

While discharging efficiency is defined as the ratio of the net heat extracted by cold air and the total heat released by the solid materials during a certain period of discharging time, which can be expressed as equation (4):

$$\eta_d = \frac{\int_0^{t_d} [T_{ai} - T_{ao}] c_a \dot{m}_a \, dt}{A(1-\varepsilon)\rho c_s \int_0^H [T(t_0, h) - T(t_d, h)] dh} \times 100\% \qquad \text{(eq.5)}$$

Figure 9 shows the charging and discharging efficiency changes of the TES unit under various working conditions, in which the discharging peirod of time is chosen as the moments before the discharging outflow temperature is not less than 100℃.

From the figure, the highest charging and discharging efficiency are respectively about 80% and 90%, which indicates that the TES unit can achieve to store and release heat effectively.

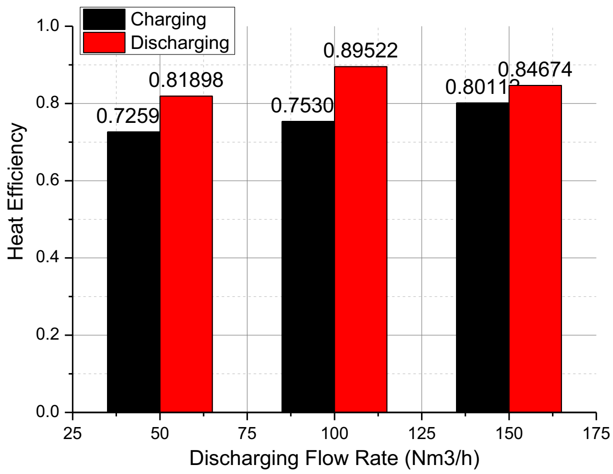


Figure 9. Charging and discharging efficiency changes of TES unit under various working conditions

Thermal efficiency of TES unit is directly related to its heat loss to the surrounding environment. Seen from the figure, the value of thermal efficiency is not so much high which indicates that the insulation measures of the TES unit remains to be further strengthened. However, it's worth noting that heat capacity of this system is limited due to a lab-scale device, and heat loss accounted for a larger proportion with a samller scale compared to the total storage heat. Therefore, the heat loss can be almost negligible and the thermal efficiency will be raised by big percentages when the heat storage system expand to the industrial scale.

4. Conclusions

A pilot-scale TES system based on a packed bed of ceramic balls with air as heat transfer fluid was designed, built, tested, and evaluated. Seris of contrast experiments under specified working conditions were carried out and the indicators including thermal stratification, radial temperature difference, discharge outflow temperature, discharging power output and thermal efficiency were analyzed to assess the heat performance of the TES unit. It was shown that temperature distribution in axial direction of the packed bed and thickness of thermal stratification can be manually controlled by adjusting the air flow rate or the heating power during charging to achieve a better discharging performance. The packed bed has a good temperature uniformity along the radial direction which means a less exergy loss and smaller convective mixing radially. The TES unit has a highest discharging heat power of 16.5 kW, and discharging efficiency of 90%, indicating that the

TES unit could achieve to storage and release heat effectively. However, good performance as the TES unit has, some optimization measures need to be further taken both in strucutres and controlling strategies optimization, such as the strengthened insulation, the expended scale and the optimally designed and controlled charging conditions etc..

5. Acknowledgments

This work was supported by the National Natural Science Foundation of China (No. 51306170) and the National Key Technologies R&D Programme of China (No.2014BAA01B00).

6. References

Antoni G., Marc M., Ingrid M., Ana L,, Pablo D., 2010. State of the art on high temperature thermal energy storage for power generation. Part 1—Concepts, materials and modellization. J. Renewable and Sustainable Energy Reviews 14 31–55.

Florian O., Peter T., 2014. Packed bed thermal energy storage model—Generalized approach and experimental validation. J. Applied Thermal Engineering 73 243-250.

G. Zanganeh, A. Pedretti, S. Zavattoni, M. Barbato, A. Steinfeld, 2012. Packed-bed thermal storage for concentrated solar power–Pilot-scale demonstration and industrial-scale design. J. Solar Energy 86 3084–3098.

G. Zanganeh, A. Pedretti, A. Haselbacher, A. Steinfeld, 2015. Design of packed bed thermal energy storage systems for high-temperature industrial process heat. J. Applied Energy 137 812–822.

Jon T., Peiwen Li et al., 2011. Analysis of heat storage and delivery of a thermocline tank having solid filler material . J. Journal of Solar Energy Engineering 133/ 021003-1.

Markus H., Sarah B., Aldo S., 2011. High-temperature thermal storage using a packed-bed of rocks-Heat transfer analysis and experimental validation. J. Applied Thermal Engineering 31:1798-1806.

Appendix

Table 1: Symbols for miscellaneous quantities

Quantity	Symbol	Unit
Area	A	m^2
Air mass flow rate	$\dot{m}$	Kg s^{-1}
Mass	m	kg
Height of packed bed	H,h	m
Temperature	T	K
Time	t	s
Power	P	kW
Specific heat	c	J kg^{-1} K^{-1}
Density	ρ	kg m^{-3}
Efficiency	η	
Porosity of pecked bed	ε	

Table 2: Subscripts

Quantity	Symbol
Air	a
Charging	c
Discharging	d
Solid material	s
Number of testing section	i
Number of testing point	j
Air flow into TES unit	ai
Air flow out of TES unit	ao