Numerical evaluation of thermal performance for diverse configurations of pin fin heat sink with and without phase change materials (PCM)

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Abstract

Regulation of the thermal performance of electrical components is a key aspect. Phase-change materials can be incorporated into a fin heat sink (FHS) to enhance thermal management by maintaining a stable temperature. Three types (square, triangular, and circular) of aluminum FHSs of different configurations are investigated numerically in this paper. Studies are conducted with and without PCMs. Paraffin wax, stearic acid, and polyethylene glycol are used as PCMs to find the best combinations for thermal cooling and to determine the impact of using PCMs in the heat sinks. The results obtained show that, by adding PCMs, temperature rise can be delayed, and polyethylene glycol performs better than other PCMs. Moreover, the square fin heat sink increases the thermal regulation period. As the height of the fins increases from 10 mm to 16 mm, thermal efficiency increases. Hence, the findings of this paper would be beneficial for effective thermal management in the electronic industry.

Title Page

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1. Introduction :

1.1. Overview :

Electronics have become an inevitable part of this digital era. Hence, effective thermal management is one of the biggest concerns, not only for cost effectiveness but also for safety purposes. The miniaturization of electrical components has made this issue more complex. Working temperatures should be kept within a limited range to maintain the proper functioning of electronics. Conventional cooling systems (natural convection and forced convection) are insufficient to meet the cooling requirements for high-performance and smaller-sized electronic components. A temperature decrease of 1°C can lower the failure rate of electric components by as much as 4% [1].

Cooling systems can be broadly categorized as active cooling and passive cooling. A heat sink is utilized in active cooling to dissipate heat from the chip. Generally, it uses fins to increase the surface area for convection and to facilitate removing heat from the attached surface. A fan may be added to enhance the overall thermal performance of a heat sink. However, there are some drawbacks of using fans, such as noise and vibration. Therefore, the use of passive cooling systems is necessary to achieve high performance and longevity of electrical components.

A passive cooling system can be fabricated using PCM because of its ability to store and release a large amount of energy as latent heat during the phase transition process. PCM also has the capability of maintaining a constant temperature when transitions occur from solid to liquid states in most cases. Hence, PCM has started to be added to the heat sink in recent years to decrease the temperature rise in the electrical components. PCM-based thermal management systems offer effective working conditions for electronic components, enhance cooling performance, and reduce energy consumption [2,3]. Besides, several articles [4-6] have discussed the thermophysical properties, different types, phase transition behaviors and applications of phase change materials.

A thermal management system with and without PCM is investigated in this paper. COMSOL finite element simulation software is used to study the temperature distribution, rise time, effect of fin height, fin numbers and power supply on the base of the heat sink and compare the performance of different PCMs.

1.2. Literature review :

S.A. Isaacs et al. [7] have investigated the performance of heat sinks by using phase change materials. They evaluated the heat transfer and flow in pin-fin microgaps. It has been shown that the pin-fin structure can significantly increase the convective heat transfer coefficient in single-phase flow conditions. They used R245fa as a working fluid. Experimental investigations have been carried out by R. Baby and C. Balaji [8] by using n-eicosane as a phase change material that is placed inside a heat sink made from aluminum. They studied both the finned and un-finned heat sinks, and constant heat loads were applied. They found that the overall performance of the heat sink can be increased by filling the fins with PCMs.

Pakrouh et al. [9] numerically studied the pin fin heat sink with paraffin RT44 as a PCM. They estimated the effect of different geometrical parameters, such as height, thickness, and number of fins. They also considered volume expansion in phase transition as well as natural convection. Ali et al. [10] concluded the experimental performance of two types of pin fin heat sinks with n-eicosane and paraffin wax PCMs. They found that circular fins performed better than square fins with these PCMs, along with a 90% volume of fins. Kandasamy et al. [11] used a 3-D CFD model to compare the performance of rectangular-profile fins filled with paraffin wax as PCM. They found an increase in the cooling performance of a heat sink filled with PCM as compared to a heat sink without PCM when the power input is sufficiently high (power input $>$ 2W).

Jaworski [12] performed a numerical simulation of a hollow circular pin fin heat sink filled with PCM and cooled by forced convection. Results showed that the thermal resistances of hollow round pin FHS were much lower than those of simple PCM-filled heat sinks. Arshad et al. [13] experimented with three types of square pin fins of length 1, 2, and 3 mm filled with PCMs (paraffin wax and n-eicosane). They found that 2 mm square fins performed better than other fin types. Siyabi et al. [14] studied experimentally three different heat sinks to evaluate the effects of PCM combinations, thickness, melting temperature, and intensity of heat source. They concluded that the RT50-RT55 combination of PCMs increased the thermal regulation period as well as reduced the temperature of the heat sink. They also found that the thermal regulation period increased with the thickness of phase change materials.

Ashraf et al. [15] experimented with square and circular fins in a partially filled PCM container. They used six types of PCMs with power levels ranging from 4 to 8 watts. They found that square fins were most effective without using PCM, but with PCM, circular fins performed well. They also showed that paraffin wax performed best at an 8W power level. Liu et al. [16] explored the effects of power losses, fin height, air velocity, and the thickness of the phase change materials on the protection ability of the heat sink filled with PCM. They optimized the heat sink design to increase the thermal performance. They had found an 80-s protection period and a 100-s recovery time after optimization.

Table-1

Specific paremeters of the PCMs in solid phase.

not-yet-known not-yet-known not-yet-known unknown

Phase Change Materials	Melting temperature (°C)	Latent heat(kJ/kg)	Density(kg/m3)	Thermal conductivity(W/m
Paraffin wax	46-48	200-250	900	0.2-0.4
Stearic acid	69.3	199.02	847	0.172
Polyethylene glycol	18	190	1125	0.33

not-yet-known not-yet-known

not-yet-known

unknown

Table-2 Specific parameters of the PCMs in liquid phase.

not-yet-known not-yet-known not-yet-known unknown

Phase change materials	Latent heat (kJ/kg)	Density(kg/m3)	Thermal conductivity (W/m.K)	Heat capacity (J/kg.K
Paraffin wax	200-250	770	0.2-0.4	2000
Stearic acid	199.2	940	0.147	1640
Polyethyleneglycol	190	1125	0.27	1950

2.3. Governing equations :

2.3.1. Equations used in the heat transfer in solid surface :

$\rho C_p \frac{dT}{dt}$ + [?].q = Q

q = - k.[?]T

Where,

ρ = Density of the material

C_p = Heat capacity

q = Heat flux

k = Thermal conductivity

Q = Heat source

2.3.2. Fluid heat transfer equation used in the liquid metal model :

$\rho C_p \frac{dT}{dt}$ + [?].q + ρC_p u. [?]T = Q

Where,

$\rho = \frac{P}{RT}$ in ideal gas domain

R = Universal gas constant

u = velocity of the fluid

2.3.3. Equation for thermal insulation :

$-\mathbf{n}\ .\ \mathbf{q} = 0$

Here,

$\mathbf{n}$ = Unit vector

2.3.4. Equations for heat flux :

$-\mathbf{n}\ .\mathbf{q} = \mathbf{q_o}$

$q_o = h * (T_{ext.} - T)$

Where ,

q_o = Inward heat flux

h = Convection heat transfer co-efficient

2.3.5. Equations for the phase change materials :

$\rho = \vartheta_1.\rho_1\vartheta_2.\rho_2$

$C_p = \frac{1}{\rho} (\vartheta_1\rho_1 C_{p,1} + \vartheta_2\rho_2 C_{p,2}) + L_{1\text{-}2}\frac{\partial}{\partial T}\frac{\partial \alpha_m}{\partial T}$

$$\alpha_m = \frac{1}{2}\frac{\theta_1\rho_1\ .\ \theta_2\rho_2}{\theta_1\rho_1 + \theta_2\rho_2}$$

$k = \vartheta_1 k_1 + \vartheta_2 k_2$

$\vartheta_1 + \vartheta_2 = 1$

Where,

$C_{p,1}$ = Constant pressure heat capacity of the solid phase

$C_{p,2}$ = Constant pressure heat capacity of the liquid phase

k_1 = Thermal conductivity of the solid phase

k_2 = Thermal conductivity of the liquid phase

ϑ_1 = Volume fraction of the solid phase

ϑ_2 = Volume fraction of the liquid phase

$L_{1\text{-}2}$ = The latent heat of melting

2.4 : Numerical implementation :

A finite element method-based simulation software, "COMSOL Multiphysics 5.6," had been used to solve the governing equations. Constant heat was applied to the base of the heat sink, and boundary walls were kept insulated. Tetrahedral and triangular meshes were selected, with maximum and minimum values of the element size of 0.0055 m and 0.00099 m, respectively. Figure-2 shows the temperature profiles of the three types of heat sinks after simulation.

[insert figure-2 here]

3. Results and discussions :

3.1. Verification of the present model :

The present model is verified by using the experimental study represented in [8]. In the experimental study of C. Baby and R. Balaji [8], a heat sink was modeled with a vertical height of 25 mm, a length of 80 mm, and a width of 62 mm. A plate heater of 2 mm thickness and a slot area of 60*42 mm^2 was used. The height of the square pin fins was 20 mm, with an area of 2*2 mm^2. N-eicosane was used as a PCM.

The verification test is performed by using the numerical model of a square-pin fin heat sink with a height of 16 mm. A constant power of 3 W is applied to the base of the heat sink for 180 minutes. Figure-3 shows the relationship between the results of the present model and the experimental model proposed by C. Baby and R. Balaji [8]. There is a strong correlation between these two models, where the maximum error is 1.7%. Hence, it can be said that the present model is appropriate for studying the thermal performance of a heat sink with PCMs.

[insert Figure-3 here]

3.2. The effects of using PCM :

The test is performed to visualize the effects of using PCMs in the micro-pin fin heat sink. A square fin heat sink with a height of 16 mm is used. A constant power of 30 W is applied to the base of the heat sink, and the ambient temperature is kept at 20 °C. Insulation is applied to the boundary walls. Figure-4 shows the temperature vs. time graph of a heat sink with three different types of PCMs as well as without PCM. The graph represents that the temperature of the base plate of a heat sink without PCM is much higher than that of a heat sink with PCM. It takes around 2.5 minutes to reach a temperature of 60 °C for a heat sink without PCM, whereas this time is almost twice as long for a heat sink with PCM in the same conditions. Because after melting, PCMs can absorb and store energy as latent heat, decrease the temperature of the base plate, and increase the cooling process for effective thermal management of electronic equipment.

Another important finding is that polyethylene glycol performs better than the other two PCMs. Polyethylene glycol has a melting temperature of 18 °C, which is much lower than paraffin wax and stearic acid, which have melting temperatures of 46 °C and 69.3 °C, respectively. Therefore, polyethylene melts quickly, and it can be used efficiently in such micro-pin fin heat sinks where the temperature rise is below 70 °C.

[insert Figure-4 here]

3.3. Effects of geometry of the fins :

Square, triangular, and circular fins with a height of 16 mm are investigated in this study. Polyethylene glycol is used as a phase change material. A constant heat of 30 W is applied to the base of the heat sinks. The convective heat transfer coefficient of the fins is 25 $W/m^2.K$ and the ambient temperature is maintained at 20 °C. Figure-5 shows the time-temperature curve of the study. After 10 minutes, the base plate temperature of the square fin heat sink is 71.19 °C, whereas for triangular and circular fin heat sinks, this temperature is 82.97 °C and 80.95 °C, respectively. So, it can be said that square fins have a higher ability to reduce temperature rise than triangular and circular fin heat sinks because square fins have a larger convective heat transfer area.

[insert Figure-5 here]

3.4. Effects of height of the fins :

Figure-6 shows the temperature vs. time graph for three types of fins with heights of 16 mm and 10 mm. From this graph, it is seen that, as the height of the fins increases, it reduces the temperature rise of the base plate of the heat sink. This is because with the increase in the height of the fins, the convective heat transfer area also increases, causing faster dissipation of heat. For square fin heat sink, the temperature rise is 25 °C less for 16 mm height of the fins in comparison to the 10 mm height of the fins. For triangular and circular fins, this temperature difference is almost 27 °C and 29 °C, respectively. However, longer fins also increase the cost of the heat sink because of the higher volume of the heat sink. Hence, the height of the heat sink should be carefully designed.

Figure-7 shows the comparative results of the height of the heat sinks in a column chart when constant heat is applied for 10 minutes.

[insert Figure-6 here]

[insert Figure-7 here]

3.5. Effects of the number of fins with and without PCM :

Three types of heat sinks with fin numbers of 84 and 45 are being studied. At first, polyethylene glycol is used as a phase change material, then air convection without PCM is observed. Figure-8 shows the time-temperature curve for square, triangular, and circular fins with fin numbers of 84 and 45. For an 84-square-foot heat sink, it takes only 6 minutes to reach a temperature of 60 °C, whereas for a 45-square-foot heat sink, it takes at least 8 minutes. So it can be said that the 45-fin heat sink performs better than the 84-fin heat sink with PCM. This is because as the volume of the fins increases, it decreases the volume of the PCM as well. The cooling effect of the PCM is much greater than the natural convection cooling of the fins.

However, the scenario is completely different without PCM. Figure 9 shows the temperature vs. time graph to illustrate the effect of the number of fins without PCM. As the number of fins increases, it increases the volume of air convection heat transfer, which results in a smaller temperature rise. As the effect of PCM does not exist, a higher number of fins is preferable for the effective cooling performance of a heat sink.

4. Conclusion :

The present numerical study is carried out to estimate the thermal performance of a micro-pin fin heat sink. Heat sinks with three different geometrical shapes (square, triangular, and circular) and three types of PCMs (paraffin wax, stearic acid, and polyethylene glycol) are used to quantitatively visualize their effects on the thermal behavior of heat sinks. To summarize the research findings, the following points can be drawn to consider:

- By using PCMs, the temperature rise of a heat sink can be reduced.
- For the micro-pin fin heat sink, polyethylene glycol is better than paraffin wax and stearic acid when the temperature is below 70 °C.
- A square fin heat sink performs better than a triangular or circular fin heat sink.
- As the height of the fins increases, the area for natural convection heat transfer also increases, resulting in a higher thermal performance of the heat sink.
- Increasing the number of fins without using PCMs increases the effectiveness of a heat sink. But when PCMs are used in this case, thermal performance gets lower.

Declaration of competing interest :

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Figure captions :

Fig. 1. Schematic diagrams of the heat sink models : (a) square (84 fins, height =16 mm), (b) square (84 fins, height = 10 mm), (c) square (45 fins, height = 16 mm), (d) triangular (84 fins, height = 16 mm), (e) triangular (84 fins, height = 10 mm), (f) triangular (45 fins, height = 16 mm), (g) circular (84 fins, height = 16 mm), (h) circular (84 fins, height = 10 mm), (i) circular (45 fins, height = 16 mm)

Fig. 2. Temperature profiles : (a) square fins heat sink, (b) triangular fins heat sink, (c) circular fins heat sink

Fig. 3. Relationship between the results of the present model and the experimental model of [8]

Fig. 4. Temperature distribution of a heat sink with three different types of PCMs as well as without PCM

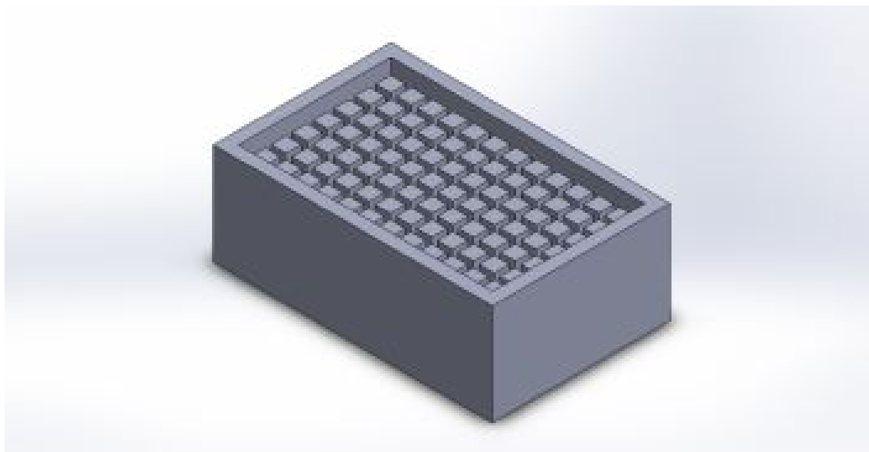
Fig. 5. Temperature distribution of three types of heat sinks using polyethylene glycol as PCM

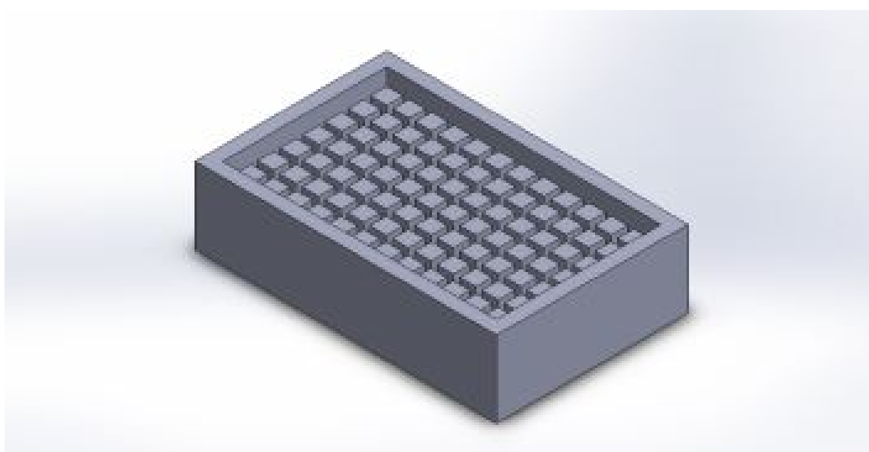
Fig. 6. Temperature vs time graph of heat sinks for three types of fins with a height of 16 mm and 10 mm

Fig. 7. A column chart showing the temperature of different types of heat sinks with a height of 16 mm and 10 mm

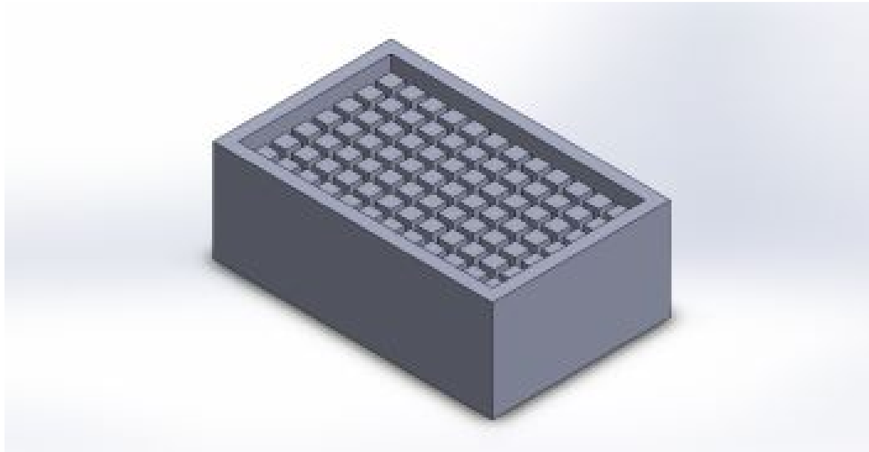
Fig. 8. Time-temperature curve of three types of heat sinks with a fin number of 84 and 45 using polyethylene glycol as PCM

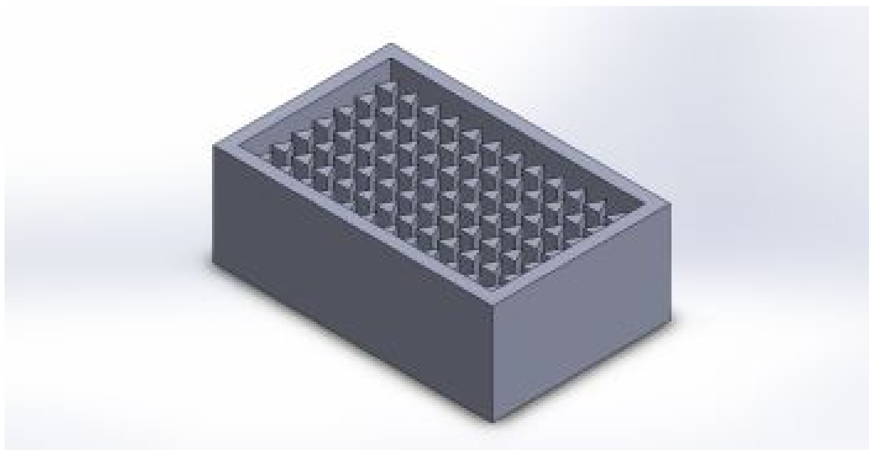
Fig. 9. Time-temperature curve of three types of heat sinks with a fin number of 84 and 45 without PCM



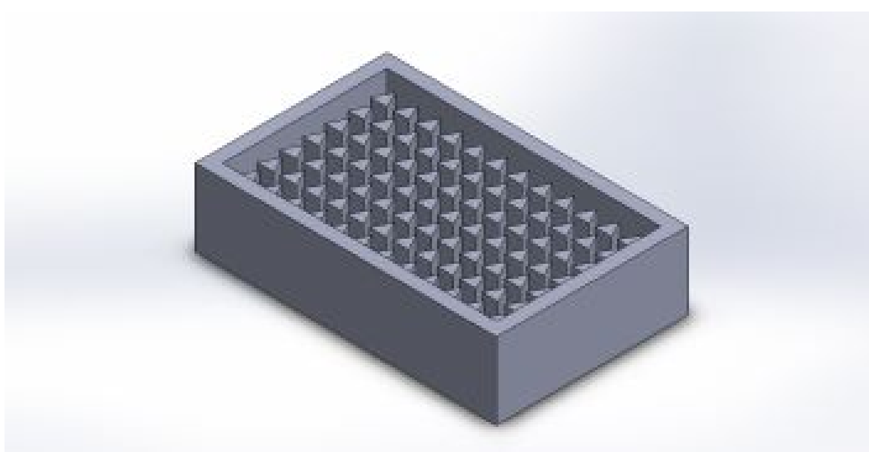


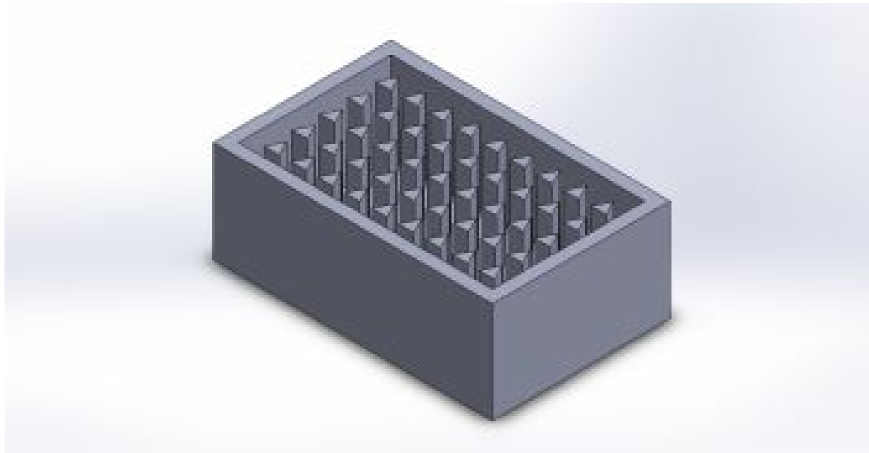
(b)



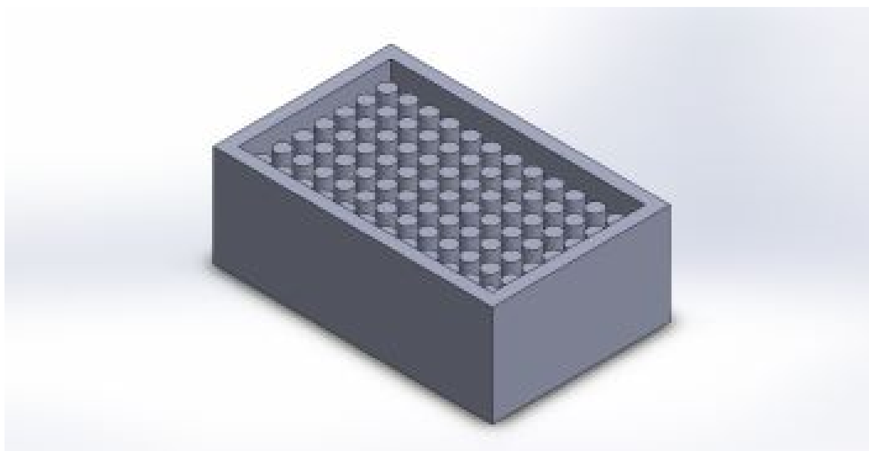


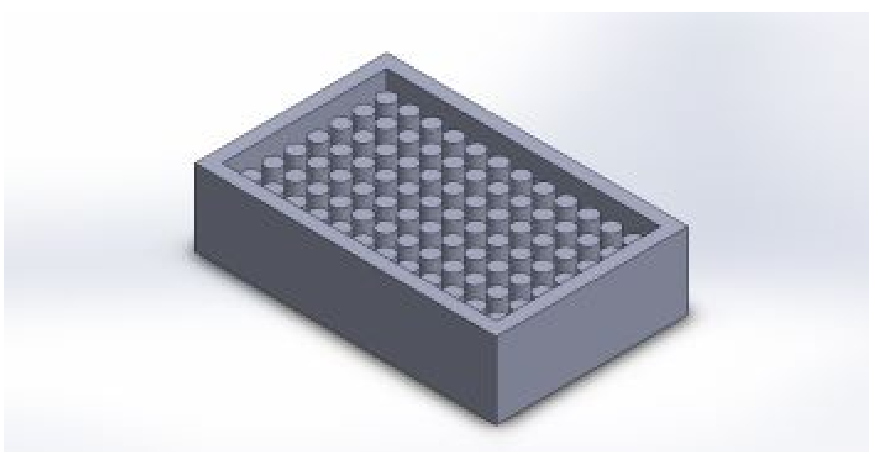
(c) (d)



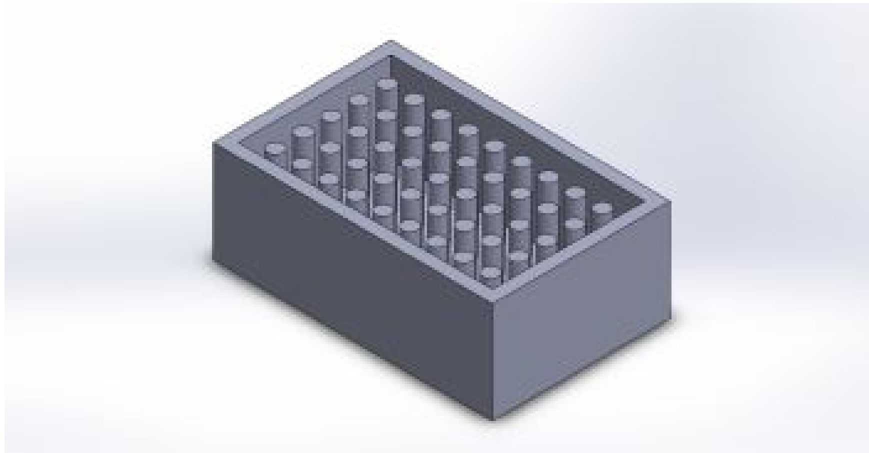


(e) (f)





(g) (h)



(i)

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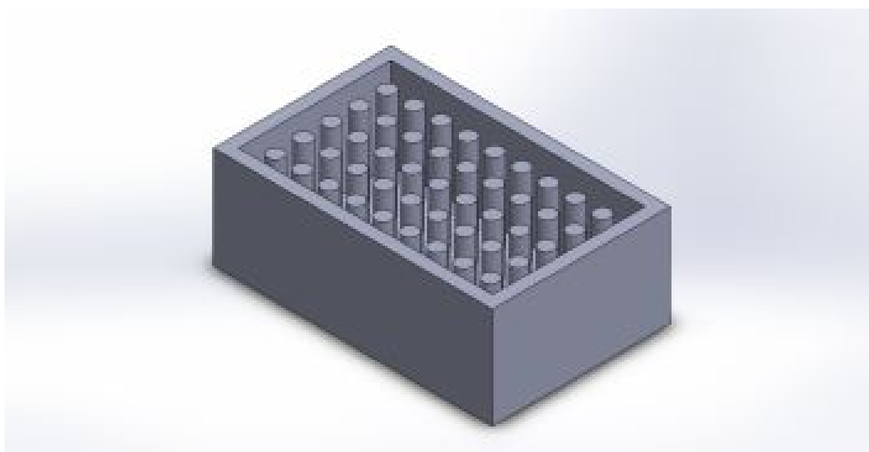
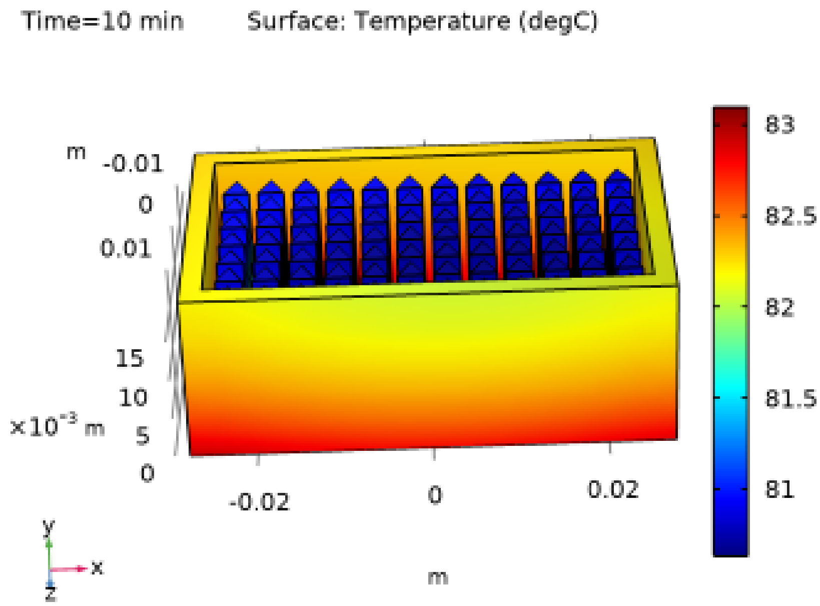
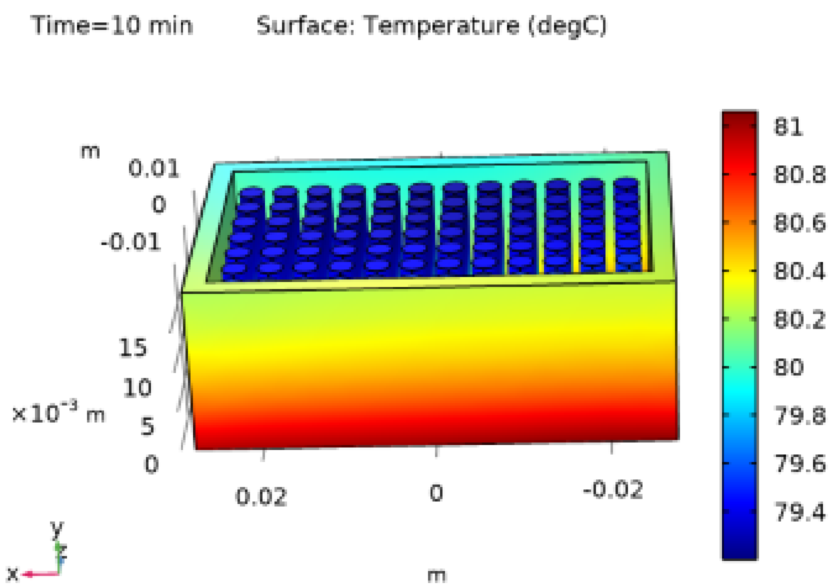
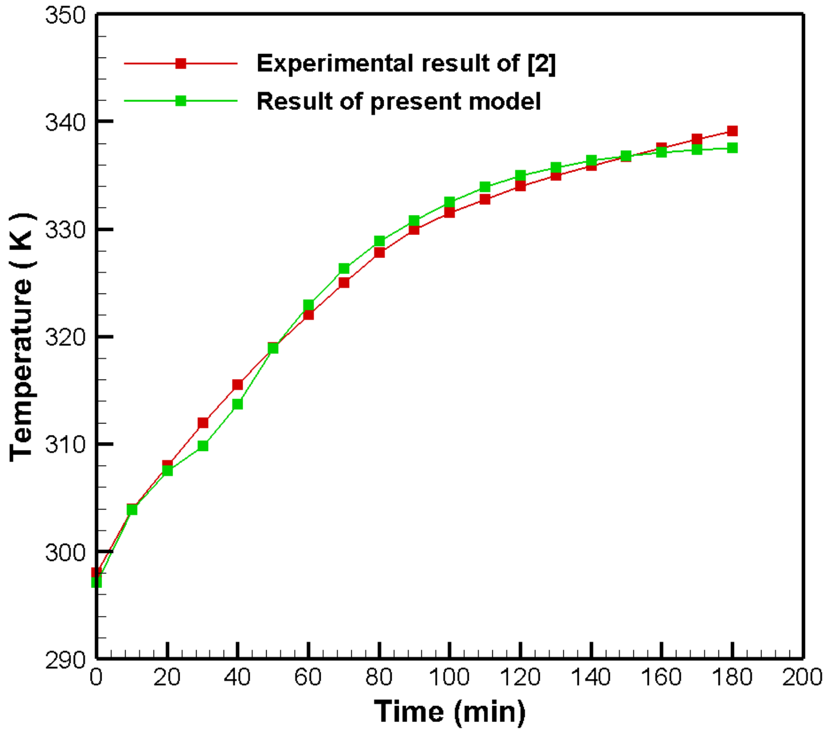






(c)

Fig. 2. Temperature profiles : (a) square fins heat sink, (b) triangular fins heat sink, (c) circular fins heat sink



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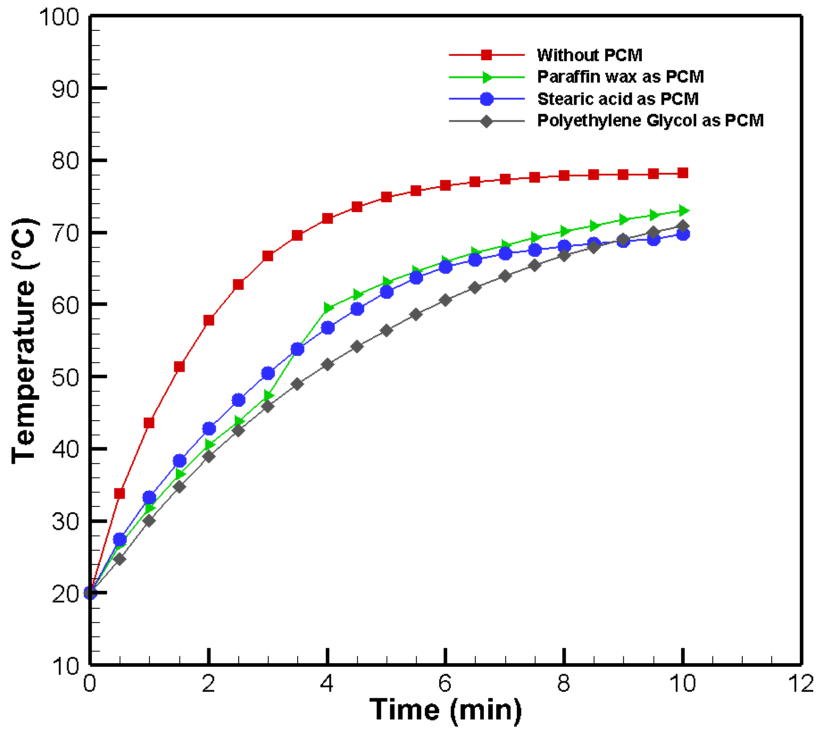

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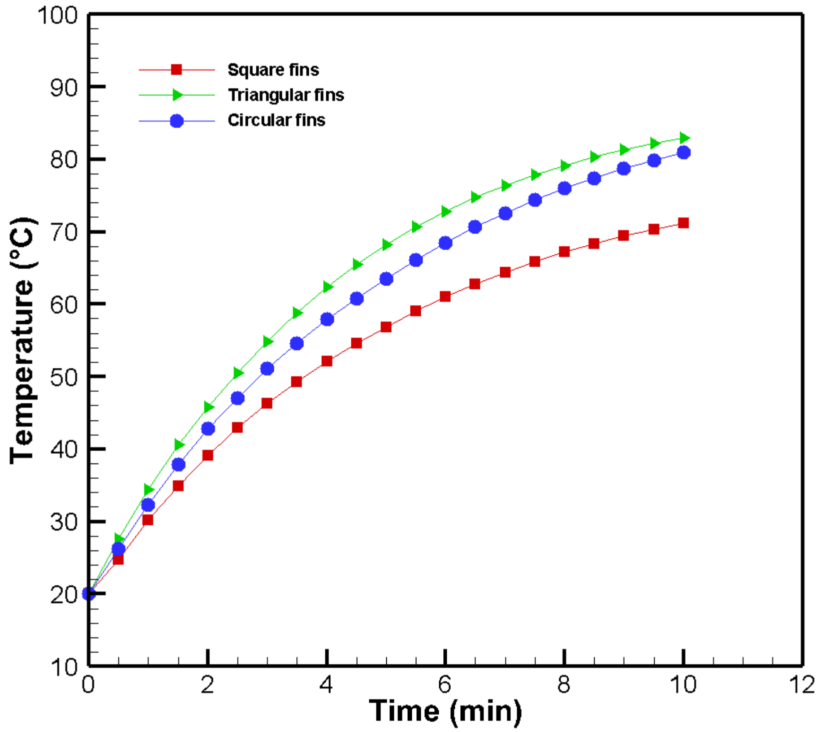

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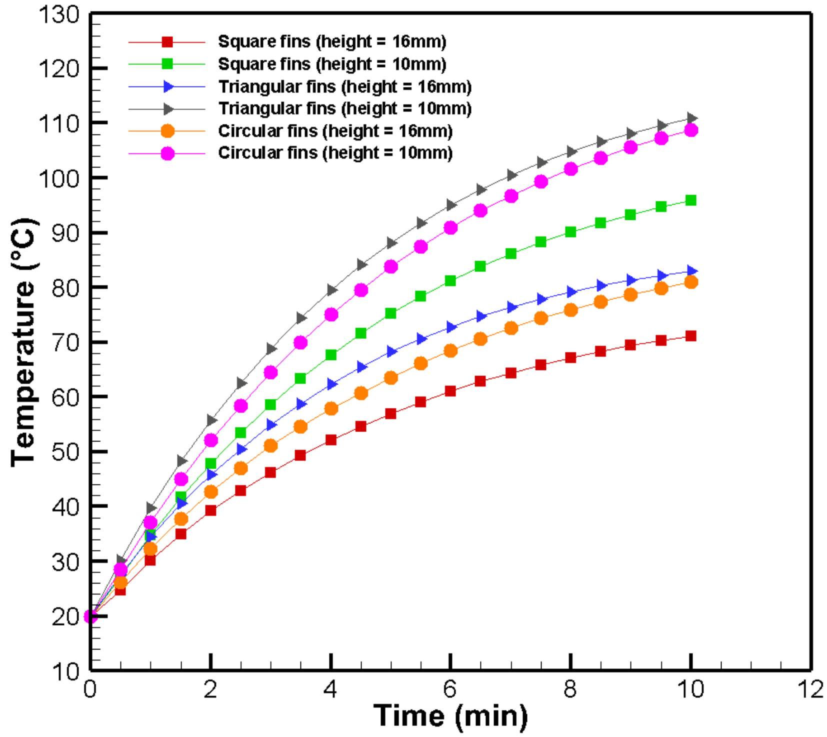

Fig. 6. Temperature vs time graph of heat sinks for three types of fins with a height of 16 mm and 10 mm

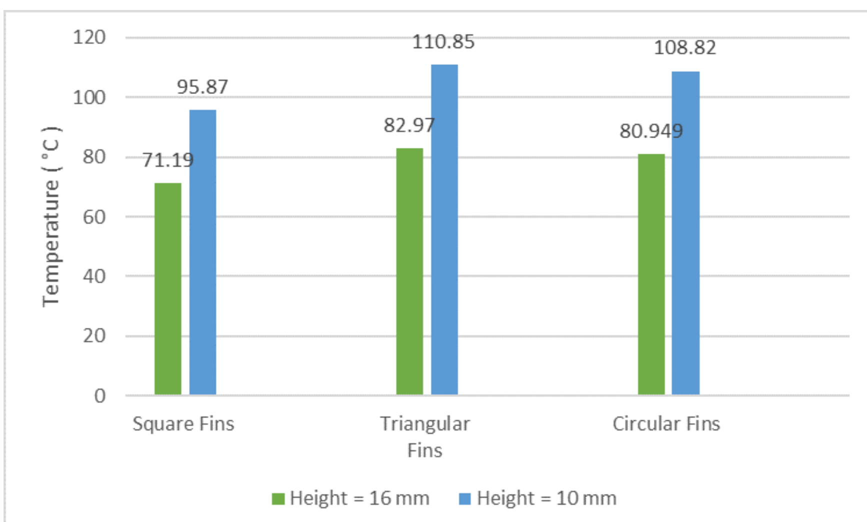

Fig. 7. A column chart showing the temperature of different types of heat sinks with a height of 16 mm and 10 mm

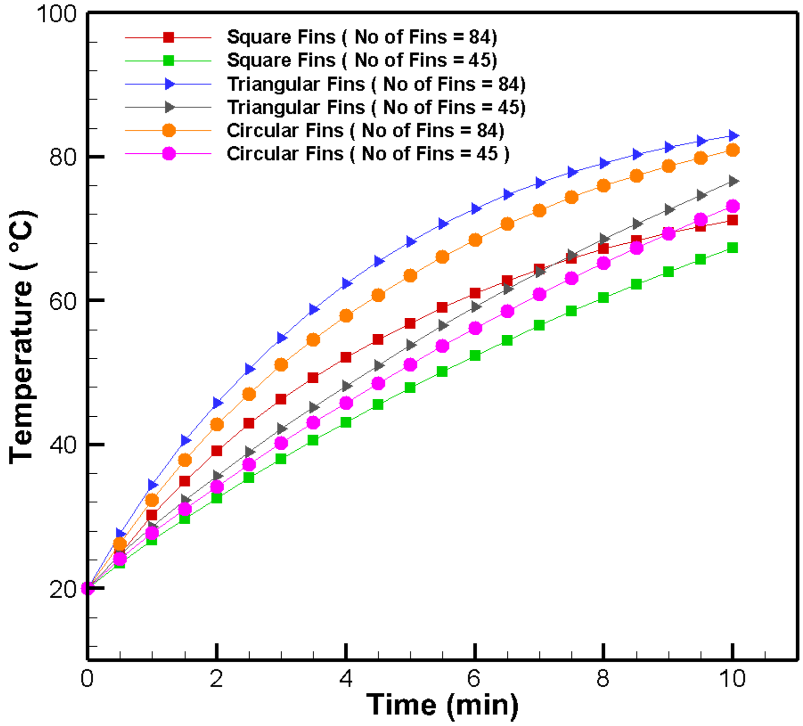

Fig. 8. Time-temperature curve of three types of heat sinks with a fin number of 84 and 45 using polyethylene glycol as PCM

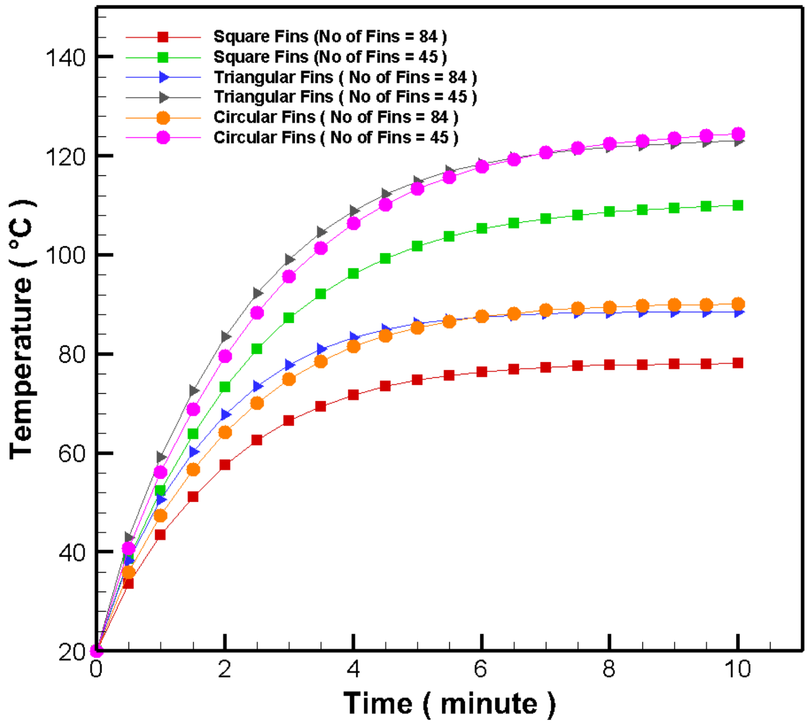

Fig. 9. Time-temperature curve of three types of heat sinks with a fin number of 84 and 45 without PCM