

# Experimental investigation on heat pipes supported by soy wax and lauric acid for electronics cooling

Paweł Szymanski<sup>a</sup>, Radosław Paluch<sup>b</sup>

<sup>a</sup>Faculty of Mechanical Engineering, Gdańsk University of Technology, Narutowicza 11/12, 80-233, Gdańsk, Poland

<sup>b</sup>KP Labs Sp. z o.o., Bojkowska 37J, 44-100 Gliwice, Poland

## Abstract

This paper presents an experimental study of heat pipes for electronics cooling that were supported by energy storage materials (i.e. phase change materials - PCMs) coated at the adiabatic section. The PCMs utilized included two materials, namely lauric acid and soy wax, the latter being considered as a more cost-effective alternative. The study focused on three different power levels: 20W, 25W, and 30W. Both heating, cooling, and thermal cycling experiments were performed in order to compare the thermal performance of cooling units. The experimental results showed that the incorporation of lauric acid as a thermal energy storage material reduced the maximum temperature by 11.6%, 14.6%, and 14.5% for the examined power levels. On the other hand, the utilization of soy wax resulted in temperature reductions of 4.3%, 6.3%, and 6.8%. Furthermore, it was observed that lauric acid could store 25% of the energy during the maximum power dissipation test, whereas soy wax could store 12%. It was shown that lauric acid improved the thermal performance of the unit by approximately twice as effectively as soy wax. However, it is noteworthy that soy wax exhibits a significantly lower cost, making it a potentially viable alternative for less demanding applications where cost considerations are crucial.

*Keywords:* electronics cooling; phase change material; energy storage; heat pipe; heat transfer;

## Nomenclature

### Abbreviations

HB	Heater Block
HP	Heat Pipe
LHTES	Latent Heat Thermal Energy Storage
PCM	Phase Change Material
TMS	Thermal Management System

### Symbols

C	sensible heat, $J g^{-1} °C^{-1}$
L <sub>H</sub>	latent heat, $J g^{-1}$
m	mass, g
Q	heat, J
T	temperature, °C

### Subscripts

s	starting point
e	end point
c	condenser
L	loss

## 1. Introduction

With the advancements in the field of miniaturization of electronic components comes an increase in input power and more computational capabilities offered to the users [1]. This consequently creates significant challenges in terms of thermal management of microprocessors and other elements found in modern electronic devices. In fact, in many cases, the self-heating of electronics becomes a bottleneck to their performance and reliability [2]. In addition, operation under elevated temperatures and periodic changes in the temperature of the unit create thermal stresses, which are one of the main causes of failures in electronic components [3]. Therefore,

a proper cooling method plays a crucial role in assuring reliability and reducing risks of malfunction. The importance of temperature control is increasing, and thermal management systems (TMS) are gaining more attention from the scientific and engineering communities worldwide [4]. Most TMS are currently suffering from significant amounts of energy required for their operation, space requirements, and noise generation [5]. Hence, passive, noise-free, and compact solutions are of interest for the thermal management of electronics.

Heat pipes (HP) are one of the most common, passive, and highly efficient components used in electronics cooling [6]. They have many advantages such as low cost, high thermal conductivity, stable performance, and little efficiency degradation after long application periods [7]. HPs are widely used to transport large heat fluxes to fan air-cooled heat sinks inside modern computers. In most cases, the adiabatic section of the HP is exposed within a small space inside the device. This causes part of the energy transported through the pipe to dissipate, heating surrounding components and, as a result, decreasing the cooling capability [8]. It would be beneficial to mitigate this issue by capturing the waste heat and reusing it to improve the overall performance of the thermal management system.

In recent years, there has been a rise in interest in latent heat thermal energy storage (LHTES) systems and materials. Thermal management of electronics is one of the fields that can benefit from the utilization of PCMs. Those materials can store large amounts of heat per unit volume with little temperature rise due to isothermal nature of phase change [9]. This behavior can be used to reduce maximum temperature of the cooled element and protect the device from overheating. In addition, energy stored during melting process of PCM can be later released during its solidification. This process stabilizes the temperature of an electronic component in case of variations in power dissipation and during periodic operation of the device [10]. PCMs can be classified as organic, inorganic, and eutectic materials. Organic PCMs are most commonly used due to their availability, low cost, and ease of handling [11]. The most popular are paraffins ( $C_nH_{2n+2}$ ) and fatty acids ( $CH_3(CH_2)_{2n}COOH$ ) [12].

Jaworski [9] proposed a heat sink for electronics cooling with encapsulated lauric acid. He found that utilization of PCM significantly improved the efficiency of removing heat from electronic devices at steady state operation. Setoh et al. [13] investigated eicosane paraffin as a PCM for cooling mobile phones. The researchers concluded that utilization of PCM was effective under intermittent moderate usage. Fabrykiewicz et al. [14] studied the performance of stearic acid as a PCM and proved its ability to store thermal energy. Arifin et al. [15] studied the effect of soybean wax on the cooling performance of photovoltaic cells and demonstrated a reduction in maximum temperature after the application of PCM. Leong et al. [16] experimentally verified finned heat sinks filled with two PCMs: paraffin wax and 1-hexadecanol and concluded that both materials allowed for reduction of device's base temperature.

One of the biggest disadvantages of organic PCMs is their low thermal conductivity, which can seriously affect their thermal performance [12]. Therefore, combining HPs with PCMs is a very promising direction for the development of state-of-the-art TMS for electronics cooling. Hayat et al. [17] developed and tested empirically a hybrid heat sink utilizing PCMs, HPs, and copper foam. Paraffin RT-35HC was used as an energy storage material. It was proven that such a device provides excellent cooling results at all considered heat fluxes, with a maximum temperature reduction of about 50% in all cases. Tso et al. [18] studied HPs with eicosane paraffin as a PCM, coated at its condenser section. They found that even though the HP itself malfunctioned during tests, the PCM allowed for a reduction of the maximum temperature of a heated element of almost 40% in comparison to HP without PCM.

However, it is more beneficial to utilize LHES at the adiabatic section of the HP. In such an approach, most of the heat flux can be transferred to the main heat sink, while PCM can act as a secondary condenser or evaporator, depending on temperature distribution in the system. Such an approach was presented by Chogule and Sahu [19]. The researchers used HP with paraffin covering its adiabatic section, acting as LHTES. Experiments showed that such a cooling module reduced the cooling fan power consumption compared to a device with HP without a PCM. Weng et al. [20] investigated HP with its adiabatic section embedded with three different PCMs. i.e.: tricosane, lauric acid, and palmitic acid. The condenser section of HP was cooled actively by electric fan. The results depicted that tricosane showed the highest positive impact on the performance of the system. At 40W of dissipated power, it reduced the maximum temperature in the device by 16°C and lowered the amplitude between the highest and lowest temperature points. Krishna et al. [21] carried out experimental research on different energy storage materials introduced around HPs adiabatic section. The investigated materials were water, tricosane, and tricosane with 1% addition of  $Al_2O_3$  nanoparticles. The condenser section was cooled by forced convection heat transfer. The researchers found that nano-enhanced tricosane provided the best results with the highest reduction of heater's temperature in comparison to reference HP (without PCM).

The above-mentioned studies proved the effectiveness of combining HPs with PCM for improvements in electronic cooling. However, most studies utilized forced convection cooling (i.e. electric fan) of the condenser section of the HP, which requires some amount of energy and generates noise and vibration. In electronics cooling

applications, purely passive solutions are preferred [22]. Moreover, no studies fully addressed the cost efficiency of PCMs in relation to their thermal performance, and little attention was given to possible cheaper alternatives.

This article compares two PCMs: 99% pure lauric acid (a.k.a. dodecanoic acid) and soy wax. The first is the expensive option and the second is a cost-effective solution, sustainable, and widely available alternative. The authors investigated the thermal performance of an entirely passive cooling unit with natural convection utilized at the condenser section of the HP.

## 2. Experimental set-up

### 2.1. Test rig design

The experimental rig was built to study the thermal performance of PCM-assisted HPs for electronics cooling applications. It consisted of three main sections, i.e. (I) heater block (HB) acting as a hot electronic component; (II) thermal energy storage tank consisting of PCM; (III) condenser with attached passive heat sink. All sections were connected by a copper-water HP, with the middle part of it embedded by PCM. The length of HP's evaporator section was 50mm, adiabatic section was coated with PCM at 160mm, and the condenser section was 100mm in length. Tab. 1 contains detailed parameters of HPs used in this study. The schematic view of the test rig presented in Fig. 1. In order to compare the thermal performance of the cooling unit three test rigs were constructed, i.e.: (1) for testing lauric acid as PCM; (2) for testing soy wax; and (3) without energy storage tank, which acted as a reference. The heater blocks were created from cuboid aluminum pieces with dimensions of 50mm x 50mm x 20mm. A cartridge heater with dimensions of  $\Phi 6\text{mm} \times 20\text{mm}$  was inserted inside each block. Then, thermally insulating cotton and 3D printed covers were applied on top of the heating section to minimize heat losses to ambient. Electric power for heaters was provided by a programmable laboratory DC power supplier (model RS-D3305P). The LHTES tanks were made from glass. Their outside dimensions were 160mm x 110mm x 50mm with a maximum volume of 350ml. Aluminum finned heat sink (model SK 628 100 AL) with dimensions of 100mm x 75mm x 45mm was attached at each condenser section. To obtain the thermal performance of the cooling units, temperature was measured by T-type thermocouples mounted in multiple sections of the test units (seen in Fig 1). Two measurement points were located in each heater block (one inside aluminum and one on the HP), two thermocouples were installed in PCM tanks (one on HP, and one directly into PCM 10mm from adiabatic section), and one thermocouple was attached at each condenser section. Temperature data was captured by two PicoLog TC-08 data loggers connected to a PC.

Tab. 1. Properties of HPs used in the study.

<b>Main properties of utilized Heat Pipes</b>	
Manufacturer	<i>Quick-cool®</i>
Casing material	<i>Copper</i>
External diameter	<i>6mm</i>
Total HP length	<i>400mm</i>
Working fluid	<i>Ultrapure water</i>
Working range	<i>5°C to 250°C</i>
Transferable heat output at 70°C	<i>55W</i>
Thermal resistance	<i>0.2°C/W</i>



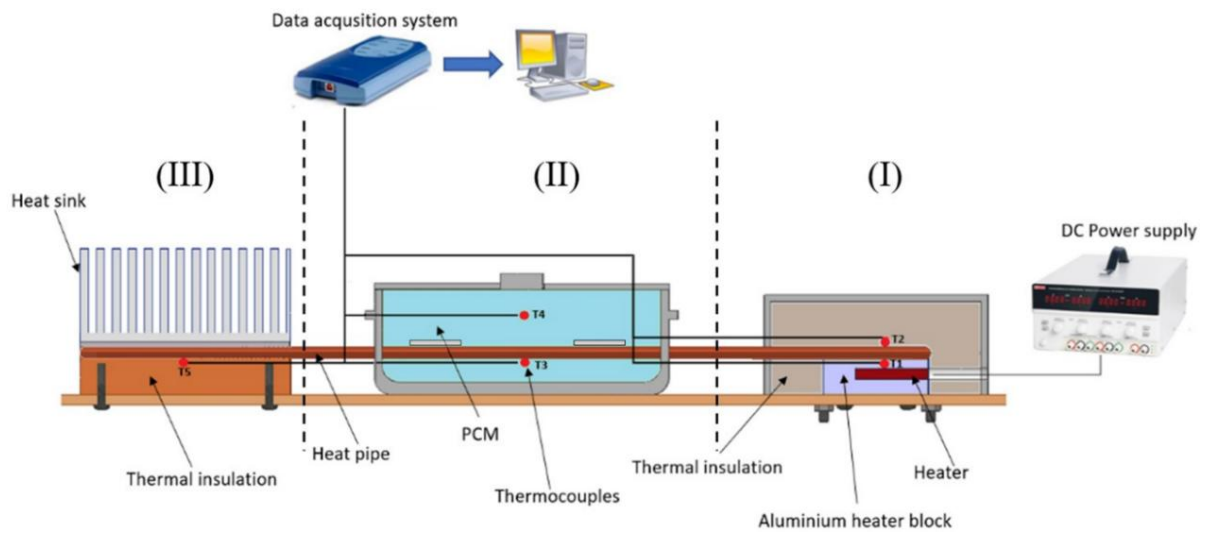


Fig. 1. Schematic of the test rig with location of thermocouples and division into three thermodynamic sections.

The test rigs were attached to a wooden plate for thermal insulation and secured in place by screws. Each unit was thermally insulated during the tests to avoid heat losses to the ambient. To further enhance heat transfer in the PCM, two rectangular aluminum fins were installed at adiabatic section of HPs, with dimensions of 60 mm x 20mm, as presented in Fig. 2. This solution increased the overall heat transfer area from an initial 30cm<sup>2</sup> to 54 cm<sup>2</sup> which is an 80% improvement. The perforations in the glass containers were sealed with silicone. Fig. 3 presents the assembled experimental test rigs before filling PCMs into LHTES containers.



Fig. 2. Aluminum fins added inside PCM container.



Fig. 3. The experimental stand for investigating PCM-assisted HPs for electronics cooling. Two rigs are for testing lauric acid and soy wax, the third being a reference.

In addition, to improve the thermal performance of the system, all metal-metal contact points in the system were treated with thermally conductive paste (AG Silver) with a thermal conductivity of 3.8 W m<sup>-1</sup> K<sup>-1</sup>.

## 2.2. Uncertainty analysis

In order to determine the accuracy of the results obtained in the research using the developed experimental setup, an analysis of measurement uncertainty was conducted. In the first step, the measurement uncertainties arising from the operation of the laboratory power supplier were analysed. This device was intended to provide electrical power to resistive heaters, simulating the heat dissipation of the electronic component. However, according to the datasheet, the voltage and current generated by the power supply were subject to the following uncertainties:

Tab. 2. Uncertainties of voltage and current supply as stated in RS-D3305P datasheet.

Voltage uncertainty	$\pm (0.5\% + 20\text{mV})$
Current uncertainty	$\pm (0.5\% + 10\text{mA})$

Having determined the maximum values of voltage and current during the operation of the power supply, the upper limits of uncertainty were calculated in accordance with the guidelines presented in Table 2. The uncertainty of the voltage value was found to be  $\pm 0.11$  V, and the uncertainty of the current was equal to  $\pm 0.018$  A.

To measure the temperature, T-type thermocouples made by Czaki Thermo-Product (serial number TP-202T-1-100-2) were selected. The measurement uncertainty for these sensors was read from the datasheet provided by the producer, which complied with the PN-EN 60584-2 standard. According to the specifications, the uncertainty of the sensors for the range from  $-40^{\circ}\text{C}$  to  $+125^{\circ}\text{C}$  was  $\pm 0.5^{\circ}\text{C}$ . However, the total measurement uncertainty was not only due to the tolerance of the thermoelement but also the Picolog TC-08 data logger. Using the technical documentation of this device, the description of the temperature measurement uncertainty with its use was obtained, which amounted to  $\pm (0.2\% \text{ of reading} + 0.5^{\circ}\text{C})$ . To consider both the sensor error and the Picolog data logger error in the analysis of the results, the following formula was applied:

$$u(T) = \sqrt{\left(0.2 \cdot \frac{T}{100} + 0.5\right)^2 + (0.5)^2} \quad (1)$$

Where:  $u(T)$ - uncertainty of temperature reading,  $T$ - temperature reading

Based on the maximum and minimum temperature readings obtained in experiments equal to  $120^{\circ}\text{C}$  and  $23^{\circ}\text{C}$  the temperature reading uncertainty was estimated to fall in the range between  $\pm 0.74^{\circ}\text{C}$  to  $\pm 0.89^{\circ}\text{C}$ .

### 3. Phase change materials

#### 3.1. Properties of selected LHTES

A typical maximum operating temperature for electronic components should not exceed  $85^{\circ}\text{C}$ , which is necessary to ensure reliable operation and long lifespan [12][23]. Therefore, selected PCMs have melting points well below that temperature. The first PCM considered for the study was lauric acid, which is a fatty acid ( $\text{C}_{11}\text{H}_{23}\text{COOH}$ ) with a well-documented successful history of implementation in a role of LHTES [9, 20]. Its melting temperature range is  $41.5^{\circ}\text{C}$ - $44.5^{\circ}\text{C}$  [10][24]. The material used was chemically pure (99% purity) and was purchased from the manufacturer. The alternative proposed by the authors and compared with lauric acid was soy wax. It is a softer paraffin wax, made from soybean oil. It is a completely renewable material, and its production is ecological and sustainable. In addition, this PCM is abundant on the commercial market and is much cheaper than lauric acid. However, it is a mixture of different organic compounds and there is little to no data about its thermal properties, so in order to determine it properly, differential scanning calorimetry (DSC) was utilized. As a calorimeter, used a device manufactured by Mettler-Toledo (model DSC 822e). The obtained temperature melting range for soy wax was  $42.5^{\circ}\text{C}$ - $67.6^{\circ}\text{C}$  which was much broader than that of lauric acid, due to the more complex chemical composition of soy wax. Tab. 3 summarizes the most important thermodynamic properties of both PCMs used in the study. In addition, the costs of obtaining 500 grams of both materials were also provided for comparison. The densities of materials were measured in-house.

Tab. 3. Thermophysical properties of lauric acid and soy wax

PCMs	Lauric acid	Soy wax
Melting range, $^{\circ}\text{C}$	41.5 - 44.5 [24]	42.5 - 67.6
Latent heat, $\text{J g}^{-1}$	180 [24]	67.6
Sensible heat of solid, $\text{J g}^{-1} \text{K}^{-1}$	2.34 [9]	2.66
Sensible heat of liquid, $\text{J g}^{-1} \text{K}^{-1}$	2.17 [9]	2.06
Density liquid, $\text{g/ml}$	0.88	0.91
Density solid, $\text{g/ml}$	0.90	0.95
Cost per 500g, $\text{€}$	62.75	4.48

It is easy to notice, that soy wax is around 14 times cheaper than chemically pure lauric acid. Both materials share a similar starting point of the melting process. However, lauric acid possesses almost two times higher latent heat. On the other hand, soy wax goes through a phase change over much broader range of temperatures and can improve the performance of cooling units for a longer period of time. Hence, the authors decided to perform a

comparable study of those two materials in terms of their influence on the HP operation in passive heat exchangers for electronics cooling.

### 3.2. PCMs energy storage

To describe energy absorption by PCMs during tests, energy balance equations for both lauric acid and soy wax were defined. The following relation between heat stored within PCM and temperature was used:

$$Q_{PCM} = \begin{cases} mC_{solid}\Delta T & \text{for } T < T_{m,s} \\ mL_H & \text{for } T_{m,s} < T < T_{m,e} \\ mC_{liquid}\Delta T & \text{for } T_{m,e} < T \end{cases} \quad (2)$$

where:  $m$ - mass of the PCM,  $C_{solid}$ - sensible heat in solid state,  $\Delta T$ - temperature change,  $T_{m,s}$ - starting temperature of the melting process,  $L_H$ - latent heat,  $T_{m,e}$ - end temperature of melting process,  $C_{liquid}$ - sensible heat in liquid state.

The total energy balance for the considered system can be expressed as follows:

$$Q_{heater} = Q_C + Q_{PCM} + Q_L \quad (3)$$

where:  $Q_{heater}$ - energy supplied to the heater block,  $Q_C$ - energy transferred to condenser,  $Q_{PCM}$ - energy stored in PCM,  $Q_L$ - heat losses to ambient

It was assumed that heat losses to ambient were negligible due to utilization of thermal insulation at all surfaces that could cause heat leaks.

## 4. Experimental procedure

### 4.1. Reference measurements

Before placing lauric acid and soy wax into their containers, measurements were performed with all three test rigs in order to compare their thermal performance. It was an important step, because all three HPs, even though they were supplied from the same batch by the manufacturer, displayed slightly different temperature gradients between their evaporators and condensers. The obtained results are shown in Fig. 4. The main differences became visible with higher power inputs. Therefore, the authors suggest that potential small differences in the thermal resistance of HP and manufacturing errors have caused this behavior. In addition, energy at condenser sections was being rejected in a purely passive way. Heat transfer rate espoused by natural convection from heat sinks directly depends on their temperature. Therefore, initial differences in temperature distributions in the system are caused by small differences in HP properties could be possibly amplified by the passive and self-tuning nature of proposed cooling systems.

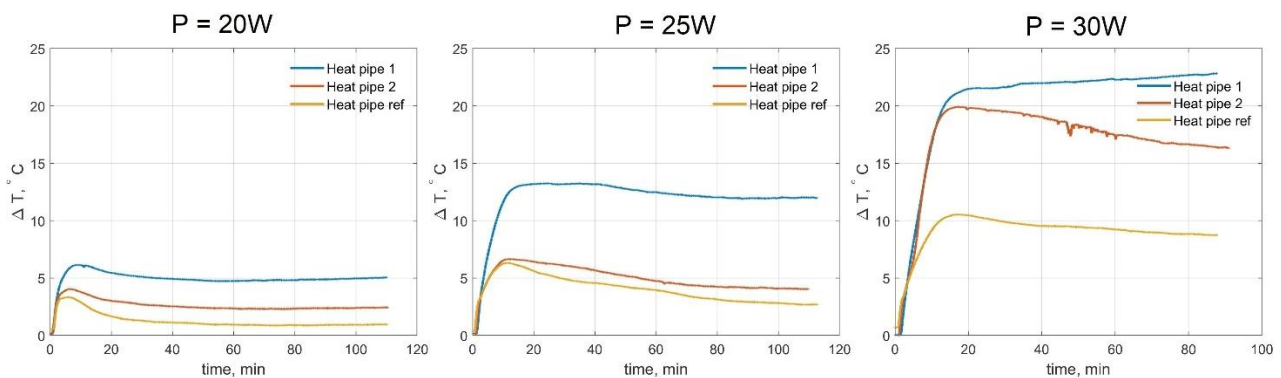


Fig. 4. Evaporation-condensation temperature difference for 3 heat pipes used in the study, for 20W, 25W and 30W of heating power. HP 1 was used in test rig and later filled with soy wax. HP 2 relates to lauric acid rig. HP ref is the reference pipe.

In order to isolate the impact of PCM on the thermal performance of the cooling unit, the test procedure was modified accordingly to take into account observed behavior of HPs



## 4.2. Established procedure

After the initial (reference) measurements, PCMs were melted and poured into the glass containers. Both containers were filled with 230ml of LHTES. Due to density differences this translated to 202g of lauric acid and 210g of soy wax. A laboratory syringe was used to dispense a precise amount of PCMs volume.

As mentioned above, the HPs displayed different thermal performances, which caused different temperature distributions in the test rigs. In order to compare the two PCMs it was inadvisable to make direct comparisons between the test rigs. Instead of this, thermal performance of each test rig was first evaluated without the PCM and then, all tests were repeated but with the filled energy storage tank. This allowed for relative comparison of improvement for used materials.

The first part of the experiment investigated LHTES impact on the steady-state temperature achieved by the system. Three different heating powers were used: 20W, 25W and 30W. Then, temperature evolutions during cooldown from the starting points of 65°C, 70°C, and 90°C for 45 minutes were recorded and compared. Finally, thermal cycling was performed to simulate the real-live operating conditions of a typical electronic device. In the last experiment, the reference HP was used because, during the evaluation of the results, only the relative quantities were compared between the test stands.

## 5. Results and discussion

### 5.1. Steady-state heating tests

Fig. 5-7 shows temperature curves of heater blocks (simulating the electronic component) and condenser sections of HPs. For all investigated power dissipations there was a clear reduction in maximum temperature achieved by the cooling module in steady state after application of both PCMs. For the test rig used for evaluation of lauric acid, before the LHTES was poured into the container, the steady-state levels of heater block were: 73°C, 86°C and 109.5°C for corresponding powers of 20W, 25W, and 30W. In the assembly dedicated to soy wax, the HP maximum temperatures with an empty energy storage tank were: 74.7°C, 90.4°C, and 112.9°C. When the PCMs were introduced to the systems, the maximum temperatures of the heater were: 64.5°C, 73.5°C, 93.6°C for lauric acid and 71.57°C, 84.7°C, 105.2°C for soy wax.

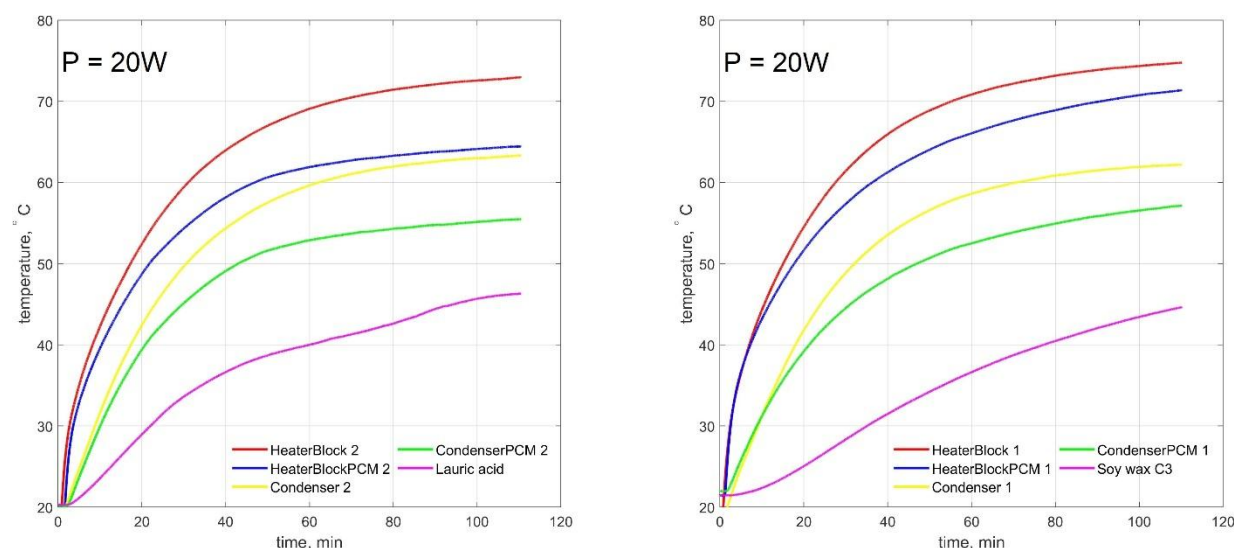


Fig. 5. Temperature variations of heater block and condenser for 20W of power. Curves for lauric acid are presented on the left and for soy wax on the right.



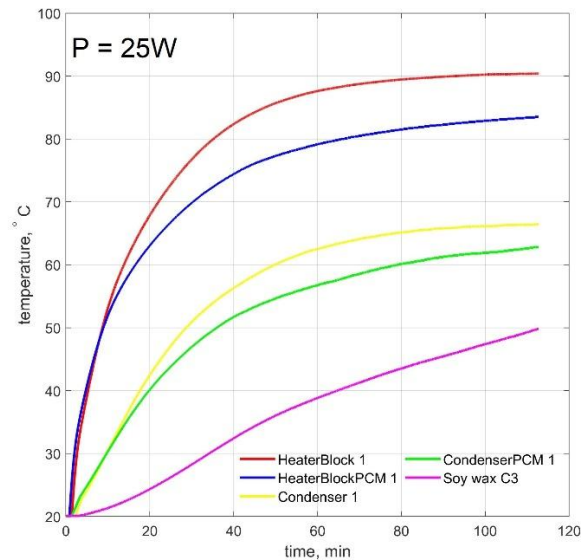
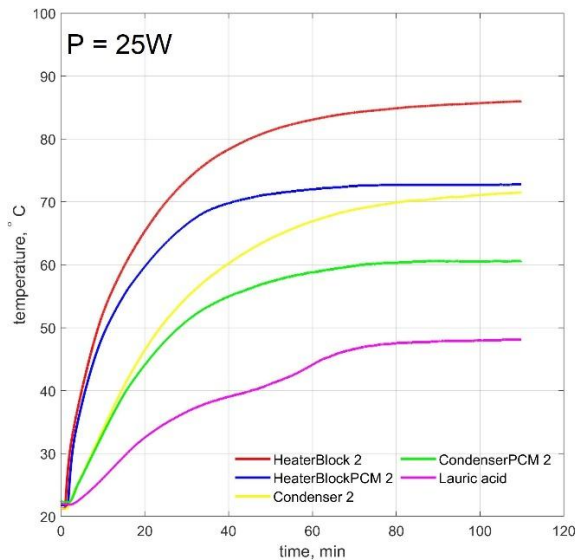


Fig. 6 Temperature variations of heater block and condenser for 25W of power. Curves for lauric acid are presented on the left and for soy wax on the right.

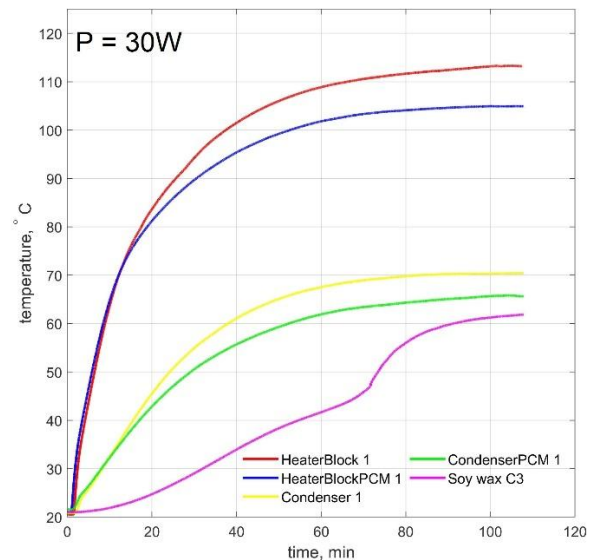
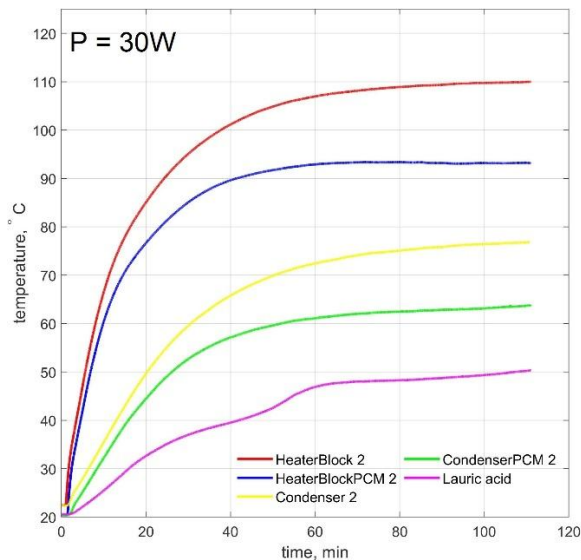


Fig. 7 Temperature variations of heater block and condenser for 30W of power. Curves for lauric acid are presented on the left and for soy wax on the right.

Fig. 8 compares the maximum temperature reduction of cooled component for both PCMs. It is clearly visible that the influence of lauric acid was much higher than that of soy wax. For 20W, lauric acid allowed for an 11.6% temperature decrease, and soy wax lessened the maximum value by 4.3%. For 25W, the reduction was 14.6% and 6.3% for lauric acid and soy wax, respectively. Similar results were obtained for 30W, with 14.5% and 6.8% of temperature reduction provided by PCMs, respectively. The temperature drops at condenser sections followed the heater blocks trend, therefore, utilization of LHTES allowed for reduction of maximum temperature in the whole cooling unit regardless of the material used.

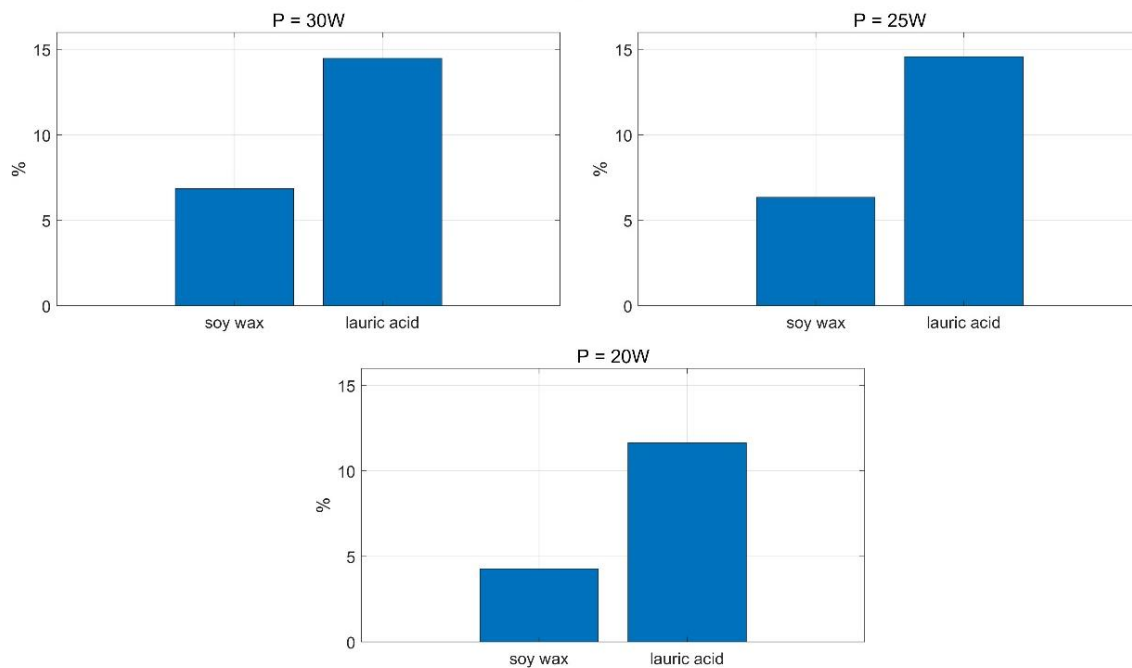


Fig. 8. Percentage of the heater's maximum temperature decrease after application of lauric acid and soy wax at HP adiabatic section.

In Fig. 5-7 presented temperature variations of both PCMs. The measurements were taken 10mm from the adiabatic section of the HPs. Lauric acid displayed a visible decrease in temperature rise rate when the phase change front reached the thermocouple. For soy wax, the phase change was not clearly visible due to the much broader temperature range of the process and lower latent heat of the material. At 30 W of heating power, a sudden rise in temperature of soy wax was observed. After investigation, it turned out that due to the poor thermal conductivity of the material, a liquid reservoir had been created, surrounded by a solid phase. This caused the melted wax to quickly overheat. After the solidification, the boundaries of the reservoir were clearly visible (Fig. 9). This phenomena commonly occurs for many organic PCMs [12], however, such behavior was not observed for lauric acid which was melting uniformly in the whole container's volume.



Fig. 9. Visible left-out liquid and solid phase boundaries after solidification of the soy wax.

The amount of energy stored in the LHTES was estimated with equations (1) and (2). Calculations were performed for maximum heating power (30W). Since soy wax didn't melt completely during tests, the liquid-state specific heat was not taken into account in order to include this behavior in the estimations. Lauric acid stored around 48933 J and soy wax stored around 26765 J of heat. This corresponds to 25% and 14% of the total energy dissipated for 110min in the experiments at 30W of power supplied to the heaters.

## 5.2. LHTES discharge

After a steady state was achieved, the heaters were turned off, and the temperatures of the heater blocks during discharge of the PCMs were recorded. The temperature curves were obtained starting from three different temperatures, to compare the cooldown behavior under different conditions. The starting temperatures were: 65°C, 70°C, 90°C. Fig. 10–12 shows the cooldown process for heater blocks in experimental stands with lauric acid and soy wax. The temperatures were compared with the same measurements taken when the LHTES tanks were empty.

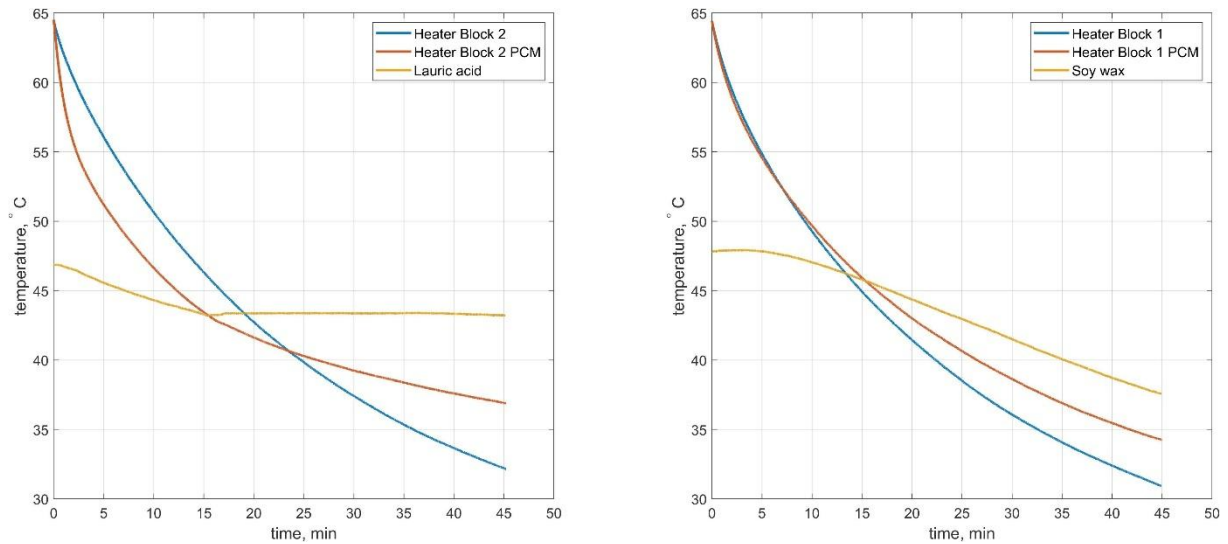


Fig. 10 Temperature variations of heater block for cooldown from 65°C. Results for lauric acid are presented on the left and for soy wax on the right.

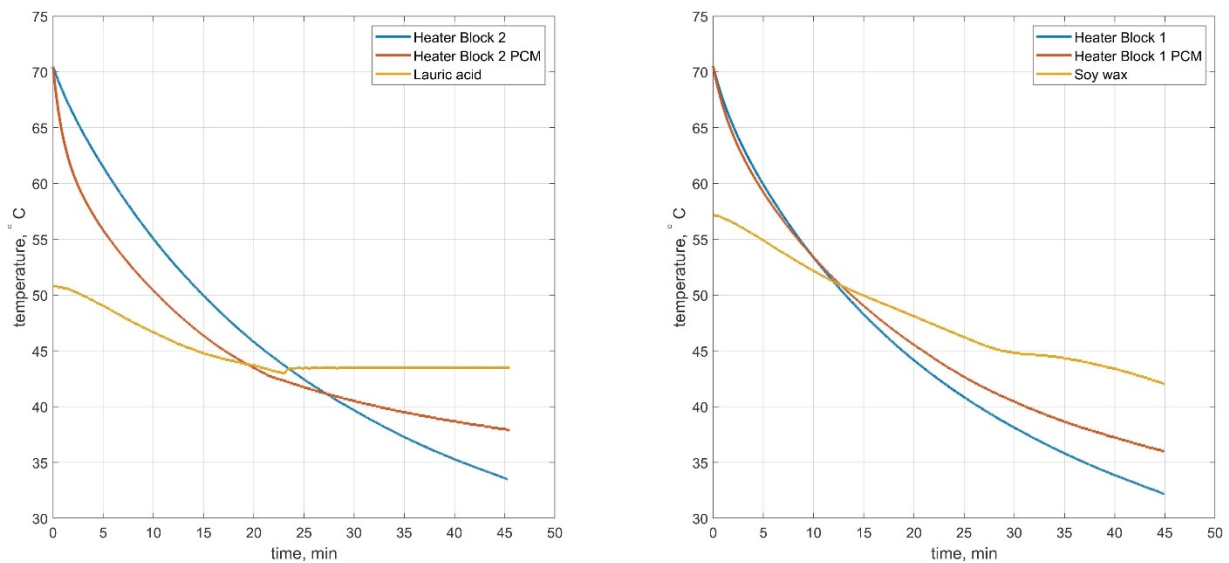


Fig. 11 Temperature variations of heater block for cooldown from 70°C. Results for lauric acid are presented on the left and for soy wax on the right.

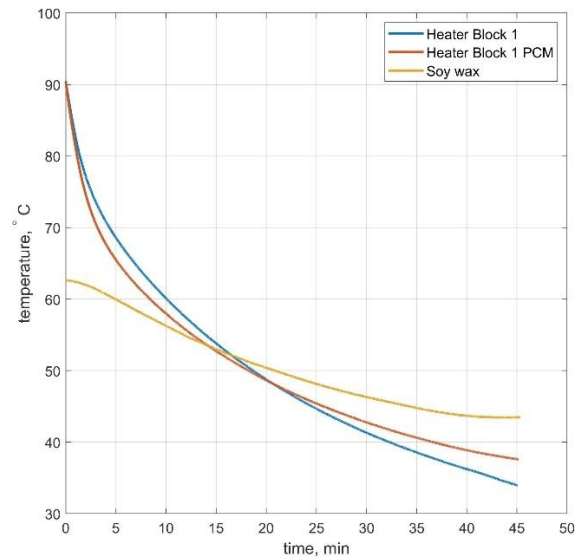
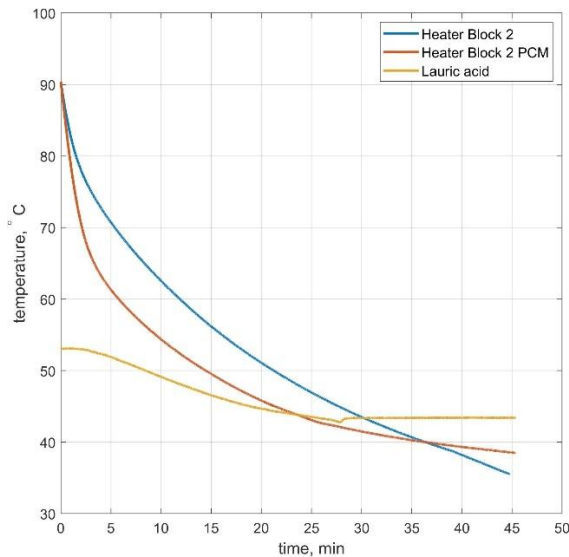


Fig. 12 Temperature variations of heater block for cooldown from 90°C. Results for lauric acid are presented on the left and for soy wax on the right.

It is visible that in all cases presence of PCM increased the final temperature of the heaters after 45 min. of cooling. Heater block with lauric acid experienced final temperatures 4.5°C, 4.4°C, and 2.6°C higher than unit without PCM. The impact of the material on the temperature evolution was clearly visible. In the beginning, it caused the heater block to quickly reduce its temperature, and then PCM slowed down the cooldown significantly during the solidification process. Less impact on the final temperature was noticeable when the cooling process was recorded from 90°C, because the phase change started near the end of the measurements. In addition, lauric acid started cooling down at a much lower temperature than the heater block. This caused the heater block to dissipate heat much faster than without the PCM, which is visible in Fig. 12. For soy wax, no single clear phase change temperature was observed due to the broad melt range of the material. However, at around 45°C the temperature curve for the PCM became nearly isothermal for a short time (visible in Fig. 11), meaning that temperature was probably the peak of the phase change process. Final temperatures for test rig with soy wax were 3.3°C, 4.05°C, and 4.8°C higher than for HP without LHTES at adiabatic section. The results were comparable with those of lauric acid, and in fact, soy wax performed even better in terms of increasing the final temperature during cooldown from 90°C. This was a result of its higher initial temperature, which didn't cause a rapid cooldown as in case of lauric acid.

The experiments showed the great potential of both materials to reduce temperature amplitudes in the system by increasing minimum temperatures during the cold case and reducing maximum temperatures during the hot case, acting as good thermal stabilizers for the TMS.

### 5.3. Thermal cycling

To simulate the real operation of an electronic device, a thermal cycling test was performed to investigate PCM's impact on periodic heating-cooling cycles. The reduction of peak-valley difference was the main goal of the experiments, as previous tests showed the ability of LHTES to reduce temperature amplitudes and therefore decrease thermal stresses in the device. The test procedure was initiated by turning on the heaters with power set to 30W for 1h 15min. After this, three cycles of 30 min. of cooling and 30 min. of heating with the same power level were recorded. Both PCMs temperatures were also monitored during the whole duration of the tests. The temperature variation curves are shown in Fig. 13. A reference HP was also used in the experiment to compare the temperature amplitude in the system without LHTES.

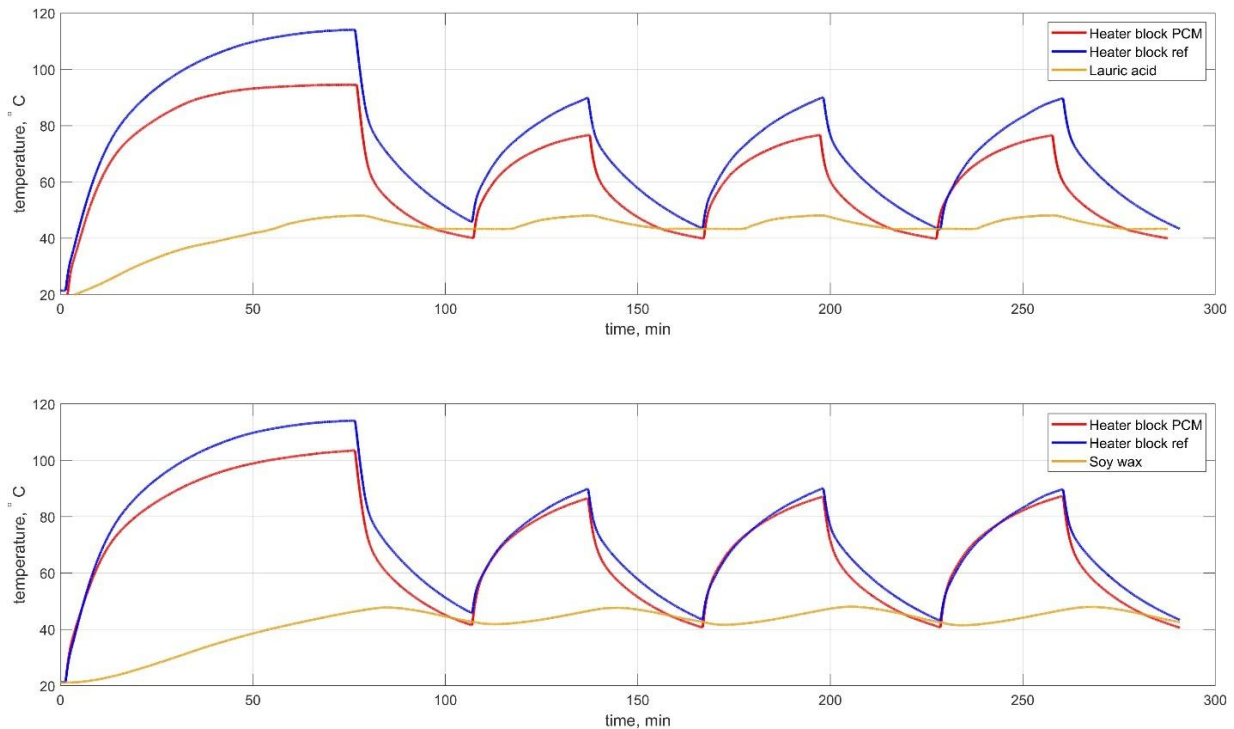


Fig. 13 Recorded temperatures of heater blocks and phase change materials during periodic operation. Lauric acid performance (top) was significantly better than soy wax (bottom) in considered conditions.

From the graph presented in Fig. 13, there is a clearly visible a significant influence of lauric acid on the peak-valley temperature difference during the periodic operation of the device. For lauric acid, the mean  $\Delta T$  (excluding the initial heating step) was around  $36^{\circ}\text{C}$ . In addition, phase changes with near-isothermal behavior are visible on PCM's temperature graph. For the soy wax, the average amplitude was higher, about  $42^{\circ}\text{C}$ . Similarly to previous measurements, there was no sharp melting temperature for this material. The reference HP difference between the maximum and minimum points was equal to  $48^{\circ}\text{C}$ , which means that lauric acid performed substantially better than soy wax, however, the utilization of the second still improved the overall thermal performance of the unit. Tab. 4 summarizes the results obtained from the cycling test.

Tab. 4. Mean temperature difference during cycling operation of the cooling unit with percentage of  $\Delta T$  reduction in comparison to reference HP.

	Mean peak-valley $\Delta T$	Improvement relative to reference
Reference test rig	$48^{\circ}\text{C}$	$0\%$
Lauric acid test rig	$36^{\circ}\text{C}$	$25\%$
Soy wax test rig	$42^{\circ}\text{C}$	$12\%$

## 6. Conclusions

The presented study experimentally evaluated the thermal performance of HPs assisted by lauric acid or soy wax for electronics cooling. The application of both materials significantly enhanced the cooling performance and temperature stabilization capabilities of the cooling unit. Lauric acid and soy wax proved to be able to slow down the temperature rise of heated components, reducing the thermal loads and ensuring safe operation of electronic devices. In addition, both PCMs were able to reduce temperature amplitudes during simulated real-life operation of a component, therefore decreasing thermal stresses and prolonging lifetime of a unit. It was shown that lauric acid performs around two times better than soy wax in terms of maximum temperature reduction and decrease of peak-valley temperature difference during cycling operation. Moreover, lauric acid stored around 25% of the total energy dissipated in the tests, with soy wax absorbing 14%. Furthermore, soy wax poor thermal conductivity should be addressed by the introduction of additional fins, metallic foams, or foil inside the PCMs container to prevent the formation of an overheated liquid reservoir surrounded by a solid phase. However, besides its downsides, soy wax is 14 times cheaper than pure lauric acid, and it's a sustainable and renewable material. This in turn suggests that for less demanding applications soy wax could be implemented as a cheaper LHTES alternative.

## References

- [1] Moore, A.L., Shi, L., 2014. "Emerging challenges and materials for thermal management of electronics." *Materials Today*. <https://doi.org/10.1016/j.mattod.2014.04.003>
- [2] Garimella, S.V., et al., 2008. "Thermal Challenges in Next-Generation Electronic Systems." *IEEE Trans. Comp. Packag. Technol.* <https://doi.org/10.1109/tcapt.2008.2001197>
- [3] Y.A. Cengel, A.J. Ghajar, *Heat And Mass Transfer: Fundamentals And Applications*. 5/e: McGraw-Hill Education, 2015
- [4] S. Anandan Shanmuga and V. Ramalingam, "Thermal management of electronics: A review of literature," *Thermal Science*, vol. 12, no. 2. National Library of Serbia, pp. 5–26, 2008. doi: 10.2298/tsci0802005a.
- [5] M. Motevalizadeh, et al., "Cooling enhancement of portable computers processor by a heat pipe assisted with phase change materials," *Journal of Energy Storage*, vol. 56. Elsevier BV, p. 106074, Dec. 2022. doi: 10.1016/j.est.2022.106074.
- [6] Dunn, P., & Reay, D. A. (2014). "Heat Pipes Sixth Edition", Butterworth Heinemann.
- [7] Z. G. Qu, et al., "Passive thermal management using metal foam saturated with phase change material in a heat sink," *International Communications in Heat and Mass Transfer*, vol. 39, no. 10. Elsevier BV, pp. 1546–1549, Dec. 2012. doi: 10.1016/j.icheatmasstransfer.2012.09.001.
- [8] Mahdavi, Mahboobe, Saeed Tiari, and Songgang Qiu. "Numerical Investigation of the effect of adiabatic section location on thermal performance of a heat pipe network with the application in thermal energy storage systems." *APS Division of Fluid Dynamics Meeting Abstracts*. 2015.
- [9] M. Jaworski, "Thermal performance of heat spreader for electronics cooling with incorporated phase change material," *Applied Thermal Engineering*, vol. 35. Elsevier BV, pp. 212–219, Mar. 2012. doi: 10.1016/j.applthermaleng.2011.10.036.
- [10] E. M. Alawadhi and C. H. Amon, "PCM thermal control unit for portable electronic devices: experimental and numerical studies," *IEEE Transactions on Components and Packaging Technologies*, vol. 26, no. 1. Institute of Electrical and Electronics Engineers (IEEE), pp. 116–125, Mar. 2003. doi: 10.1109/tcapt.2003.811480.
- [11] X.-H. Yang, S.-C. Tan, Z.-Z. He, and J. Liu, "Finned heat pipe assisted low melting point metal PCM heat sink against extremely high power thermal shock," *Energy Conversion and Management*, vol. 160. Elsevier BV, pp. 467–476, Mar. 2018. doi: 10.1016/j.enconman.2018.01.056.
- [12] A. S. Fleischer, *Thermal Energy Storage Using Phase Change Materials*. Springer International Publishing, 2015. doi: 10.1007/978-3-319-20922-7.
- [13] G. Setoh, F. L. Tan, and S. C. Fok, "Experimental studies on the use of a phase change material for cooling mobile phones," *International Communications in Heat and Mass Transfer*, vol. 37, no. 9. Elsevier BV, pp. 1403–1410, Nov. 2010. doi: 10.1016/j.icheatmasstransfer.2010.07.013.
- [14] M. Fabrykiewicz and J. T. Cieśliński, "Thermal energy storage using stearic acid as PCM material," *Journal of Mechanical and Energy Engineering*, vol. 2, no. 3. Politechnika Koszalin, pp. 217–224, Dec. 06, 2018. doi: 10.30464/jmee.2018.2.3.217.
- [15] Z. Arifin et al., "The Effect of Soybean Wax as a Phase Change Material on the Cooling Performance of Photovoltaic Solar Panel," *International Journal of Heat and Technology*, vol. 40, no. 1. International Information and Engineering Technology Association, pp. 326–332, Feb. 28, 2022. doi: 10.18280/ijht.400139.
- [16] K. Y. Leong, S. P. Chew, B. A. Gurunathan, K. Z. Ku Ahmad, and H. C. Ong, "An experimental approach to investigate thermal performance of paraffin wax and 1-hexadecanol based heat sinks for cooling of electronic system," *International Communications in Heat and Mass Transfer*, vol. 109. Elsevier BV, p. 104365, Dec. 2019. doi: 10.1016/j.icheatmasstransfer.2019.104365.
- [17] M. A. Hayat, H. M. Ali, M. M. Janjua, W. Pao, C. Li, and M. Alizadeh, "Phase change material/heat pipe and Copper foam-based heat sinks for thermal management of electronic systems," *Journal of Energy Storage*, vol. 32. Elsevier BV, p. 101971, Dec. 2020. doi: 10.1016/j.est.2020.101971.
- [18] CP Tso, FL Tan, J Jony, Transient and cyclic effects on a pcm-cooled mobile device, *Therm. Sci.* 19 (2015) 1723–1731, <https://doi.org/10.2298/TSCI121206112T>.
- [19] S. S. Chougule and S. K. Sahu, "Thermal Performance of Nanofluid Charged Heat Pipe With Phase Change Material for Electronics Cooling," *Journal of Electronic Packaging*, vol. 137, no. 2. ASME International, Jun. 01, 2015. doi: 10.1115/1.4028994.
- [20] Y.-C. Weng, H.-P. Cho, C.-C. Chang, and S.-L. Chen, "Heat pipe with PCM for electronic cooling," *Applied Energy*, vol. 88, no. 5. Elsevier BV, pp. 1825–1833, May 2011. doi: 10.1016/j.apenergy.2010.12.004.
- [21] J. Krishna, P. S. Kishore, and A. B. Solomon, "Heat pipe with nano enhanced-PCM for electronic cooling application," *Experimental Thermal and Fluid Science*, vol. 81. Elsevier BV, pp. 84–92, Feb. 2017. doi: 10.1016/j.expthermflusci.2016.10.014.ra
- [22] I. Zahid et al., "Thermal Performance Analysis of Various Heat Sinks Based on Alumina NePCM for Passive Cooling of Electronic Components: An Experimental Study," *Energies*, vol. 15, no. 22. MDPI AG, p. 8416, Nov. 10, 2022. doi: 10.3390/en15228416.
- [23] A. Sari and A. Karaipekli, "Thermal conductivity and latent heat thermal energy storage characteristics of paraffin/expanded graphite composite as phase change material," *Applied Thermal Engineering*, vol. 27, no. 8–9. Elsevier BV, pp. 1271–1277, Jun. 2007. doi: 10.1016/j.applthermaleng.2006.11.004.
- [24] L. Desgrosseilliers, C. A. Whitman, D. Groulx, and M. A. White, "Dodecanoic acid as a promising phase-change material for thermal energy storage," *Applied Thermal Engineering*, vol. 53, no. 1. Elsevier BV, pp. 37–41, Apr. 2013. doi: 10.1016/j.applthermaleng.2012.12.031.