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Phase change material heat storage performance in the solar thermal storage structure employing experimental evaluation

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ABSTRACT

One of the most investigated and broadly used mediums in the solar thermal storage systems is using phase change materials. In this research, a comprehensive performance test bench for solar thermal utilization system using a controllable heater to substitute different levels of solar input was established. The test bench is not limited by the weather and equipped with alternative heat storage tanks for different PCMs. The heat storage structure and the performance of paraffin in low temperature system was examined using numerical simulation method. The results showed that the heating power received by PCM was stable at 6–8 kW under the heating condition of 85 °C. At the stage of incompletely melting, the temperature difference between the inside and outside was as high as 31.6, which can reduce the loss of heat to a great extent.

1. Introduction

Solar thermal utilization is one of the most promising renewable energy resources. Although the medium and low temperature solar collectors have the advantages of simple structure and low cost, the intermittentness and instability greatly limit its development. Using thermal energy storage systems (TES) to improve solar thermal efficiency is one of the important ways to enhance the utilization of solar energy. The effectiveness of TES integration in a solar thermal system would be high by increasing the flexibility of the system [1], thereby accelerating its commercial applications.

Currently, the solar TES system has attracted so much attention. Kumar et al. [2] applied a TES to the solar-assisted heating system in an industrial process. A useful model was developed based on the combination of the solar photovoltaic thermal collectors (PVT) and flat panel solar collectors (FPC), which produced as high as 1420 W power, 75% thermal efficiency and 12.72% exergy efficiency. Erdenedavaa et al. [3] conducted a performance analysis of the solar thermal system in Ulaanbaatar. The system built with 30 vacuum tube solar collectors, a 3 kW auxiliary electric heater and a 500 L heat storage tank. In the eight-month experimental measurement, the total heat output of the solar system was 11.3GJ accounting for 23.8% of the area's total heating energy, which significantly reduced the use of fossil fuels.

TES can indeed bring great improvements to solar thermal utilization systems in many practical applications. Therefore, people began to further expand its positive impact on the solar thermal utilization by improving the heat storage performance [4]. The researches on the TES can be divided into two directions [5], i.e. the structural design and the working fluids. The structure design mainly includes the study of heat pipes [6] and fins [7–9]. Kumar et al. [10] designed a shell-and-tube latent heat storage tank with an inclined shell surface and proposed a funnel-shaped heat storage system, which improved the melting and solidification speed of the PCM and the heat absorption rate. Qaiser et al. [11] proposed three different designs of multiple heat transfer tubes and shells to construct a heat storage system. It is concluded that compared with the basic design, the storage rate of the new schemes was increased by more than 80%, which saved nearly half of the time. Ma et al. [12] proposed a hybrid heat storage system that combined a two-box thermal energy storage and a packed bed thermal energy storage. The heat and economic performance of the hybrid storage system was compared with

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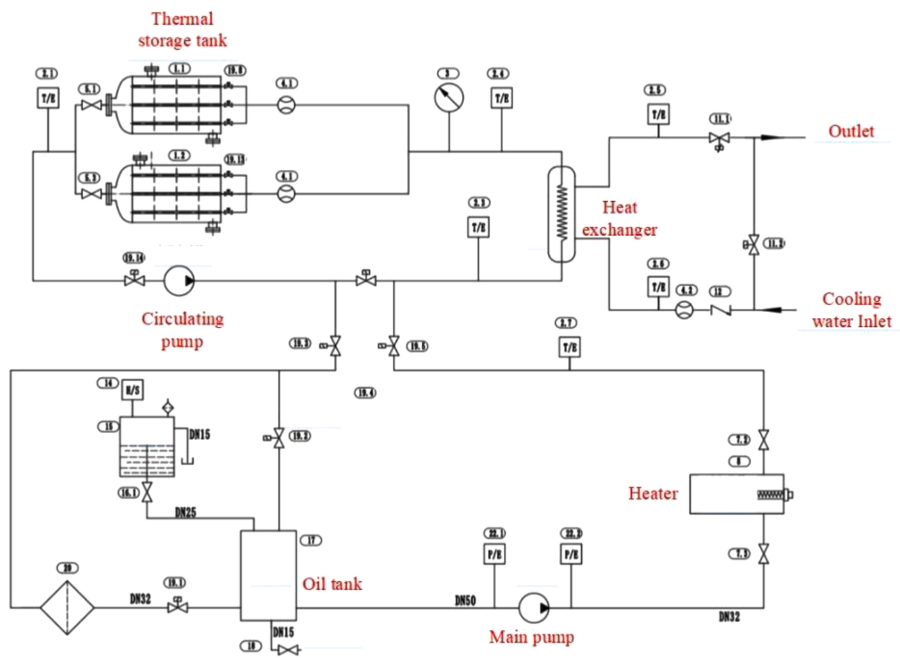

Fig. 1. System piping diagram.

a standard single-tank storage system to demonstrate an annual power generation increase. Literature review shows that different structures produce different enhancement degrees to the working capacity of the TES systems. Among them, the structure of multiple heat pipes and fins is one of the most effective methods [13]; therefore, this structure type is selected and improved in this study.

Applying useful heat storage materials for solar thermal utilization is an important way to improve the heat storage capacity. TES plays a vital role in improving the overall efficiency and reliability of thermal energy utilization systems and heat storage materials used in the TES are the core that determine the system performance [31]. PCM is usually used as the heat storage materials. PCM refers to a kind of material that emits or absorbs a lot of heat during phase change process. PCM is widely used own to its advantages of high heat storage density, high efficiency, easy process control, and stable temperature during heat storage/release process. It is one of the most suitable solar energy storage methods. According to different forms of the phase change, the heat storage capacity of PCMs is different. PCMs can be divided into organic materials, inorganic materials and composite materials. Organic PCMs mainly include the paraffin wax and fatty acid. Industrial paraffin can be used in a wide temperature range with high melting heat and low cost [14]. Therefore, the industrial paraffin is one of the most widely used PCMs [15]. Fatty acid has a higher melting calorific value than the paraffin, but its cost is about 2–2.5 times of the paraffin, which hinders its practical applications [16]. Inorganic PCMs are mainly hydrates of the inorganic compounds. They play an important role in heat storage because of the high latent heat storage density [17]. The combined use of multiple PCMs can increase the flexibility of the storage system and improve the heat storage efficiency [18].

Currently, the PCM research generally adopts numerical simulation methods [19–22], which can reduce the cost and the time. Pirasaci and Goswami [23] studied the influence of the structural design, storage time, working fluid flow rate and other factors on the PCM heat storage efficiency by numerical analysis, and evaluated the PCM performance in the latent heat storage unit of a direct steam power plant. Valenzuela [24] proposed an integrated thermal storage scheme, which combines the sensible heat and latent heat using multiple materials to improve the energy storage efficiency. Kargar et al. [25] proposed a numerical analysis of a new type of heat storage system for direct steam power plants. The performance of the heat storage system was analyzed, and the effect of different design parameters such as the thermal conductivity of the PCM, the heat transfer fluid flow rate and the diameter of the heat exchange tube on the system performance was studied. It was concluded that the thermal conductivity of PCM is the most important parameter to improve the performance of the heat storage system. Li et al. [26] proposed a new type of a solar thermal system coupled with an active PCM heat storage wall using a composite of the paraffin wax and perlite, and continuously monitored the indoor temperature to verify the accuracy of the heat transfer model. The system effectively improved the utilization rate of solar energy, and can keep the temperature of the test room at 23–30 °C. Michels and Pitz-Paal [27] also proposed the concept of cascaded latent heat storage. Five different PCMs were used in the temperature range from 300 °C to 380 °C to form a TES system, and the performance of the simulation model was compared with experimental data. Existing literature shows that the hybrid systems can make better use of the PCM storage capacity, reduce costs, and increase the heat storage ratio, which is one of the important research directions of phase change heat storage in the future [28].

Simulation and numerical researches have the advantages of convenience and low cost [32–35]. As a result, most existing researches of PCMs still adopted numerical simulations, and there are much fewer studies that combine simulation with experiment which is an important way to verify the simulation models. To this avail, this study performs the simulation analysis and experimental verification to analyze the PCM performance in a specially designed energy storage structure from two aspects of sensible heat and latent heat for different levels of solar heat.

2. Experimental bench test

In order to investigate the thermal energy collection efficiency of PCMs and the improvement effect of the overall system performance under different input levels of the solar energy, the design and construction of the experimental bench were carried out. Through this experimental platform, it is possible to study the improvement using the PCMs for the TES systems under different temperature conditions; it can also realize the comparative analysis of the performance of different types of PCMs.

Fig. 2. The actual experimental bench.

2.1. Experimental bench design

In order to meet the requirements of different working conditions, the experimental bench is required to have the ability to switch between different operating modes. The specially designed integrated system pipeline is shown in Fig. 1, including the following three operating modes.

(1) When the solar energy level is low, the heat transfer oil receives less solar radiation and the temperature rise is not high. Under this condition, when the low power mode of the heater is turned on, the temperature of the heat transfer oil will not increase significantly after passing through the heater; and the absorbed heat is only used for heating the heat transfer oil.
(2) After the solar energy level rises, when the temperature of the heated heat transfer oil reaches the operating requirements of the heat exchange or heat storage tank, the high temperature heat transfer oil is delivered to the heat exchanger and the heat storage tank through the main pump. The heat transfer oil has a certain temperature increase after passing through the heater, which can be used for the energy storage by the PCMs. In this mode, the heat transfer oil passes through the heat exchanger, and the heat release function can be selected according to the set solar energy level and the heat release requirements.
(3) When the energy output is required without the solar energy input, the circulating pump transfers the oil to the heat storage tank to absorb the heat energy of the PCMs, and then to the heat exchanger for releasing heat outside.

The experimental bench can simulate different input levels of the solar energy by using a heater that can adjust the temperature. At the same time, it can also increase the experimental efficiency of the experimental bench and shorten the experiment cycle. As the core component, the heat storage tank needs to be specifically designed to improve the heat transfer efficiency. In addition, the heat exchanger here is only used as a reference for heat utilization. In the actual application process, specific research should be conducted for different heat using purposes.

The actual experimental bench is shown in Fig. 2. The experimental bench is equipped with a 380 V, 20 kW variable power electric heater, and the heating power of the heater is dynamically adjusted through PLC control to simulate solar energy input under different conditions. The temperature, pressure and flow parameters of the working fluid are obtained in various parts of the system during operation through the sensors and flow meters. According to different levels of the heat source, there are high, medium, low and no heat source operating modes, which provide a research basis for studying the optimization of the solar energy utilization and solar thermal storage. The specific configurations are shown in Table 1.

Table 1
Main configurations.

Components	Parameters
System Power	380 V; 25 kW; 50Hz
Heater	380 V; 20 kW; 50Hz
Main pump	380 V; 2.2 kW; Flow: 12m3/h; Lift: 25m
Circulating pump	380 V; 750 W; Flow: 56 L/min; Lift: 38m
Oil tank	50L
Data acquisition card	NI-6008
PLC	FX-2N-44M

The measurement system of the test bench is composed of sensors and the control system consists of acquisition modules, industrial computer and PLC integrated computer. The main measurement and control logic are shown in Fig. 3. First, set the working mode through the operation panel to control the heater, circulating pump and other components to work; after the system starts running, the signals are transmitted to the acquisition module by various sensors, flow meters, pressure sensors, etc.; and the result is displayed on the display interface of the industrial computer.

PCMs are stored in the thermal storage tanks. There are two tanks assembled on the bench in order to provide a research foundation for studying the influence of different PCMs and structures on the heat transfer efficiency in phase change heat storage technology. The multi-tube bundle fin structure is optimized in this bench, which significantly improves the heat exchange efficiency. The three-dimensional structure of the thermal storage tank is shown in Fig. 4. The two heat storage tanks each contain 12 temperature sensors, which can accurately obtain the temperature distribution inside the heat storage tank, providing an important basis for studying the phase change process.

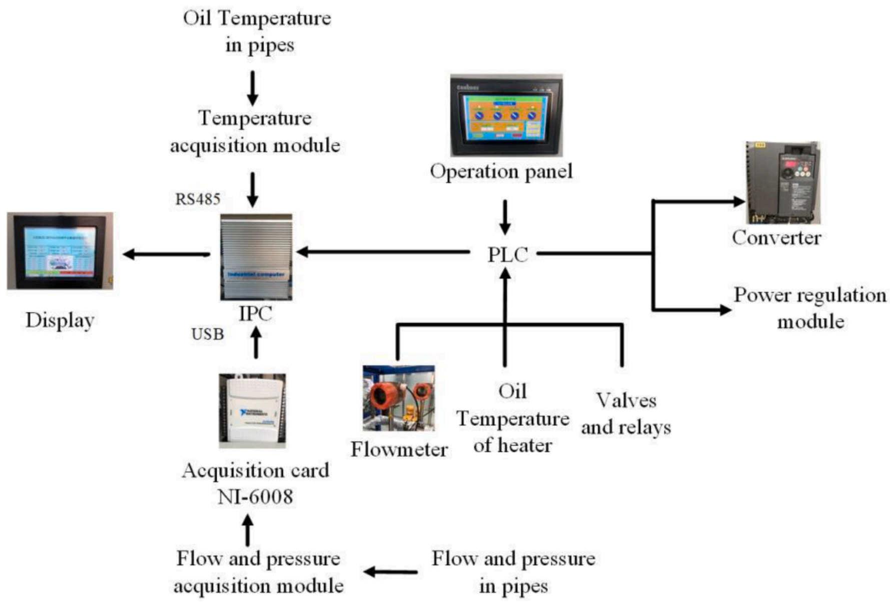

Fig. 3. Measurement and control logic diagram.

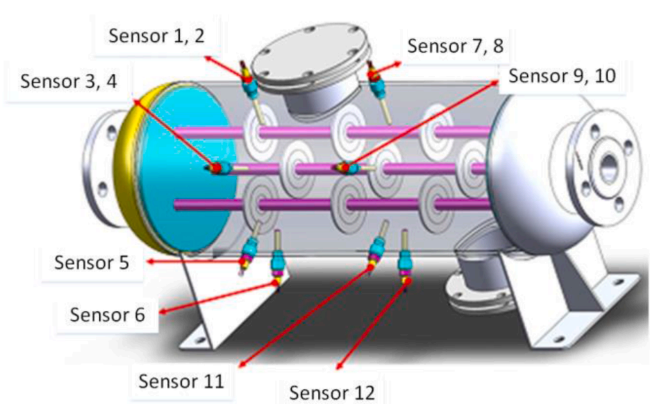

Fig. 4. Schematic diagram of the internal structure of the storage tank.

Table 2
Physical properties of paraffin.

Properties	Values
Density (kg/m3)	800
Cp (J/kg-K)	2100 (T<60); 2000 (T>60)
Thermal conductivity (W/m-K)	0.2516
Viscosity (kg/m-s)	0.00324
Melting heat (j/kg)	170,000
Phase transition temperature (°C)	60
Weight (kg)	14

2.2. Selection of working fluid

The heat conduction oil used in this experiment is L-QB300, which has the characteristics of high specific heat and good thermal conductivity. It can be used for heat conduction work below 300 °C. The object of this paper is mainly the phase change storage of the solar thermal utilization in the middle and low temperature state, and the working temperature is generally below 120 °C. As a PCM with a low phase change temperature, the paraffin has the characteristics of high latent heat, good stability and low cost. It is very suitable for this research. Therefore, we used the paraffin as the PCM for the heat storage, and the specific performance parameters are shown in Table 2.

Table 3
uncertainty of the experiments.

Parameters	Instrument	Uncertainty
Flow temperature, T_f	Temperature sensor probe, PT-100	±0.3 °C
Temperature, T_s	Temperature signal acquisition module, DAS-RTD	±0.1%FS °C
Flow, q_f	Liquid turbine flowmeter, ECLWGY-01G	±1%R
Ambient temperature	Thermometer	±0.5 °C

2.3. Experimental uncertainty analysis

Uncertainty analysis is an indispensable part of experimental researches [36]. Referring to the manufacturer's data and following the similar studies in recent years [37–41], values of the relative uncertainty are given to evaluate the accuracy of the experiment system in Table 3.

The uncertainty of the test can be attributed to the measurement inaccuracies of temperature, flow rate and mass. The uncertainty U_T of the system is ± 1.05% by using the following Eq. (1) [42]:

$$U_T = \pm\sqrt{\left(\frac{\delta T_f}{\Delta T_f}\right)^2 + \left(\frac{\delta T_s}{\Delta T_s}\right)^2 + \left(\frac{\delta q_f}{\Delta q_f}\right)^2} \times 100\% \quad (1)$$

3. Simulation and experimental analysis

Numerical simulation using ANSYS/Fluent and experiment analysis have been combined to investigate the PCM performance. Through numerical simulation, different PCM and different operating conditions can be analyzed, so as to provide important guidance for actual experimental work to reduce costs and consumption time. Through experiments, the working status and physical phenomena of PCM can be obtained, so as to correct the simulation model and promote the development of practical applications.

The melting process of PCM is mainly divided into three stages: low temperature sensible heat stage, melting latent heat stage and high temperature sensible heat stage. There are complex physical phenomena such as heat conduction, convection heat transfer, volume expansion,

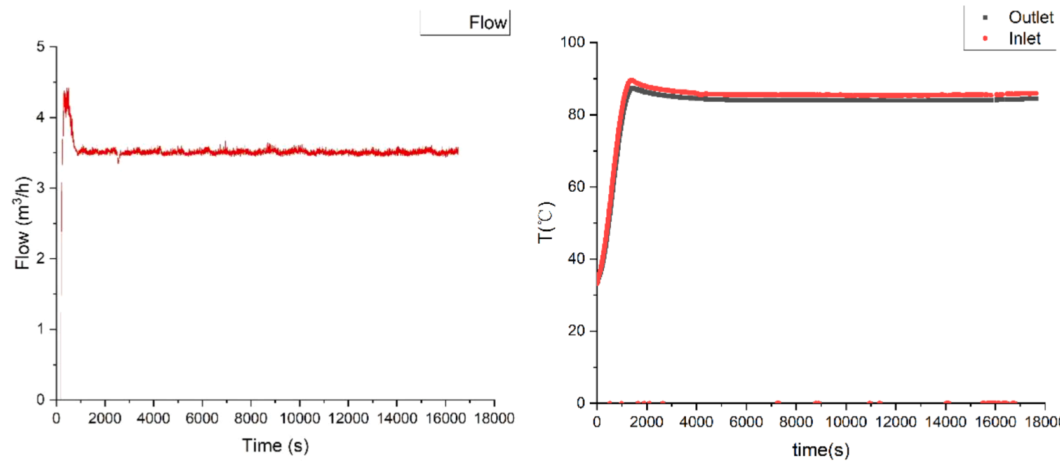

Fig. 5. Flow in the pipes.

material movement, etc. during the melting, which makes the heat transfer process have obvious nonlinear characteristics, and it is difficult to obtain an accurate solution. As a result, numerical analysis is the common way to get the detail of melting process. The temperature method is adopted in the present model. The SOLIDWORKS is used to build a three-dimensional model, the ANSYS /ICEM is used for meshing, and the CFD-POST is for post-processing. The operating mechanism of the paraffin melting and heat storage is analyzed to further improve the performance of the heat storage device. In setting the paraffin properties, the following reasonable assumptions are made.

(1) In the process of phase transition, the temperature change range is not large, and the physical properties of the paraffin can be regarded as constant and isotropic.
(2) The melted liquid paraffin is an incompressible fluid, and the natural convection is laminar. The Boussinesq hypothesis is valid.
(3) The temperature of the internal heat transfer oil is constant, the heat transfer resistance between the oil and the inner wall of the tube is negligible, and the wall is regarded as a constant temperature.

3.1. Numerical model establishment

During the paraffin phase change process, the heat is provided by the heater. As it shown in Fig. 5, the actual temperature of the heat transfer oil does not change significantly under the flow of 3.5 m^3/h and the heating power of 20 kW. The internal fins conduct heat very quickly, so the wall surface can be approximated to a constant temperature.

In the numerical simulation, the heating wall is set as the first type of constant temperature thermal boundary condition. The control equation of the phase change process simulation is as follows:

(1) Continuity equation:

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \vec{u}) = 0 \quad (1)$$

(2) Momentum equation:

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \vec{u} \mu) = -\nabla P + \nabla (\mu \nabla \vec{u}) + \rho g + F \quad (2)$$

(3) Energy equation:

$$\frac{\partial (\rho H)}{\partial t} + \nabla \cdot (\rho \vec{u} H) = \nabla \cdot (k \nabla H) \quad (3)$$

Where: t- time (s); ρ- density (kg/m3); $\vec{u}$- velocity (m/s); μ- viscosity (Pa•s);P- pressure (Pa); k- thermal Conductivity (W/m•K); H- Phase transition enthalpy (kJ/kg). $F$is the source term for momentum equation and related to the melting state of the PCM. The phase change process involves the parameters of the mushy zone. When setting the melting properties during the simulation, set the Mushy Zone Parameter to 10,000 [29,30]. The total heat stored during the numerical simulation can be calculated by Eq. (4):

$$Q = m \cdot [C_s \cdot (t_m - t_0) + H + C_l \cdot (t_e - t_m)] \quad (4)$$

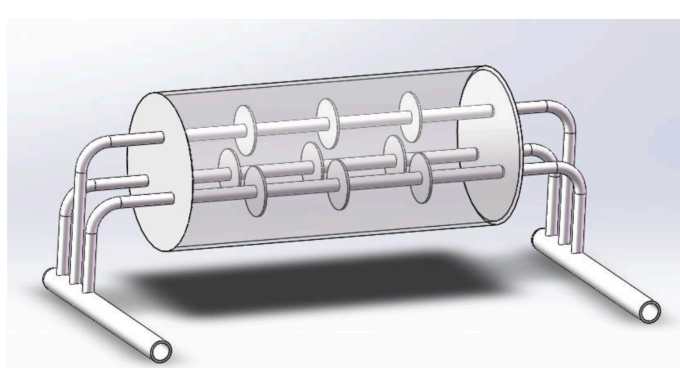

Fig. 6. Thermal storage tank structure diagram.

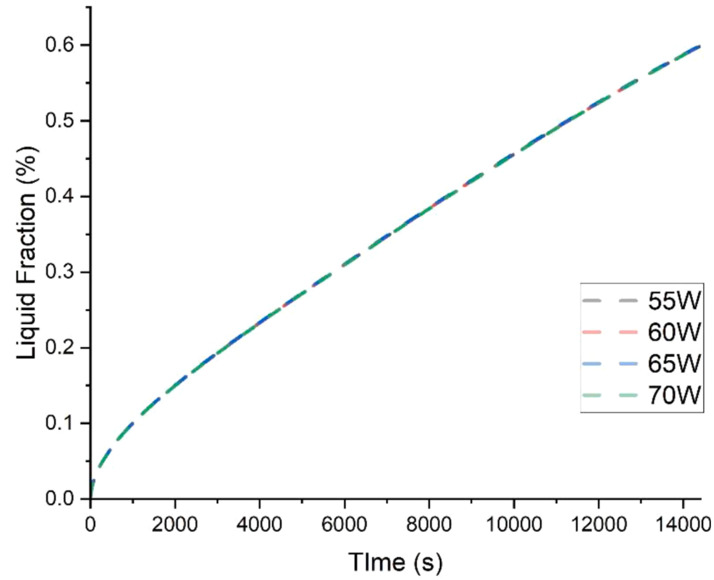

Fig. 7. Grid independence verification.

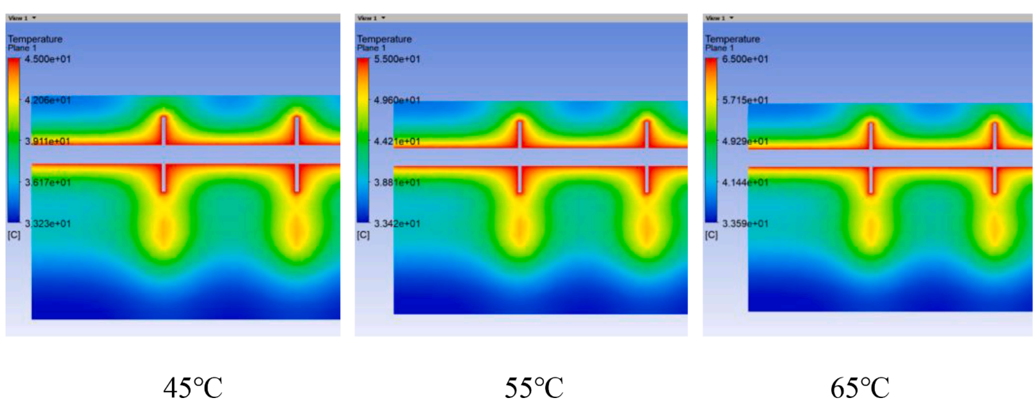

Fig. 8. The heat storage effect of paraffin under low temperature conditions.

Where: Q- total heat (kJ); m- flow (m^3/s); C_s- Solid specific heat capacity (kJ/kg); t_m- Phase transition temperature (°C); t_0- initial temperature (°C); C_l- Liquid specific heat capacity(kJ/kg); t_e- Final temperature (°C).

A shell-and-tube phase change energy storage heat exchanger was designed in order to study the paraffin phase change process in the heat

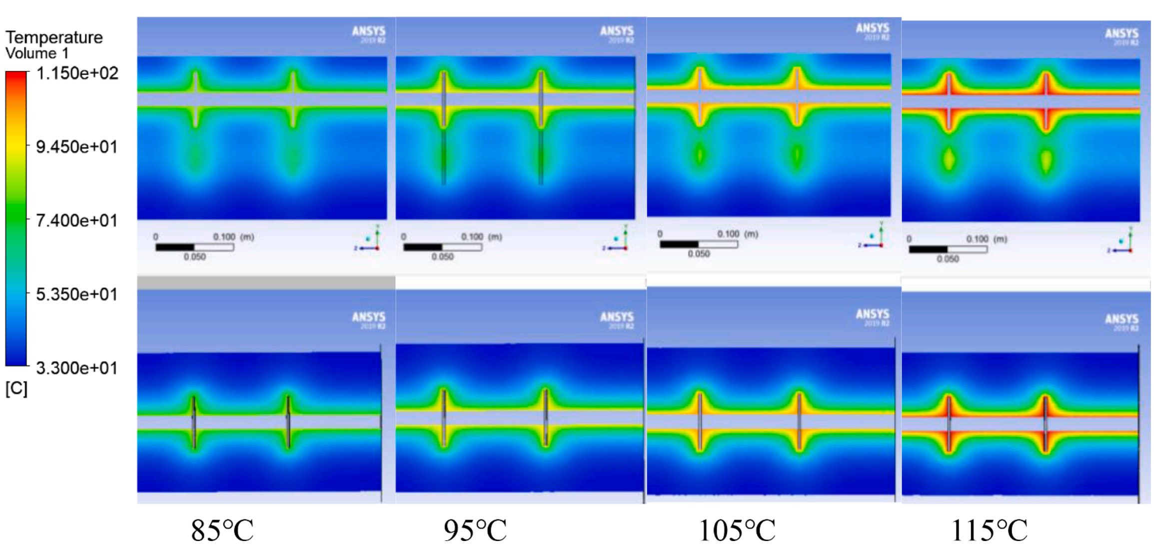

Fig. 9. Phase transition state of paraffin at 3000 s.

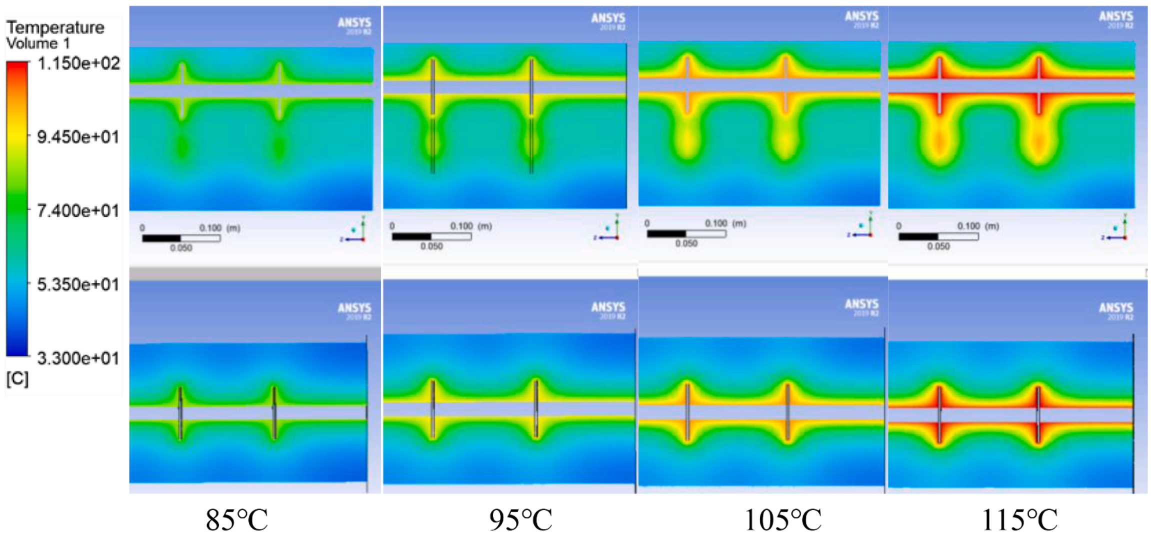

Fig. 10. Phase transition state of paraffin at 9000 s.

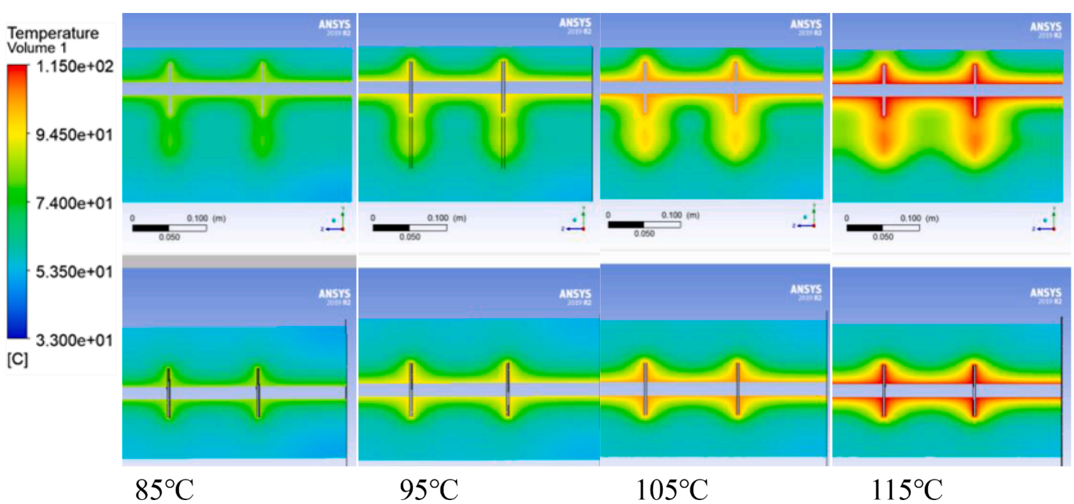

Fig. 11. Phase transition state of paraffin at 15,000s.

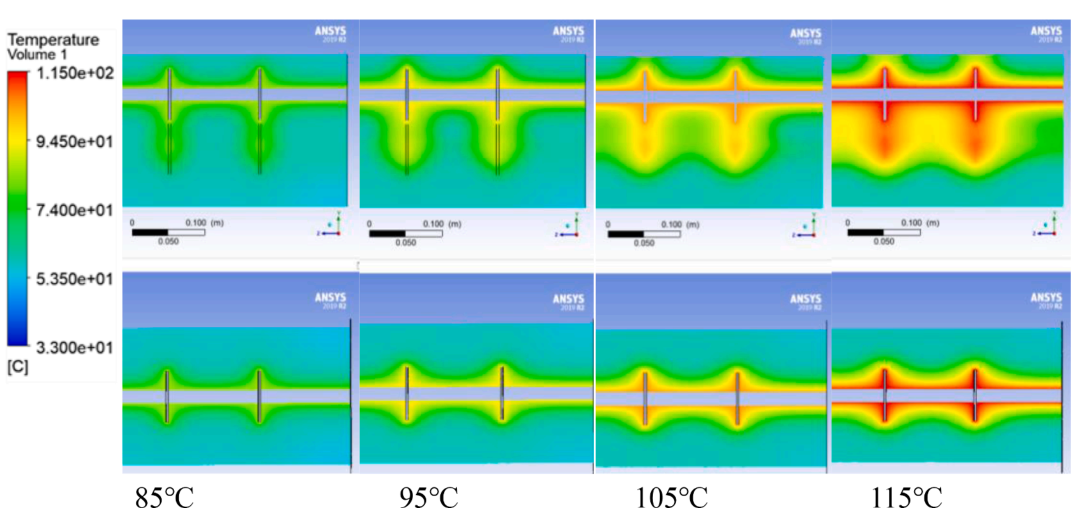

Fig. 12. Phase transition state of paraffin at 18,000s.

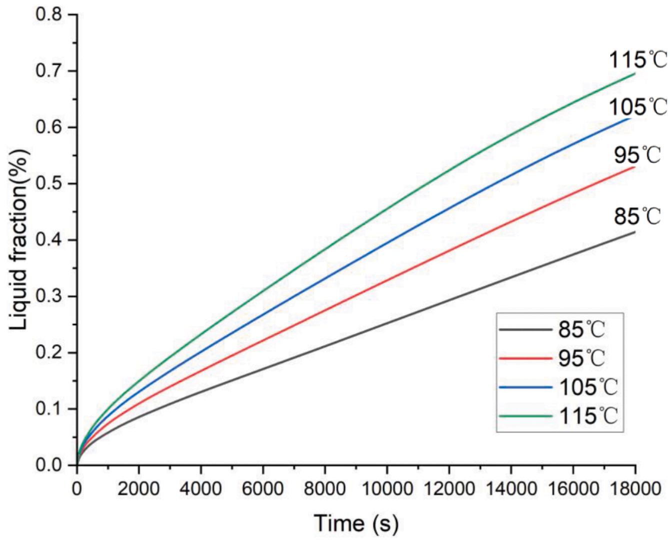

Fig. 13. Melting process under different temperature.

storage tank under different levels of energy input. The three-dimensional simulation model is established through SolidWorks, and the schematic diagram of the structure is shown in Fig. 6. The heat transfer oil enters and exits the heat storage tank through the pipeline, and the tank is filled with paraffin. The heat is carried by the heat transfer oil to the pipeline in the heat storage tank, and then transferred to the outer wall of the tube and a series of fins to complete the heating of the paraffin.

In terms of numerical simulation, many scholars have analyzed practical problems on the basis of finite difference method, finite element method and other numerical simulation methods, which are simple and effective in solving moving boundary problems. [43–46] According to the simplified physical model, ANSYS/ICEM is used to perform three-dimensional unstructured meshing of the paraffin. ICEM is more professional to build unstructured grids and easier than other programs in this case which is not so complexed. Fig. 7 shows the result of grid independence verification with the melting process under the grid cells of 55 w, 60 w, 65 w and 70 w. The fluctuation curve of liquid fraction over time was small. As a result, the final model has a total of 551,077 grid cells and the maximum grid size was set at 0.01.

3.2. Result analysis

In order to study the heat storage process of the paraffin under different solar energy levels, a simulation was carried out on two levels of medium temperature and low temperature. Under low temperature conditions, the heating temperature was set to 45, 55 and 65 °. The heating process was carried out for 1 h. The final heating section of the paraffin is shown in Fig. 8. It can be seen that when the phase change temperature is hardly reached, the paraffin cannot play the advantages of PCM, but it still has a good ability to absorb heat in the tube. Moreover, the designed heat storage structure can well distribute the limited heat to the inner center of the paraffin, and the outer part close to the wall of the tank is more difficult to obtain heat, which ensures that the heat in the heat storage tank can be stored in the PCM for a longer time to reduce the heat dissipation.

The solar heat storage was carried out at a medium temperature. By setting the heating temperature to 85, 95, 105 and 115 °, and the simulation time was set for 5 h, the phase transition process of paraffin wax was analyzed. Figs. 9–12 show the internal temperature distribution changes of the paraffin wax at 3000 s, 9000 s, 15,000 s and 18,000 s at the four different temperatures. The two views are respectively a left sectional view and a top sectional view of the top heating tube. The curve of the melting ratio of the paraffin with time at different temperatures is shown in Fig. 13.

By comparing the phase transition process of the paraffin at different temperatures, it can be found that the paraffin is in a relatively stable state under two heating conditions of 85 and 95 °, which can easily absorb the heat brought by the heat transfer oil and still leave a lot of redundancy. It can be seen from the melting curve that the melting rate of the paraffin gradually stabilizes under the condition of the constant temperature. The paraffin can maintain the phase change process for

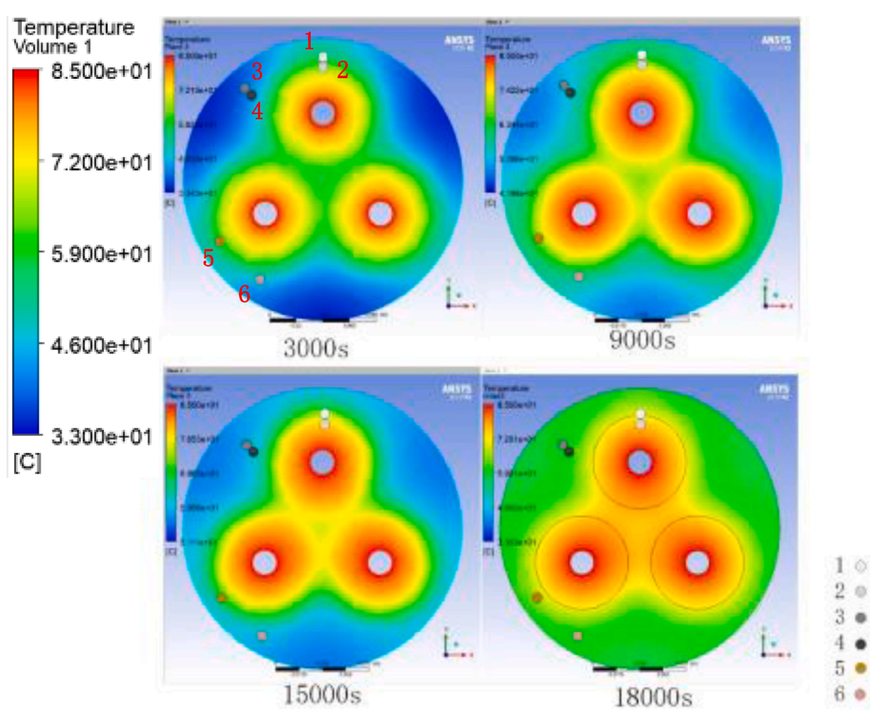

Fig. 14. Temperature distribution of Face 1.

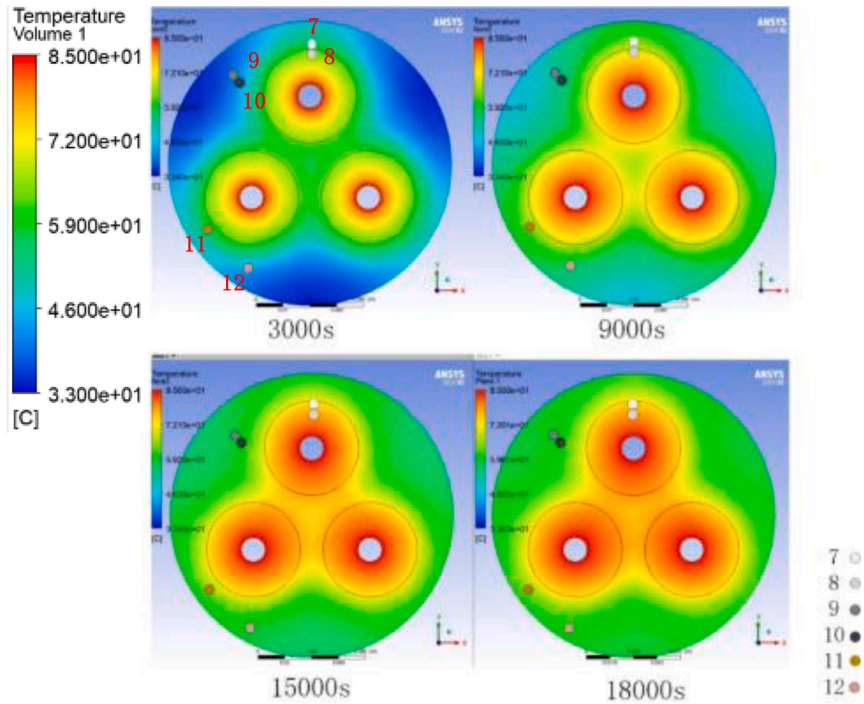

Fig. 15. Temperature distribution of Face 2.

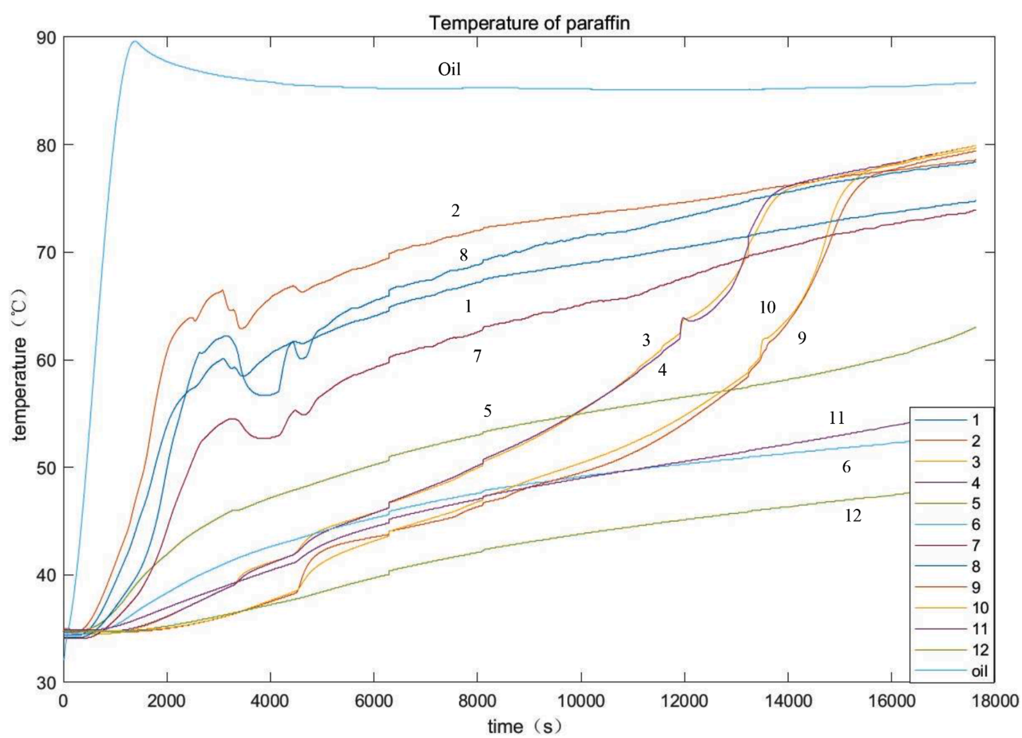

Fig. 16. The temperature change of paraffin.

about 10 h at this temperature, which fully meets the requirements of the solar thermal storage. When the temperature reaches 105 ° and 115 °, the utilization rate of the paraffin in the thermal storage tank was further improved. The paraffin in the center part completed the phase change process with the increase in temperature and reached a relatively high temperature. The temperature of the part close to the tank wall was still at a relatively low temperature, although it was also gradually increasing. It can reduce the heat dissipation through the wall and ensure the heat storage performance. In the 5 h simulation process, it can be seen that although the melting speed becomes faster with the increase of heating temperature, the speed decayed. In the end of the melting at 115 °, 30% of the paraffin was still in an unmelted state after 5 h of heating. Therefore, the heat storage device and the PCM paraffin used in this bench are fully capable of thermal energy storage under medium temperature conditions.

Table 4
The results of temperature at the specific time.

Senor number	3000s		9000s		15,000s		18,000s	
	exp	sim	exp	sim	exp	sim	exp	sim
1	59.8	55.5	68.2	66.3	73	70.3	74.8	72.8
2	66.2	72.6	72.8	75.2	77	79.5	78.6	83.4
3	38.4	38.3	52.4	53.3	77.1	78.7	79.7	79.7
4	38.4	40.2	52.7	55.8	77.3	81.7	79.9	82.6
5	45.3	52.5	54.1	55.3	59.1	63.3	63	68.6
6	40.8	45.7	48.5	49.6	51.8	55.3	53	56.9
7	53.9	55.3	64	68.1	71.7	73.6	73.9	74.6
8	61.9	64.8	70.3	72.9	76.6	78	78.4	81.1
9	36	38.3	48.2	50.4	73.3	70.7	79.4	76.4
10	36	39	48.8	51.1	75	71.2	79.9	75.6
11	38.7	41.2	48.1	58.1	53	63.8	55.5	65.3
12	36.2	40	43.1	52.7	46.9	53.6	48.3	55.1

3.3. Comparison between simulation and experiments

There are 12 temperature sensor probes inside the heat storage tank to detect the real-time changes in the temperature of the PCM during the experiment. Select the section where the temperature sensor is located in the simulation results. Compare the results with the actual experiment results, and check whether the simulation results have good accuracy. Figs. 14 and 15 are the temperature distributions of face 1 and face 2 of the cross-sectional view of the installation position of the temperature sensor in the heat storage tank. The actual position of each sensor is marked on the figures for comparison and analysis with the experiment results.

The temperature sensors are respectively installed 6 mm and 11 mm away from the center fin on both sides. In order to check the rationality of the thermal storage tank and test the performance of the paraffin, the paraffin was heated at 85 ° for 18000s. During the experiment, the heater was set at a constant temperature of 85 °C. The heater was controlled by PLC, so that the heater can work in a dynamic working state, and the temperature of the heat transfer oil is continuously ensured. Collect the temperature of the sensor in the heat storage barrel through the acquisition card, and display the record at all times. The temperature changes of the paraffin in the heating process are shown in Fig. 16. Table 4 listed the temperature of each sensor at the specific time of the experiment and simulation, respectively. The difference value between simulation and experiment results are shown in Fig. 17.

The difference value is mainly related to the position of sensors. In the early stage, the temperature of the oil increased rapidly, forming an enlarged temperature difference with the paraffin, and the overall temperature of the interior increased rapidly. Sensors 1, 2, 7, and 8 closed to the fins were heated up particularly quickly. In the time period of 2000–4000 s, the temperature of the oil gradually exceeded the set value, and the PLC controls the heater to stop heating. At this time, the temperature of the above four positions has dropped, but the paraffin was still in a state of being heated. When the time came to 12,000s-14,000 s, the central part of the paraffin melted, the paraffin at the sensors 3, 4, 9, and 10 gradually became liquid, and the temperature rises rapidly. But the temperature of the sensors 5, 6, 11, and 12 located at the bottom and far away from the fins were still maintained below the phase transition temperature and were still in a solid state. In general,

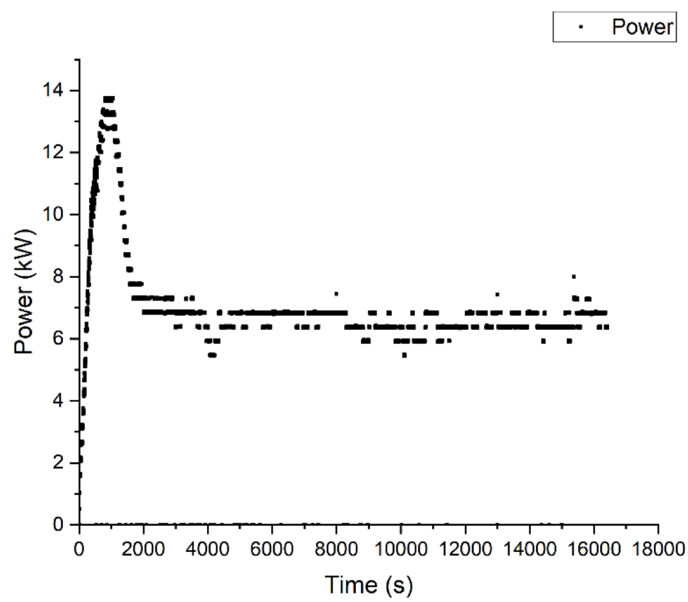

Fig. 18. Heating power to the paraffin.

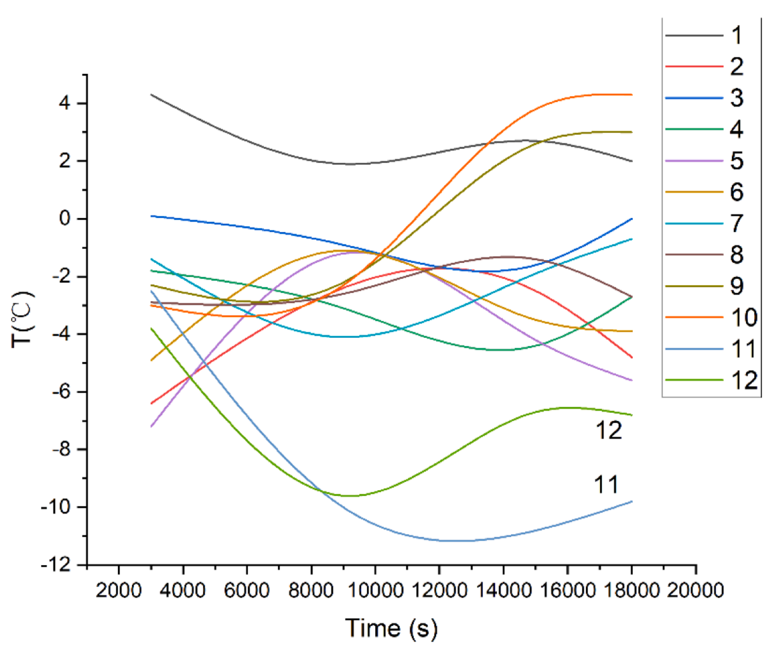

Fig. 17. The difference value between simulation and experiment results.

the temperature distribution in the tank was very reasonable. The maximum temperature at the center and the minimum temperature inside the tank differed by 31.6 ° in this case, which greatly reduces the heat loss caused by the contact part with the tank wall. The heating power to the paraffin is shown in Fig. 18 and the power is mainly 6–8 kW under the heating temperature of 85 °C.

4. Conclusion

The medium and low temperature solar thermal storage technology was researched in this paper, and the rationality of the heat storage structure was verified through simulation and experiment investigation. The phase change process of the PCM under different energy input levels was discussed, and the heat storage capacity of PCM was analyzed.

(1) A comprehensive performance test bench for solar thermal utilization system was established. It is much more efficient and flexible without the limitation of weather conditions by using a controllable heater with the max power of 20 kW to substitute different levels of solar input.
(2) A research method of solar medium and low temperature heat storage technology was proposed by combining simulation and experiment investigation. The performance of the designed heat storage tank and the PCM was evaluated. The results showed that the heating power received by PCM was stable at 6–8 kW under the heating condition of 85 °C. The structure can centrally raise the temperature of the central part during the PCM melting. Under the condition of continuous heating at 85 ° for 5 h, the temperature difference between the inside and outside of the PCM was as high as 31.6 °, which greatly reduced the heat exchange between the PCM and the outer wall of the heat storage tank, and improved the energy storage system performance.
(3) At present, PCMs used in solar thermal system is mainly binary mixed nitrate composed of 40% KNO_3 and 60% $NaNO_3$ (Solar Salt, melting point is 220 °C) and ternary nitrate composed of 53% KNO_3, 40% $NaNO_2$ and 7% $NaNO_3$ (Hitec Salt, melting point is 142 °C). The future research is to analyze the performance of Solar Salt and Hitec Salt in order to expand the heat storage temperature range to 40–280 °C. Using the proposed dual heat storage tanks, compare and analyze the heat storage performance of different PCMs under the same heating condition. The most suitable PCM will be selected for different energy input conditions.

CRediT authorship contribution statement

Mingyang Huang: Formal analysis, Writing – original draft. **Wei He:** Methodology, Software, Data curation, Funding acquisition. **Atilla Incecik:** Visualization, Investigation, Writing – review & editing. **Munish Kumar Gupta:** Methodology, Data curation, Writing – review & editing. **Grzegorz Królczyk:** Resources, Software, Writing – review & editing, Funding acquisition. **Zhixiong Li:** Conceptualization, Resources, Supervision, Funding acquisition.

Declaration of Competing Interest

The authors declare no conflict of interest.

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References

[1] Mingyang Huang, Wei He, Atilla Incecik, Andrzej Cicho, Grzegorz Królczyk, Zhixiong Li, Renewable energy storage and sustainable design of hybrid energy powered ships: A case study, J. Energy Storage 43 (2021), 103266.
[2] Kumar L., Hasanuzzaman M., Rahim N.A., et al. Modeling, simulation and outdoor experimental performance analysis of a solar-assisted process heating system for industrial process heat. Renew. Energy, 164: 656–673.
[3] P. Erdenedavaa, A. Adiyabat, A. Akisawa, et al., Performance analysis of solar thermal system for heating of a detached house in harsh cold region of Mongolia, Renew. Energy 117 (2018) 217–226.
[4] Q. Al-Yasiri, M. Szabó, Influential aspects on melting and solidification of PCM energy storage containers in building envelope applications, Int. J. Green Energy (2021) 1–21.
[5] Z. Li, M. Sheikholeslami, M. Jafaryar, et al., Time-dependent heat transfer simulation for NEPCM solidification inside a channel, J. Therm. Anal. Calorim. 138 (1) (2019) 721–726.
[6] S. Mousavi, M. Siavashi, M.M. Heyhat, Numerical melting performance analysis of a cylindrical thermal energy storage unit using nano-enhanced PCM and multiple horizontal fins, Numer. Heat Transf. Part A Appl. 75 (8) (2019) 560–577.
[7] M. Gürtürk, B. Kok, A new approach in the design of heat transfer fin for melting and solidification of PCM, Int. J. Heat Mass Transf. 153 (2020), 119671.
[8] S.B. Chen, S. Saleem, M.N. Alghamdi, et al., Combined effect of using porous media and nano-particle on melting performance of PCM filled enclosure with triangular double fins, Case Stud. Therm. Eng. 25 (2021), 100939.
[9] T. Bouhal, O. Limouri, Y. Agrouaz, et al., Numerical analysis of PCM melting filling a rectangular cavity with horizontal partial fins[C]//MATEC Web of Conferences, EDP Sci. 307 (2020) 01011.
[10] Kumar A., Saha S.K., Performance study of a novel funnel shaped shell and tube latent heat thermal energy storage system. Renew. Energy, 165: 731–747.
[11] R. Qaiser, M.M. Khan, L.A. Khan, et al., Melting performance enhancement of PCM based thermal energy storage system using multiple tubes and modified shell designs, J. Energy Storage 33 (2021), 102161.
[12] Z. Ma, M.J. Li, K.M. Zhang, et al., Novel designs of hybrid thermal energy storage system and operation strategies for concentrated solar power plant, Energy (2020), 119281.
[13] M.E. Nakhchi, J.A. Esfahani, Improving the melting performance of PCM thermal energy storage with novel stepped fins, J. Energy Storage 30 (2020), 101424.
[14] P. Huang, G. Wei, L. Cui, et al., Numerical investigation of a dual-PCM heat sink using low melting point alloy and paraffin, Appl. Therm. Eng. 189 (2021), 116702.
[15] A. Sharma, V.V. Tyagi, C.R. Chen, et al., Review on thermal energy storage with phase change materials and applications, Renew. Sustain. Energy Rev. 13 (2) (2009) 318–345.
[16] M.H.M. Yasin, T. Yusaf, R. Mamat, et al., Characterization of a diesel engine operating with a small proportion of methanol as a fuel additive in biodiesel blend, Appl. Energy 114 (2014) 865–873.
[17] N. Xie, Z. Huang, Z. Luo, et al., Inorganic salt hydrate for thermal energy storage, Appl. Sci. 7 (12) (2017) 1317.
[18] W. Tomaszewski, M. Kudra, M. Szadkowski, Melt-blown nonwovens from polypropylene blended with unencapsulated paraffins as PCM. Properties of paraffin and blends, Fibres Text. East. Eur. 6 (120) (2016) 65–72, https://doi.org/10.5604/12303666.1226220.
[19] M.A.A. Shak, A.M. Bayomy, S.B. Dworkin, et al., Thermal behavior of phase change material (PCM) inside a cavity: numerical approach, in: Proceedings of the International Conference on Computational & Experimental Engineering and Sciences, Cham, Springer, 2019, pp. 99–104.
[20] W. Li, W. Chen, Numerical analysis on the thermal performance of a novel PCM-encapsulated porous heat storage Trombe-wall system, Sol. Energy 188 (2019) 706–719.
[21] C. Zhao, M. Opolot, M. Liu, et al., Numerical study of melting performance enhancement for PCM in an annular enclosure with internal-external fins and metal foams, Int. J. Heat Mass Transf. 150 (2020), 119348.
[22] Y.M. Chu, D. Yadav, A. Shafee, et al., Influence of wavy enclosure and nanoparticles on heat release rate of PCM considering numerical study, J. Mol. Liq. 319 (2020), 114121.
[23] T. Pirasaci, D.Y. Goswami, Influence of design on performance of a latent heat storage system for a direct steam generation power plant, Appl. Energy 162 (2016) 644–652.
[24] Valenzuela L. Thermal energy storage concepts for direct steam generation (DSG) solar plants. Advances in Concentrating Solar Thermal Research and Technology. Woodhead Publishing, 2017: 269–289.
[25] M.R. Kargar, E. Baniasadi, M. Mosharaf-Dehkordi, Numerical analysis of a new thermal energy storage system using phase change materials for direct steam parabolic trough solar power plants, Sol. Energy 170 (2018) 594–605.
[26] H. Li, J. Li, X. Kong, et al., A novel solar thermal system combining with active phase-change material heat storage wall (STS-APHSW): Dynamic model, validation and thermal performance, Energy 201 (2020), 117610.
[27] H. Michels, R. Pitz-Paal, Cascaded latent heat storage for parabolic trough solar power plants, Sol. Energy 81 (6) (2007) 829–837.
[28] C. Zauner, F. Hengstberger, B. Mörzinger, et al., Experimental characterization and simulation of a hybrid sensible-latent heat storage, Appl. Energy, 189 (2017) 506–519.
[29] A.R. Abdulmunem, P.M. Samin, H.A. Rahman, et al., Numerical and experimental analysis of the tilt angle's effects on the characteristics of the melting process of PCM-based as PV cell's backside heat sink, Renew. Energy 173 (2021) 520–530.

[30] C. Zhao, M. Opolot, M. Liu, et al., Numerical study of melting performance enhancement for PCM in an annular enclosure with internal-external fins and metal foams, Int. J. Heat Mass Transf. 150 (2020), 119348.
[31] Q. Xu, X. Liu, Q. Luo, et al., Bifunctional biomorphic SiC ceramics embedded molten salts for ultrafast thermal and solar energy storage, Mater. Today Energy 21 (2021), 100764.
[32] A. Mahmoudan, P. Samadof, S. Hosseinzadeh, et al., A Multigeneration cascade system using ground-source energy with cold recovery: 3E analyses and MultiÂ, Energy 233 (2021), 121185.
[33] S. Hoseinzadeh, M.H. Ghasemi, S. Heyns, Application of hybrid systems in solution of low power generation at hot seasons for micro hydro systems, Renew. Energy 160 (2020) 323–332.
[34] R. Dadsetani, G.H.A. Sheikhzadeh, M.R. Safaei, et al., Exergoeconomic optimization of liquefying cycle for noble gas argon, Heat Mass Transf. 55 (7) (2019) 1995–2007.
[35] S. Mehrdad, R. Dadsetani, A. Amiriyoon, et al., Exergo-economic optimization of organic rankine cycle for saving of thermal energy in a sample power plant by using of strength pareto evolutionary algorithm II, Processes 8 (3) (2020) 264.
[36] M.M. Sarafraz, M.R. Safaei, Diurnal thermal evaluation of an evacuated tube solar collector (ETSC) charged with graphene nanoplatelets-methanol nano-suspension, Renew. Energy 142 (2019) 364–372.
[37] A. Sohani, S. Hoseinzadeh, K. Berenjkar, Experimental analysis of innovative designs for solar still desalination technologies; an in-depth technical and economic assessment, J. Energy Storage 33 (2021), 101862.
[38] Y. Shen, S. Liu, C. Zeng, et al., Experimental thermal study of a new PCM-concrete thermal storage block (PCM-CTSB), Constr. Build. Mater. 293 (2021), 123540.
[39] A. Sohani, S. Hoseinzadeh, S. Samiezadeh, et al., Machine learning prediction approach for dynamic performance modeling of an enhanced solar still desalination system, J. Therm. Anal. Calorim. (2021) 1–12.
[40] M.M. Sarafraz, I. Tlili, M. Abdul Baseer, et al., Potential of solar collectors for clean thermal energy production in smart cities using nanofluids: experimental assessment and efficiency improvement, Appl. Sci. 9 (9) (2019) 1877.
[41] M.M. Sarafraz, I. Tlili, Z. Tian, et al., Smart optimization of a thermosyphon heat pipe for an evacuated tube solar collector using response surface methodology (RSM), Phys. A 534 (2019), 122146.
[42] X. Han, S. Liu, C. Zeng, et al., Investigating the performance enhancement of copper fins on trapezoidal thermochemical reactor, Renew. Energy 150 (2020) 1037–1046.
[43] H. Olia, M. Torabi, M. Bahiraei, et al., Application of nanofluids in thermal performance enhancement of parabolic trough solar collector: state-of-the-art, Appl. Sci. 9 (3) (2019) 463.
[44] Y. Peng, A. Zahedidastjerdi, A. Abdollahi, et al., Investigation of energy performance in a U-shaped evacuated solar tube collector using oxide added nanoparticles through the emitter, absorber and transmittal environments via discrete ordinates radiation method, J. Therm. Anal. Calorim. 139 (4) (2020) 2623–2631.
[45] S. Hoseinzadeh, R. Ghasemiasl, D. Havaei, et al., Numerical investigation of rectangular thermal energy storage units with multiple phase change materials, J. Mol. Liq. 271 (2018) 655–660.
[46] S. Hoseinzadeh, A. Sohani, S. Samiezadeh, et al., Using computational fluid dynamics for different alternatives water flow path in a thermal photovoltaic (PVT) system, Int. J. Numer. Methods Heat Fluid Flow 31 (2020) 1618–1637.