

Beeswax And Palmitic Acid Utilization With Heat Pipes For Electronics Cooling

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Abstract

This paper presents an experimental study of heat pipes supported by phase change materials (PCMs) coated at their adiabatic sections in application for electronics cooling. The PCMs investigated in this research were palmitic acid and beeswax, the latter being considered as a more cost-effective alternative. The study focused on three powers: 20W, 25W, and 30W. The experimental results revealed that the incorporation of palmitic acid as a PCM led to a reduction in component's maximum temperature by 13.3%, 12.6%, and 11.8% for the respective powers. Utilization of beeswax resulted in temperature reductions of 5%, 5.2%, and 8.4%. Notably, for higher heat flux conditions, the influence of beeswax on temperature control was comparable to that of palmitic acid. Furthermore, beeswax demonstrated a significantly higher capability to mitigate temperature decrease during cooldown, serving as a superior measure against overcooling. Moreover, during the thermal cycling scenario considered in this study, beeswax reduced the peak-valley temperature by 25%, while palmitic acid achieved a reduction of 14.6%. These findings suggest that beeswax has the potential to serve as an alternative to traditional organic PCMs in electronics cooling applications that utilize heat pipes.

Keywords: electronics cooling; phase change materials; heat pipe; advanced energy materials; energy storage;

Nomenclature

Abbreviations

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

Symbols

C	specific heat at constant pressure, $\text{J g}^{-1} \text{ } ^\circ\text{C}^{-1}$
L_H	heat of phase transition, J g^{-1}
m	mass, g
Q	heat, J
T	temperature, $^\circ\text{C}$

Subscripts

s	starting point
e	end point
c	condenser
L	loss

1. Introduction

The electronic components in modern devices offer high computational capabilities but, in turn, require large power inputs [1]. This consequently creates significant challenges for the thermal management of microprocessors. In fact, often the self-heating due to Joule-Lenz law becomes a bottleneck to the performance and reliability of computing units [3].

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Furthermore, operation at elevated temperatures and regular changes in the unit's temperature generate thermal stresses, serving as a primary factor contributing to electronic component failures [4]. The significance of temperature control is rising, and thermal management systems (TMS) are gaining increased attention among industrial engineers and research groups worldwide [5]. Currently, the majority of TMS face notable challenges, including high energy consumption, limited space, and noise generation [6]. Consequently, there is a growing interest in passive, quiet, and compact solutions for thermal management of electronics.

Heat pipes (HP) are superior two-phase heat transfer devices widely used in many cooling applications [7]. They are completely passive devices, meaning they don't require an additional power source for operation. HPs offer numerous benefits, including low cost, excellent thermal conductivity, consistent performance, and minimal efficiency degradation even over extended time periods of exploitation [8]. They are widely used to transport heat to fan air-cooled heat sinks in applications such as PCs, radio receivers, or mobile devices. In many instances, the adiabatic section of the HP is situated within a confined space inside the device. This causes a portion of the energy transported through the pipe to be dissipated into the device, resulting in the reduction of the overall cooling effectiveness [9]. This issue should be addressed in order to improve the thermal performance of TMS and to utilize the waste heat generated by electronic components for stabilization of the thermal environment in which they operate.

The common thermal stabilization method is latent heat thermal energy storage (LHTES), which is achieved through the application of phase change materials (PCMs). Thermal management of electronic devices can certainly benefit from PCM utilization in TMS [10-11]. Thanks to the isothermal properties of the phase change processes, these materials can trap and store large amounts of heat with little or no increase in temperature [9]. This characteristic can be used to lower the maximum temperature of the electronic component and protect the device from overheating. Furthermore, the energy that is stored as the PCM undergoes melting is subsequently released when it solidifies. This mechanism serves to maintain the temperature of electronic components steady when there are variations in power usage and when the device operates periodically [13]. The majority of PCMs available on the market can fall into one of two categories: organic and inorganic materials. Organic PCMs are most commonly used due to their wide availability, low cost, and low handling hazard [14]. The most common are paraffins and fatty acids [15].

Fabrykiewicz et al. [16] experimentally verified the performance of stearic acid as a PCM. They studied both the charging and discharging of the PCM and the behavior of the heat flux transferred in the material during melting and solidification processes. Jaworski [9] investigated a heat sink dedicated to electronics cooling with lauric acid encapsulated within the fins. He concluded that PCM application significantly improves efficiency of heat rejection from electronic chips. Kandasamy et al. [17] developed and experimentally verified a heat sink for electronics thermal management which incorporated paraffin wax as a PCM. Obtained results indicated the potential of PCM-based heat sinks for utilization in intermittent-use devices. Krishnan et al. [18] described a concept for a plate-finned heat sink immersed in a PCM. They considered different paraffins: eicosane, heneicosane and Suntech P116 as PCMs. Based on the simulations, the hybrid heat sinks showed improved thermal performance when compared to traditional design without PCM. Sari and Kaygusuz [19] experimentally studied palmitic acid as a PCM for LHTES systems. They concluded that the PCM is useful for domestic applications with relatively high heat of phase transition and a suitable melting point of 61°C.

The limited thermal conductivity found in organic PCMs can significantly reduce their effectiveness in thermal applications [15]. Consequently, combining HPs with PCMs emerges as a highly promising path for advancing TMSs. As it was mentioned above, in most cases the adiabatic section of HP is exposed in a limited space inside of the device. Application of LHTES to this section would allow for most of the heat flux to be transferred to the main heat sink, while PCM could act as a secondary condenser or evaporator. Such an approach would minimize heat losses from the main heat path and allow to utilize of waste heat for the thermal stabilization of the unit.

Motevalizadeh et al. [6] developed a TMS for laptop cooling. As part of their work, three temperature control system configurations were investigated: a traditional system with an HP and a fan, a heat sink with a condenser section of the HP immersed in PCM, and a hybrid solution utilizing both a fan and a tank with PCM placed in the adiabatic section of the HP. Two paraffins: RT35 and RT42, were used as PCMs, and their impact on the cooling system parameters was subsequently compared. The experiments demonstrated the PCM's ability to reduce overall thermal loads in the system. Furthermore, it was shown that the use of a PCM with a lower melting point increases energy absorption efficiency. Zhuang et al. [20] developed a hybrid HP with an integrated tank installed on its adiabatic section, containing RT55 paraffin wax. It was demonstrated that increasing the volume of PCM positively influences the performance of the HP. The maximum temperature in the system was reduced by 9.31% compared to a system without PCM. Additionally, the device was shown to have the capability to counteract thermal shocks, and the conducted thermal cycles demonstrated a reduction in peak-to-valley temperature amplitudes, proving the PCM's ability to provide thermal stabilization. Krishna et al. [21] carried out experimental investigations involving various energy storage materials placed in the adiabatic section of an HP. The studied materials included water, tricosane, and tricosane with a 1% addition of Al₂O₃ nanoparticles. Forced convection heat transfer was employed to cool the condenser section. The findings of the study revealed that tricosane enhanced with nanoparticles exhibited the most favorable outcomes, achieving the greatest reduction in heater temperature when compared to a conventional HP. Putra et al. [22] studied experimentally passive cooling systems with PCM and HP

for batteries cooling. The researchers compared beeswax and Rubitherm RT 44 paraffin wax as PCMs. Based on their results, RT 44 appeared to be more effective in latent heat storage, due to its lower melting temperature.

The benefits of integrating HPs with PCMs to enhance electronic cooling are clearly visible. Nevertheless, the majority of presented studies relied on forced convection at the HPs condenser section, which requires additional energy and results in noise and vibration generation. In electronics cooling applications, there is a preference for passive thermal management systems [23]. Furthermore, there is a limited number of studies comprehensively addressing the cost-effectiveness of PCMs concerning their thermal performance. In addition, little attention is given to accessibility of a given PCM and its sustainability and toxicity.

In this paper, a comparative experimental investigation was performed for two PCMs: 99% pure palmitic acid, representing the more expensive choice, and beeswax, which presents itself as a potentially cost-effective, sustainable, and readily accessible alternative. Furthermore, the authors examined the thermal performance of a fully passive cooling system, employing natural convection in the condenser section of the HP.

2. Experimental set-up

In order to investigate the thermal performance of PCM-assisted HPs for electronics thermal management, the experimental setup was constructed. It consisted of three main sections, i.e. (I) heater block (HB) simulating hot electronic component; (II) thermal energy storage tank consisting of PCM container; (III) condenser with attached passive heat sink. All sections were connected by a copper HP utilizing water as a working fluid. The adiabatic part of the HP was embedded in PCM. The length of evaporator section was 50mm, the adiabatic section coated with PCM was 160mm long 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 is presented in Fig. 1. Three test rigs were constructed: two for testing palmitic acid and beeswax as PCMs, and one without energy storage tank, acting as a reference. The heater blocks were created from aluminum pieces with dimensions of 50mm x 50mm x 20mm. A $\Phi 6$ mm x 20mm cartridge heater was placed inside each block, followed by the application of thermally insulating cotton and 3D printed covers on the heating section to reduce heat loss to the surroundings. Electric power for heaters was provided by a programmable laboratory DC power supplier (model RS-D3305P). The LHTES tanks were made of glass. Their outside dimensions were 160mm x 110mm x 50mm with maximum capacity of 350ml. Aluminum finned heat sinks with dimensions of 100mm x 75mm x 45mm were attached at each condenser section. To assess thermal performance, temperature measurements were conducted using T-type thermocouples positioned at various points of the test rigs. In each heater block, two measurement points were located, one within the aluminum block and another on the surface of the HP. Additionally, two sensors were placed inside the PCM containers, with one on the HP and the other positioned directly within the PCM, approximately 10mm away from the adiabatic section. Furthermore, a single thermocouple was mounted to each condenser section. Temperature data was acquired using two PicoLog TC-08 data loggers connected to a PC. Based on in-house measurements and datasheets, the accuracy of the thermocouples was estimated to be $\pm 0.4^{\circ}\text{C}$ or $\pm 0.75\%$, whichever was greater.

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

Manufacturer	<i>Quick-cool®</i>
Type	<i>Copper- water</i>
External diameter	<i>6mm</i>
Length	<i>400mm</i>
Working temperature 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>

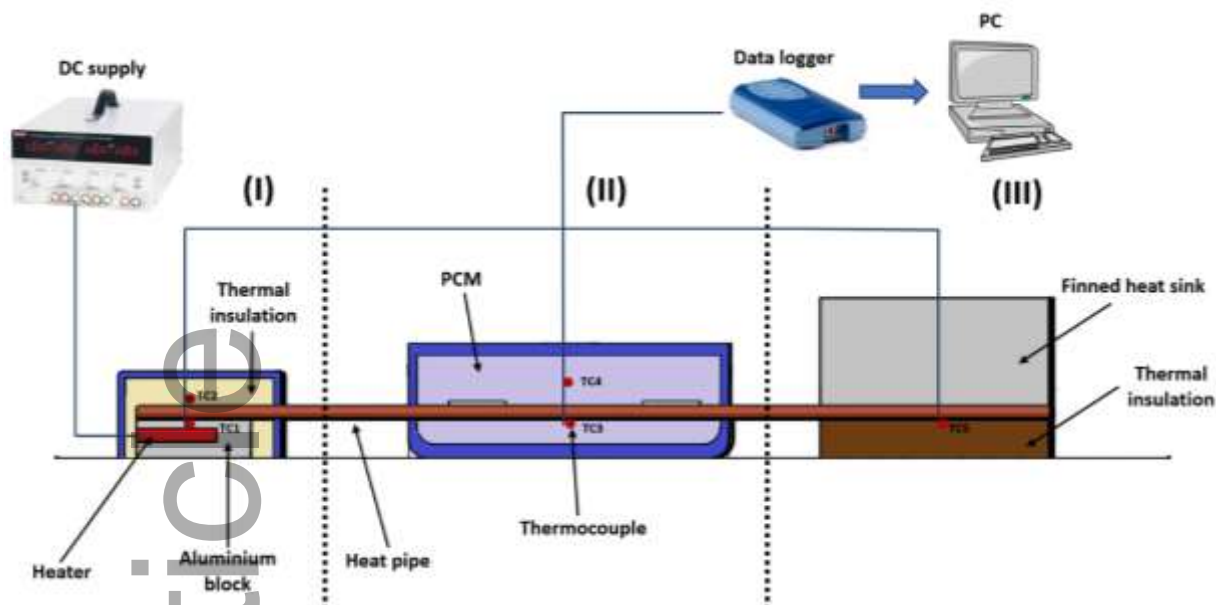


Fig. 1. Schematic of the experimental apparatus with location of thermocouples and division into three thermodynamic sections.

The test rigs were mounted on a wooden plate for thermal insulation and secured in place by screws. All potential sources of heat losses were covered with thermally insulating cotton. To enhance heat transfer within the PCM, it was determined that two rectangular aluminum fins, measuring 60 mm x 20 mm, would be attached to the adiabatic sections of HPs embedded with palmitic acid and beeswax. Fig 2. shows the LHTES container with fins mounted to the HP. The perforations in the glass containers were sealed with silicone. Fig. 3 presents the assembled experimental system after pouring PCMs into LHTES containers. Furthermore, to enhance the thermal performance of the system, thermally conductive paste with a thermal conductivity of $3.8 \text{ W m}^{-1} \text{ }^\circ\text{C}^{-1}$ was applied to all metal-to-metal contacts within the system.



Fig. 2. Aluminum fins added inside PCM container.

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Fig. 3. The experimental stand for investigating PCM-assisted HPs for electronics cooling.

3. Phase change materials

3.1. Properties of selected PCMs

To ensure reliable operation and lifetime, it is recommended that electronic components should not exceed a typical maximum operating temperature of 85°C [24]. Hence, the chosen PCMs had to possess melting points significantly lower than this temperature. Palmitic acid is a fatty acid ($\text{C}_{15}\text{H}_{31}\text{COOH}$) with documented successful attempts of implementation in a role of LHTES [19]. Its typical melting temperature range falls between $59.9^{\circ}\text{C} - 64.2^{\circ}\text{C}$ [25]. The material used was 99% chemically pure and was purchased from a manufacturer. This article suggests an alternative to palmitic acid, which is a yellow beeswax. Beeswax is a natural wax produced by bee colonies, making it an entirely renewable material with an eco-friendly and sustainable production process. Furthermore, this PCM is easily available to purchase in the commercial market and is more cost-effective than palmitic acid. Nevertheless, it consists of a mixture of various organic compounds, and there is limited available data regarding its thermophysical properties. To assess these properties, a differential scanning calorimetry (DSC) was employed. The device used was a calorimeter DSC 822e manufactured by Mettler-Toledo. The obtained temperature melting range for beeswax was $42.5^{\circ}\text{C} - 67.6^{\circ}\text{C}$ which was much broader than that of palmitic acid, due to more complex chemical composition of beeswax.

Tab. 2 summarizes the most important thermophysical properties of both PCMs used in this study. In addition, the costs of obtaining 500 grams of both materials were also provided for comparison.

Tab. 2. Thermophysical properties of palmitic acid [25, 26] and beeswax.

Properties of PCMs used in the study		
	Palmitic acid	Beeswax
Melting range, $^{\circ}\text{C}$	59.9 – 64.2	42.5 – 67.6
Heat of phase transition, J g^{-1}	208	168
Specific heat at constant pressure of solid, $\text{J g}^{-1} \text{ } ^{\circ}\text{C}^{-1}$	2.2	2.47
Specific heat at constant pressure of liquid, $\text{J g}^{-1} \text{ } ^{\circ}\text{C}^{-1}$	2.48	2.05
Cost per 500g, €	30	10

Based on Tab 2. it is apparent that beeswax is approximately three times cheaper than chemically pure palmitic acid. Additionally, beeswax has a lower initial melting point. However, palmitic acid is characterized by a greater heat of phase transition during the phase change process. On the other hand, beeswax undergoes phase change over a broader temperature range, potentially enhancing the cooling unit's performance for an extended time. Based on just the thermal properties of the considered PCMs it is unclear which material is more suitable for the TMS in electronics cooling. Therefore, it was decided to conduct a comparative study of these two materials to assess their impact on the operation of an HP with a passive heat exchanger.

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3.2. PCMs energy storage

In order to characterize the energy absorption by PCMs during the tests, energy balance equations were formulated for both palmitic acid and beeswax. The following relationship between the heat stored within the PCM and temperature was employed:

$$Q_{PCM} = \begin{cases} mC_{solid}\Delta T & \text{for } T < T_{m,s} \\ mL_H & \text{for } T_{m,s} < T < T_{m,e} \\ mC_{liquid}\Delta T & \text{for } T_{m,e} < T \end{cases} \quad (1)$$

where: m - mass of the PCM; C_{solid} - specific heat at constant pressure in solid state; ΔT - temperature difference; $T_{m,s}$ - initial temperature of the melting process; L_H - heat of phase transition; $T_{m,e}$ - end temperature of melting process; C_{liquid} - sensible specific heat at constant pressure in liquid state.

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

$$Q_{heater} = Q_C + Q_{PCM} + Q_L \quad (2)$$

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 surroundings.

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

4. Experimental procedure

4.1. Preliminary tests

Prior to filling the containers with palmitic acid and beeswax, measurements were conducted using all three test rigs to assess and compare their thermal performance. This step held significant importance due to the different temperature gradients observed between the evaporators and condensers of all three HPs, despite their common origin. The outcomes of these measurements are depicted in Figure 4. These differences become more visible with higher power inputs. As a result, the authors propose that subtle variations in the thermal resistance of the HPs and potential manufacturing discrepancies are responsible for this behavior. Furthermore, the energy dissipation at the condenser sections occurred passively, relying solely on natural convection, which is temperature-dependent. Consequently, the initial differences in temperature distributions within the system, caused by minor differences in HP properties, could potentially be magnified by the passive and self-regulating characteristics of the proposed cooling systems.

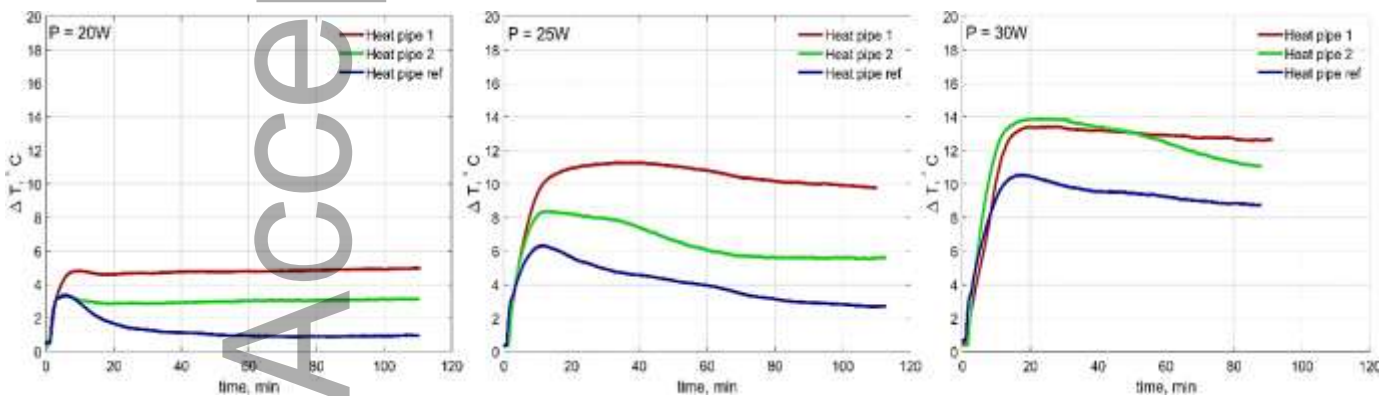


Fig. 4. Temperature difference between evaporator and condenser temperature for three HP used in the study, at different heating power.

4.2. Test procedure

After conducting the initial measurements, the PCMs were melted and poured into glass containers, with both tanks being filled to a volume of 230ml. Precise dispensing of the PCM volume was achieved using a laboratory syringe.

The HPs exhibited varying thermal performance, resulting in different temperature distributions within the testing setups. To perform a comparative study of PCMs impact on heat exchange, direct comparisons between the experimental setups were abandoned as not representative. Instead, the thermal performance of each test setup was initially assessed

without the PCM, followed by a repetition of all tests with the energy storage tanks filled. This approach allowed for a relative assessment of the improvement achieved with the beeswax and palmitic acid.

The initial phase of the experiments focused on evaluating the impact of LHTES on the steady-state temperature reached by the system. Three different heating powers: 20W, 25W, and 30W were studied. Subsequently, temperature profiles during the cooldown phase from initial temperatures of 65°C, 70°C, and 90°C during 45 min. were recorded and compared. Finally, thermal cycling was carried out to simulate real-life operating conditions of electronic devices. The reference HP was utilized in this last experiment, as the evaluation of results involved relative quantities between the test setups.

5. Results and discussion

5.1. Heating tests

Figures 5-7 show temperature curves recorded for HBs, which simulated electronic components. Across all examined power dissipation levels, there is a noticeable decrease in the maximum temperature reached by the cooling module in steady-state after the application of both PCMs.

In the test setup utilized to evaluate palmitic acid, before its introduction into the container, the steady-state temperatures of the HB were: 78°C, 98°C, and 119°C for powers of 20W, 25W, and 30W, respectively. In the configuration designed for beeswax, the HBs maximum temperatures without the energy storage tank were 72.5°C, 83.7°C, and 101°C for the same corresponding powers. After introducing the PCMs into the systems, the maximum temperatures of the HB exhibited the following values: 68°C, 85.7°C, and 107.8°C for palmitic acid, and 68.8°C, 79.5°C, and 93°C for beeswax.

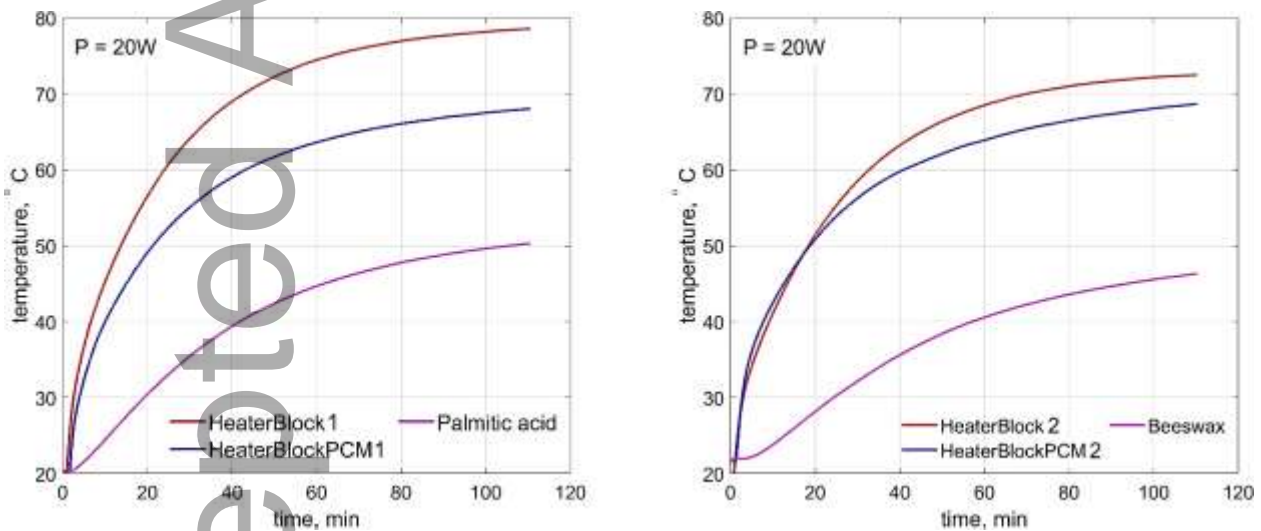


Fig. 5. Temperature variations of heater block for 20W of power. Curve for palmitic acid is presented on the left and for beeswax on the right.

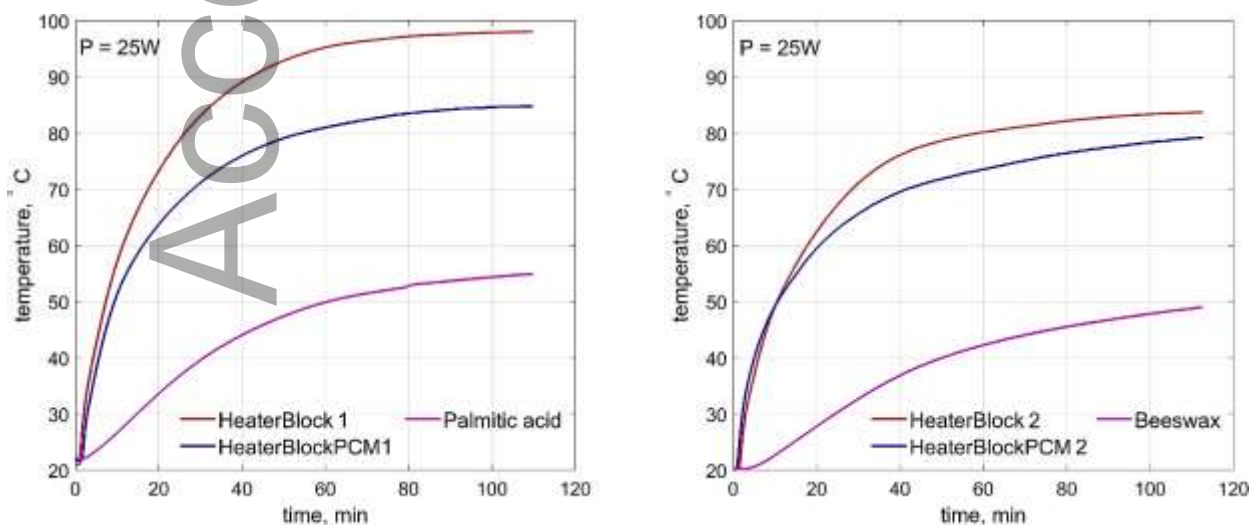


Fig. 6 Temperature variations of heater block for 25W of power. Curve for palmitic acid is presented on the left and for beeswax on the right.

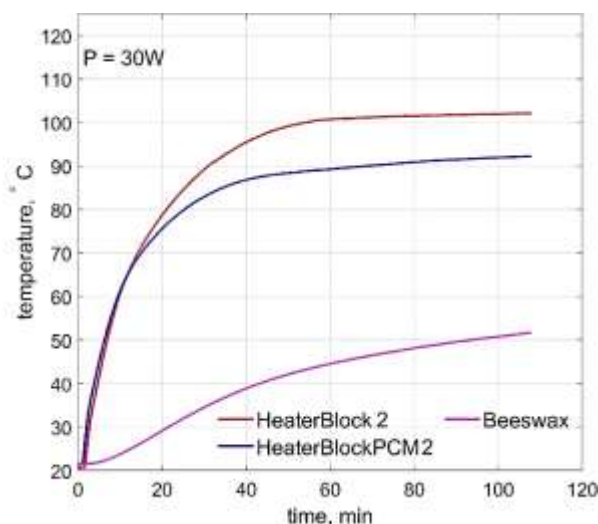
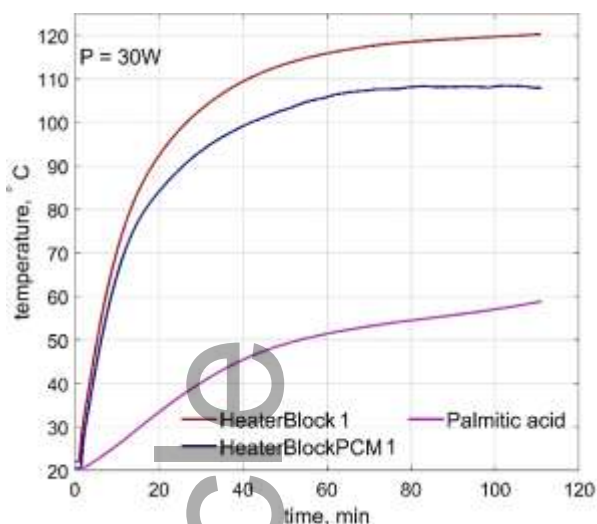


Fig. 7 Temperature variations of heater block for 30W of power. Curve for palmitic acid is presented on the left and for beeswax on the right.

Fig. 8 provides a comparative analysis of the maximum temperature reduction achieved in the cooled component when both PCMs were used. The bar graphs displayed in the left column represent this reduction as a percentage of the maximum heater block temperature, while the corresponding temperature differences in degrees Celsius are presented in the right column. This dual representation allows for a direct assessment of the maximum temperature decrease resulting from the implementation of the PCMs and their relative influence on the respective experimental setups. In most of the experiments, the influence of palmitic acid exceeded that of beeswax. For instance, at a heating power of 20W, palmitic acid lowered the maximum temperature by 10.5°C (13.3%), while beeswax achieved a reduction of 3.7°C (5%). At 25W, the reductions were 12.4°C (12.6%) for palmitic acid and 4.2°C (5.2%) for beeswax, respectively. However, at 30W, beeswax demonstrated a comparable impact to palmitic acid, particularly in terms of their relative influence on the heat exchangers. Here, the fatty acid reduced the maximum temperature by 11.8°C (9.85%), and beeswax achieved a reduction of 8.6°C (8.4%).

This increased influence of beeswax at higher power dissipation levels was caused by the intensification of the phase change process within the material. At lower heating powers, palmitic acid exhibited a faster and more uniform melting process, facilitating effective energy storage as heat of phase transition. On the other hand, beeswax was going through the phase change at a slower rate and not uniformly within its volume. Therefore, at heating powers below 30W, the wax predominantly stored energy as specific heat at constant pressure. However, an increase in input power enabled more efficient energy storage as heat of phase transition.

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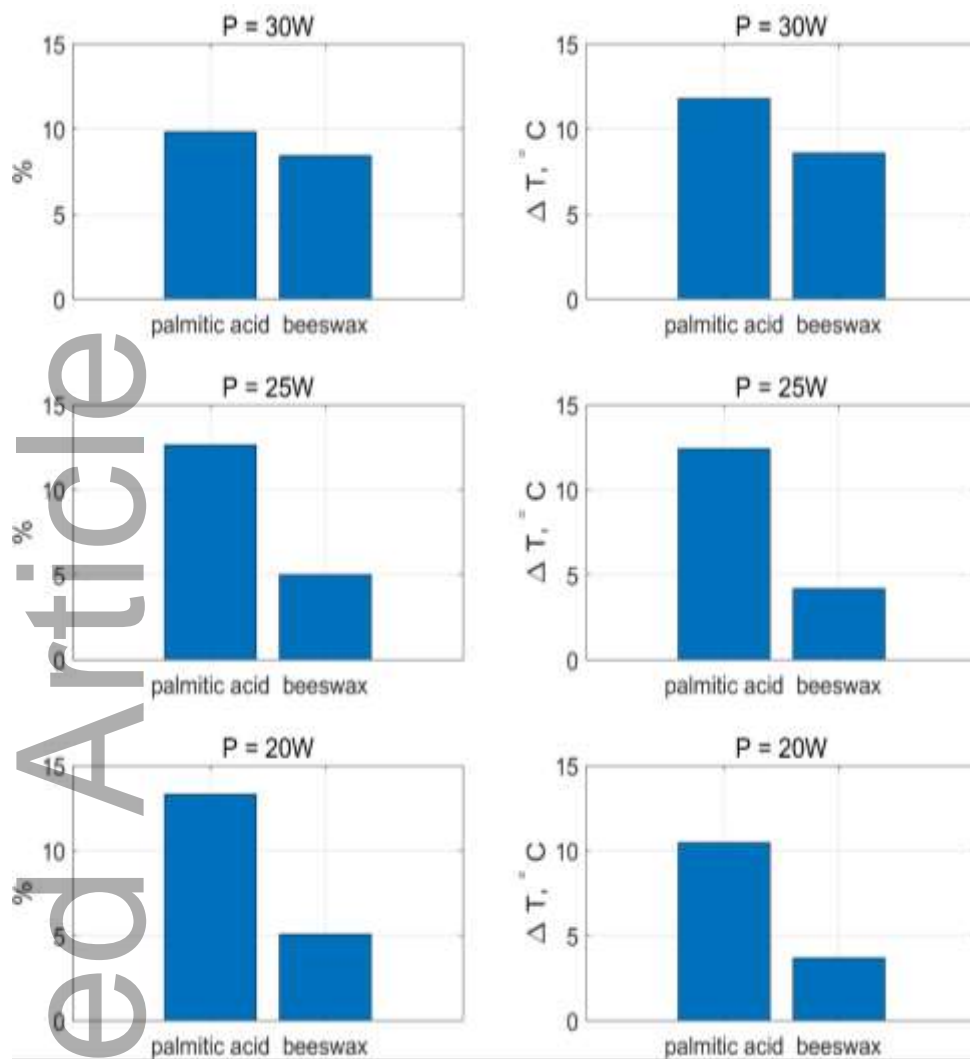


Fig. 8. Graphs showing the impact of both PCMS on the heat exchanger performance after their introduction to the system. Graphs on the left side represent the heater's temperature decrease as percentage of the maximum value, and the bars on the right side show the absolute value of temperature difference in Celsius.

Moreover, as one can observe in Fig. 5-7 the overall temperatures in the test rig for beeswax were lower than in the one for palmitic acid, therefore the melting processes in the second test rig were generally slower. However, the performed experiments clearly showed that both organic PCMs have a positive impact on the maximum temperature in the system, reducing its value. For higher heat fluxes, the relative influence of beeswax was even comparable with pure and more expensive palmitic acid. This finding highlights the practical significance of beeswax as an effective alternative for temperature control and heat management.

5.2. LHTES discharge

After achieving steady-state conditions, the heaters were turned off, and the temperatures of the HBs were monitored during the discharge of the PCMs. To assess the cooldown behavior under various conditions, temperature curves were obtained starting from three distinct initial temperatures: 65°C, 70°C, and 90°C.

Figures 10-12 illustrate the cooldown process for HBs within the experimental setups utilizing palmitic acid and beeswax. These temperature profiles were then compared with measurements taken under identical conditions when the LHTES tanks were empty.

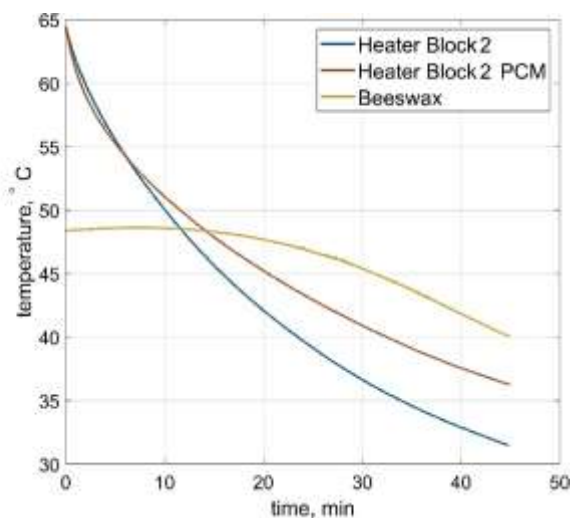
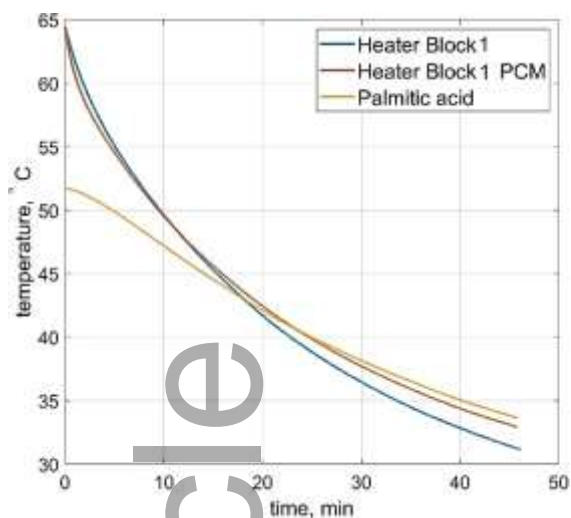


Fig. 9 Temperature variations of heater block for cooldown from 65°C. Results for palmitic acid are presented on the left and for beeswax on the right.

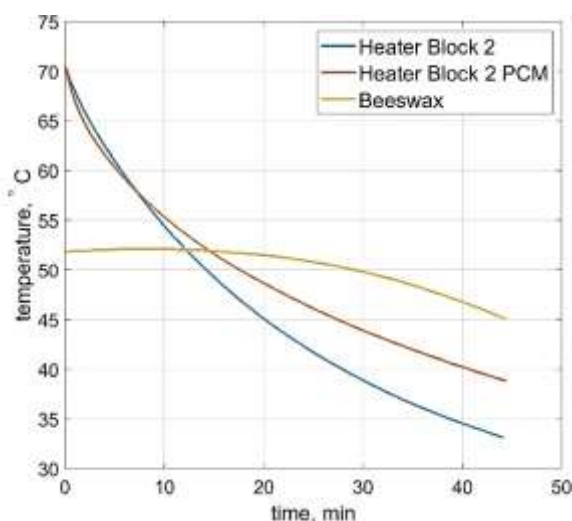
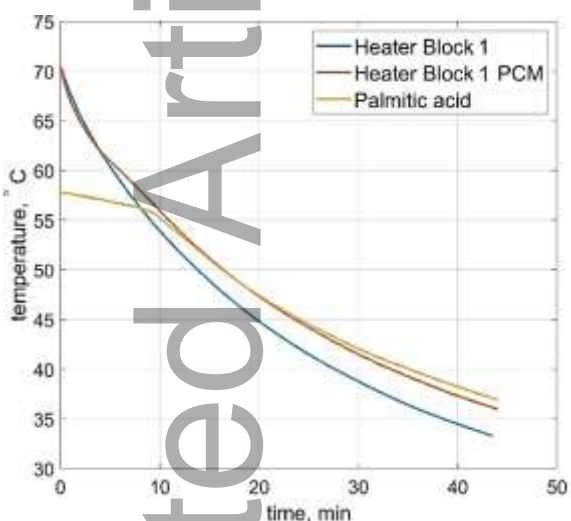


Fig. 10 Temperature variations of heater block for cooldown from 70°C. Results for palmitic acid are presented on the left and for beeswax on the right.

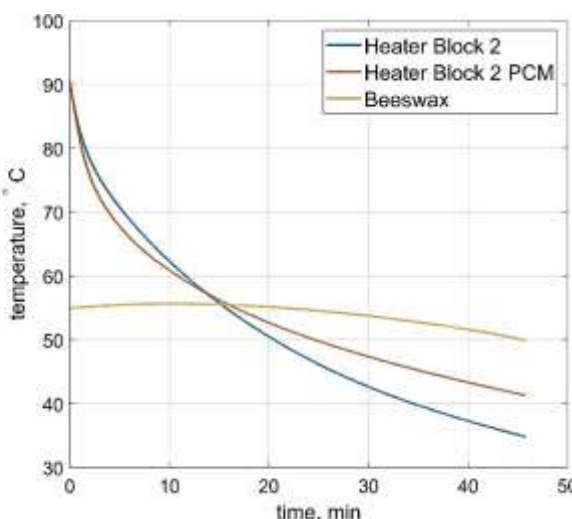
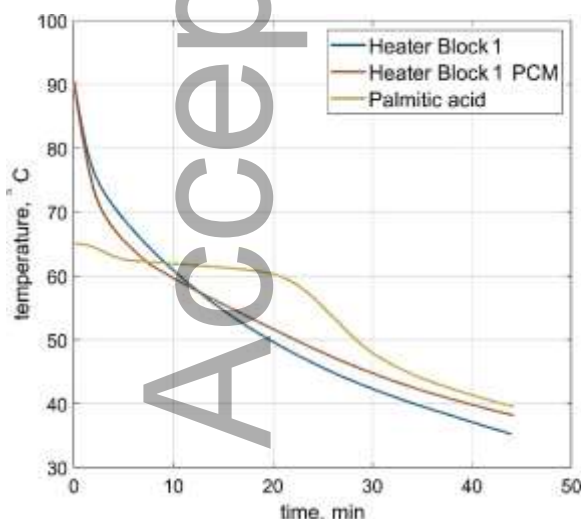


Fig. 11 Temperature variations of heater block for cooldown from 90°C. Results for palmitic acid are presented on the left and for beeswax on the right.

It is visible that in all cases presence of PCM increased the final temperature of the heaters after 45 minutes of cooling. Specifically, the HBs of the units containing palmitic acid registered final temperatures that were 2.5°C, 3.2°C, and 3.6°C higher than those without PCM. In contrast, when beeswax was employed, the final temperatures exhibited a more significant increase, measuring 4.6°C, 6.1°C, and 6.7°C higher than those in the empty LHTES tank. This observation shows that beeswax is a material with a considerably greater capacity for reducing the cooldown rate compared to palmitic

acid. In authors' opinion, this behavior was caused by lower thermal conductivity of beeswax and slower heat transfer rate in the material. Recorded cooldown curves in Fig. 10-12 illustrated that beeswax's temperature exhibited a delayed response to the deactivation of the heater. Beeswax temperature was not reacting for around 10 minutes before it started to fall, for all considered initial conditions. Palmitic acid exhibited a clear phase change around 60°C in Fig.12 which can be observed as near isothermal behavior of its temperature. Such phenomena was not noticeable in beeswax case, possibly due to much broader range of the phase change temperatures in the material and its lower heat transfer rate.

Performed experiments demonstrated the potential of both PCMs to reduce the cooldown rate of the cooled component, offering means to mitigate the risk of overcooling electronic devices. Furthermore, beeswax exhibited a superior capability in slowing down the temperature decrease compared to palmitic acid.

5.3. Thermal cycling tests

To simulate the real-life operation of an electronic device, a thermal cycling test was conducted to assess the influence of PCMs on periodic heating and cooling cycles. The primary objective of these experiments was to reduce the peak-to-valley temperature differences. Previous tests indicated the potential of LHTES to decrease temperature fluctuations, which is crucial for reducing the thermal stresses within the device. The test procedure started with turning on the heaters at a power setting of 30W for a duration of 1h 15 min. Following this initial phase, three cycles of 30 min. of cooling and 30 min. of heating, both at the same powers, were recorded. Throughout the entire duration of the tests, the temperatures of both PCMs were continuously monitored. The temperature variation curves are presented in Fig. 13. Additionally, a reference heat pipe was employed in the experiment to provide a reference for comparing temperature amplitudes in a stand operating without any PCMs.

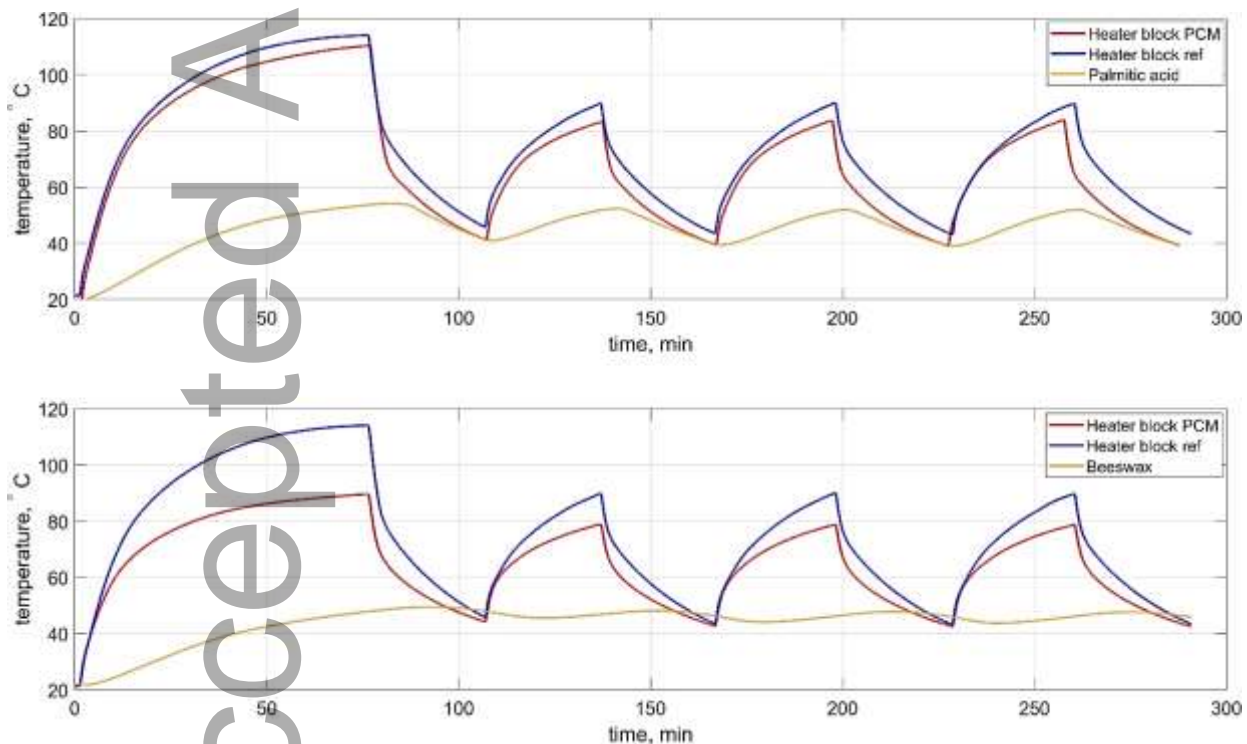


Fig. 12 Recorded temperatures of heater blocks and PCMs during periodic operation. Beeswax performance (bottom) was better than palmitic acid (top) in considered experimental conditions.

Observations of periodic operation showed a significant impact of beeswax on the peak-valley temperature difference. The mean ΔT (excluding the initial heating step) was around 36°C in comparison to 48°C obtained for the reference test stand without any PCM employed. It should be emphasized that temperature characteristics obtained from the graphs presented in Fig. 13 should not be directly compared due to differences in the operating parameters of the HPs used. However, it was possible to compare the temperature amplitudes achieved during the cyclic operation of heating blocks. Palmitic acid also exhibited a reduction in peak-to-valley temperature, although it was slightly lower than that achieved with beeswax, with a mean value of approximately 41°C. Tab. 3 summarizes temperature amplitudes obtained during these tests.

The excellent performance of beeswax can be explained by its superior capability for slowing down the temperature decrease as it was established in paragraph 5.2. In Fig. 13 the temperature graph of beeswax shows a noticeable delay in response to the heater's activation and deactivation. Moreover, palmitic acid did not reach its initial melting temperature during the investigated cycles, so during the experiment, no isothermal processes were occurring in it. Combination of these factors caused beeswax to exhibit a better performance than palmitic acid in a considered scenario. These results

highlight the potential of beeswax as a viable and cost-effective alternative to traditional PCMs, particularly in specific applications.

Tab. 3. Mean temperature difference during cycling operation of the cooling unit with percentage of ΔT reduction in relation to reference HP.

	Mean peak-valley ΔT	Improvement relative to reference
Reference test rig	48 °C	0%
Palmitic acid test rig	41 °C	14.6%
Beeswax test rig	36 °C	25%

6. Conclusions

This paper presents an experimental study of the thermal performance of HPs supported by either palmitic acid or beeswax for the application of electronic cooling. The impact of both materials on cooling efficiency and temperature stabilization capabilities was compared. The results demonstrated that both PCMs can reduce the rate of temperature increase in heated components, thereby reducing thermal loads and ensuring the safe operation of electronic devices. In addition, both PCMs exhibited the capacity to reduce temperature fluctuations during simulated real-life operation of electronic components, consequently reducing thermal stresses and extending the operational lifespan of these devices.

In terms of maximum temperature reduction, palmitic acid demonstrated superior performance in comparison to beeswax. However, the latter exhibited a comparable influence to palmitic acid at higher heat flux levels (30W). Moreover, beeswax showed a greater capability of delaying the temperature decrease during cooldown. In considered thermal cycling scenario beeswax outperformed palmitic acid in the context of reducing peak-to-valley temperature variations. The findings presented in this paper suggest that beeswax can serve as an environmentally sustainable and cost-effective alternative to traditional organic PCMs.

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This paper presents an experimental study of Heat Pipes supported by different Phase Change Materials coated at their adiabatic sections in application for electronics cooling. The experimental results revealed that the incorporation of PCM led to significant reduction in component's maximum temperature for the respective powers.



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