



Article

The Effect of Arachidic Acid Mixtures on the Cooling Performance of a Heat Sink

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Abstract: The temperature of an electronic device is one of the most important parameters to deal with. Any increase above the temperature limits results in a failure in the device. Thus, to ensure good operation, an electronic device should be cooled. One promising technique is the use of Phase Change Materials (PCMs) for their well-known ability to absorb the heat dissipated by the device, thanks to their high latent heat of fusion. Arachidic acid is a fatty acid that, when mixed with sodium decanoate and potassium oleate salts, can be used as a promising PCM due to its high latent heat. This paper aims to shed light on the use such mixtures of Arachidic acid for cooling in a heat sink. An experimental setup was built for this purpose. The results show that the Arachidic acid mixtures are suitable for applications requiring intermediate heat dissipation.

Keywords: phase change material; fatty acids; Arachidic acid; mixtures; thermophysical properties; melting range; heat sink



Citation: Hammoud, M.; Mjallal, I.; Farhat, H.; Abdallah, N.; Habchi, C.; Lemenand, T. The Effect of Arachidic Acid Mixtures on the Cooling Performance of a Heat Sink. *Appl. Sci.* **2021**, *11*, 9201. <https://doi.org/10.3390/app11199201>

Academic Editor: Adrián Mota Babiloni

Received: 10 September 2021
Accepted: 27 September 2021
Published: 3 October 2021

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1. Introduction

Economic development and environmental problems have been two opposing aspects of technological advancement throughout human history, but the recent peak in technological development has shed more light on environmental issues; therefore, it has become important to improve energy use, for example, through thermal energy storage techniques. This fact has led thermal management to become a critical feature of successful system design, and finding new cooling techniques, especially passive ones, has subsequently become much more valuable.

Electronic devices such as computers, mobile phones and toys have found their way into almost every aspect of human life. The reliability of any system is a function of the reliability of the electronics of that system. An increase in the amount of heat generated per unit volume can be harmful to electronic devices. Electronic devices' failure rates increase with increasing temperature. There are many ways in which excess heat can be extracted from electronic devices.

In electronics, the increase in processing demands and data clock frequencies has forced manufacturers to increase the performance and functionality of integrated electronic chips, increasing component power consumption and reducing design tolerances, while also minimizing their size for portability purposes, leading to the necessity of the dissipation of large amounts of power through smaller packages; electronic components such as micro-processors, integrated circuit (IC) boards, transistors, resistors, batteries, etc., generate heat. The high efficiency required and the fast calculation speeds demand effective cooling to maintain good performance and to minimize failure risk.

The high temperature of electronic devices reduces their effectiveness and life span, as shown in Figure 1. As shown in this figure, a small increase in the operating temperature causes a sharp decrease in lifetime. Various cooling mechanisms are used to prevent the malfunction of electronic devices, including microchannels [1], natural convection [2], forced-air cooling [3], immersion cooling [4], and heat pipes [5].

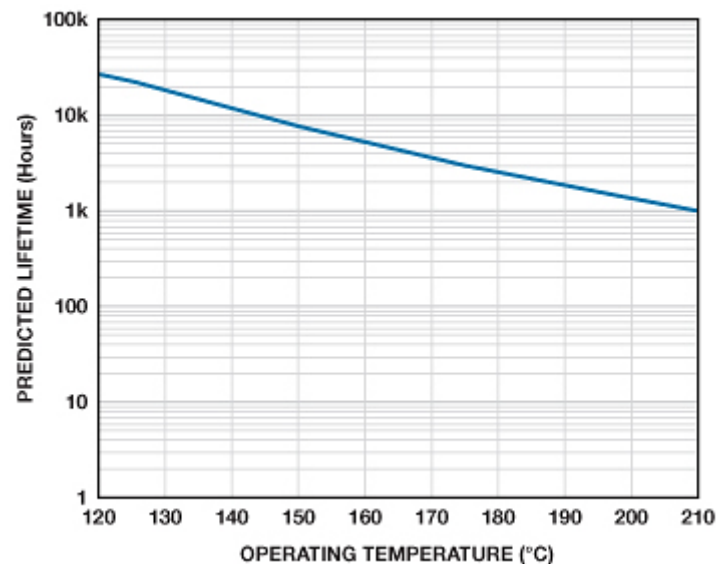


Figure 1. Lifetime degradation of AD8229 electronic device as a function of the operating temperature [6].

Because of the heat transfer ability restrictions with respect to conventional coolants like oil, air, and water, along with dire heat transfer characteristics, especially thermal conductivity and the convective heat transfer coefficient, the majority of cooling methods are not able to attain the required efficiency. In this project, PCMs are used for cooling electronic devices in order to reduce their temperature when carrying out their preferred applications. PCM is used to retain energy to prevent the enclosure from overheating.

The use of PCMs as thermal energy reservoirs [7] or temperature regulators appears to be a promising passive cooling technique that benefits from their thermophysical properties, mainly the latent heat of fusion and the melting temperature. The higher the latent heat of fusion, the more energy can be absorbed by the material during melting.

PCMs possess high latent heat storage capacity, which can be used to absorb the thermal energy of the surroundings as latent energy and change it from one phase to another [8]. Usually, solid–liquid phase change materials are used, but other types, such as solid–solid, solid–gas, and liquid–gas, also exist. PCMs have been used in many applications, such as thermal cooling of photovoltaic panels [9,10], thermal comfort of buildings [11], water heating [12], thermal management in batteries [13], and cooling of electrical equipment [14,15].

During the phase change, the PCM’s temperature remains constant until all the material is completely melted; then, the temperature increases again, in theory to what it would have increased to without the PCM. When the heat source is turned off, the material re-solidifies and emits the absorbed heat. This is why PCMs are recommended for use in applications with non-continuous operation [16]. For example, when cooling portable devices such as palm pilots, cellular phones and personal digital assistants, these devices are not used for more than a few hours continuously at peak load. In addition, their ‘idle’ time is typically long enough to solidify the molten PCM for reuse.

Studies on PCMs have focused on the thermal management of electronic devices at the system level. Mjallal et al. [2] performed a numerical study of the distribution of temperature of a heat sink filled with two types of PCMs: salt-hydrate and wax. After performing multiple simulations, they concluded that an increase of heat flux leads to a reduction in the melting time of PCM. Moreover, they found that the salt-hydrate delayed the peak temperature more effectively than the wax. They also checked the significance of

the density and thermal conductivity in delaying the steady state temperature. Experiments and numerical simulations of PCMs in cooling chips were performed by [17], where they discovered that this method decreases the resistance of thermal heat transfer from the chip to the ambient. Various configurations of heat sinks with two PCMs—namely paraffin wax and n-ecoisane—were studied in [18]. It was also found that circular pipes embedded with wax or n-ecoisane were more effective than a 2-mm-square pin fin heat sink. A numerical study of several configurations of a micro-channel heat sink with four PCMs (paraffin wax, n-eicosane, p116 and RT4) was performed by [19]. They concluded that PCM placed inside the base and channels of the heat sink grants a lower temperature. Another numerical and experimental study was conducted by [20] focusing on a PCM-based heat sink in the transient thermal management of plastic quad flat package electronic devices. The results showed that the presence of PCM in the cavities of the heat sinks increased the cooling performance more than the case without PCM. The usage of four heaters placed on the top of a heat storage unit filled with PCM (n-ecoisane) to cool a mobile electronic device was investigated by [21]. They concluded that using a larger amount of PCM could stabilize the mobile electronic device's temperature for a longer time.

Previously, the heat was stored in the form of sensible heat, such as by heating water, oil, or rocks, but with developments in the energy domain, it was found that latent heat storage was one of the most efficient ways to store thermal energy [22], in addition to the various possible enhancements that could be applied to increase efficiency. Despite that latent heat storage techniques store a higher amount of heat compared to sensible heat storage ones, the charging and discharging processes of the former are slower. The hyper system takes advantage of the properties of both sensible and latent heat storage systems. In this paper, different thermal management techniques for chips using PCMs will be applied [23,24], bearing in mind that the usage of PCMs in electronic devices leads to improved efficiency as well as reliability in electronic devices.

In this work, the focus will be on the use of Arachidic acid ($C_{20}H_{40}O_2$) as a PCM. The use of the Arachidic acid mixed with some salts was investigated by [25] and found to be a promising PCM in a variety of applications. Arachidic acid was mixed with different salts: ammonium acetate, potassium oleate, sodium decanoate, sodium oleate, and sodium hydroxide. The thermophysical properties of the mixtures were measured using differential scanning calorimetric (DSC). As a continuation of that work, the promising mixtures of Arachidic acid will be used to experimentally test the thermal performance of a heat sink. Thus, the novel contribution of this paper lies in the investigation of fatty acids as potential PCM candidates in the cooling of electronic devices.

2. Experimental Setup

As stated in the objectives, an experiment is performed on a heat sink (THOMSON TELECOM BELGIUM NV, Edegem, Belgium) in order to study and compare its temperature profile with and without PCM. The heat sink presented in Figure 2 has an area of $20 \times 20 \text{ mm}^2$ with a bottom thickness of 1 mm. The fins are 5 mm long.

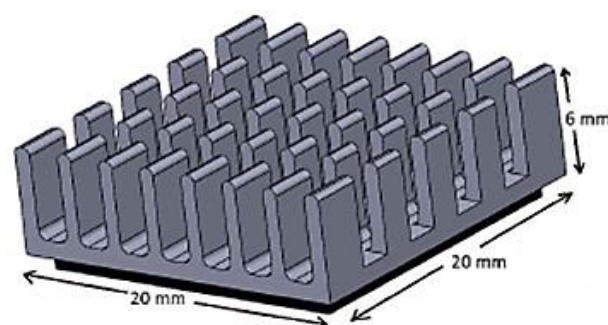


Figure 2. Heat sink used in the experimental setup.

2.1. Apparatus and Instruments

As shown in Figures 3 and 4, the heat sink of a modem is used in the experimental setup. At the bottom of the heat sink, a Peltier thermo-electric heater (Transfer Multisort Elektronik Sp. Z o. o., Lodz, Poland) with a resistance of 0.4Ω is used. The heater is placed at the top of the electric board. A K-type thermocouple touching the tip of the center fin of the heat sink with accuracy $\pm 0.5 \text{ }^\circ\text{C}$ is used to measure the instantaneous temperature of the sink which is connected to an Arduino device to record these temperatures. Two other thermocouples (YU FUNG COMPANY LIMITED, Hong Kong, China) are used to measure the ambient temperature in and outside the modem. A DC power supply (XinYue Electronic Technology CO., Guangzhou, China) is used to regulate the heater's temperature with a significant amount of power. For the case with PCM, the PCM will be added between the fins of the sink.

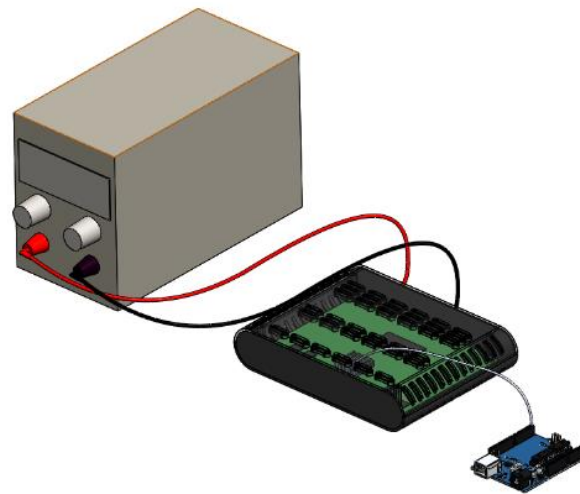


Figure 3. Three-dimensional drawing of the experiment.

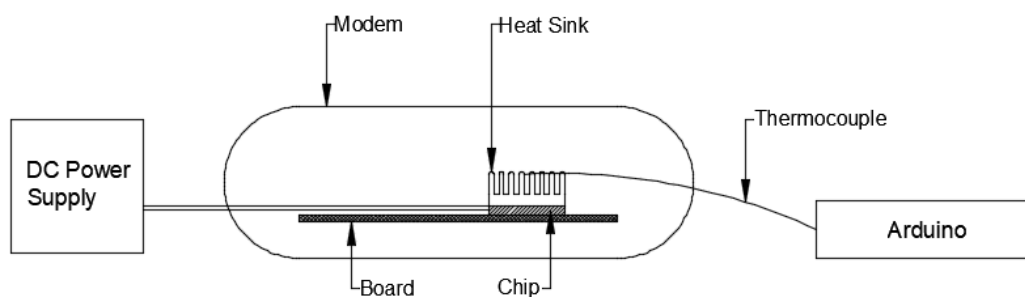


Figure 4. Schematic of the experiment.

2.2. Experimental Procedure

The DC power supply is turned on and regulated to 1.12 A in order to dissipate heat equal to 0.5 W. At the same time, the Arduino device is turned on to record the temperature of the heat sink and the surrounding. The power supply is kept turned on until the heat sink temperature becomes constant despite the continuous supply of power. This defines the steady-state temperature of the heat sink. The time to reach the steady state is recorded during the experiment. The same procedure is repeated for 1.58 A and 2.23 A, which are equivalent to 1 W and 2 W of heat dissipated, respectively.

The PCM is embedded in the heat sink in order to study its influence on the thermal performance of the heat sink. The PCM is melted externally, then poured in between the fins and secured sideways by a strap of aluminum. After the PCM re-solidifies and its

temperature becomes equal to the ambient temperature, the same power input procedure as that of the case without PCM is repeated.

2.3. Uncertainty Analysis

To evaluate the trust in the outcomes, an uncertainty analysis is performed. The uncertainty in the experiments can be due to: the temperature measurements, the DC power supply, and heater temperature stability, as summarized in Table 1.

Table 1. Experimental uncertainty.

Equipment	Experimental Error
Thermocouple	± 0.5 °C
Power supply	$\pm 1\%$
Heater temperature stability	± 0.1 °C

The absolute uncertainty in percentage is calculated using Equation (1):

$$e = \frac{\text{absolute uncertainty}}{\text{value read by the equipment}} \quad (1)$$

For the thermocouple, the minimum value that can be read is equal to 23 °C; thus, the thermocouple uncertainty (e_t) is equal to:

$$e_t = \frac{0.5}{23} = 2.17\%$$

Similarly, the heater temperature stability is equal to $e_h = 0.43\%$. The uncertainty of the power supply (e_p) is equal to 1%.

The total uncertainty is the norm of all uncertainties and is calculated using Equation (2):

$$e = \sqrt{e_t^2 + e_h^2 + e_p^2} \quad (2)$$

Substituting all the above values in the equation for e , the total uncertainty was $e = 2.4\%$, which is in the acceptable range.

3. PCM Thermophysical Properties

A wide study has been performed on Arachidic acid [25] in which different mixtures were produced to enhance thermophysical properties. The promising mixtures of Arachidic acid suitable for electronic applications were: Arachidic acid +10% potassium oleate; and Arachidic acid +10% sodium decanoate.

3.1. Differential Scanning Calorimetric Study

A Differential Scanning Calorimetric (DSC) study was performed to find the latent heat, specific heat and melting range for the Arachidic acids and the two mixtures.

As shown in Table 2, the pure Arachidic acid had the highest latent heat of 257.4 kJ/kg. Meanwhile, the mixture with 10% sodium decanoate had the highest specific heat for the solid phase and 10% potassium oleate had the highest specific heat for liquid phase of 2.33 kJ/kg K and 2.36 kJ/kg K, respectively. Finally, for the melting points, and the solidus and liquidus temperatures for the Arachidic acid were equal to 73.3 °C and 80.1 °C, while the melting range for the mixtures was much wider and was equal to 50.0 °C and 83.3 °C for the 10% potassium oleate mixture and 48.0 °C and 82.7 °C for the 10% sodium decanoate mixture.

Table 2. Latent heat, specific heat and melting range of the Arachidic acid and its mixtures.

Materials	Latent Heat (J/kg)	Specific Heat for Solid Phase (kJ/kg K)	Specific Heat for Liquid Phase (kJ/kg K)	Solidus Temperature (°C)	Liquidus Temperature (°C)
Arachidic acid (AA)	257.4	1.90	2.19	73.3	80.1
AA + 10% potassium oleate	214.0	1.90	2.36	50.0	83.3
AA + 10% sodium decanoate	222.1	2.33	2.30	48.0	82.7

It is worth noting that different mol percentages of salts were considered, and were generally kept low (<15 mol%), since the added chemicals were considered to be impurities. After a wide study, it was found that the 10% mixture was suitable for electronic cooling application, since it decreased the melting temperature to the allowable range and maintained considerably high latent heat of fusion [25].

3.2. Thermal Conductivity Measurement

The thermal conductivity of the PCMs was measured using a device manufactured in [26]. The experiment was repeated three times, and the average value for the three experiments was taken as the thermal conductivity of the PCM. As shown in Figure 5, the average thermal conductivity for the pure Arachidic acid was 0.181 W/m K.

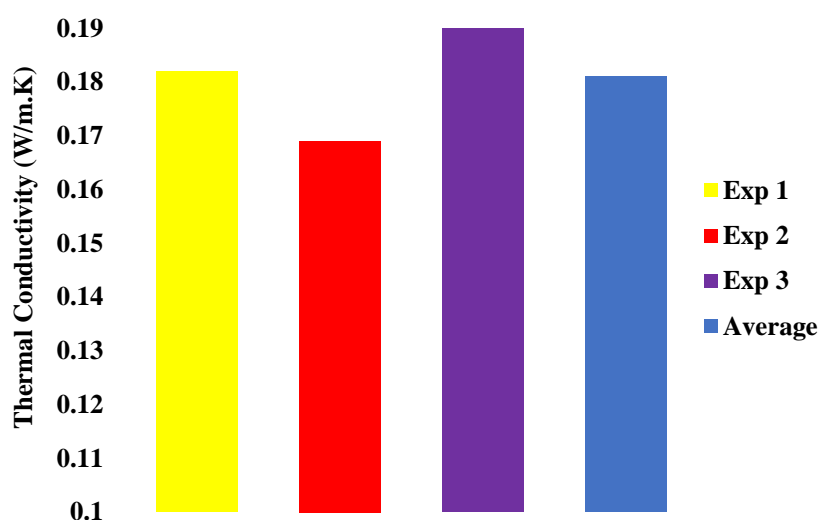
**Figure 5.** Thermal conductivity for Arachidic acid.

Figure 6 shows the thermal conductivity of pure Arachidic acid, potassium mixture and sodium mixture. For the potassium mixture, the thermal conductivity increased by 66%, reaching 0.300 W/m K, while the thermal conductivity decreased by 20% for the sodium mixture, reaching 0.145 W/m K.

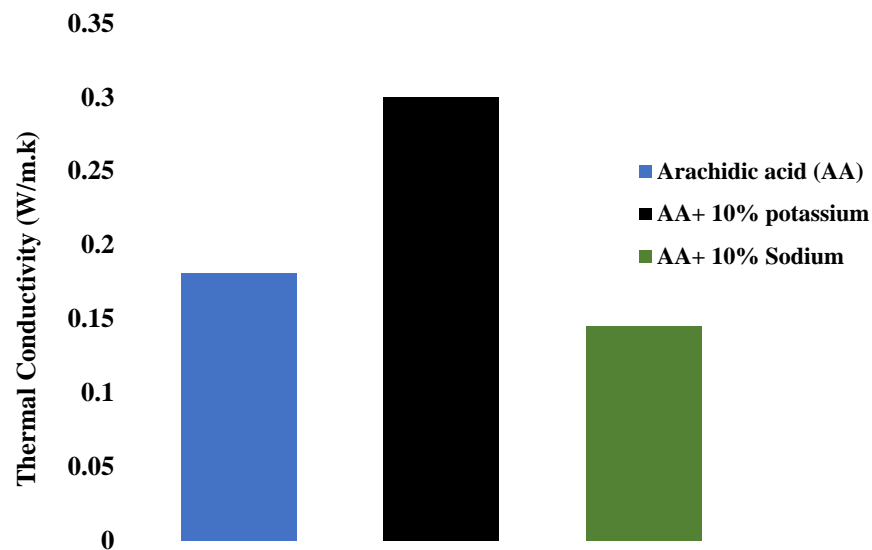


Figure 6. Thermal conductivity of Arachidic acid and its mixtures.

4. Results

The first experiment was performed for the case without PCM at a generated heat of 0.5 W. Figure 7 shows the temperature variation over time of the heat sink. As seen in Figure 7, the temperature started to increase, from an ambient temperature of 23 °C, until it reached a steady-state temperature of 50 °C. At the beginning, the temperature increased remarkably; then, its rate of increase decreased over time until the temperature became constant at a steady state. The reason behind this variation is that the heat rejected by convection increases when the temperature of the sink increases; and at steady state, the heat rejected from the sink is equal to the heat gained by the heater—0.5 W in this case. The time taken by the sink to reach the steady state was about 900 s.

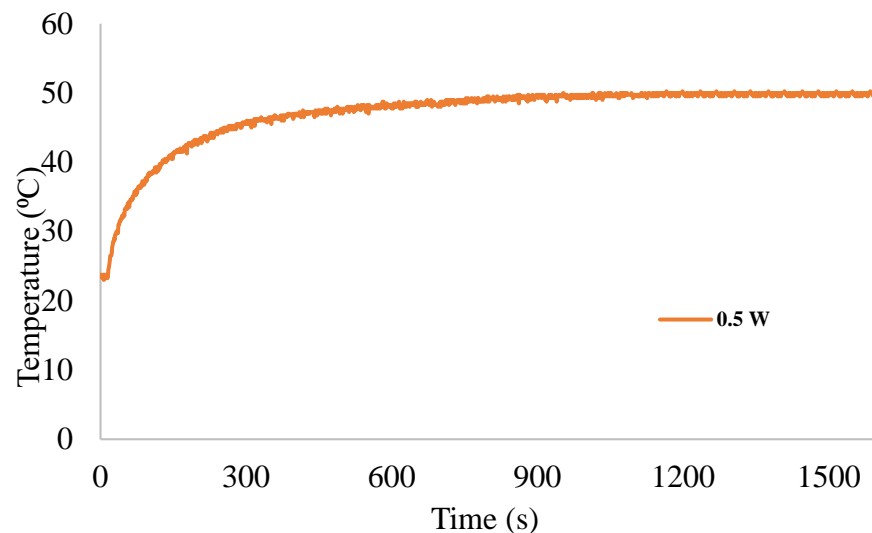


Figure 7. Temperature distribution for the heat sink at 0.5 W.

As shown in Figure 8, when the heat generated by the chip increased, the steady-state temperature increased. In this experiment, the steady-state temperature increased from 50 °C at 0.5 W to 72 °C and 109 °C at 1 W and 2 W, respectively.

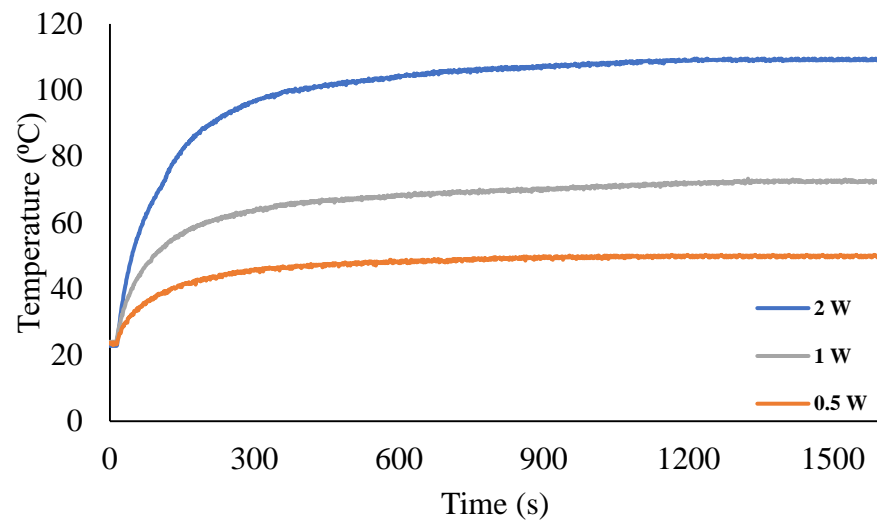


Figure 8. Temperature distribution for the heat sink for 0.5, 1, and 2 W.

To investigate the effect of Arachidic acid and its mixtures on the cooling of the heat sink, a set of experiments was performed. By adding the Arachidic acid (being considered as a PCM), the steady-state temperatures for 0.5, 1 and 2 W were 41.75 °C, 65 °C and 104.5 °C, respectively. As one can see from Figure 9, the PCM does not melt at 0.5 and 1 W, because the steady-state temperature for those powers is lower than the melting temperature of Arachidic acid. It took 500 s and 1000 s to reach the steady-state temperature for the cases of 0.5 W and 1 W, respectively. Meanwhile, in the case of 2 W, the PCM melted completely after about 1180 s, delaying the peak temperature of the sink by 300 s. It can be seen that the steady-state temperatures of the three cases, even without the melting of PCM, were decreased compared to that without PCM.

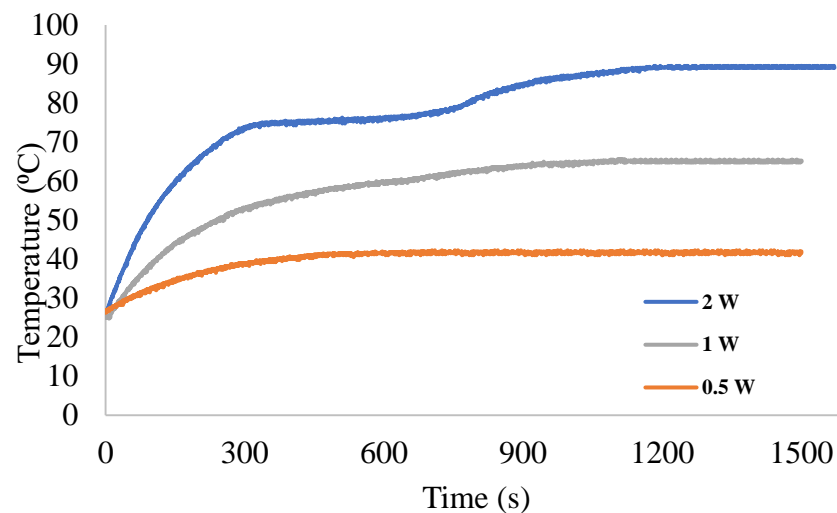


Figure 9. Temperature distribution for the heat sink with Arachidic acid for 0.5, 1 and 2 W.

The temperature profiles for the heat sink without PCM, the heat sink with potassium mixture as PCM, the heat sink with sodium mixture as PCM and the heat sink with Arachidic acid as PCM for 0.5, 1 and 2 W of heat dissipated are depicted in Figures 10–12, respectively.

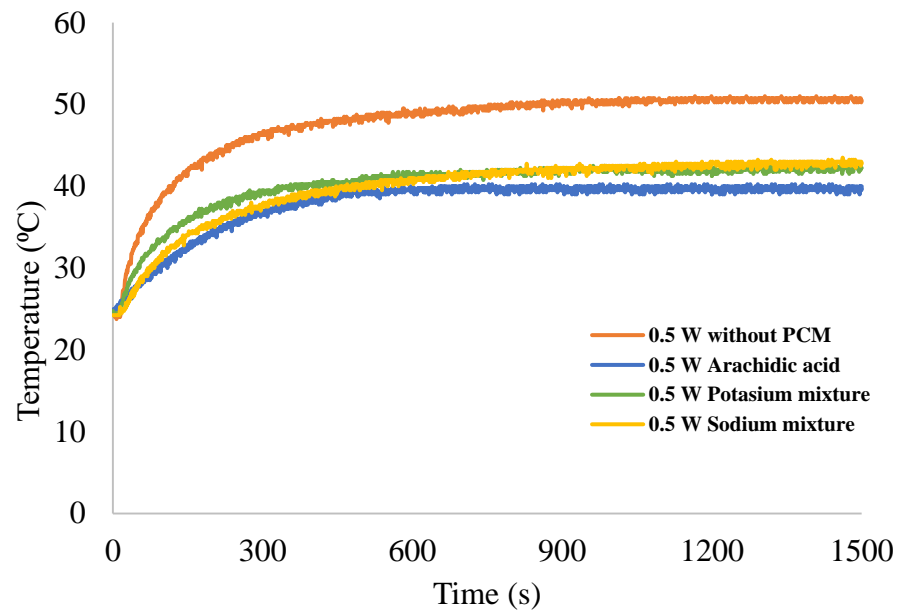


Figure 10. Temperature distribution for the heat sink without and with PCMs at 0.5 W.

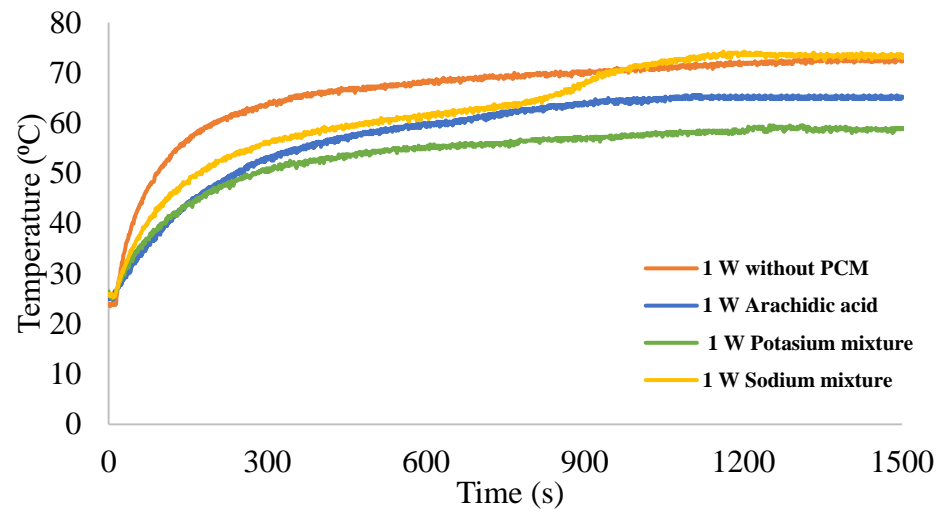


Figure 11. Temperature distribution for the heat sink without and with PCMs at 1 W.

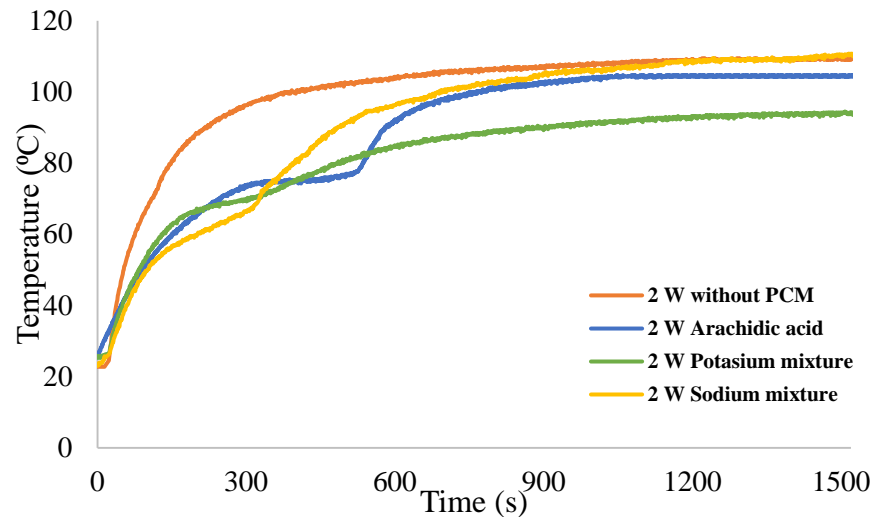


Figure 12. Temperature distribution for the heat sink without and with PCMs at 2 W.

For 0.5 W, the Arachidic acid and its mixtures did not melt, but it can be seen that the peak temperature reached by the heat sink without PCM (50 °C) was much higher than that for the heat sink with PCM (approximately 42 °C).

As for the case at 1 W, the temperature profile for the heat sink without PCM and the heat sink using Arachidic acid and potassium mixture as the PCM continued to increase until reaching a steady-state temperature, while for the sodium mixture, the PCM melted, and the temperature decreased during melting, delaying the steady-state time by 320 s. The steady-state temperature for the sodium mixture and the sink without PCM was approximately the same. For the cases of Arachidic acid and potassium mixture, they did not melt, but the steady-state temperature (59 °C) was lower than the case without PCM (72 °C).

Finally, for the case 2 W, all PCMs melted, with differences in the peak temperatures and delay times. For the Arachidic acid, the peak temperature (104.5 °C) was lower than in the case without PCM (109 °C), with a time delay equal to 300 s. For the sodium mixture, the peak temperature (111 °C) was higher than in the case without PCM, with a delay equal to 900 s. The best results were obtained for the potassium mixture, which achieved the lowest peak temperature of 95.25 °C and the highest time delay of 1050 s.

Table 3 summarizes the peak temperature for all cases without and with PCMs and the time required to reach the steady state.

Table 3. Peak temperature and time to reach steady state.

	Peak Temperature (°C)	Time to Steady State (s)
0.5 W	50	900
1 W	72	850
2 W	109	800
0.5 W (AA)	41.5	473
1 W (AA)	65	1120
2 W (AA)	89	1100
0.5 W (AA + Potassium)	42.5	500
1 W (AA + Potassium)	58.5	560
2 W (AA + Potassium)	95.25	1500
0.5 W (AA + Sodium)	42	908
1 W (AA + Sodium)	73	1160
2 W (AA + Sodium)	104	1607

5. Discussion

On the basis of the several experiments performed, some conclusions can be outlined. First, when the generated heat increases, the peak temperature of the sink also increases. The effect of the PCM with respect to delaying the peak temperature is clearly shown in Figure 9. When the PCM melts at 2 W, it absorbs a large amount of energy during the phase transition, leading to enhanced thermal performance of the heat sink. Another important thermophysical criterion that affects the thermal performance of the sink is the specific heat C_p . This is clearly shown in Figure 10, where the PCMs do not melt at 0.5 W, but have a smaller peak temperature due to the energy absorbed by the PCM as specific heat during temperature change from ambient to peak temperature. The effect of the thermal conductivity of the PCM is demonstrated in Figure 12, where all PCMs are totally melted and have almost the same specific heat. The higher the thermal conductivity is, the lower the peak temperature is reached. As the thermal conductivity increases, the heat transfer rate between the bottom and the top surface of the PCM will increase, making the temperature gradient uniform. In addition, when the surface temperature of the PCM increases, the natural convection at the surface will increase, making it possible for the heat to dissipate faster.

Moreover, the influence of the mixtures was investigated in this work. Unlike Arachidic acid, the sodium mixture makes the PCM suitable for applications with lower heat dissipation, as shown in Figure 11, where the sodium mixture was completely melted

at 1 W and the peak temperature of the sink was delayed by 320 s. Thus, this PCM is appropriate for electronic devices with intermediate heat dissipation.

Finally, for the potassium mixture, despite this PCM not melting at 1 W, it is appropriate for application in electronic devices with intermediate heat dissipation, because the melting point of this mixture is 50 °C. The reason for it not melting significantly at 1 W is that the potassium mixture enhances the thermal performance of the heat sink by lowering its melting peak from 72 to 59 °C. Therefore, the potassium mixture enhances the performance for the pure Arachidic acid, making this PCM suitable for electronic devices with lower heat dissipation and enhancing the thermal performance for the electronic chip by increasing the specific heat and thermal conductivity. In addition, the potassium mixture has a much greater time delay than pure Arachidic acid. This is shown in Figure 12, where potassium delays the peak temperature by 1050 s instead of 300 s, as in the case of the pure Arachidic acid, thus resulting in a 3.5 time greater delay than pure Arachidic acid, and with better thermal performance for electronic devices with higher heat dissipation.

6. Conclusions

The goal of this paper was to investigate the effect of Arachidic acid and some mixtures on the thermal performance of heat sinks. It shed light on the effect of the thermophysical properties of the PCM on the thermal behavior of the heat sink.

The potassium mixture had the best effect in terms of enhancing the cooling performance of the sink. Meanwhile, the deficiency of the thermal conductivity of the sodium mixture negatively affected its thermal cooling performance compared to the potassium mixture.

For electronic applications with lower heat dissipation, the pure Arachidic acid has better performance than the potassium and sodium mixtures. However, for intermediate applications, it was observed that only the sodium mixture melted completely at about 50 °C, and the peak temperature was delayed by 320 s compared to the case without PCM. As for the potassium mixture, it exhibited a better performance for electronic applications with high heat dissipation, with a melting temperature of about 65 °C and a peak temperature delay of 1050 s.

In summary, the thermal conductivity of the sodium mixture can be enhanced to improve its thermal performance. Additionally, numerical modeling of PCMs can be implemented to decrease the cost of the experimental setup. This model can be validated on the basis of experimental results. This will help to study different configurations and applications.

Author Contributions: Conceptualization, M.H., I.M., C.H. and T.L.; methodology, M.H., I.M., N.A. and H.F.; validation, I.M., N.A. and H.F.; formal analysis, I.M. and H.F.; writing—original draft preparation, M.H., I.M. and H.F.; writing—review and editing, M.H., C.H. and T.L.; supervision, M.H., C.H. and T.L. All authors have read and agreed to the published version of the manuscript.

Funding: The APC was funded by the Lebanese International University LIU.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Data sharing is not applicable.

Conflicts of Interest: The authors declare no conflict of interest.

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