Experimental study of minimum - temperature hydrated salt latent heat thermal energy storage with sodium acetate trihydrate as phase change materials

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Abstract. There's a lot of hope for phase change material (PCM) in applications like sustainable energy generation and retrieval of heat loss. Latent heat thermal energy storage (LHTES) systems containing hydrated salt (HS) at minimum-temperature have been the topic of much study, particularly with regards to their thermal behavior and charging-discharging properties. The PCM was prepared by adding sodium acetate trihydrate (SAT), a nucleation agent, and a thickness agent to the test tube. We monitored PCM's temperature behavior and analyzed its thermal characteristics. Natural convection was the dominant way of heat transmission while the phase change material temperature was over the fusion threshold, whereas conduction was the dominant mode when liquid phase change material formed during the phase transition progression. Heat storage and release efficiency as a function of tube diameter and flow rate was analyzed. Internal stainless-steel fins and aluminium fins of varying thicknesses were added to the tube to increase heat transmission. The shape of the storing tube and fins was shown to have a significant impact on the heat transmission among the thermal fluid and the phase change material. Charging and discharging duration may be cut by 28 % and 25 %, respectively, because to the revised fins shape. Our findings from this study can serve as an experimental foundation for using the minimum-temperature hydrated salt LHTES system.

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Keywords: TES system, stainless steel, plates, tubes, temperature, heat transfer.

1. Introduction

Overuse of fossil fuels has led to a worldwide energy problem and environmental degradation, which many see as solvable through the usage of sustainable energy and increased energy efficiency [1]. The inconsistency of the energy supply and the lack of synchronicity between production and consumption limit its application in engineering. Thermal energy storage (TES) is required to link renewable energy or waste heat sources to consumers through steam or water conveyance [2]. Thermal energy storage (TES) can be accomplished in 3 variant ways: with latent heat, with sensible heat, or with thermochemical energy [3]. LHTES distinguishes out from the other two technologies because it can store and release latent heat throughout the phase evolution process, allowing for a high energy storage density to be maintained at a practically constant temperature [4]. It's also chemically stable, which is a plus. Therefore, its use in thermal energy storage shows great potential. There has been much research into and optimization of phase change materials [5]. Hydrated salt has a number of benefits over organic phase transition materials that make it a promising candidate for industrial use. These include a cheaper price, a greater enthalpy of fusion, and a superior thermal conductivity [6]. The TES system configuration and heat transfer area expansion are two further areas where research has focused [7]. The LHTES system's charging phase is responsible for the radial temperature gradient within the PCM's interior, as heat is transferred from the thermal fluid to the PCM tube. Yet, PCMs are all the same in that they have a low thermal conduction (0.5-0.8 W/(mK)), making it difficult for heat to spread through the material [8]. This means that TES charging may take longer than expected, and internal PCM melting may not start at the same time. Similar temperature differences are observed during discharge from PCM [9]. As a result, there has been a flood of research and attempts to address this problem. It is common practice to rise the heat transferring area among the phase change material and the thermal fluid by strategically placing metal fins [10]. Our research aims to better the thermal behavior of LHTES by creating a storage tube with metal fins. Aluminum and stainless steel are used for making fins because to their maximum thermal conduction and minimal cost [11]. Variant types of fins have been the subject of numerous reports. The authors [12] shown that a heat exchanger system (HES) with internal and exterior fins could efficiently transport heat from PCM (Paraffin C-18) to air, allowing for a substantially higher rate of energy extraction. The boosting time for the shell-and-tube latent heat thermal energy storage system was reduced by 12.5 % and 24.52 %, respectively, when the authors [13] used stearic acid as the PCM and a thermal fluid input temperature of 80°C. The same result, a shorter charging time for paraffin wax utilizing a shell-and-tube latent heat thermal energy storage system with Y-shaped fins, was found by researchers [14]. In order to optimize the shape of the LHTES system, the authors conducted experimental and theoretical study using commercial paraffin. They settled that the boosting and releasing performance of PCM is intricately tied to the geometry of the tubes, but no such link has been provided. Most of these studies used organic PCM in their LHTES setups, and few have looked at how hydrated salt PCM behaves during charging and discharging [15]. Researchers found that among three plate-encapsulated PCMs used in air heat exchangers, the salt hydrated TES module had the largest energy absorption capacity and was thus the best option [16].

This research suggests an LHTES system that uses low-temperature hydrated salt to address these problems. Since its phase transition temperature is favorable (about 359 K), its latent heat is relatively large (268 kJ/kg), and it is cheap to produce, SAT was recommended as the
phase change material [17]. Some of the various uses for this technology include storing solar energy, shifting peak loads in power networks, decreasing energy consumption in buildings, and reusing waste heat in industries [18]. For this reason, we employed the composite SAT we had developed, which incorporated both nucleating agents and thickening agents [19]. Researchers looked at the thermal efficiency of sodium acetate trihydrate energy storage devices presence and absence of metal fins to see how the two types fared. Using computational models, we looked at how adding fins to a tube might affect its ability to store and distribute heat [20].

2. Experiment’s arrangement and method

2.1. Experimental arrangement

Fig. 1 displayed the schematic of the TES test section. Five distinct components made up the experimental system, as shown below: a heating portion, a flow control section, an experiment proper, a cooling section, and a data collection section.

Fig. 1. An outline of the sodium acetate trihydrate energy storage experimented system.

The cooling subsystem. A heat transfer, water storage tank, water cooling storage tank, and water pumping made up this subsystem. Water temperature in the experimental portion decreased when cooling water was utilized to cool circulating water in the heat exchanger.

The experimental section. A 2 mm thick by 500 mm long stainless-steel tube served as the experimental module unit into which PCM was inserted. The apparatus used to examine the melting and solidifying of phase change material is depicted in Fig. 3: One end of the tube had a quartz glass plate and flange attached to it. The exposed end was protected by a plate of steel two millimeters thick. Within the PCM tube, far from the 320 mm-long glass plate, two K-thermocouples were inserted to monitor the experimental module's temperature. To get an accurate readout of the PCM's wall temperature, a second thermocouple was placed
near its inner wall, and a third was introduced halfway inside the PCM to measure the core temperature.

**The heating subsystem.** Superheated steam was generated via an electric heating boiler (LDZ0. 1-0.7-D), a heat exchanger, and pipelines to replicate steam generated from waste heat in industry. Water in the tank had been softened by a device that extracted magnesium and calcium ions. The distilled water then went into the boiler, where it was heated to a pressure of 0.7 MPa and turned into steam. In a heat exchanger, steam may be used to transmit heat to water.

**The flow controlling segment.** Water was used as the heat transfer fluid (HTF) throughout this section. The water pump worked in conjunction with the ball valve to regulate the flow. The rate of flow was determined with the use of a flowmeter.

**The data collecting subsystem.** K-thermocouples were used to take the readings, and an Omega temperature recorder was used to keep track of everything. An ultrasonic flowmeter was used to measure the flow rate (FLUXUS G601). Data collection was used to get all of the information. The tetrasodium pyrophosphate decahydrate (Na₄P₂O₇·10H₂O) and through cooling process and phase parting during the phase evolution can be successfully managed using polyacrylamide (PAAm) [21-22]. As a result, the tube unit was filled with a composite

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**Fig. 2.** Pattern of tube with variant fins.

**Fig. 3.** An outline of tube system.

**Table 1.** Therm and physical characteristics of phase change material.

<table>
<thead>
<tr>
<th>Properties</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>CH₃COONa·3H₂O</td>
<td></td>
</tr>
<tr>
<td>Melting temperature</td>
<td>K</td>
</tr>
<tr>
<td>Specific heat conductivity</td>
<td>J/kg·K</td>
</tr>
<tr>
<td>Thermal conductivity</td>
<td>W/m·K</td>
</tr>
<tr>
<td>Density</td>
<td>kg/m³</td>
</tr>
</tbody>
</table>

**Table 2.** Structural parameters of various tubes.

<table>
<thead>
<tr>
<th>Tube</th>
<th>Length (L)</th>
<th>Outside diameter (D)</th>
<th>Wall thickness (δ)</th>
<th>Fin length (L')</th>
<th>Fin height (h)</th>
<th>Fin thickness (d)</th>
<th>Fin material</th>
<th>Fin configuration</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>500</td>
<td>4.5</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>4</td>
<td>Stainless steel</td>
<td>Plate</td>
</tr>
<tr>
<td>B</td>
<td>500</td>
<td>5.5</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>4</td>
<td>Stainless steel</td>
<td>Plate</td>
</tr>
<tr>
<td>C</td>
<td>500</td>
<td>6.5</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>4</td>
<td>Stainless steel</td>
<td>Plate</td>
</tr>
<tr>
<td>D</td>
<td>500</td>
<td>6.5</td>
<td>2</td>
<td>3.9</td>
<td>4</td>
<td>3</td>
<td>Stainless steel</td>
<td>Plate</td>
</tr>
<tr>
<td>E</td>
<td>500</td>
<td>7.5</td>
<td>2</td>
<td>3.9</td>
<td>4</td>
<td>40</td>
<td>Stainless steel</td>
<td>Plate</td>
</tr>
<tr>
<td>F</td>
<td>500</td>
<td>7.5</td>
<td>2</td>
<td>3.9</td>
<td>4</td>
<td>40</td>
<td>Aluminum</td>
<td>Cross</td>
</tr>
<tr>
<td>G</td>
<td>500</td>
<td>7.5</td>
<td>2</td>
<td>3.9</td>
<td>4</td>
<td>40</td>
<td>Aluminum</td>
<td>Cross</td>
</tr>
</tbody>
</table>
phase change material consisting of CH3COONa3H2O, 1.5 weight percent Na4P2O710H2O, and 1.5 weight percent PAAm. Table 1 indicates the thermophysical characteristics of phase change material.

Table 1. Thermal and physical characteristics of phase change material.

<table>
<thead>
<tr>
<th>Properties</th>
<th>Units</th>
<th>CH3COONa·3H2O</th>
</tr>
</thead>
<tbody>
<tr>
<td>Melting temperature</td>
<td>(K)</td>
<td>359</td>
</tr>
<tr>
<td>Specific heat conductivity</td>
<td>(J/kg·K)</td>
<td>2710</td>
</tr>
<tr>
<td>Thermal conductivity</td>
<td>(W/m·K)</td>
<td>0.15</td>
</tr>
<tr>
<td>Density</td>
<td>(kg/m³)</td>
<td>810</td>
</tr>
</tbody>
</table>

2.2. Experimental process

Heat from the water in the circulation tank was transferred to the CH3COONa3H2O inside the experimental tube. The experimented tube was only 95 percent full of liquid PCM to provide room for the SAT to expand during the phase shift process. Different inner fins, such as plate fins and cross fins, and tubes of varying sizes were used in the tests depicted in Fig. 2. The results of this adjustment on heat transport and phase transition were also analyzed. Table 2 lists the structural properties of tubes.

Table 2. Structural parameters of various tubes.

<table>
<thead>
<tr>
<th>Tube</th>
<th>Length (L)</th>
<th>Outside diameter (D)</th>
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<tr>
<td>Units</td>
<td>mm</td>
<td>mm</td>
<td>mm</td>
<td>mm</td>
<td>mm</td>
<td>mm</td>
<td></td>
<td></td>
</tr>
<tr>
<td>A</td>
<td>500</td>
<td>45</td>
<td>2</td>
<td></td>
<td></td>
<td></td>
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<tr>
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<td>500</td>
<td>55</td>
<td>2</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>C</td>
<td>500</td>
<td>65</td>
<td>2</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>D</td>
<td>500</td>
<td>65</td>
<td>2</td>
<td>390</td>
<td>25</td>
<td>3</td>
<td>Stainless steel</td>
<td>Plate</td>
</tr>
<tr>
<td>E</td>
<td>500</td>
<td>75</td>
<td>2</td>
<td>390</td>
<td>40</td>
<td>3</td>
<td>Stainless steel</td>
<td>Plate</td>
</tr>
<tr>
<td>F</td>
<td>500</td>
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<td>2</td>
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</tr>
</tbody>
</table>

Both charging and discharging were part of the experimental protocol. The charging processes. Boiler feed water was softened by a device that took out the calcium and magnesium ions. The circulation tank worked to move the heated water from the heat exchanger, which was heated by steam from the heating boiler. The experimented tube system transmitted heat from the descending water to the phase change material as the water cooled. The glass window also displayed the charging time and melting temperature. The discharging processes. The circulating water was cooled by the heat exchanger before it was discharged. The cold water was pumped from the cooling water tank. As a result, the PCM within the test tube cooled and hardened.
2.3. Uncertainty analysis

Standard procedures were used to calculate the observed values and their associated propagation uncertainties. Table 3 shows the uncertainty associated with the observed parameters.

<table>
<thead>
<tr>
<th>Factors</th>
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<tbody>
<tr>
<td>Temperature (K-thermocouple)</td>
<td>± 2.6 °C</td>
</tr>
<tr>
<td>Flow rate</td>
<td>± 0.6%</td>
</tr>
<tr>
<td>Temperature (Omega temperature recorder)</td>
<td>± 0.5% + 0.6 °C</td>
</tr>
</tbody>
</table>

The experimented statistics was gathered three times, and mean was calculated, to provide greater test reliability. The following criteria were used to assess the degree of temperature uncertainty [23]:

\[
T = \frac{\sum_{i=1}^{N} T_i}{N} \quad (1)
\]

\[
D = \sqrt{\frac{\sum_{i=1}^{N} (T_i - T)^2}{N-1}} \quad (2)
\]

whereas

Ti & T - measured temperatures at the moment.
N - number of times taken.
D - margin of error for the heat transferring rate.

It was determined that the temperature evaluation errors were less than 5%.

3. Results and discussions

Table 1 shows the tubes into which the composite PCM made with CH3COONa3H2O, Na4P2O710H2O as the nuclear agent, and PAAm as the thickening agent was poured. Thermal characteristics were evaluated and compared by measuring the temperature changes associated with charging and discharging procedures. The effects of water flow rate, tube diameter, and fins on energy storage performance were discussed.

3.1. Metal inner fin improvement of Heat transfer

Larger tube diameters were advantageous for energy storage, but their technological uses were constrained by the length of time required for charging and discharging due to inefficient heat transferring among the external heat source and the internal PCM. In this section, we analyzed the temperature changes that resulted from using different fin designs to improve heat transmission.
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\[
T = \frac{\sum T_i}{N_i} = \frac{1}{N} \sum T_i
\]

\[
D = \sqrt{\frac{\sum (T_i - T)^2}{N_i - 1}} = \frac{1}{N} - 1
\]

where \(T_i\) & \(T\) - measured temperatures at the moment.
\(N\) - number of times taken.
\(D\) - margin of error for the heat transfer ring.

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**Fig. 4.** The heating process evaluation of temperature with various fins and tubes.

Tubes D and E with plate inner fins inserted within them, as illustrated in Fig. 3, were able to store sensible heat energy at a higher temperature and reach a pure solid/liquid state considerably more quickly than PCM in the smoothen tube. Because of this, phase change material in the tube with the platter fins quickly melted and the charging process was completed. Shorter indicting times are associated with smaller tube diameters. If tube D had the same diameter as smooth tube C, the boosting time could be cut by greater than 9 minutes. Tube F, which had aluminium cross fins 3 mm thick and could store as much energy as tube E while having a smaller diameter, could be charged in around 28 minutes. Even though tube G's bigger fin of 5 mm might assist Phase change material absorbing more heat and reach the melting point more rapidly, there was no discernible variation in indicting time between tubes F and G.

**Fig. 5.** The Cooling Process evaluation of temperature with various fins and tubes.

Discharging characteristics of CH\(_3\)COONa\(_3\)H\(_2\)O in various tube types were displayed in Fig. 5. After turning off the heating system's pump, the circulation water was sent through the heat exchanger, where it met the cold water and lost heat to it, bringing the temperature of the phase change material in the experimental tube down. The phase change material in tube D with plate fins cooled significantly more quickly in the liquid zone and attain the solidification temperature in a shorter amount of time than the phase change material in tube
C with the same tube diameter. Discharging was finished in 35 minutes, saving 24 percent of the time required by tube C. Compared to tube C, which has fins, tube E's wider diameter only needed 41 minutes to release the energy. In contrast to the aluminium cross fins, PCM in the tube showed no discernible variation in sensible heat emission before solidification. Although the time to discharge the energy was only four minutes longer, the discharging curvature was substantially flatter. It took 40 minutes to finish discharging, but the thicker fin helped transmit heat from the water to the PCM.

3.2. Variations in thermal energy storage temperature

The decrease in PCM temperature is indicated in Fig. 6. The first rise was probably caused by the warmer tank water circulation. The Phase Change Material in the test tube gradually cooled to its solidification temperature [25]. The rise in temperature, which would limit PCM solidification, was caused by the heat emitted during solidification. This meant that the PCM at the tube's centre had to crystallize at a considerably slower rate than it had melted. It took about 25 minutes for the CH3COONa3H2O in the 45 mm diameter tube to harden at around 345.5 K, during the phase evolution phenomenon of discharging; however, the much larger volume of CH3COONa3H2O in the 65 mm diameter tube solidified last, and its temperature was able to rise to 356 K as a result of the heat it released. It was found that the discharging phase of the LHTES system took 50 minutes, significantly longer than the inducing process. Conduction and convection were used to heat and cool the phase change material in the experimental tube. The PCM melted when the temperature was raised over its melting point, resulting in a liquid. Since the solid and liquid phases have different densities, natural convection was later observed. The melting process would be accelerated by this spontaneous convection, which would play a significant role in the phase transitions [26]. In addition to the cooling effect of water, heat transmission inside the hardened layer and usual convection at the solid-liquid boundary both played significant roles in the solidification of CH3COONa3H2O. Unfortunately, natural convection worked against PCM solidification. As a result, the PCM solidification process would be slowed down or perhaps stopped [27].
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Unfortunately, natural convection worked against PCM solidification. As a result, the PCM solidification process would be slowed down or perhaps stopped [27].

The first major emphasis of the experimental data was on the phase transition behaviors found when PCM was heated in the tube unit. Temperature changes of PCM heated by circulation water are displayed in Figs. 7 and 8 for volume flow rates of 0.5 m³/h and 0.51 m³/h, respectively. Figure 7 shows that after 30 minutes of heating, a tube with a diameter of 45 mm experienced melting phenomena of PCM near to the wall because sensible heat was absorbed at temperatures less the melting point of PCM. At about 359 K, PCM material near to the tube wall melted and fell off the glass plate. For 20 minutes, the temperature was maintained at or just below the melting point. However, with the tube with a diameter of 65 mm, the entire charging process took 30 minutes, and even then, there was some CH₃COONa₃H₂O crystal remaining in the core. In Fig. 8, if the water flow rate were increased, the PCM would absorb sensible heat considerably more quickly, but this would have minimal influence on the phase transition.
3.3. Development of Heat transfer through inner metal fin

![Graph showing temperature change over time for different tubes]

**Fig. 9.** The mean temperature of phase change material of the tube with fins.

The fins altered the heat conduction pattern. As an outcome of the great thermal conduction of the stainless-steel fins on tubes D and E, substantially more heat was able to be promptly supplied to the central of PCM. Material next to the wall/fins was heated rapidly, whereas phase change material among two together fins was heated slowly, simulated melting at the conclusion of the melting phase. We may have found, as evidenced by the reduced charging time, that tube F with aluminium cross fins provides much higher thermal performance. Table 4 shows how the addition of 4 plate fins to a tube increases heat transfer and decreases charging time by 28.8 percent compared to a smooth tube of the same diameter and melting procedure. Charging energy for tube E with higher PCM quality took around 30 minutes. Tube F with aluminium cross fins had a much higher liquid percentage than tube E. Using its shape and strong heat conductivity to their fullest, as shown in Fig. 9, tube A5 was able to achieve a substantially quicker melting speed than tube E. A 26-minute test confirmed our suspicion that the aluminium cross fins would speed up charging.

**Table 4.** The liquid fraction through melting process (%).

<table>
<thead>
<tr>
<th>Tube</th>
<th>500 s</th>
<th>900 s</th>
<th>1300 s</th>
<th>1700 s</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>65</td>
<td>87</td>
<td>99</td>
<td>100</td>
</tr>
<tr>
<td>B</td>
<td>56</td>
<td>76</td>
<td>90</td>
<td>97</td>
</tr>
<tr>
<td>C</td>
<td>32</td>
<td>46</td>
<td>55</td>
<td>62</td>
</tr>
<tr>
<td>D</td>
<td>61</td>
<td>86</td>
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</tbody>
</table>

The temperature distribution showed that the aluminium cross fins were significantly colder than the tube walls at the start of the melting process because of the space between the fins and the walls. The core of Tube F is connected by fins, and it has a stronger heat conductivity than stainless steel. As a result, there was a substantially smaller difference in the radial temperatures of the fins, and the heat was transferred through the aluminium fin in just 1380 seconds. Since the temperature was relatively constant throughout the core, the PCM melting process proceeded more rapidly. However, the PCM cross fins in the core did not melt like...
the stainless-steel fins in tube E did because they were held at a lower temperature. That's why in our experiment tube E charged faster than tubes F and G.

3.4. Thermal behavior of TES system

Before phase change and melting phenomena started to occur from PCM towards the inner wall and spread to the depth of PCM, heat conductivity among the tube wall and solid phase change material was the primary mechanism. In accordance with the experimented outcomes depicted in Fig. 7 and 8, it was predicted that increasing the tube diameter would restrict heat transmission, resulting in a substantially longer charging period. As shown in Fig. 10 (a), the reported mean temperature evolution of the PCM provides a clear example of this.

![Fig. 10. (a) The mean temperature of phase change material in the smoothen tubes (b) The phase change material liquid fraction of the smoothen tubes.](image)

Energy storage capacity was studied by measuring the proportion of phase change and the mean liquid fraction as a percent of the perpendicular section while CH3COONa3H2O was heated in smooth tubes at a constant heating temperature of 368 K (Fig. 10b). At 600 s, it was simple to calculate the liquid phase mass of PCM, and at 1200 and 1700 s, the differences in liquid volume between the three tubes grew. Tube A's charging time of 20 minutes is the shortest since the PCM melted at a faster rate in that tube. However, PCM in tube C received far more heat to sustain the phase change process, and the size of the solid zone shrank as the experiment progressed [28]. The 33-minute charging time was significantly longer than that of tube A. The success of thermal energy storage relied heavily on the ability to rapidly charge and raise the operating temperature of the PCM core.

4. Conclusions

The thermal performance of a CH3COONa3H2O energy storage system was investigated through a series of tests in this work. Preliminary results on PCM's heating-cooling performance in the tubes and its effect on temperature evolution are summarized below.

- Due to heat conduction during the charging procedure, the phase change material nearest to the wall of the experimented tube melted and dispersed at around 359 K. As a result, PCM was able to rapidly absorbing heat and reach the phase evolution temperature without the charging rate slowing down.
- Melting behaviour of PCM in tubes of varied smoothness. A smaller tube diameter will absorb sensible heat more slowly and hold onto that heat for a shorter period of time.
For PCM, similar outcomes were seen in tubes with different fin arrangements. Heat conduction was found to be largely unaffected by the phase change.

- Fins made of plate stainless steel or aluminium cross-sections can boost the PCM system's charging and discharging efficiency. The energy charging time for PCM may be lowered by at least 8 minutes for the same diameter tube due to the fins' higher efficiency in transferring heat to the core; the energy discharge time can be reduced by at least 11 minutes, or 25, compared to PCM in the smooth tube.

References

17. J. Gao, B. Zhao, F. He, T. Li, Huagong Xuebao/CIESC J 72, 3328 (2021).