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Numerical Study of Nano Enhanced PCM Incorporated Heat Sink with Wavy Shaped Plate Fins

Abstract

Modern electronics with increasing compactness require superior cooling/heat removal from its components. With the introduction of PCM-based heat sinks, the cooling of the electronic components in transient applications has been developed. In this study, an analysis of the heat extracted from the electronic device is conducted for a heat sink with internal cavities filled with Phase Change Material (PCM) nano enhanced with copper oxide (CuO) nano particles i.e. NePCM. Focus of this study is the exploration of novel cavity geometries to maintain electronic devices at their optimum operating temperature. Parametric investigative approach of the melting of NePCM in a heat sink in which the partitions of cavities are wavy plate fins. The heat sink is numerically studied to find the best suited cavity count and fin height for practical use. Two-dimensional continuity, momentum, and energy equations are used for finding out the difference in performance between conventional heat sink without PCM and heat sink with NePCM. Computational parameters such as number of cavities and height of fins are varied. A constant heat flux of 10,000 W/m^2 is applied to bottom of the PCM-filled heat sink and the value of convective heat transfer coefficient is kept at 10 W.m^{-2}.K^{-1} for the calculation. The results show that the use of nano enhanced PCM between the cavity of the fins in heat sink makes it more effective due to the joint effect of convection in the PCM melt and natural convection from the heat sink compared to conventional heat sink. In PCM filled heat sinks, with the increase in number of cavities for the same PCM volume, the effectiveness of the heat sink will increase due to faster melting rate of PCM. Increment in height of the PCM filled heat sink causes a negligible increment of volume of PCM and the contact area between the PCM and the fins also increase, which results to a lesser temperature increase in the sink.

Article Info:

1. Introduction

The miniaturization and development of newer power intensive processors, integrated circuits, MOSFETs and LED lights has led to the need of maintaining these devices at their optimum operating temperature. Resultant increase in the heat flux greatly reduces the capabilities and life of the electronics [1]-[2]. Hence, continuous efforts are being made to provide them with optimal cooling performance for ensuring better performance and longer operational life. The conventional method of passive cooling of these electronic components by natural convection from heat sinks and heat pipes have been deemed insufficient owing to large heat load [3].

Existing cooling systems are usually active coolers, incorporating forced convection inducing fans and circulation pumps [4]-[8]. Recently there has been emergence of thermoelectric coolers operating using Peltier effect [9]. But both the types of cooling devices use external power and are often cumbersome. Moving parts give rise to vibrations and undesirable noise and are maintenance intensive. For the afore mentioned drawbacks the need for the development of better performing cooling systems. In this quest PCM incorporating heat sinks can be instrumental in addressing the challenge of maintaining electronics devices and components at their optimal temperature. The high latent heat of fusion of PCMs has promoted it amongst researches to be used in electronics cooling apparatuses [10]-[14]. PCM was first introduced as coolant in electronics by NASA for the robotic arm of spacecrafts [15]-[17]. PCMs absorb and hold high amount of latent heat during melting and releases it back on freezing. This absorption high latent heat can become instrumental in developing better heat sinks with ability to vent off heat at a faster rate. Phase Change Materials (PCM) inherently also have high specific heat, high stability after repeated charging and discharging cycles. The afore mentioned properties contribute in maximized heat storage, low expansion on heating, repeated use over a long duration of time and predictable freezing behavior owing the property of thermal stability even after numerous cycles of melting and freezing. With also these positive qualities suffers from low thermal conductivity, hindering faster heat conduction.

To address this problem, two types of approaches has been undertaken. One is using Thermal Conductivity Enhancing structures (TCE) and by addition of nanoparticles to pure PCM. Baby et al. compared heat sinks having pin and plate fins with and without PCM [18]. Results showed that the finned heat sink incorporating PCM performs better than the one without PCM and fin. Heat sinks with PCM filled cavities was experimented with by Kalbasi et al. [19]. Results revealed that fins aided in the melting of the PCM. Bhuyian et al. from his study on various shapes of cavities of heat sinks concluded that the cavity with maximum PCM holding capacity performs the best [20]. It is applicable for enclosed parts with lower convection rate. Plates finned heat sink was studied by Deng et al. varying in pitch and cavity thickness [21]. More fins lead to increased thermal performance and ability to operate longer. Heat sink with fins extending above the PCM led to more natural convection and longer operation time [22]. In a similar study by Bayat et al. found out that heat sinks with plate fin and PCM are more responsive to change sin heat flux coming from electronic components [23]. In other method to improve thermal conductivity of PCM nanoparticles are added. Vitorino et al. added 10% graphite to paraffin wax to achieve better thermal conductivity [24]. Similarly other nanoparticles of CuO, silver, Sci.Si3N4, were used by various researchers [25]-[29].

The numerical study of novel PCM containing heat sink was envisioned and pioneered by and numerically presented by Shatikian et al. [30]-[31]. The formulation attempted in calculating the unsteady velocity and temperature inside the domain by solving the conservation equations of energy, continuity, and momentum. This has since been a standard approach for numerical simulations.

In recent years, several studies have reported the application of PCM based heat sink to address the problem of overheating in electronic devices. In these studies, PCM have been placed inside the heat sink in varied quantities [18]-[20]. PCM is either enclosed within the heat sink or kept in open cavities, built in the heat sink. Balaji et al. experimentally studied constant heat input with intermittent heat load applied to PCM based heat sink and the results showed that size of PCM based heat sink under intermittent load is smaller than that of under continuous heat [2]. Signifying need for increased cavity size. Ramesh et al. proposed the develop a heat sink for the LED array cooling using heat sink with PCM and concluded that 10mm or more cavity width increases the melting rate of PCM in the heat sinks [3]. Kalbasi et al. proposed a hybrid heat sink with air and PCM in alternate cavities of the heat sink to increase natural convective heat transfer. With a convective heat transfer coefficient (h) equal to 10Wm−2K−1, natural convection performs better than forced convection (higher value of h). Ambient temperature plays an important role in PCM's ability to absorb and store thermal energy in case of forced convection system; hence natural convection is places with everchanging ambient temperature [4]. Heat sink with PCM has better cooling efficiency for longer usage under both free and forced convection system whereas the heat sink with nano PCM is preferable for intermittent and temporary usage [4]. Nazir et al. compared different PCM for energy storage based on thermo-physical properties like melting point, thermal energy storage density. The results showed that for enhancing PCM qualities and properties, encapsulation and using nanomaterial additives are the two best ways because protection from environment, corrosion, energy storage compatibility can be achieved by these two methods [5].

Mozafari et al. experimented using both single and multiple PCM heat sink for electronic device cooling revealing that multiple n-eicosane based heat sink has better operational performance than single n-eicosane based heat sink for prolonged operational hours by 4%-12% [6]. Farzanehnia et al. investigated the thermal management of nano-PCM heat sink and found that chipset's peak temperature increases while operating at constant power [7]. Mahmoud et al. studied PCM based heat sink behavior during charging and discharging process using different fin-types. It was found that the parallel rectangular plate fin arrangement with six cavities performed better in charging process by absorbing more heat but in contrast the honeycomb patterned heat sink exhibited more efficient discharging with a short heat rejection time [8]. Hence shapes close to the honeycomb pattern are expected to exhibit improved discharging property. Kozak et al. performed a compared PCM filled heat sink and hybrid heat sink from which the paper was concluding that under high power load, PCM based heat sink performs better [9]. Hosseinizadeh et al. studied the application of a PCM-based heat sink for cooling computer chipset, revealing that increasing the number of fins and fin height results in a significant increase in overall thermal performance whereas increasing the fin thickness only leads to negligible improvement in thermal performance. There is a critical fin thickness equal to 4 mm and beyond this opting for a thicker fin will not lead to further improvement of thermal performance [10]. Having same geometry, the Nusselt number and melt fraction depend on the product of the Fourier and Stefan numbers [3].

From the literature survey it can be identified that heat sinks containing PCM can outperform conventional heat sinks in heat removal performance. Natural convection is more advantageous than forced convection being free of external power need, scalable and requiring least maintenance. The shape and arrangement order of the cavities influence the thermal performance, while the nanoparticle addition enhances the thermal conductivity of the PCM. The proposed system can respond to both constant and intermittent heat loads.

The current work is aimed at mitigating the limitations of current cooling systems for electronics, and solve continuity, momentum, and energy equations for the melting of PCM, neglecting for PCM expansion [16], convection in the fluid media (melted PCM and air), and solid phase motion in the liquid. This approach has been implemented successfully in the previous study by Shatikian et al., where the numerical study of melting and solidification of PCM for a chosen geometry, namely a heat sink having vertical plate fins [30]. Details of transiting temperature and phase is obtained as functions of time, showing evolving melt fraction of the PCM. In the current numerical study, the approach is of a parametric investigation of melting in a compact heat sink, with a nano-enhanced PCM stored between the fins. Based on this the best performing heat sink is numerically studied to find the best suited cavity height for practical use. The heat sink is tested for extracting heat from an electronic component working at constant power [32]-[41]. The shapes of the fins considered in this study are wavy. These cavities between the fins are filled with paraffin nano enhanced with copper oxide (CuO) nano particles.

2. Methodologies

2.1. Problem Discussion

A processor cooling unit with wavy shaped plate fins has been shown in Fig. 1 showing the length (L), width (W) and height (H). The value of length (L) and width (W) equals to 120mm and 120mm respectively. Constant heat flux is applied from the bottom of the plate. The cavity between the fins are filled with Phase Change material. The pcm used in this present study is paraffin and CuO nanoparticles have been dispersed as thermal conductive enhancer. Considering heat will only flow in the x, y direction, two-dimensional domain has been taken. Fig 2(b) labels the two dimensional computational domain by a length (L), height of fins (HF), thickness of fins (TF), thickness of cavities (TC), thickness of bottom plate (TP) and amplitude of wavy fins (A). In this study, the thickness of the bottom plate (Tp) and the amplitude of the wavy fins (A) are taken as 5mm and 1 mm respectively. Firstly, a comparison has been made between a conventional heat sink and a heat sink with nano-enhanced PCM enclosed between the wavy plate fins. To identify the optimal geometry of the nano-enhanced PCM filled heat sink the number of PCM filled cavities (N) has been varied keeping the volume of the PCM constant. So, the thickness of the fins are also changed accordingly. Table 1 represents the dimensions of the heat sinks with different number of cavities. The height of fins (HF) have also been varied with 40mm, 45 mm and 50 mm height. The %wt composition of CuO dispersed in paraffin is taken as 3% in this study [42].

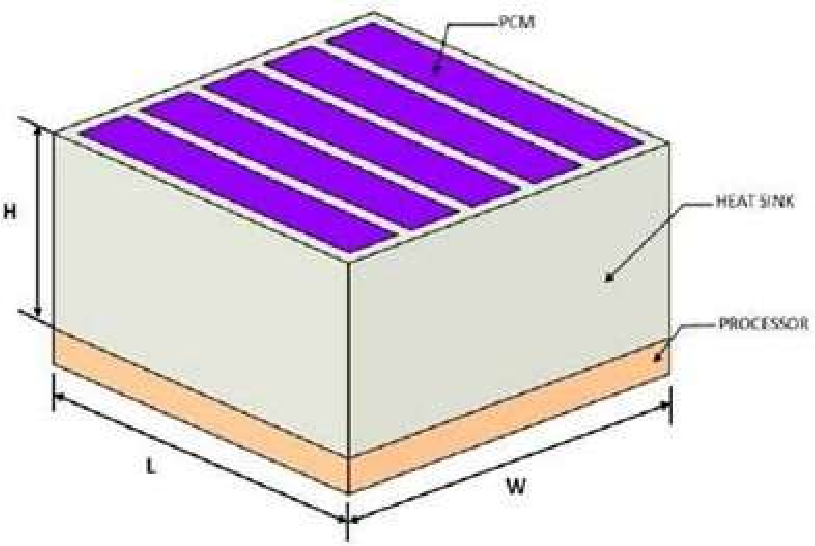
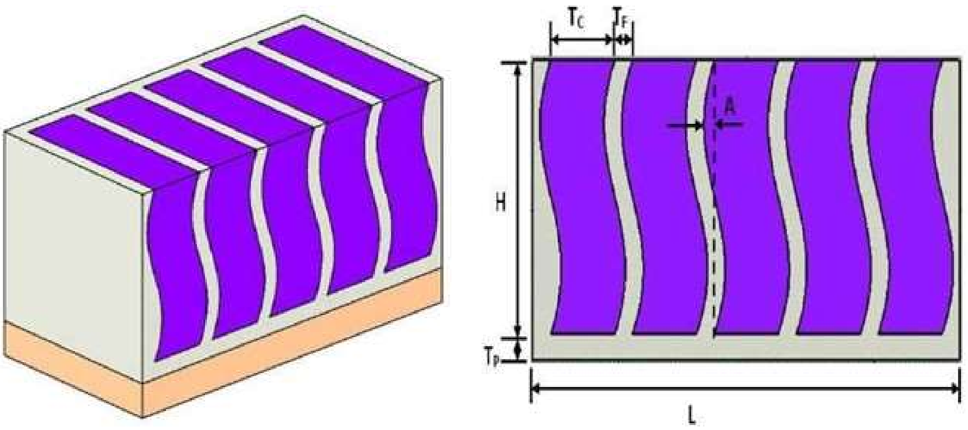


Figure 1. Isometric view of processor cooling unit.



(a) (b)

Figure 2. Processor cooling unit (a) Side view (b) Cross-sectional view

Table 1. Dimensions of the heat sinks with different number of cavities

Number of Cavity	Total Width of Cavity	Width of each cavity (Wc) (mm)	Number of Fins	Width of each Fins (Wt) (mm)
3	90	30	4	7.5
5	90	18	6	5
7	90	12.857	8	3.75

2.2. Governing Equation and Boundary Conditions of Mathematical Modelling

In this present work, the transient phase change of PCM has been simulated as 2D, laminar, incompressible flow. The Boussinesq approximation is used to simulate the buoyancy force term. In this present work, volume change is ignored during the PCM phase change process. The enthalpy porosity method is used for modelling the melting process of PCM. It considers the mushy zone as a porous medium with porosity equal to the liquid PCM volume fraction. Accordingly, the porosity varies from 0 to 1 when the PCM transforms from solid to liquid. Based on the above assumptions, the mathematical model is used as follows: -

The continuity equation:

$$\frac{\partial \rho}{\partial t}+\frac{\partial(\rho u)}{\partial x}+\frac{\partial(\rho v)}{\partial y}=0 \tag{1}$$

The momentum equation:

$$\frac{\partial(\rho u)}{\partial t}+\frac{\partial(\rho u u)}{\partial x}+\frac{\partial(\rho u v)}{\partial y}=-\frac{\partial P}{\partial x}+\frac{\partial}{\partial x}\left(\mu\frac{\partial u}{\partial x}\right)+\frac{\partial}{\partial y}\left(\mu\frac{\partial u}{\partial y}\right)+F_x \tag{2}$$

$$\frac{\partial(\rho u)}{\partial t}+\frac{\partial(\rho u v)}{\partial x}+\frac{\partial(\rho u v)}{\partial y}=-\frac{\partial P}{\partial y}+\frac{\partial}{\partial x}\left(\mu\frac{\partial v}{\partial x}\right)+\frac{\partial}{\partial y}\left(\mu\frac{\partial v}{\partial y}\right)+\rho g\beta\left(T-T_{ref}\right)+F_y \tag{3}$$

The energy equation:

$$\frac{\partial(\rho H)}{\partial t}+\frac{\partial(\rho u H)}{\partial x}+\frac{\partial(\rho v H)}{\partial y}=\frac{\partial}{\partial x}\left(\alpha\frac{\partial T}{\partial x}\right)+\frac{\partial}{\partial y}\left(\alpha\frac{\partial T}{\partial y}\right) \tag{4}$$

where ρ is the PCM density, u and v are respectively the superficial velocities in the x and y directions, μ is the dynamic viscosity, P is the pressure, g is the gravitational acceleration, T is the temperature, Tref is the reference temperature taken as 30 °C (the average value of PCM melting point) in this study, β is the thermal expansion coefficient, $\alpha = k/(\rho c_p)$ is the thermal diffusivity, Fx, and Fy are sources terms, and H is the total enthalpy of PCM.

The source terms Fx and Fy in the momentum equations are Darcy Law damping terms accounting for the effect of phase change on convection. They are given as:

$$F_x=-\frac{(1-\xi)^2}{\xi^3+\varepsilon}A_{mush}u \tag{5}$$

$$F_y=-\frac{(1-\xi)^2}{\xi^3+\varepsilon}A_{mush}v \tag{6}$$

Where A is mushy zone constant which is taken as $5\text{x}10^6$ and ε = 0.001 is a small number to prevent division by zero for when ξ = 0, and ξ is the melt fraction.

The melt fraction ξ is calculated in Eq. (7).

$$\xi=\begin{cases} 0\ if\ T\le T_s \\ \dfrac{T-T_s}{T_l-T_s}\ if\ T_s<T\le T_l \\ 1\ if\ T>T_l \end{cases} \tag{7}$$

The total enthalpy of PCM (H) is calculated as the sum of the sensible enthalpy (h) and the latent heat (L)

$$H=h+\Delta H=h+\xi L \tag{8}$$

The sensible enthalpy is defined as:

$$h=h_{ref}+\int_{T_{ref}}^{T}C\rho dT \tag{9}$$

In the current numerical simulation, the boundary conditions applied to the domain under study are as follows: -

(1) A constant heat flux of 10,000 W/m^2 is applied to bottom of the PCM-filled heat sink is given in Equation. (10).

$$-k\frac{\partial T}{\partial y}|_{y=0} = q \tag{10}$$

(2) All the outside walls and top boundary of the PCM containing heat sink is subjected to natural convection. The value of convective heat transfer coefficient and free stream temperature considered in this study are equal to 10 W.m-2.K-1 and 300K respectively. Convection heat transfer at other walls of the heat sink and the top boundary of PCM is calculated as:

$$-k\frac{\partial T}{\partial n} = h(T - T_{amb}) \tag{11}$$

where T_{amb} is the ambient temperature.

(3) Coupled boundary conditions has been applied at the interface between fin and PCM surfaces which is defined as:

$$-K_{fin}\frac{\partial T_{fin}}{\partial \mathrm{n}} = -K_{PCM}\frac{\partial T_{PCM}}{\partial \mathrm{n}} \tag{12}$$

$$T_{fin} = T_{PCM} \tag{13}$$

where n is the normal vector of interfaces.

(4) No-slip condition is assumed at the walls and is given as:

$$u = 0, v = 0 \tag{14}$$

2.3. Numerical Methods

The two-dimensional continuity, momentum, and energy equations in the solid PCM along with the energy equation of the solid walls are used for the numerical simulation. The heat sink is made of copper. Nano enhanced Phase Change Material (NePCM) has been incorporated in the computational model as a heat storage material in the heat sink with constant thermo-physical properties such as thermal conductivity k, density ρ and viscosity μ. The constant property of copper and thermo-physical property of nano-enhanced PCM with respect to temperature have been mentioned in Table 2.

Table 2. Thermo-physical properties of Nano-Enhanced PCM and Copper

Properties	NePCM	Copper
Density (kg/m^3)	1033.6	8978
Viscosity (Pa.s)	0.0470	
Latent heat (KJ/Kg)	115.28	
Thermal conductivity (W/mK)	0.576	387.6
Specific Heat (J/KgK)	2408.34	381
Thermal expansion coefficient	0.00962	
Solidus temperature (K)	331	
Liquidous temperature (K)	335	

The boundary conditions applied to the heat sink for the current study of the different cavities remains same for all the cases. The heat sink is placed over an electronic component producing constant heat flux applied at the base of the heat sink. Nano enhanced PCM (Paraffin wax with 3% CuO nanoparticles) is used as the heat absorbing material with the objective of maintaining the optimum operating temperature of electronic component by removing the heat flux. Initially, the NePCM and the heat sink is at a temperature T in equal to 300 K. At the solid-fluid interface, no slip conditions with same temperature and conductive flux at the solid-fluid interfaces have been applied.

The ANSYS 16 Fluent solver has been implemented by finite volume method to solve the governing equation along with the boundary conditions. The numerical solution is carried out with SIMPLE algorithm. The pressure correlation for the simulation was done by PRESTO scheme. Third order upwind MUSCL scheme has been selected for the discretization of the momentum and energy equations. In the iteration the 0.9,0.3, 0.7 and 1.0 relaxation factors for density, pressure, velocity, and temperature respectively are chosen. Residual values of 10−6 and 10−9 respectively for momentum and energy conservation equations respectively are chosen as the convergence criteria of the numerical solution. Three different grid sizes equal to 600×275, 240×110, and 120×55 were chosen for performing the grid independency test for the computational domain. The time step size for the computation was chosen to be equal to 0.1 sec [1]. For the study, double precision, parallel computations with 20 numbers of processor cores were performed in a workstation with Intel Xenon silver CPU operating at a frequency of 2.5 GHz, and 64 Gb of RAM.

2.4. Validation

For validation, the above numerical results for PCM melting in an enclosure equipped with three horizontal fins are compared to the experimental study conducted by Kamkari et al. and numerical investigations conducted by Karami et al. as shown in Fig. 3 [43]-[44]. The enclosure is 120 mm in length and 50 mm in breadth. The thickness of the aluminum fin base is equal to 5 mm. The length and thickness of the 3 straight fins are equal to 25 mm and 4 mm respectively. The base of the fin in the right extreme of the domain is isothermally heated at 333 °K, with the remaining walls being insulated. The PCM is initially at 300 °K. These studies used lauric acid (99% pure) as phase change material with melting temperatures ranging between 43.5-48.2 °C. The results reveal that the simulations of PCM melting in a vertical rectangular enclosure heated from a sidewall closely agrees with prior experimental and computational results.

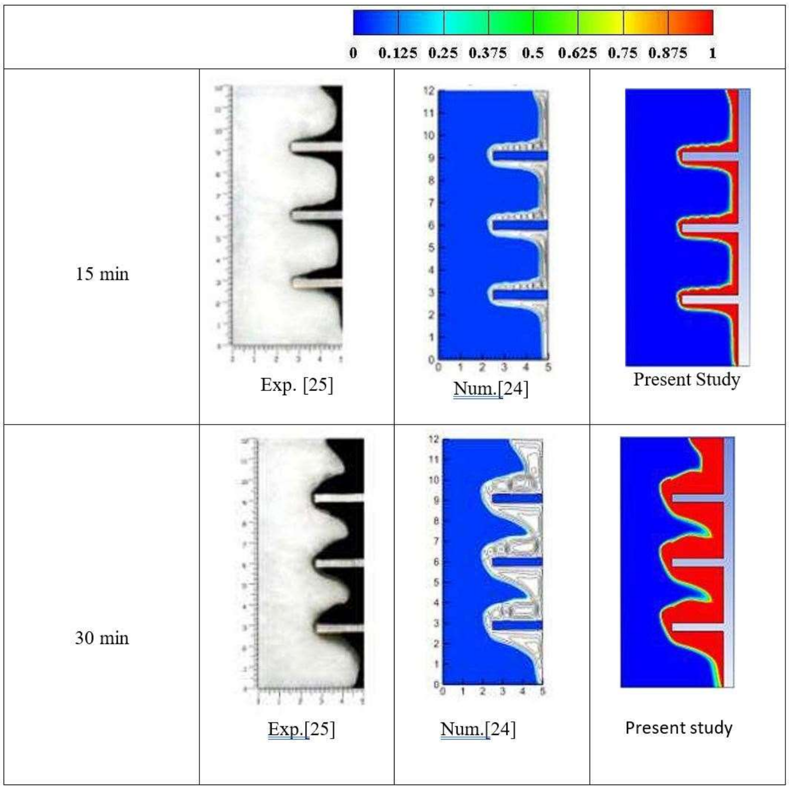


Figure 3. Validation of liquid fraction contours in the three-fin enclosure with prior experimental and numerical investigations [43,44].

2.5. Mesh Independency Test

In the mesh independency study, 1 mm, 0.5 mm, and 0.2 mm element sizes corresponding to grids (120 × 55), (290 × 110) and (600 × 275) are used as shown in Table 3. The graph in Figure 4 shows the variations in liquid fraction and temperature with respect to time for three different grid sizes. In the graph the plots for respective grids nearly overlapped. Therefore, to make calculations easier and faster the grid size of (290 × 110) with total elements equal to 26,400 is selected for numerical investigation.

Table 3. Mesh Independence Test Parameters

Grid	No. of elements
240×110	26,400
600×275	1,65,000
120×55	6,600

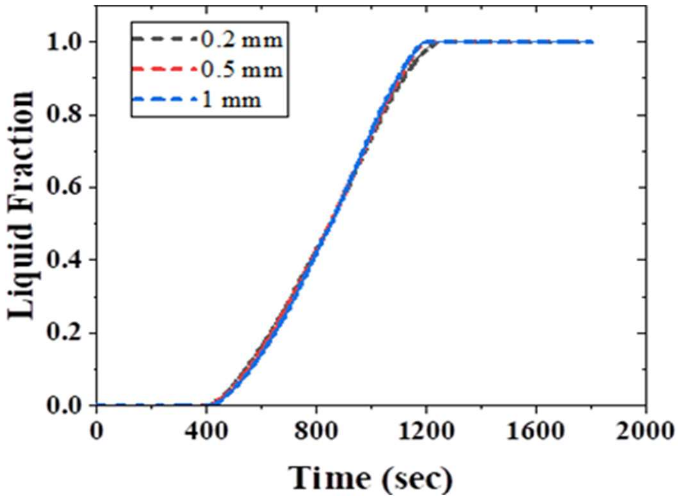


Figure 4. Mesh independency test for 5 cavity heat sinks with PCM enclosed between wavy shaped fins

3. Results and Discussion

The simulation results provide a comprehensive insight into the thermal performance of wavy finned heat sinks filled with nano-enhanced phase change materials (NePCM) compared to conventional designs. A detailed thermal analysis revealed that the incorporation of paraffin-based NePCM with CuO nanoparticles significantly enhances heat dissipation due to the synergistic effects of latent heat absorption and improved thermal conductivity. Comparative studies show that while the conventional heat sink reaches temperatures as high as 438 K after 30 minutes of operation, the NePCM-based counterpart maintains much lower temperatures, around 381 K, under identical conditions. This substantial temperature reduction is attributed to the latent heat storage capacity of PCM, which effectively delays temperature rise by absorbing thermal energy during the melting process. Furthermore, varying the number of cavities within the heat sink structure while keeping the total volume of PCM constant demonstrates that increasing the number of cavities (from 3 to 7) markedly improves thermal performance. This is due to the increase in contact area between the PCM and fins, which accelerates the melting process and allows for more efficient thermal regulation. Among the configurations tested, the 7-cavity heat sink outperformed others, reaching a lower peak temperature and achieving a higher melt fraction over the same time span. Additionally, increasing the fin height from 40 mm to 50 mm further improves thermal performance, offering larger PCM volumes and extended contact surfaces for heat absorption. The 50 mm-high configurations exhibited the lowest temperatures throughout the simulation, validating the design's superior capacity for thermal storage and dissipation. These findings conclusively demonstrate that geometry optimization—through cavity count and fin height—plays a critical role in maximizing the effectiveness of NePCM-integrated heat sinks, positioning them as a robust solution for thermal management in compact, high-power electronic systems.

3.1. Comparison between heat sinks with and without nano-enhanced PCM

To study the effect of using nano-enhanced PCM in the heat sink, a comparison has been drawn between heat sinks, one conventional heat sink and another with nano-enhanced PCM enclosed between the wavy plate fins.

After a duration of 15 min and 30 min heat sink temperature is compared. Figure 5 shows the temperature contours of the heat sinks after 15 min and 30 min. From the results, the conventional heat sink has reached to an average temperature of 398.6 K (125.44° C) and 438.02 K (164.86° C) after 15 min and 30 min respectively. The bottom wall temperature of the heat sink was 399.88 K (126.72° C) after 15 min and 439.37 K (166.21° C) after 30 min.

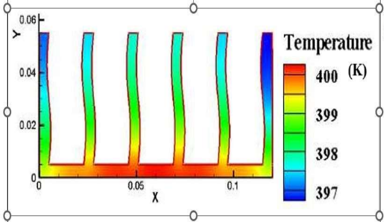
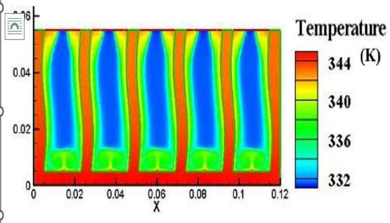
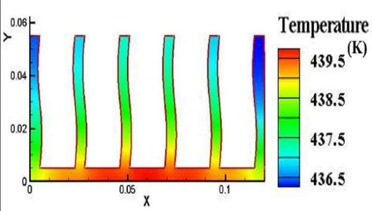
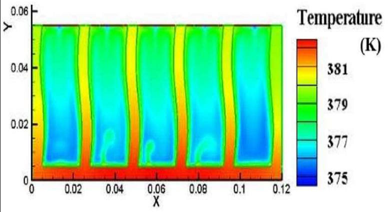
Time	Heat Sink without PCM	Heat Sink with PCM
15 min		
30 min		

Figure 5. Comparison between Conventional and nano-enhanced PCM heat sinks

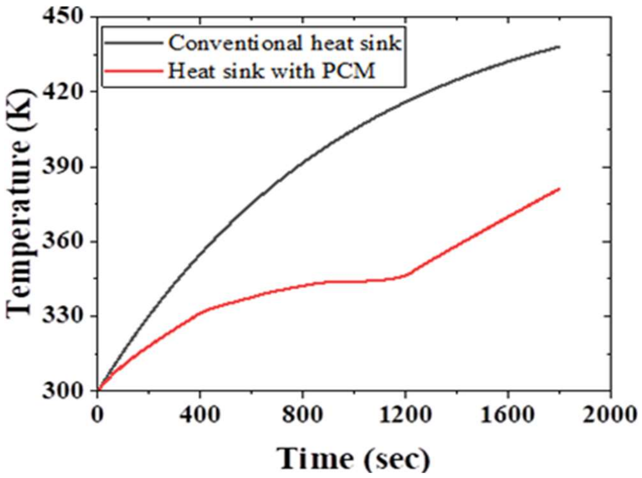


Figure 6. Temperature vs time curve of Conventional heat sink and Heat sink with PCM

Conversely, the sink with NePCM at a similar duration of 15 min and 30 min is seen to attain an average temperature of 343.67 K (70.51° C) and 381.079 K (107.9° C) respectively. The bottom wall temperature of the heat sink was 344.58 K (71.42° C) and 382.17 K (109.01° C) respectively after 15 min and 30 min. Fig 6 shows the temperature variation with time in the heat sinks. From the graph, it can be easily identified that the use of PCM in between the fins are more effective to keep the system cool. The variation in the bottom wall temperature and average temperature attained by the conventional and NePCM incorporated heat sink can be attributed to the presence of PCM that absorbs heat energy and stores it in form of latent heat. In conventional heat sinks the heat transfer solely depends on the natural convection. But, in case of PCM filled heat sinks the combined effect of natural convection and heat absorption by the PCM performs the task of cooling down the heat sink. A significant part of the heat flux coming from the base of the heat sink gets expended in melting the PCM. This phenomenon compliments the natural convention. Resultantly, temperature rise in the PCM filled heat sink is much lower, which makes it a better solution for heat dissipation challenges, by distribution of heat to the upper regions of the heat sink and maintaining a better thermal potential difference towards the base of the heat sink.

3.2. Comparison between heat sinks with different number of cavities

To identify the best geometry of the NePCM incorporated heat sink, the number of cavities between the fins has been varied keeping the volume of the PCM constant. The width of the wavy plate fins is also varied accordingly.

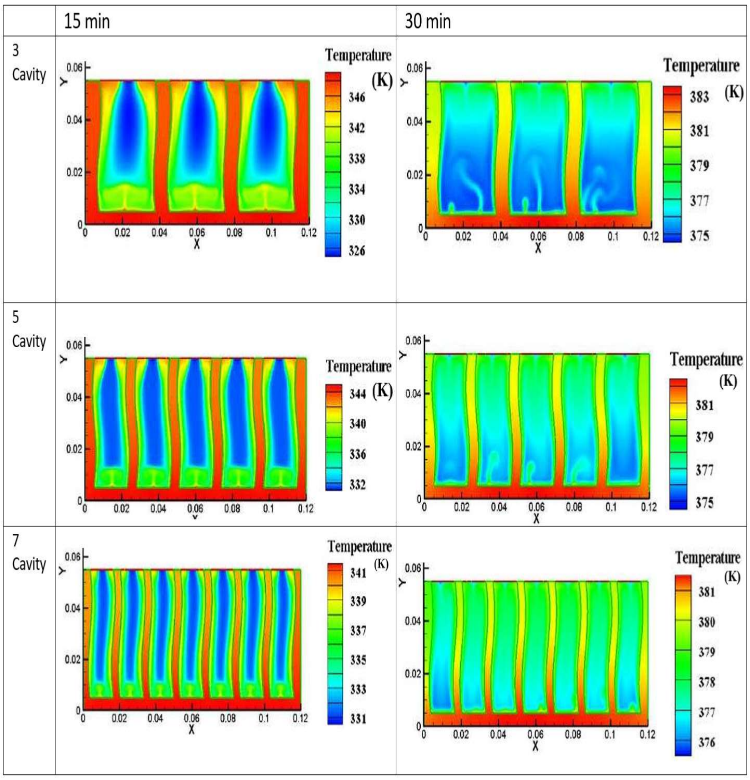


Figure 7. Temperature contours of heat sinks with different number of cavities

The numerical simulation has been performed for 30 minutes. Figure 7 and 8 represents the Temperature and Liquid Fraction contours after 15 minutes and 30 minutes. Result shows that the heat sink with 7 number of cavities gives the best result. After 15 min and 30 min the average temperature of the 7-cavity heat sink are 340.97 K (67.81° C) and 380.78 K (107.62° C) respectively. The bottom wall temperature of the heat sink after 15 min and 30 min are 341.86 K (68.7° C) and 381.86 K (273.16° C) respectively.

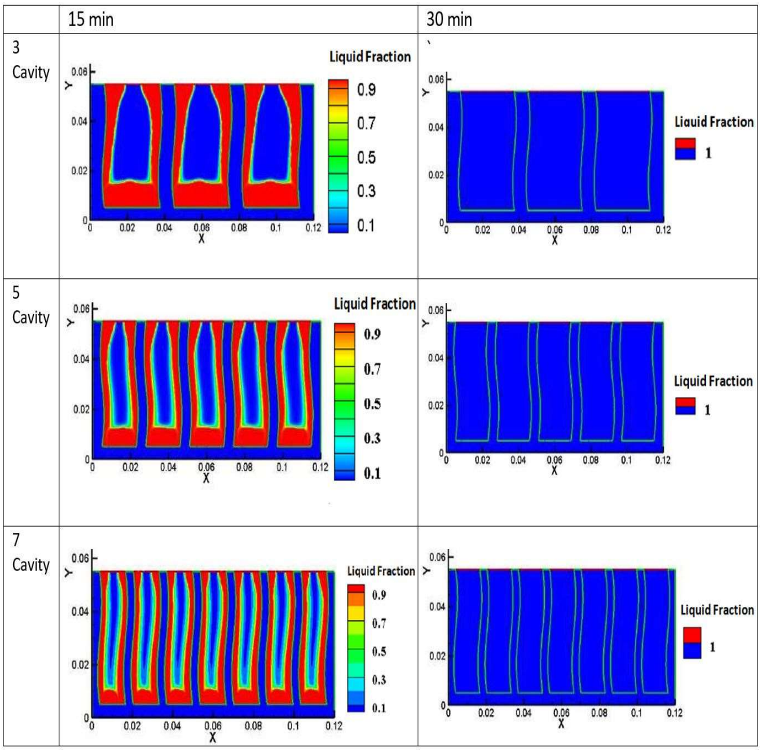
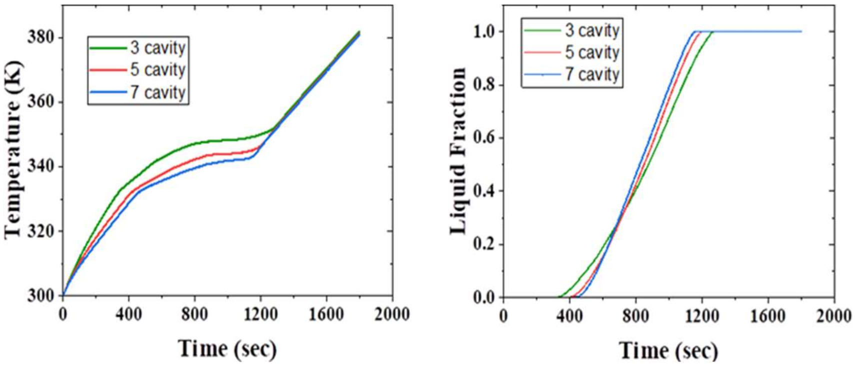


Figure 8. Liquid Fraction of heat sinks with different number of cavities

For 3 and 5 cavity heat sinks, the average temperature reaches 347.86 K (74.7° C) and 343.67 K (70.51° C) after 15 min and 381.72 K (108.56° C) and 381.07 K (107.91° C) after 30 min. The bottom wall temperature of the 3-cavity heat sink is 348.87 K (75.71° C) after 15 min and 382.88 K (109.72° C) after 30 min. For the 5-cavity heat sink the bottom wall of the sink attains a temperature of 344.58 K (71.42° C) and 382.17 K (109.01° C) after 15 min and 30 min respectively. Figure 9 represents the temperature and liquid fraction variation with time in heat sinks with different number of cavities.



(a) (b)

Figure 9. Graphs of heat sinks with different number of cavities. (a) Temperature variation (b) Liquid Fraction

The 7-cavity heat sink performs better because of the increased contact area between the fins and the NePCM. Hence, melt fraction of PCM increases for the same time duration as compared to heat sinks with lesser number of cavities, which absorbs more amount of latent heat. The heat sink with 7 cavities is capable of providing more heat to the PCM for melting. Hence, the heat removal capacity of the 7-cavity heat sink is better.

3.3. Comparison between 7 cavity heat sinks with different heights

From the above simulations, it can be seen that the 7 cavity heat sinks are giving best results. To study the effect of the height of fins (HF), the height of the 7 cavity heat sink is varied with 40 mm, 45 mm and 50 mm values. Figure 10 and 11 represent the temperature and liquid fraction contours of the different heat sinks after 15 min and 30 min.

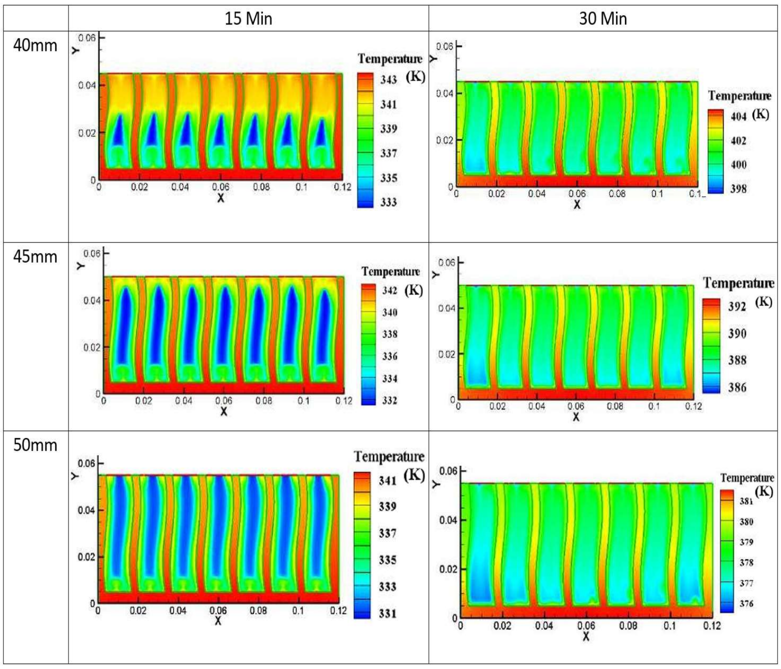


Figure 10. Temperature contour of 7 cavity heat sinks with different heights

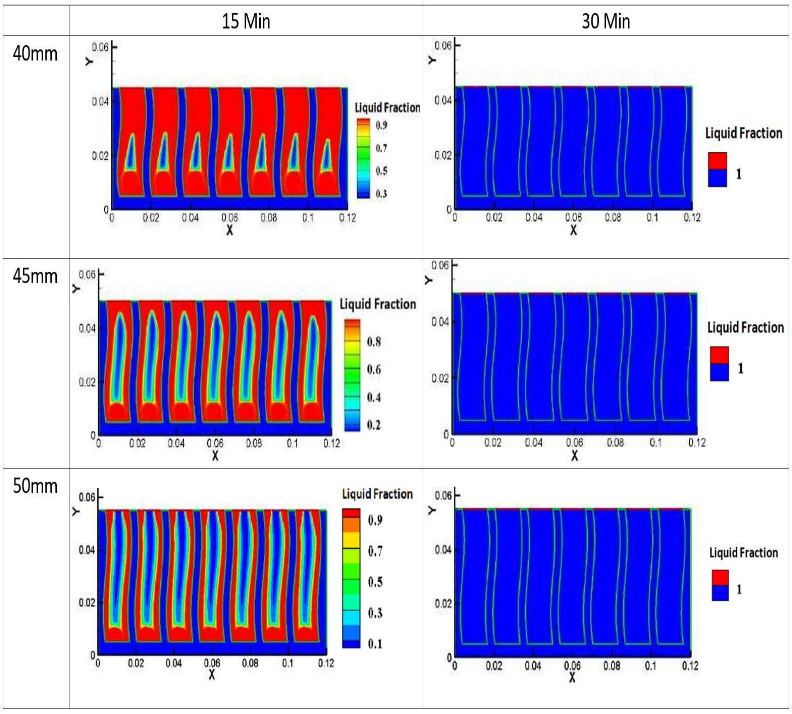
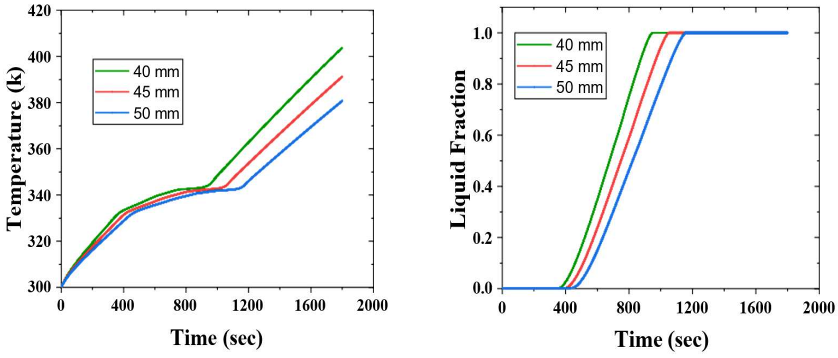


Figure 11. Liquid Fraction contour of 7 cavity heat sinks with different heights

Results shows that the average temperature of the heat sink with 50 mm height after 15 min and 30 min are 340.97 K (67.81° C) and 380.78 K respectively. The bottom wall temperature after 15 min and 30 min are 341.86 K (68.7°C) and 381.86 K (108.7^{O}C) respectively. Figure 12(a) shows the temperature vs time plot for the different height heat sinks. From the graph it can be clearly seen that the heat sink with maximum height (50 mm) attains a much lower temperature than the other heat sinks for the whole simulation time.

The average temperature and bottom wall temperature of the 40mm height heat sink was 343.27 K (70.11° C) and 343.9 K (70.74° C) after 15 min and 403.77 K (130.61° C) and 404.61k (131.45°C) after 30 min. For the 45mm height heat sink the average temperature after 15 min and 30 min was 342.19 K (69.03° C) and 391.24 K (118.08° C) respectively and bottom wall temperature was 342.99 K (69.83° C) and 392.21K (119.05°C) respectively. Figure 12(b) shows the liquid fraction variation with time for the different height heat sinks.



(a) (b)

Figure 13. Graphs of 7 cavity heat sinks with different heights (a) Temperature variation (b) Liquid fraction

The heat sink with maximum height is giving the best result because in that heat sink the volume of PCM is more and the surface contact area between the PCM and the fins are also more. Due to this dual advantage, the PCM between the fins absorbs the heat faster and also capable of storing more heat. That’s why the heat sink with maximum height is capable of keeping the system temperature less than that of the other heat sinks for all the time as indicated from the temperature vs time curve.

4. Conclusions

A two-dimensional numerical study has been performed to find the optimal geometry of nano enhanced PCM incorporated wavy shaped plate fin heat sink, applied with a constant heat flux from the bottom. The conventional and nano-enhanced PCM filled improved heat sink have been compared to study the effectiveness of the use of nano-enhanced PCM in cooling apparatuses. Keeping the volume of the PCM constant the number of cavities on the heat sink has been varied. The effect of the height of heat sinks has also been studied. The major conclusions of the analysis are listed below:

(a) The use of nano enhanced PCM between the cavity of the fins in heat sink are very much effective than conventional heat sink. In PCM filled heat sink the heat coming from the bottom are expended to melt the PCM. So, temperature rise is slow. Besides, this natural convection at the outside walls is also present. This joint effect of PCM melting and natural convection makes it much better than conventional heat sinks.

(b) In PCM filled heat sinks, if the number of cavities increases keeping the PCM volume same, the effectiveness of the heat sink will increase. As, if the number of cavity increase, the contact area between the PCM and the fins increase, resulting the faster melting of the PCM, which keeps the temperature of the heat sink less.

(c) When the height of the PCM filled heat sink is increased, the volume of PCM and the contact area between the PCM and the fins also increase, resulting to a lesser temperature increase in the sink. Because the heat supplied from the bottom is absorbed by the PCM in a faster manner due to the increased surface area and the amount of heat absorption capacity also increased due to the higher volume of the PCM.