Study on Thermal Performance of a Phase Change Thermal Storage Device by Utilizing Off-peak Power

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Abstract. Based on the background of peak load shifting, this paper proposes a phase change thermal storage device by utilizing off-peak power. Experimental investigations on its thermal performance is conducted, it shows that the regenerator has high density of thermal storage and good thermal storage efficiency of 91.3%. At the same time, numerical simulations of the heat transfer enhancement by using fins are performed on the exothermic process, the results show that the addition of fins can effectively improve the exothermic efficiency to 80%. The experimental and simulation results have some reference value for exploring the application of latent heat thermal storage in real life.

1. Introduction

With the continuous development of China in recent years, the peak-valley difference of the power grid has been increasing year by year, and the problem of grid peak regulation has become increasingly prominent. The solution, evaluating the domestic power supply and demand situation and adopting the method of peak load shifting to ease the pressure on the power grid, is widely promoted by energy management department in various countries [1]. Peak load shifting [2] refers to the storage of surplus electric energy during low period of electricity consumption, it is released during the peak period of electricity consumption and used in daily life. The energy storage technology as an effective means can solve the problem that energy supply and energy using cannot be matched in time and space [3].

Latent heat thermal storage [4] is an advanced thermal storage technology that uses PCM (phase change materials) which can absorb or release heat during phase change to achieve energy storage. The Combination of off-peak power and phase change energy storage is valuable for peak load shifting and reduce heating costs. It means that Latent heat thermal storage technology would be used for energy storage during valley period, then energy is released for building heating during peak period. Liu et al. [5] prepared a high-temperature phase change thermal storage heater, and the experimental research on the charging and discharging thermal performance was addressed. The results show that the rate of heat release could meet the general heating requirements, but the heat storage efficiency is not high. Zhu et al. [6] studied the latent thermal storage equipment using valley electricity, and the device is in the ground source heat pump system. The results show that the use of phase change material for heat storage can make full use of valley electricity, saving operating costs and having good economic returns.

It can be seen that in the background of peak load shifting and valley utilization, PCM storage applications which are suitable for actual production are still not much. So this paper proposes a PCM storage device by utilizing off-peak power that is suitable for building heating. The device has compact size and high heat storage density. Especially, it is easy to install them modularly.

2. PCM storage device

2.1. Phase change material

The goal of the thermal storage system designed in this paper is building heating, which is mainly to provide domestic water. In the general building heating, the common temperature of domestic water is 30~50 ℃. Therefore, the material should not have a high phase change temperature. By comparing the properties of various types of phase change materials, $NH_4Al\ (SO_4)_2{\cdot}12H_2O$ is used in this paper. Its phase transition temperature is about 95 ℃, the latent heat value is about 254 kJ/kg. It has a high thermal conductivity (0.53 W/m·k) and low rate of volume change, also the material has a relatively stable performance as inorganic salts. Certainly, it is low-cost and recyclable.

2.2. Device design

The comparative study [7] found that the square PCM storage device has the advantages of simple packaging and high density per unit volume of heat storage. Therefore, a square plate type phase change heat storage structure is adopted in this paper, as shown in figure 1.

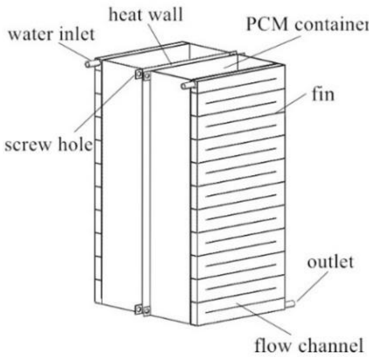

Figure 1. PCM storage device

The flexible double-sided electric heating plate is adopted, and the internal heating resistance wire of the heating plate is evenly distributed, which has the characteristics of high electrothermal conversion efficiency and long service life, also a temperature control device can be used to adjust the heating temperature in real time. In order to avoid the corrosion of the PCM to the electric heating plate, the heating plate is bolted between two symmetrically arranged body surfaces of the thermal storage unit and the PCM is heated by heating the wall surface of the thermal storage unit. Certainly, the size of the electric heating plate is equivalent to the wall surface of the unit. And the polyurethane insulation material is wrapped outside the entire heat accumulator to prevent heat loss.

3. Experimental study

In order to search the thermal performance of the designed PCM storage device, it is necessary to test the charge and discharge efficiency and the best operating conditions through experiments. Since the two sides of the thermal storage unit are symmetrically arranged, the experimental conditions and working conditions are completely same, this experiment and the subsequent numerical simulations would only test the single sided unit.

3.1. Test system

The test device is mainly composed of four parts: an electric heating system, a phase change thermal storage unit, a heat release system that mainly includes water tanks, pumps, pipeline valves, a data acquisition system which consists of flowmeter, temperature sensor, signal transmission module, and computer.

During the charge experiment, the electric heating plate was energized and heated while the flow channel was closed. The temperature at each measuring point during the phase change process and the

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amount of electricity consumed during the entire process were recorded.

The electric heating was turned off and the valves on the pipeline were opened in the discharge experiment. HTF (heat transfer fluid) was drawn from the water tank and exchanged with the thermal storage unit through the heat exchange flow path and then transferred to the hot water tank for storage. The temperature of the inlet and outlet was recorded in real time. Also, the experiment was repeated with changing the test conditions (Table 1) in the exothermic process.

Table 1. Test conditions

Variable flow rate			
6.5L/h	9.5L/h	12L/h	15.5L/h
Variable flow direction			
top injection		bottom injection	

3.2 Experimental results and analysis

3.2.1 Thermal storage process. Since the PCM selected in this paper starts to dehydrate the crystal when the temperature is higher than 120 ℃, the target temperature of the heating wall is set below 120 ℃. Also, after the initial heat storage experimental observation, the upper surface of the phase change unit would be encapsulated.

The figure 2 shows the temperature change of three points in the vertical direction (P1 is highest, P3 is lowest) on the same section during the thermal storage process. It could be seen that the temperature changes at three points generally go through three processes: at the beginning, it is the solid sensible thermal storage stage, where the temperature rises quickly; when the temperature reaches the melting point, the PCM enters the latent thermal storage stage and the temperature rise is gentler; then the molten liquid PCM continues to start sensible thermal storage and gradually reaches the heat temperature. Meanwhile, it can be seen that the temperature of the upper PCM is always higher than the lower part during the whole process. This is similar to the experimental result of Martin et al. [8], although this trend is less obvious. The main reason for this is as follows: after heating starts, the PCM increases rapidly. At this time, heat conduction occupies a major position, and then the PCM near the heating surface firstly melts into liquid, and then the liquid with a higher temperature at the bottom will rise upward which causes natural convection, so that the upper temperature will be higher than the lower part. At this time, the convective heat exchange occupies a dominant position, the entire phase change interface presents a trend of moving from the top to bottom and from the heating surface to the outer wall surface.

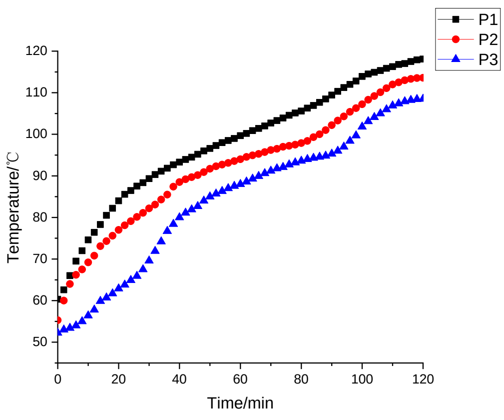


Figure 2. The temperature of three points inside the PCM

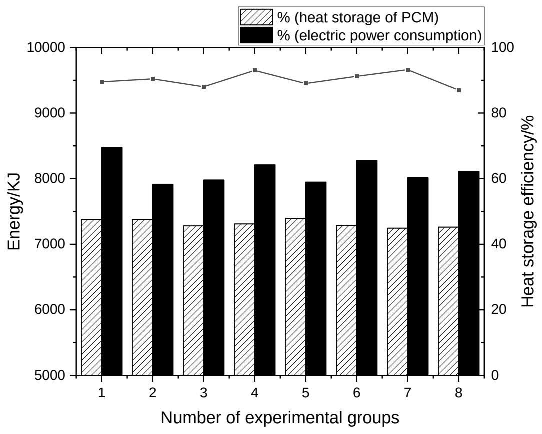


Figure 3. Energy consumption and the thermal storage of the PCM

Of course, the most important thing is that we need an indicator to measure the performance of the thermal storage process of this device. As a ratio of PCM thermal storage and power consumption, the thermal storage efficiency is of great significance to evaluate the efficiency and economy of electro-thermal conversion, the formula is as follows:

$$\eta_{\mathrm{st}} = \frac{Q_{\mathrm{st}}}{Q_{\mathrm{E}}} \tag{1}$$

$$Q_{st} = m_{pcm}[C_{p,s}(T_{pcm} - T_{pcm,ini}) + L + C_{p,l}(T_{pcm,end} - T_{pcm})] \tag{2}$$

A number of thermal storage tests were performed to calculate the energy consumption and the thermal storage of the PCM in the phase change unit, the result is shown in the figure 3. Since the thermal storage experiment and the thermal release experiment are alternately performed, the amount of thermal release each time is not the same, so the time required for the material to reach the same initial state (the average temperature of PCM reaches to 105℃) during each thermal storage experiment is different, resulting in different power consumption.

By calculating the efficiency of multiple thermal storage processes, shown in figure 3, the average thermal storage efficiency of the thermal accumulator is calculated to 91.3%, it shows that the consumed electrical energy cannot be fully converted to the energy stored in the PCM.

3.2.2. Thermal release process. Similar to the above mentioned thermal storage efficiency, the effective thermal release efficiency (equation (3)) based on the first law of thermodynamics is used to evaluate the performance of the phase change unit, and the effective thermal release performance of the phase change unit with different flow rates and different flow directions is mainly discussed. The effective thermal release efficiency is the ratio of the energy contained in the cumulative water during the thermal release (outlet water temperature $T_{out} \geq 30°C$) to the energy contained in the unit at the beginning of the thermal release process. Taking into account the actual operation of the storage and release process is a cycle, with 70 ℃ as a reference temperature when calculating the storage heat.

While focusing on effective heat extraction, the thermal release rate which measured by the instantaneous exothermic power (equation (5)) and the average exothermic power (equation (6)) should not be ignored.

$$\eta_{dis} = \frac{Q_{dis}(t_u)}{Q_{st}} \tag{3}$$

$$Q_{dis}(t_u) = q_v \rho_w V_w C_{p,w} \Delta t \sum_{n=1}^{k} (T_{out}(t) - T_{in}) \tag{4}$$

$$P_{\mathrm{dis}} = q_w \rho_w C_{p,w} (T_{out}(t) - T_{in}) \tag{5}$$

$$\overline{P_{\mathrm{dis}}} = \frac{Q_{\mathrm{dis}}(t_u)}{t_u} = \frac{q_v \rho_w C_{p,w} \Delta t \sum_{n=1}^{k} (T_{out}(t) - T_{in})}{t_u} \tag{6}$$

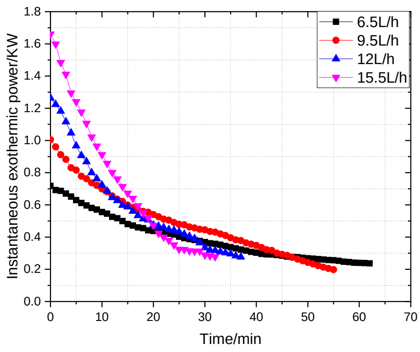


Figure 4. The variation curve of the exothermic power of top injection

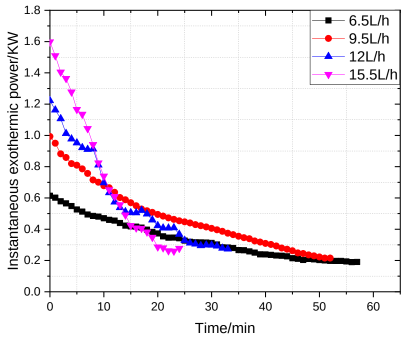


Figure 5. The variation curve of the exothermic power of bottom injection

Figure 4 and figure 5 show the variation curve of the exothermic power with different flow directions and rates, the phenomenon of varying lengths of the curve is due to the difference in effective thermal release time. The overall trend of power changes in the two figures is the same. Initially, the exothermic power is basically related to the flow rate, but it quickly decreases to a lower level as the heat exchange progresses, mainly because of the decrease of the outlet water temperature. After 20 minutes, the instantaneous exothermic power at the 9.5 L/h flow rate is greater than another three conditions, and has remained at the leading level since then. At the same time, it can be seen that the greater the flow rate, the shorter the effective thermal release time, which may be caused by insufficient heat exchange between the fluid and the PCM when the flow rate is too fast. From the perspective of thermal release efficiency and release time, the thermal release quality is higher when the flow rate is 9.5 L/h.

By calculating the effective thermal release efficiency and average thermal release power for different flow directions and flow rates, shown in figure 6, the thermal release performance when the flow direction is from bottom to top is relatively good. This is mainly due to the fact that the temperature of PCM inside the regenerator increases with the depth decreasing in the height direction, following the principle of energy cascaded utilization, the method of using the fluid from bottom to top through the heat exchange channel can extract more effective heat. The results indicate that the exothermic efficiency is only 50%-60%, and there is still a lot of heat that cannot be used effectively.

4. Numerical Simulation

4.1. Numerical model

As the PCM near the side of the heat exchange wall gradually solidifies in the heat transfer process, the thermal resistance of heat transfer is increased, so that the heat stored in the internal high temperature PCM cannot be transmitted to the external heat exchange fluid. The addition of fins to the heat transfer surface is a more economical enhancement of heat transfer [9]-[12]. So we have tried to increase the heat transfer capacity by adding horizontal fins inside the phase change unit.

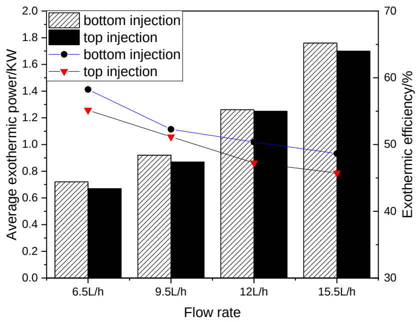


Figure 6. Effective thermal release efficiency and average thermal release power

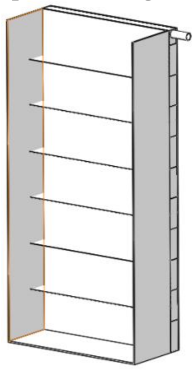


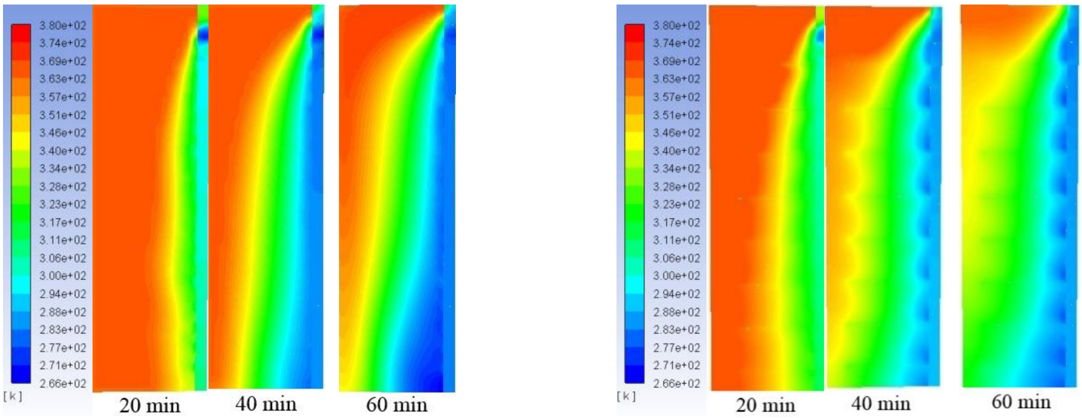
Figure 7. Numerical model with fins

A numerical simulation model is established based on the single phase change unit used in the experiment. As shown in the figure 7, the model size is the same as the actual unit size, and the fin lengths are 2, 4, 6, and 8 cm, respectively. The simulated exothermic condition is preferably flow direction from bottom to top with a flow rate of 9.5 L/h. Transient simulations of the heat exchange were conducted using the commercial CFD software Fluent, three zones were modeled: PCM, heat transfer flow channel and fins, using the melt/solidification model provided by Fluent, while simplifying and assuming the calculation process accordingly.

4.2. Numerical results

Due to the limited space, this paper has selected internal temperature changes of the PCM with a typical internal fin length of 4cm and 8cm compared with the operating conditions without fins (figure 8), the intermediate section perpendicular to the fins and the flow channels was selected.

With the progress of the thermal release, the phenomenon of temperature delamination in the lateral direction can be clearly observed, the temperature of the PCM near the flow channel decreases rapidly, while in the vertical direction, the bottom PCM is first cooled and the upper temperature is still high. When the entire device loses its ability to further thermal release due to the small temperature difference between the PCM layer near the external wall and the fluid, the inner wall and the upper PCM remain at a higher temperature. The solid PCM with a relatively low temperature near the external wall has a large thermal resistance, so that a large amount of heat is still not released in the unit. this is also the main cause of the low exothermic efficiency in the previous experimental results.



(a) no fins (b)fins with length of 8 cm

Figure 8. Comparison of temperature contour

With the addition of horizontal fins (figure 8), the overall temperature gradient of the phase change unit is smaller than before. It cuts off the continuity of the external low-temperature PCM to a certain extent, reduces the thermal resistance of heat transfer, thereby improves the heat exchange efficiency. But there is still a high temperature zone on the top.

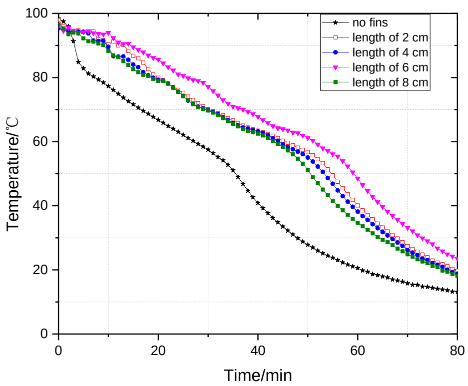


Figure 9. The temperature of outlet water

From the simulation result, it can be seen that the outlet temperature after adding fins is significantly increased, indicating that the overall thermal release performance is enhanced. But the outlet temperature and exothermic power do not increase with the length of the fins. The fin lengths of 2 cm and 4 cm have similar strengthening effects. When the length is 6 cm, the strengthening effect is further enhanced. But the result is not as expected when the length is increased to 8 cm, maybe too long fins hinder natural convection heat transfer at vertical direction. The exothermic efficiency is calculated to be 80% when the length of fin is 6cm, compared with no fins, the efficiency is much improved.

5. Conclusion

This paper proposes a phase change thermal storage device by utilizing off-peak power, experimental investigations and numerical simulation on its thermal performance are conducted.

Through experimental research, it was found that the device can complete the thermal storage within two hours and its thermal storage efficiency reached to 91.3%. When the HTF flows from bottom to

top, it is preferable to thermal release, but the overall thermal release efficiency is not high.
According to the results of numerical simulation, the addition of fins inside the unit can effectively increase the thermal release efficiency to 80% when the length of fin is 6 cm.
Further study will focus on the improvement of heating method, in order to create a more uniform temperature distribution. Additionally, more methods for heat transfer enhancement will also be explored in this device.

6. Reference

[1] Khan A S M, Verzijlbergh R A, Sakinci O C, and Vries L J D 2018 How do Demand Response and Electrical Energy Storage Affect (the Need for) a Capacity Market? *Appl. Energy.* **214** 39-62
[2] Barzin R, Chen J J J, Young B R, and Farid M M 2015 Peak Load Shifting with Energy Storage and Price-based Control System *Energy.* **92** 505-514
[3] Li G, Qian S, Lee H, Hwang Y and Radermacher R 2014 Experimental Investigation of Energy and Exergy Performance of Short Term Adsorption Heat Storage for Residential Application *Energy*. **65** 675-691
[4] Pirasaci T, Wickramaratne C, Moloney F, Goswami D Y, Stefanakos E, and Yan J 2018 Influence of Design on Performance of a Latent Heat Storage System at High Temperatures *Appl. Energy.* **224** 220-229
[5] Liu G, Wang X, Zhang Y, Di H and Jiang Y 2004 Experimental Research on High-temperature Phase Change Thermal Energy Storage Heater *J. Eng. Thermophys.* **36** 62-65
[6] Zhu J L, Li H and Zhang W 2012 Numerical Simulation and Optimization of Phase Change Heat Storage Process with Spiral Pipe *J. Tianjin Univ.* **45** 875-880
[7] Abdulateef A M, Mat S, Abdulateef J, Sopian K, and Al-Abidi A A 2017 Geometric and Design Parameters of Fins Employed for Enhancing Thermal Energy Storage Systems: a Review *Renew. Sust. Energ. Rev.* **82** 1620-35
[8] Longeon M, Soupart A, Fourmigué J F, Bruch A, and Marty P 2013 Experimental and Numerical Study of Annular PCM Storage in the Presence of Natural Convection *Appl. Energy.* **112** 175- 184
[9] Wang P, Yao H, Lan Z, Peng Z, Huang Y, and Ding Y 2016 Numerical Investigation of PCM Melting Process in Sleeve Tube with Internal Fins *Energy Conv. Manag.* **110** 428-435
[10] Kazemi M, Hosseini M J, Ranjbar A A, and Bahrampoury R 2017 Improvement of Longitudinal Fins Configuration in Latent Heat Storage Systems *Renew. Energy.* **116** 447-457
[11] Joybari M M, Haghighat F, Seddegh S, and Al-Abidi A A 2017 Heat Transfer Enhancement of Phase Change Materials by Fins under Simultaneous Charging and Discharging *Energy Conv. Manag.* **152** 136–156.
[12] Zhao D and Tan G 2015 Numerical Analysis of a Shell-and-tube Latent Heat Storage Unit with Fins for Air-conditioning Application *Appl. Energy*. **138** 381-392

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