Experimental Investigation of a Novel Solar Energy Storage Heating Radiator with Phase Change Material

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ABSTRACT: A novel solar energy storage heating radiator (SESHR) prototype filled with low-temperature phase change material (PCM) has been developed to accommodate the urgent demand in thermal storage and the fluctuation in renewable energy utilization. This equipment integrated by several independent heat storage units (HSUs) and water and paraffin wax was used as a heat transfer fluid and an energy storage material, respectively. The experimental test platform for low-temperature SESHR was designed and established. The total storage/dissipation time, average storage/dissipation capacity, and the rate and overall thermal efficiency were investigated under different operating conditions. Experimental results showed that a higher temperature difference between the heat source and the melting point of the PCM could significantly improve the heat storage capacity and rate. The heat dissipation rate of the SESHR could be controlled by adjusting the opening ratio of the air convective channel. The average storage rate of the SESHR with 28PCM reached 1106 W at a heat source temperature of 85 °C, and the average heat dissipation rate reached 80.7 W at 100% opening ratio when the SESHR was filled with 1#PCM.

INTRODUCTION

As one of the prominent renewable energy, solar energy has been widely used for domestic water or space heating around the globe due to its various merits of cleanliness, abundance, effectiveness, etc.1,2 It was reported that two thirds of the land areas of China have direct normal irradiance levels exceeding 1095 kW-h/m²/year (3 kW-h/m²/day). Solar radiation resources are quite abundant in the cold regions in the west of China and Inner Mongolia.3 However, solar radiation resources vary a lot because of different geographical situations and their intrinsic defects of intermittent and seasonal effects.

Thermal energy storage (TES) is a crucial technology to address the contradiction between solar energy supply and demand to overcome the intrinsic drawbacks of intermittent and instability of renewable energy.4,5 The present TES systems are generally classified as sensible heat storage (SHS) and latent heat storage (LHS).6,7 Comparatively, the LHS system using a phase change material (PCM) is a more effective and promising technology because of its outstanding advantages of large heat storage capacity and stable phase transition temperature.8 Therefore, the LHS system has been extensively utilized in many applications such as agricultural greenhouse and building heating, waste heat recovery, and solar heat collecting.9-14

Generally, the thermal performances of a specifically designed LHS system would be determined by geometrical structures, energy storage materials, and operation conditions. Thus, experimental and numerical investigations in various works have been conducted to study the overall performance of different LHS systems with PCMs. Sedegh et al.15 experimentally studied the effects of geometric and operating parameters on the thermal behavior of vertical shell-and-tube LHS systems. A shell-to-tube radius ratio of 5.4 showed better performance in terms of the charging time and energy storage capacity. Anish et al.16 carried out an experimental study on the PCM melting behavior in a horizontal shell and multifinned tube LHS system. They found that the inlet temperature has much influence on the performance of the system compared with the flow rate. Tao et al.17 performed detailed numerical simulations on the effect of thermophysical properties of molten salt on the thermal performance of a shell-and-tube heat storage unit. It was showed that the PCM with properties of higher density, melting enthalpy, and specific heat was beneficial to heat storage rate and heat storage capacity. A two-dimensional finite-element computational model of a novel geometrical configuration of the shell-and-tube-based LHTS system was built by Khan et al.18 The numerical results revealed that the melting rate was significantly enhanced by increasing the tube passes number and the heating fluid temperature. Khan et al.19 also conducted an experiment on the heat charging process in a novel LHS unit filled with paraffin. An analysis of the results revealed that the
heat could be accumulated at approximately 14.36 MJ within 3 h in 62 °C HTF with 1.5 L/min. Guellil et al.20 studied a novel LHS system, which was constituted of a finned U-tube heat exchanger enclosed in an insulated rectangular storage unit. The paraffin was contained in a U-tube to exchange heat with air, and the charging process was investigated under different power supplies, air mass flow rates, and flat fins.

With increasing attention on solar energy, research studies on the LHS system in combination with solar energy collection have been widely performed. Dinker et al.8 reviewed several types of solar collectors and thermal energy storage systems that were in common use and summarized materials used for sensible, latent, and chemical heat storage systems. Seddegh et al.21 performed a comprehensive review of the TES techniques for solar water heating systems, giving particular attention to the systems integrated with PCM. The performance of the most applied techniques in solar domestic hot water applications was compared and presented. Allouhi et al.22 studied a storage solar water heater integrated with a thin layer of PCM. A transient simulation was established to explore the melting and solidification process of the PCM for obtaining optimum design parameters and operating conditions. They found that PCM could greatly improve the thermal energy delivered to users during the night. Huang et al.23 proposed a solar thermal energy storage system composed of a shell and a tube LHS unit and water tank. The system efficiency, optimal PCM volume fraction, and optimal PCM melting temperature were numerically investigated. Khan et al.24 evaluated the thermal behavior of an LHS unit in connection with a flat-plate solar collector. A geometrical configuration based on a shell-and-tube heat exchanger with fins was designed to enhance the heat charging of paraffin in a unit under different inlet temperatures and volume flow rates. They found that the increased inlet temperature of HTF (from 52 to 67 °C) has a greater influence on the phase transition rate of paraffin, which was raised by 50.08%. Elbahajoui et al.25 showed a study of a rectangular heat storage unit composed of a number of PCM plates cooperating with a flat-plate solar collector. The heat storage capacity could be obtained in the range of 12–20 MJ for three melting points of commercial paraffins (RT42, RT50, and RT60) under optimum operating conditions. Mahdi et al.26 tested a helical coil LHS system filled with paraffin as a PCM. Electrically heated water (70, 75, and 80 °C) was simulated for solar energy conditions. The results showed that 80 °C with 3 L/min of HTF was conducive to the melting process of PCM.

Overall, numerous research works have been conducted with a focus on the shell and tube LHS unit or system with a cylinder configuration applied in solar energy collection applications in the past years. Nevertheless, a rectangular LHS unit with a U-tube heat exchanger can be an outperformance alternative in latent heat storage, which has been scarcely studied so far. Therefore, a modularized and integrated solar energy storage heating radiator (SESHR) prototype has been designed and developed in this work. Electrically heated water as HTF was simulated for solar heating water to exchange heat with PCM. Two kinds of modified chlorinated paraffin waxes with low melting points are used as energy storage materials, which are suitable for low-temperature energy storage applications. The latent heat storage unit (HSU) consisting of a rectangular aluminum shell and a U-shaped heating tube has been designed. Several HSUs filled with PCM are assembled in an insulated rectangular box in a parallel manner. The SESHR equipment stores thermal energy by exchanging heat with water and releases heat by natural convection. The developed novel thermal storage device has numerous outstanding thermal properties of large heat storage capacity higher heat storage rate, flexibility, and compactness compared with other LHS systems.18,27

In summary, based on previous studies, this study intends to develop efficient and large-scale energy storage LHS equipment to select suitable energy storage media and achieve good controllability in practical applications. To assure that the novel thermal storage device can be implemented in solar heating systems, this study also experimentally investigated the thermal performance of the device, the temperature of the heating fluid, ambient temperature, and opening ratio of a convective channel under different operational conditions in designed parameters during the heat storage and dissipation processes. Moreover, the transient temperature variations of PCM in three points in the HSU were recorded and analyzed to further identify the melting and solidification mechanism of PCM in the specially designed HSU.

### RESULTS AND DISCUSSION

A thorough investigation of the heat storage capacity and rate under various temperatures and the impacts of different operation conditions on the heat dissipation rate of the
SESHR were carried out and analyzed. Besides, the heat transfer mechanism during the melting and solidification process was discussed based on the temperature variations of PCM.

Heat Storage Process. Temperature Profile of PCM. The thermal performances of the SESHR were evaluated by monitoring and analyzing the temperature changes and distributions in the HSUs. All of the HSUs have the same initial temperature by circulating constant HTF temperature during the charging and discharging process. The designed configuration of the SESHR and operating conditions were two main factors that influenced the temperature distribution of PCM in the HSUs. As shown in Figure 1a,b, it displays the average temperature evolutions of PCM in HSU during the heat storage process. It should be mentioned that the phase transition process could not be completed in practical experiments when the HTF temperature was under 75 °C. The #PCM temperature remained at the melting point (approximately 62 °C) over a long time before turning into the molten state (Figure 1a). This could be attributed to the high melting point and the heat loss of equipment. Thus, the full thermal profile of #PCM was only obtained at 85 °C. Obviously, PCM went through three processes (Figure 1), i.e., solid-sensible heat absorption, latent heat absorption, and liquid-sensible heat absorption. First, the temperature of PCM increases sharply because of the high heat transfer rate due to the large temperature difference between HTF and PCM. And then, the temperature increasing trend slowed down when the temperature of #PCM reached its melting point. When the PCM melted completely, the bulk temperature of the PCM approached an equilibrium gradually as the temperature difference between the heating source and the bulk temperature was close. Figure 1b indicates that an increase in the inlet HTF temperature had an evident effect on the heat storage time. The higher the temperature difference obtained, the less time the heat storage process took. The result is consistent with that of the study by Akgün.28 The heat storage time was reduced to about 80, 170, 200, 210, and 230 min at the inlet HTF temperature of 65, 70, 75, 80, and 85 °C compared with the inlet temperature of 60 °C.

Effect of Inlet Temperature. The thermal performance of the SESHR was obtained by eqs 1–5 based on the measured parameters. The average heat storage capacity of SESHR filled with #PCM was 15.59 MJ, and the heat storage rate was 261 W at the inlet HTF temperature of 85 °C and the flow rate of 0.60 kg/s. Figures 1–3 show the influence of HTF temperature on the thermal performances of the SESHR filled with #PCM during the heat storage process. It could be seen that when the HTF temperature ranged from 60 to 85 °C, the average steady temperature of #PCM increased to 73 from 50.8 °C, while the heat storage time was decreased to 3.6 from 7.6 h by 52.63%. The heat storage capacity and the rate of SESHR were remarkably improved by about 10.14% from 13.02 to 14.34 MJ and by 132.58% from 476 to 1106 W, respectively. Compared with SESHR filled with #PCM, the results indicated that the heat storage rate of PCM with a low melting point was much greater than that of PCM with a high melting point.

Thermal Energy Utilization Efficiency of the SESHR in the Heat Storage Process. The overall thermal energy utilization efficiency of the SESHR is an important parameter in practical applications. The performance of the developed prototype with #PCM was evaluated since the heat utilization efficiency of the device filled with two kinds of PCMs was almost consistent. It could be seen that when the temperature of the HTF increased, the utilization efficiency of the SESHR equipment dropped (Figure 4). During the heat storage process, the heat loss was primarily caused by the heat convection (outer wall of the SESHR and pipeline system) and the compactness of SESHR. The higher the heat source temperature, the greater the heat loss of the device. Therefore, the overall energy utilization efficiency tended to be small.

Heat Dissipation Process. Temperature Profile of PCM. In this study, there are three factors that have notable effects on the temperature variation trends of PCM during the heat dissipation process, including the initial temperature of PCM, the ambient temperature, and the opening ratio of the air convection channel. The temperature evolutions of 1#PCM and 2#PCM in the same ambient temperature of 24 °C and 100% opening ratio are presented in Figure 5. In the heat dissipation process, the temperature profiles of the bulk PCM also experienced three stages, but the process was reversed compared with the heat storage process. Additionally, 1#PCM with a higher melting point was favorable for reducing the heat dissipation time. The reason was that when the solidification point of 2#PCM was reached, the heat transfer rate was decreased between ambient air and PCM due to the decreased temperature difference. Thus, the duration time of solidification was prolonged. Moreover, a subcooling phenomenon is observed from Figure 5b. Even though the temperature of liquid PCM was under its solidification point (~40 °C), the PCM still did not solidify and the latent heat could not be released. And then, a sudden PCM temperature increase happened as a result of the latent heat dissipation. Because of the low subcooling degree (within 2 °C in this study), paraffin was used as one of the most promising candidates for energy storage media in practical applications.29,30

Effect of Opening Ratio and Initial Temperature. Figure 6 presents the heat dissipation time and rate of SESHR with 1#PCM at an initial temperature of 85 °C and an ambient temperature of 24 °C. The larger air mass flow rate enhanced the heat convection coefficient and the heat transfer driving force. When the opening ratio was changed from 20 to 100%, the heat dissipation time was shortened to 36.8 from 43.3 h by about 15.01%, and the heat dissipation rate was considerably strengthened from 69.2 to 80.7 W by about 14.3% (Figure 6). The results indicated that the adjustable shutter designed at the bottom of SESHR was reasonable and could be used to control the heat dissipation rate of the device. The heat dissipation time...
and the rate of the SESHR with 2#PCM at an ambient temperature of 24 °C and an opening ratio of 100% are demonstrated in Figure 7. The heat transfer rate was improved by increasing the temperature difference. It can be found that the heat dissipation rate was enhanced slightly from 48.1 to 51.2 W by approximately 6.05% when the initial temperature of 2#PCM was changed from 60 to 85 °C. Although the heat transfer rate was improved between PCM and ambient air due to the large temperature difference, the stored heat in PCM was also increased and then the heat dissipation time was increased.

It can be concluded that the PCM with a low melting point has a shorter energy storage time which is favorable to the heat storage process, while the high melting point PCM has a higher heat dissipation rate. For 2#PCM, the application could be agricultural greenhouse heating in which the ambient temperature requirement is more than 15 °C. While for the 1#PCM, the application is aimed at residential house heating in which the ambient temperature requirement is around 24 °C. Thus, the selection of PCM in this study was subjected to the requirement of practical applications rather than the performance.

Effect of Ambient Temperature. Since the ambient temperature determines the driving force of the heat dissipation process, the heat dissipation experiments were conducted at the ambient temperatures of 18 and 24 °C because of the limited controllable room temperature. The heat dissipation time, heat dissipation capacity, and rate of SESHR filled with 1#PCM at an initial temperature of 85 °C as well as the minimum opening ratio are listed in Table 1. Evidently, the lower ambient temperature led to a larger temperature difference between ambient air and PCM; therefore, the heat dissipation time was

Figure 3. Effect of HTF temperatures on the thermal performance of HSU filled with 2#PCM. (a) Heat storage capacity. (b) Heat storage rate.

Figure 4. Overall thermal energy utilization efficiency of the SESHR filled with 2#PCM.

Figure 5. Temperature variations of PCM in HSU in the heat dissipation process. (a) 1#PCM and (b) 2#PCM.
shortened and the heat transfer rate was enhanced. When the ambient temperature decreased from 24 to 18 °C, the heat dissipation time dropped by approximately 11.55% from 43.3 to 38.3 h and the heat dissipation capacity and rate rose by 5.29 and 19.08%, respectively.

Figure 6. Effect of opening ratio on the thermal performance of SESHR. (a) Heat dissipation time. (b) Heat dissipation rate.

Figure 7. Effect of the initial temperature of 2#PCM on the thermal performance of SESHR. (a) Heat dissipation time. (b) Heat dissipation rate.

Table 1. Effect of Ambient Temperature on the Thermal Performance of SESHR Filled with 1#PCM

| ambient temperature (°C) | solidification time (h) | heat dissipation capacity (MJ) | heat dissipation rate (W) |
|--------------------------|------------------------|--------------------------------|--------------------------|
| 18                       | 38.3                   | 11.4                           | 82.4                     |
| 24                       | 43.3                   | 10.8                           | 69.2                     |

shortened and the heat transfer rate was enhanced. When the ambient temperature decreased from 24 to 18 °C, the heat dissipation time dropped by approximately 11.55% from 43.3 to 38.3 h and the heat dissipation capacity and rate rose by 5.29 and 19.08%, respectively.

Figure 8. Application of the solar energy storage heating radiator.
CONCLUSIONS

A novel heat storage radiator with a phase change material as the energy storage media has been designed and investigated to solve the issues of unstable and intermittent situations in the utilization of renewable energy. A series of experiments were carried out to study the thermal performance of the SESHR with two kinds of modified paraffins as PCM in the conditions of different heat source temperatures, ambient temperatures, and opening ratio. The following conclusions can be derived:

1. High charging temperature is beneficial to both the energy storage capacity and the heat dissipation rate. The heat storage capacities and the heat dissipation rate reached 14.34 MJ and 51.2 W for SESHR filled with 2#PCM at the heat source temperature of 85 °C, which is greater than the heat storage capacity (13.02 MJ) and the heat dissipation rate (48.1 W) of SESHR at the temperature of 60 °C.

2. The opening ratio of the air convection channel had a significant impact on the heat dissipation rate. It was verified that the adjustable shutter at the bottom of the equipment was reasonably designed to control the heat dissipation rate of SESHR.

3. The selection of PCM could be determined by the practical applications. In this study, low melting point PCM contributes to a higher heat storage rate, while high melting point PCM has a higher heat dissipation rate.

4. The SESHR prototype filled with PCM demonstrated good thermal performance, indicating that the prototype can be produced for low-temperature energy storage practical applications.

EXPERIMENTAL INVESTIGATION

Prototype Design. Figure 8 presents a proposed system that is comprised of a flat-plate solar collector, SESHR prototype, water tank, and a circulation centrifugal pump. During the charging period or daytime, the pump is turned on. Water as a HTF absorbs heat from solar radiation and flows through the SESHR for charging the PCM. During the discharging process or in the absence of solar radiation, the pump is turned off and the SESHR starts to release heat to an agricultural greenhouse or residential house. Simultaneously, the PCM begins to solidify and is used for the next cycle. In the present study, the SESHR prototype is studied experimentally.
The developed SESHR prototype was integrated with several HSUs, which were filled with low-temperature PCM (as shown in Figure 9). The SESHR was mainly composed of an insulated cubic box, openable top cover, adjustable shutter, and stainless steel heating pipeline. The insulation wall of the cubic box was made of polyurethane foam. A shutter was installed at the bottom of the cubic box to adjust the opening area of the air convection channel. The inlet and outlet of the U-shaped heating cube throughout the HSUs were connected by two main tubes for supplying and collecting the heating fluid.

There were six HSUs installed in the insulated cubic box in a parallel way and even a narrow space was set between the units. Two kinds of industry-grade paraffin waxes (Shanghai Jiaoer Wax Co., Ltd.) were considered to be energy storage materials because of the high latent heat capacity, wide phase change temperature ranges, nontoxicity, excellent compatibility, and low cost.31,32 The total weight of 34.0 kg of 1#PCM and 2#PCM was filled in the equipment respectively. To prevent the expanding overflow of the melting PCM from the top of HSU, 20 mm space in the upper PCM was dominated by air. As shown in Figure 10, the thermal properties of these two PCMs were measured using a differential scanning calorimeter (DSC STA449F3). The other property parameters were given by vendor. All of the designed parameters of the prototype and the thermophysical properties of the PCMs were presented in Tables 2 and 3, respectively.

**Table 2. Parameters of the SESHR**

| l (mm) | W (mm) | h (mm) | w (mm) | d (mm) | d/d (mm) | b (mm) |
|--------|--------|--------|--------|--------|----------|--------|
| 160    | 620    | 600    | 80     | 100    | 20/18    | 80     |

**Experimental Facility.** An experimental test platform was set up as illustrated in Figure 11 to verify the concept design and investigate the thermal performance of the SESHR prototype. It mainly consisted of the SESHR prototype, thermostatic heating bath, circulating pump and pipeline system, measurement equipment, data acquisition system, etc. Two kinds of PCMs were filled in the HSUs for comparison study. During the heat storage process, circulating water was heated by a heating bath at a constant temperature above the melting point of the PCM, driven by the pump through the HSUs and exchanged heat with PCM, and then flew back to the heating bath at the flow rate of 0.60 kg/s. In the heat dissipation process, ambient air driven by buoyancy flows through the space between adjacent HSUs to remove the heat. The temperature distribution within the HSUs was monitored by using a T-type TT36 thermocouple as illustrated in Figure 12. The temperature of PCM was measured by Tpc1 to Tpc3. The inlet and outlet temperatures of HTF were monitored by Tw1 and Tw2, respectively. Besides, the inlet and outlet temperature of ambient air in the convection space channel were recorded. Totally 44 thermocouples were used in the SESHR equipment, and they were connected to an Agilent data acquisition system to record automatically after each time step of 10 s.

**Test Procedure.** Prior to the experimental test, the data acquisition was started to check out if thermocouples were out of order. Both the insulated top cover and adjustable shutter were closed. Then, the circulating water as HTF was heated to the targeted temperature (60, 65, 70, 75, 80, and 85 °C) by a thermostatic heating bath. The mini pump was activated and the heat storage process was started. High-temperature HTF flowed through the U-shaped heating tube where the PCM absorbed heat from HTF and began to melt. When the temperature difference between HTF and PCM was less than 0.1 °C/min within 5 min and then, the pump and heating bath were turned off.

During the heat dissipation process, the top openable cover was kept at 100% opening and the shutter was adjusted to the required opening ratio of 20, 40, 60, 80, and 100%. The opening ratio is defined as the ratio of the cross-sectional convective area to the bottom area of SESHR, i.e., \( \epsilon = \frac{A_A}{A_S} \times 100\% \). Additionally, the heat dissipation experiments at the maximum opening ratio of 100% in ambient temperatures of 18 and 24 °C were also conducted, respectively. As the temperature difference between PCM and air was less than 0.1 °C/min within 5 min, the heat dissipation process came to an end.

**Data Analysis.** To obtain the thermal performance of SESHR with low-temperature PCM, the total heat storage and dissipation capacity, average heat storage, and dissipation rate were evaluated by measuring the temperatures in various operating conditions. Figure 13 illustrates the processes of heat storage and dissipation. There are six HSUs installed in the SESHR, and the total heat storage capacity, \( Q_{st} \), can be expressed as

\[
Q_{st} = \sum_{i=1}^{6} \left[ C_{ps} \Delta T_{si} + \Delta h + C_{pl} \Delta T_{li} \right]
\]

where \( m_i \) is the mass weight of PCM in the \( i \)th unit, \( C_{ps} \) and \( C_{pl} \) are the specific heat of PCM in the solid and liquid states, respectively. \( \Delta H \) is the latent heat of PCM. \( \Delta T_{si} \) and \( \Delta T_{li} \) are the temperature differences of PCM in the solid phase and the liquid phase in the heat charging process, respectively, and they are defined as

\[
\Delta T_{si} = T_{mi} - T_{si}
\]

\[
\Delta T_{li} = T_{li} - T_{mi}
\]

\( T_{mi} \) is the mean melting temperature of the PCM in the \( i \)th unit, which is defined as eq 4

\[
T_{mi} = \frac{\int_{t_1}^{t_2} T(t) dt}{t_2 - t_1}
\]

The average heat storage rate \( R_{st} \) is defined as eq 5

**Table 3. Thermophysical Properties of the PCMs**

| no. | specific heat (kJ·kg⁻¹·K⁻¹) | latent heat (kJ·kg⁻¹) | test melting point (°C) | density (kg·m⁻³) | thermal conductivity (W·m⁻¹·K⁻¹) |
|-----|---------------------------|----------------------|------------------------|-----------------|-------------------------------|
| 1#PCM | \( C_{ps} = 3.2 \) | \( C_{pl} = 2.8 \) | 184.9 | 62.2–76.2 | 790 | 0.28 |
| 2#PCM | \( C_{ps} = 3.2 \) | \( C_{pl} = 2.8 \) | 172.6 | 36.0–46.6 | 780 | 0.26 |
The total heat dissipation capacity can be calculated as expressed in eq 6

\[
Q_{ds} = \sum_{i=1}^{d} m_i [C_{pl}\Delta T_{li,i} + \Delta h + C_{ps}\Delta T_{si,i}] 
\]

(6)

where \(\Delta T_{li,i}\) and \(\Delta T_{si,i}\) are the temperature differences of PCM in the liquid phase and the solid phase in the heat discharging process, respectively, and are defined as

\[
\Delta T_{li,i} = T_{li,i} - T_{si,i}
\]

(7)

\[
\Delta T_{si,i} = \bar{T}_{si,i} - T_{di,i}
\]

(8)

where \(\bar{T}_{si,i}\) is the mean solidified temperature of the PCM the \(i\)th unit and can be obtained by eq 9

\[
\Delta \bar{T}_{si,i} = \frac{\int_{t_i}^{t_2} T(t)dt}{t_2 - t_i}
\]

(9)

The average heat dissipation rate \(R_{ds}\) can be defined as

\[
R_{ds} = \frac{Q_{ds}}{t_5 - t_0}
\]

(10)

In addition, the thermal energy utilization efficiency of the SESHR can be estimated by eq 11, which was defined as the ratio of the amount of heat stored in the SESHR equipment to the heat released out from the HTF.

\[
\eta_{st} = \frac{Q_{st}}{\alpha_{ht} M (T_{ht,i} - T_{ht,o})} \times 100\%
\]

(11)

where \(M\) is the mass flow rate of HTF. \(T_{ht,i}\) and \(T_{ht,o}\) are the inlet and outlet temperatures through the SESHR equipment.

For the apparatus utilized, the experimental uncertainty came from the probe thermocouples and mass. The uncertainty in the
temperature measurement was 0.1 °C. The mass of PCM was measured with an accuracy of 0.01 kg. Moreover, the uncertainty in the calculation of parameters was estimated by using the Kline and McClintock\textsuperscript{35} method. In eq 12, \( x_n \) is the independent or measured variables including mass and temperature, \( f \) is the relational variable function as expressed in eq 13, and \( U_n \) is the uncertainties of the variables.

All of the uncertainty values of the parameters are listed in Table 4. To reduce the uncertainty of the experimental tests, the heat storage and dissipation processes were repeated 3 times, respectively. The maximum standard variance was 0.36, which indicated good repeatability in this experiment.

\[
U_f = \sqrt{ \left( \frac{\partial f}{\partial x_1} U_1 \right)^2 + \left( \frac{\partial f}{\partial x_2} U_2 \right)^2 + \cdots + \left( \frac{\partial f}{\partial x_n} U_n \right)^2 } \tag{12}
\]

\[
f = f(x_1, x_2, x_3, \ldots, x_n) \tag{13}
\]

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**Notes**

The authors declare no competing financial interest.

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