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Thermal Performance Enhancement of Triplex Tube Heat Storage Using Metal Foam

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ABSTRACT

Latent heat thermal energy storage (LHTES) systems are essential for storing solar energy during sunshine and using it during the absence of solar radiation. The energy storage systems of phase-change materials (PCMs) possess comparatively low thermal conductivity values, which greatly decrease their performance. Significant thermal enhancement of PCM behaviour could be achieved adding a porous metal foam. In this work, experimental analysis was conducted on a vertical LHTES with PCM by using water as a heat transfer fluid (HTF). The effect of adding a porous metal foam on the charging process was investigated. Experimental observations showed the foamed TTHX had a superior melting rate over the non-foamed TTHX. For both TTHX configurations, the needed time for the charging process decreased with the addition of porous metal foam. The effect of Cu foam was significant for the foamed TTHX. The reduction in the whole melting time for the foamed and non-foamed TTHX was 43% for the same HTF temperature of 69 °C.

1. Introduction

Utilisation of thermal energy storage (TES) is a highly active technique for solving the incompatibility between the demand and supply of energy. The usage of TES could also increase the efficacy of the thermal energy system. TES could be categorised as latent heat storage, sensible energy storage and chemical energy storage. As a highly interested technique, the latent heat storage possesses a broad range of phase-change temperatures and high energy storage density. In the last 3 decades, the TES system founded upon the use of phase-change materials (PCMs) was implemented in numerous various civil and engineering fields, such as TES of buildings [1], air-conditioning systems [2], hot water tanks, waste heat recovery, solar water heaters, solar cookers and solar air collectors [3]. In choosing an appropriate PCM for TES, the characteristics of non-corrosiveness, a broad range of melting temperatures, high thermal storage densities, chemical stability and low cost were considered [4]. PCMs could be classified into three types: organic, inorganic and eutectic. Owing to its brilliant properties, the organic type is a highly famous PCM. Meanwhile, the disadvantages of low thermal conductivity and time consumed for the process of thermal energy charging and discharging considerably limit the use of PCMs on a big scale. Several investigators have suggested numerous techniques to improve heat transfer through phase change [5]. For nearly all techniques' goal to enlarge the surface of heat transfer to accelerate the rate of heat transfer during the absence of solar radiation, TES is required for sustainable implementation of solar

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energy. A detailed review of TESs with PCMs has been reported in [6-12].

Several enhancements on latent heat TES (LHTES) have been proposed for large-scale utilisation. Different methods of enhancement were applied by adding fins surfaces [13-20], dispersing conductive nanoparticles in PCM [21-23], multiple PCM families [24-26], PCM micro-encapsulation [27-28] and applying highly porous PCM-filled conductive materials [29-32].

According to the abovementioned literature survey, numerous investigators have attempted to apply different design parameters for optimising the TTHX geometry to reduce the melting time. In the present study, the proposed heat transfer enhancement was achieved by adding a porous Cu foam material inside the heat exchanger tube of LHTES. The thermal behaviour of PCM in LHTES was analysed with and without foam in terms of the development of transient temperature distribution through the melting procedure.

2. Experimental setup and procedureq

2.1 Experimental setup

Figure (1) illustrates the LHTES experimental setup. The main items were a TTHX test section, a flow meter, thermocouples, pumps, thermal bath (water tank) with two electrical heaters, air relief valve, pipes with valves, a data logger and a computer.

The experimental work was carried out for pure PCM tube (non-foamed TTHX) and thermal storage with foam (foamed TTHX). The thermal behaviour of LHTES was assessed in terms of the distribution of PCM temperature and the time for charging. The inlet temperature and mass flow rate of HTF were maintained at 69 °C and 4 L/min, respectively.

Figure 1. Photograph of LHTES experimental set-up. includes: 1. TTHX, 2. Flow meter, 3. thermocouple, 4. Pump, 5. water tank, 6. Pipes, 7. Valve. 8. Datlogger, 9. Computer, 10.air relieve valve

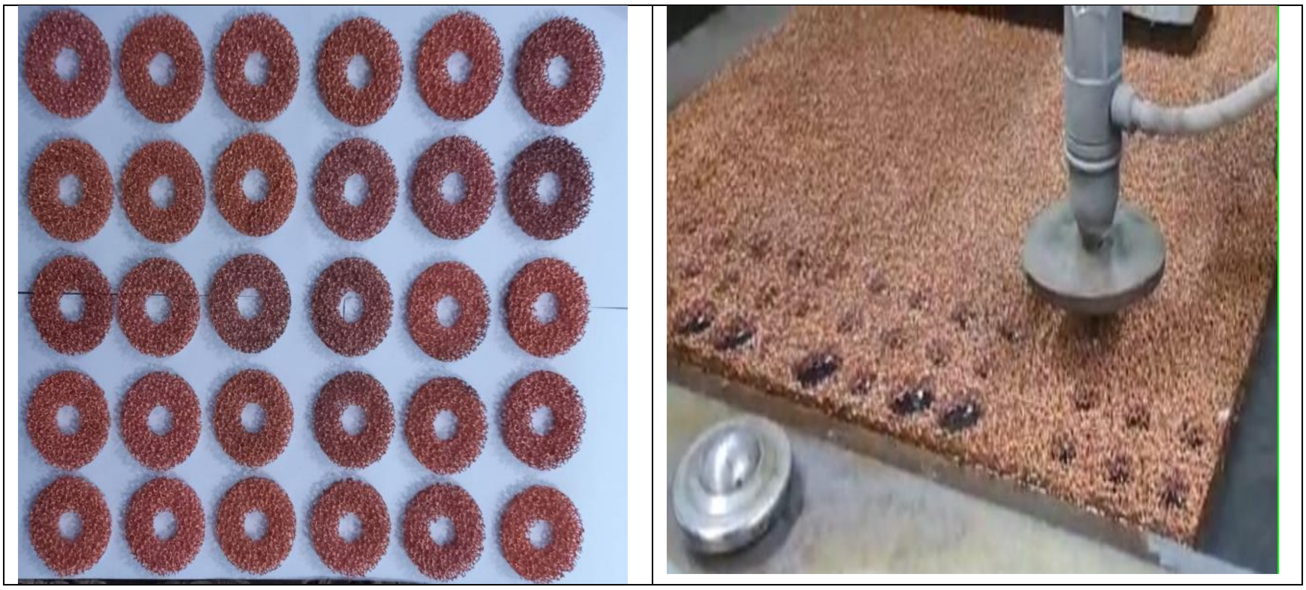

Figure 2. Ring shaped copper foam

2.2 Selection of PCM and copper foam

In this work, paraffin wax from the Iraqi Oil Company was selected as the pure PCM because it is cheap and available in the local market. It was also selected for application because it has a melting temperature close to the required operation temperature of thermal solar systems. Meanwhile, water was used as a heat transfer fluid. Differential scanning calorimetry and thermal conductivity analysis were used to measure the PCM thermal properties. The thermal properties of the PCM and the heat transfer fluid are presented in Table 2.

The thermal conductivity of the Cu foam-PCM composite is higher than of the other metal foam-PCM composites, such as nickel foam or aluminium foam, because Cu possesses the highest thermal conductivity amongst metals. Therefore, Cu foam was used in the performance enhancement of LHTES. The porosity of the Cu foam was B, and the density of pore was 10 pores per inch (PPI). The thermophysical properties of the Cu foam are listed in Table 3.

Table 1: Specifications of triplex tube

	Ineer and middle pipe	**Outer Pipe**
Material	Copper	Plexiglas
Density, kg/m^3	8960	
Specific heat (cp), J/g. °C	0.39	
Thermal Conductivity (W/m.ºK)	386	0.19
Length, m	0.5	0.54
Inner diameter, mm	19-72	110
Outer diameter, mm	23- 76	

Table 2: Properties of copper foam

Porosity, %	95
Pore density, PPI	10

Table 3: Thermo-physical properties of PCM and water

Property	**Value**
Paraffin wax (PCM)	
Melting temperature range (°C)	52.8-62
Heat of fusion(J/kg)	114540
Specific heat (J/kg.ºC)	2000
Thermal Conductivity (W/m.ºC)	0.14
Density (kg/m^3)	820
Viscosity (Pa.s)	0.033
Thermal expansion (1/K)	6×10^{-4}
property Water	
Specific heat (J/kg.ºC)	4180
Density (kg/m^3)	996

2.3 Specifications of LHTES

A schematic of the experimental setup is depicted in Figure (3). It comprises internal, middle, and external tubes with 19, 72 and 110 mm in diameter; 3, 4 and 10 mm in thickness; and 500 mm in length, respectively, as shown in Figure (4.2). The internal and middle tubes are made of Cu, while the external tube is made of acrylics with 1 cm thickness. The internal and external tubes were utilised for the heat transfer fluid, while the middle tube was filled with 1.3 kg of PCM and then metal foam with the same amount of PCM.

The test section characteristics are given in Table (1) to measure the temperature evolution in the PCM. A total of 14 thermocouples (NTC-type) with an average uncertainty of ±0.15 °C and temperature range of 0 °C–200 °C were fixed in the middle tube region. The thermocouples were installed alongside the TTHX axial direction and represented by A (12.25 mm), B (24.5 mm) and C (36.75 mm), as shown in Fig. 1. Each axial location contained a pair of thermocouples and it was located at radial positions of 8 and 16 mm from the internal tube to the middle tube. Both thermocouples were also placed at the inlet and outlet of the inside heat transfer fluid pipe to record the readings of the heat transfer fluid’s inlet and outlet temperature. A data acquisition system and a personal computer were used to record the values from the sensors. The experimental data were received every 1 min during the melting process.

A second set of Cu foamed thermal storage (foamed TTHX) was established to explore the heat transfer enhancement induced by adding a Cu foam. To prepare a composite of Cu and PCM, the foam was cut as ring-shaped. Every ring had 10 mm of thickness, 35.8 mm of external diameter and 19.6 mm of internal diameter (Figure 2). A total of 48 Cu foam rings were stacked around the HTF tube. The 2 cm space without the foam upon the two sides of the HTF heat exchanger tube are essential for letting certain void above and below the Cu foam for placing the thermocouples and welding the flanges. The two configurations were then filled by 1.4 kg of PCM.

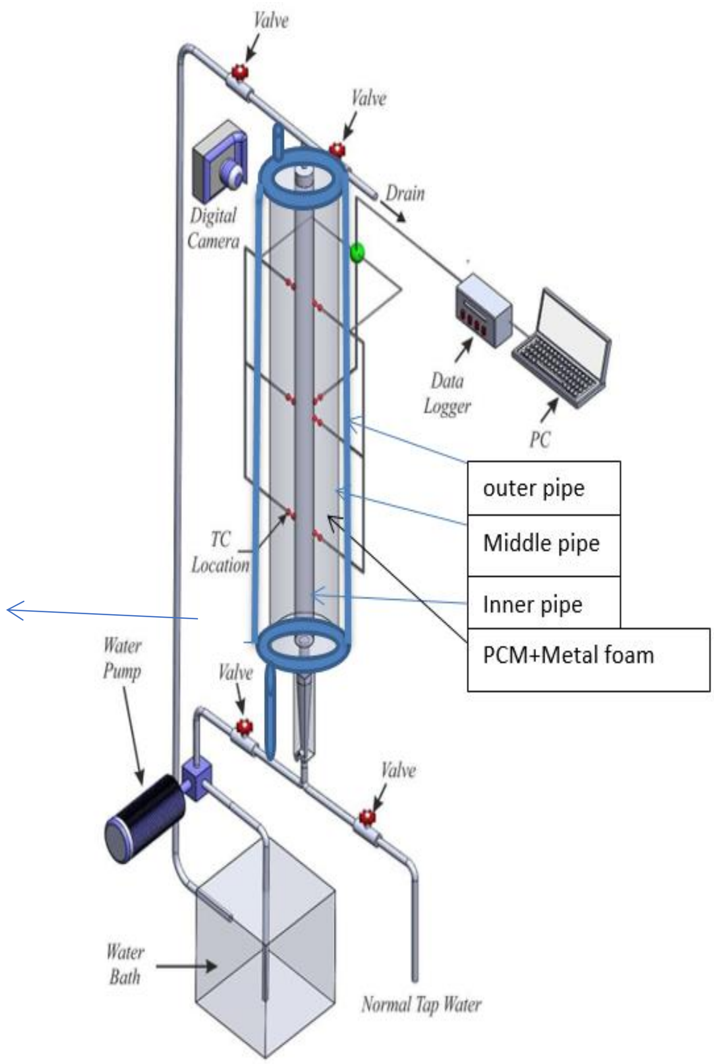

Figure 3. Present work, the schematic diagram

2.4 Experimental procedure

The triplex concentric tube's PCM thermal energy storage was synthesised to study the procedure of TES melting via charging. Water was heated with two heaters of 3.3 kW electric and circulated using a circulation pump from the storage tank (300 L) of water to the test section. A flow meter with ±4% accuracy measured the flow rate of the heat transfer fluid into the storage unit. First, primary tests were conducted to examine the leakage of the PCM into the storage system. PCM melting was tested when the PCM changed into solid state. The melting's preliminary working circumstances was indicated if the whole embedded sensors into the annular space contained the PCM records the similar temperature values, where thermocouple readings were logged in every 60 sec. Within the charging cycle, the hot heat transfer fluid from the thermal bath at a needed temperature, the essential pipes, and the valves for regulating the flow of water were pumped.

Experiments were first conducted for the TTHX section without added Cu foam (non-foamed TTH). The Cu foam added to PCM (foamed TTHX) was also measured to study the thermal behaviour inside LHTES with foam for performance comparison.

3. Results and discussions

3.1 Pure PCM

The triplex tube's (LHTES) thermal characteristics during the charging process with and without porous metal foam were assessed in terms of the PCM temperature evolution and completed phase-change time. The PCM transient temperature evolution at various axial directions inside the heat exchanger with and without Cu foam is shown in Figures 4 and 5. The transient variation of PCM was presented at 69 °C and 4 L/min of HTF and flow rate, respectively. The average temperature of PCM was measured by taking the average reading of thermocouples at different positions.

The overall overview of the development of the temperature of PCM in Fig. 4 showed that the three divided zones presented in the LHTS through the procedure of charging were as follows: the solid zone, the mushy zone and the liquid zone. The heat transfer's conduction phenomenon is in charge of heat transfer into the solid PCM. The solid PCM took the heat from the zone of liquid via convection. The convective flow of melt inside the molten zone was in charge of heat transfer. The melt convective flow evolved owing to the density gradients in the molten zone as a consequence of the discrepancies of temperature. As a result, the melt convective flow improved the heat transfer inside the melted zone of PCM.

At the start, the solid PCM's heat conduction played a prevailing role in the heat transfer. With further melting of the solid PCM, the natural convection controlled the procedure of heat transfer slowly. The melted PCM absorbed the energy from the heating tubes and the flows rising. Thus, the top portion temperature was higher than the bottom portion temperature. The fast increment in the PCM temperature at the top portion was due to the thin-layer evolution of the melted PCM around the wall of heat transfer fluid. If time progressed, the melting started from the test section's top and descended until the procedure was completed.

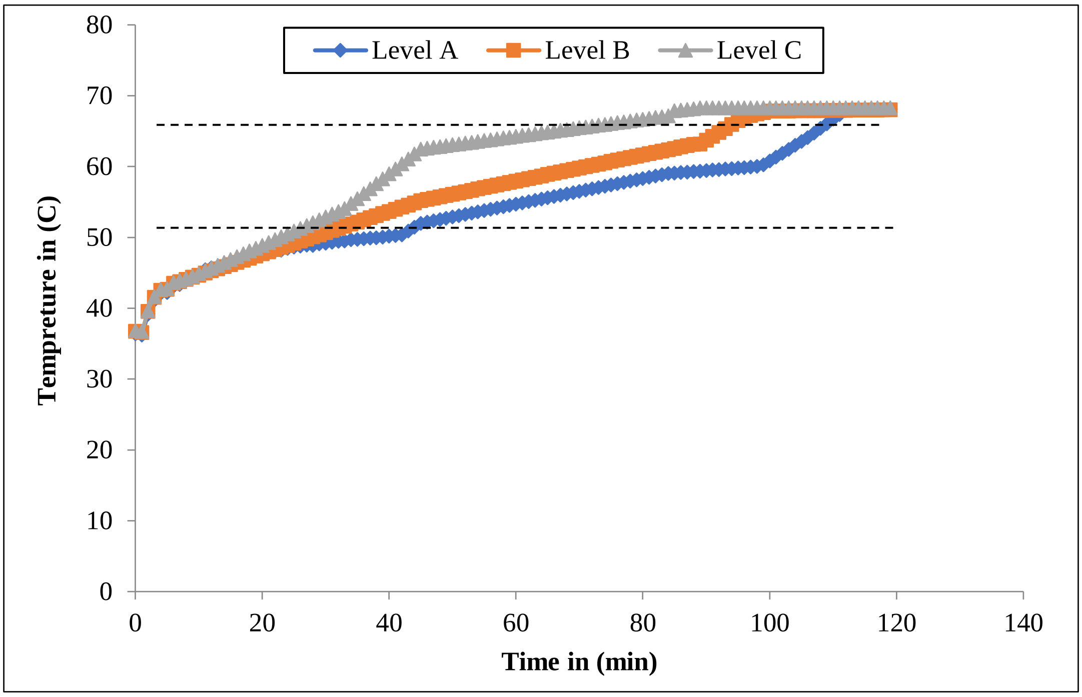

Figure 4. Melting temperature variations for thermal storage without copper foam (T_{HTF} =69 °C and m = 4L/min)

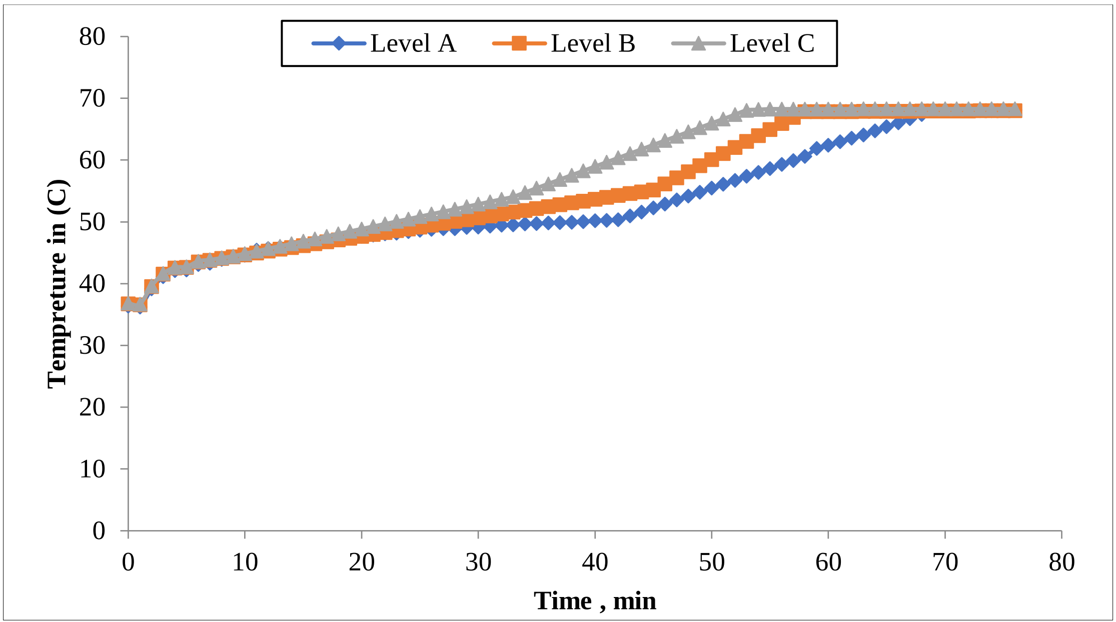

Figure 5. Melting temperature variations for thermal storage with copper foam (Vertical, T_{HTF} = 69 ºC and m = 4L /min)

3.2 PCM with coper foam

The result of temperature variations for the TTHX test section with the addition of Cu foam is shown in Figure 5. The operational conditions for foamed TTHX were THTF = 69 °C and ṁ = 4 L/min of HTF. The history of temperature of the noticed points had a similar trend to those discussed above. The top points' temperature was higher than that of the bottom points in perpendicular direction. However, the discrepancy of temperature for the composite was much less than that for pure PCM.

The transient evolution of average PCM temperature for TTHX with and without Cu foam is manifested in Figure 6. The foamed tube configuration enabled the enhancement of the convection currents during the charging process.

As expected, the more heat transfer created via the addition of Cu foam resulted in increased PCM melting rate. Therefore, the melting time of PCM shortened from 119 min to 67 min, clearly due to the addition of Cu foam. The comparative assessment suggested that the Cu foam implemented in a TTHX heat exchanger reduced the total melting time by 82% compared with TTHX without Cu foam. Figure 6 shows that the TTHX temperature outline with an embedded foamed Cu heat exchanger manifested a large heat transfer rate and thus shortened the completed melting cycle.

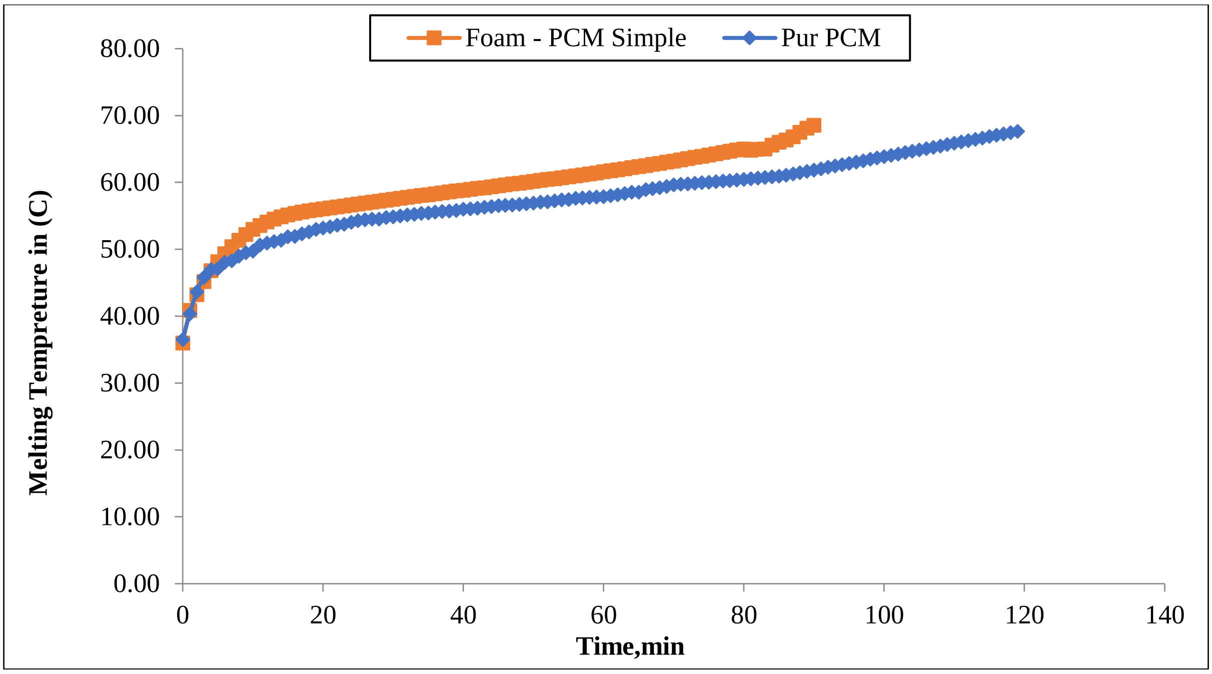

Figure 6. Temporal variation of PCM average temperature during charging of LHTS (T_{HTF} = 69°C and m = 4L/min)

4. Conclusions

The major conclusions were derived from the experimental investigation as follows:

1. The rate of heat transfer increased considerably with the addition of Cu foam compared with LHTES with PCM only. The big heat transfer area delivered via the porous Cu foam material clearly had the main effect on the progression of the melting rate.
2. The PCM temperature evolution in different axial and radial locations inside the region of heat exchange between PCM and HTF aids in determining the behaviour of heat transfer and the melted regions into the thermal storage unit.
3. The heat exchange between PCM and HTF during melting cycle is dominated by the convection currents, which drive the circulation of molten PCM due to density variation.
4. A rapid completed melting at the top part in the heat exchanger test section could be distinguished for LHTES with and without Cu foam. This finding could be ascribed to the dominated influence of the natural convection.
5. The complete melting time shortened from 119 min to 67 min because of the provision of Cu foam. Thus, the percentage decrease in melting time reached 43% due to the addition of Cu foam. The use of high-thermal-conductivity material with PCM transfers a large amount of heat into the internal part easily and thus significantly reduces the melting process.

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