EXPERIMENTAL INVESTIGATION OF THERMAL PERFORMANCE OF NANO-ENHANCED PHASE CHANGE MATERIALS FOR THERMAL MANAGEMENT OF ELECTRONIC COMPONENTS

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ABSTRACT
Present experimental investigation focuses on implementing passive cooling thermal management technique using heat sinks filled with paraffin wax as phase change material (PCM). Al₂O₃ nanoparticles are dispersed as thermal conductivity enhancer (TCE) in different weight fractions (φ) for improved performance in the PCM. Unfinned and two finned heat sinks are used in this investigation. Experimental analysis is performed on different configurations of heat sinks and nano-enhanced phase change materials (NePCMs) consisting various weight fraction of Al₂O₃ nanoparticles (φ=0%, 0.5%, 4%, and 6%) for a constant heat flux of 2.0 kW/m². Results show that latent heat and specific heat capacity decreases with increase in the Al₂O₃ nanoparticle loading. Addition of Al₂O₃ nanoparticles in the PCM results in the reduced melting time of PCM. While, pure PCM based heat sinks keeps heat sink base temperature lower for longer time duration.

Keywords: Thermal Management, nano-enhanced phase change material (NePCM), Thermal conductivity enhancer (TCE)

NOMENCLATURE

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
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<tbody>
<tr>
<td>φ</td>
<td>Weight fraction of nanoparticles</td>
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<tr>
<td>ρ</td>
<td>Density</td>
</tr>
<tr>
<td>Cᵦ</td>
<td>Specific heat capacity</td>
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<td>SPT</td>
<td>Set point temperature</td>
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Subscripts

p | Phase change material |
| n | nanoparticles |
| np | NePCM |

INTRODUCTION

Recent technological advancements made electronic devices a key factor in our modern life. Constant need for efficiency and performance is pushing them to their limits. World is moving from big to compact and handy products. Because of miniaturization, the operating temperature of electronic component is increasing. Higher temperature may result in a failure of a component leading to failure of the electronic devices [1]. Hence proper thermal management techniques are necessary for ensuring a long life as well as good performance. Thermal management techniques can be divided into two types that are active and passive cooling techniques.

Active cooling techniques unlike passive cooling technique require external power for functioning. The main advantage of passive cooling techniques over active cooling techniques is the capacity to dissipate heat, reduced power consumption, and small size. Hence, passive cooling technique is chosen in this experiment. Phase change material based latent heat thermal energy storage is more promising and efficient, for passive thermal management, compared to sensible heat energy storage due to its high heat of fusion and isothermal phase transition [1]. PCMs have various advantages such as chemical stability, high storage density and low vapor pressure at the operating temperature, a slight temperature drop during heat recovery and non-corrosiveness [2-8]. Their thermophysical properties remain same after many heating and cooling cycles. [2-8].

Low thermal conductivity of PCMs is the serious challenge to use them for various applications. In order to overcome this problem, thermal conductivity enhancers (TCEs) such as fins [9], metal foams [10] and nanoparticles [11-12] are added in the phase change material (PCM) system. Various studies have been reported in the literature to study the thermal performance of the heat sinks by adding different TCEs [13-20]. Farsani et al. [15] numerically investigated the melting of NePCM in a square cavity.
supplied with constant heat flux from the center. They reported that addition of nano particle in PCM is not recommended for the simulated geometry. Also, they reported that the observation for simulated geometry is contrary to the other geometry in the literature. Bahiraei et al. [16] performed experimental and numerical investigation of carbon based nano enhanced PCM for thermal management application. Authors have used Graphite nano platelets (GNP), Carbon nano fibers (CNF) and Graphite nano powder in the investigation. Authors reported that performance deteriorate with the addition of CNF and GNP. While, the thermal performance enhances with Graphite nano powder.

It is observed from the literature that numerous work have been reported on thermal management of electronic components using PCM and various TCEs such as fins and metal foam. The experimental studies focused on thermal management of electronic components with NePCM based finned heat sinks have not been significantly explored in the literature till date. The aim of the present work is to experimentally investigate the thermal performance of PCM and NePCM in unfinned and two finned heat sinks. An effort has been made in the present investigation to visualize the melting process and obtaining the melting time of PCM with the addition of nano particles.

1.1 Experimental Setup

Fig. 1 shows the schematic diagram of the experimental setup. It consists of various modules such as DC power supply, Data Acquisition System, thermocouples, personal computer and PCM based heat sink assembly. PCM based heat sink assembly includes heat sink container insulated with ceramic glass wool to prevent heat loss to the environment. Unfinned and two finned heat sinks are used in the present investigation as shown in Fig. 2. The heat sink having internal dimensions of 100×100 mm² and 20 mm depth is placed above a plate heater of same dimension and 4 mm thickness. Plate heater is attached to a DC power source (Aplab L3260, 0-30V/0-4A, India) for providing a constant heat flux of 2 kW/m². Paraffin wax is used as the phase change materials. The thermophysical properties of PCM, TCE and insulators are shown in Table 1. Digital Camera (Sony Rx10 MII) is used to capture the melt front at the regular time intervals. Thermocouples (K type) are embedded at different locations of the heat sink, to monitor the overall temperature distribution in the NePCM. Pre calibrated K-type thermocouples with accuracy of ±0.2°C are used to measure temperature at various points of heat sink. Temperature readings obtained from various thermocouples is recorded through Data Acquisition System (Agilent make 34972A, 32 channels), which is connected to the computer. The uncertainty in current and voltage measurement is obtained as ±0.1 V and ±0.1 A respectively. The uncertainty in heat flux measurement is found to be ±6.02%.

1.2 Preparation Of Nano-Enhanced PCM

Firstly, solid paraffin wax and Al₂O₃ nanoparticle is weighed on weighing machine (Wensar PGB 301). The total weight of PCM and Al₂O₃ is taken as 136.5 gm and kept constant in this study. After weighing paraffin wax and Al₂O₃ nanoparticles, the paraffin wax is melted with the help of hot-plate at 75°C. Al₂O₃ nanoparticles are added periodically into the melted PCM while it is being stirred on the magnetic stirrer (REMI 2ml/h) up to 2 hours. Subsequently, the mixture is sonicated for next 2 hours at constant frequency with the help of ultrasonic vibrator (RICO Scientific Industries, USBT 6) for ensuring uniform distribution of nanoparticles in the PCM. Afterwards, the mixture is allowed to cool at room temperature.

![FIGURE 1: SCHEMATIC DIAGRAM OF THE EXPERIMENTAL SETUP](image1)

![FIGURE 2: PHOTOGRAPHS OF THE HEAT SINKS](image2)
1.3 Characterization Of NePCM

1.3.1 DSC Analysis Of NePCM

The increment in temperature of the paraffin wax results in the loosened structure of PCM. Further increase causes the molecules to absorb the more heat, i.e., its latent heat and changes its phase from solid to liquid, as absorbed energy gets converted into kinetic energy. Hence the measurements of the latent heat and melting temperature of the phase change materials are of extreme importance. The thermal energy storage properties of the pure PCM and NePCMs with different weight fractions of Al\textsubscript{2}O\textsubscript{3} nanoparticle are measured with the help of Differential Scanning Calorimetry (DSC214 Polyma, Netzch, Germany).

Figs. 4 and 5 show the DSC curve for paraffin wax dispersed with different weight fractions of nanoparticles. It can be observed from Fig. 4 that the melting temperature variation is not significant after addition of Al\textsubscript{2}O\textsubscript{3} nanoparticles in the PCM. However, it can be seen from the Table 2 that the changes latent heat is not significant for nanoparticle loading upto 4%. However, the change in latent heat is significant for higher loading of nanoparticle (6%). The maximum decrement of 28.65% in the latent heat is obtained for NePCM (φ=6%). This is due to the replacement of paraffin wax with nanoparticles that do not change its phase and absorb less amount of energy during phase transition compared to nanoparticle loading of 0.5, 2.0 and 4.0%. Similar results have been reported by various researchers for different loading of Al\textsubscript{2}O\textsubscript{3} in paraffin wax [21-22].

The density and specific heat capacity of NePCM is equal to the corresponding weight fraction of constituent [23-24] and expressed as:

\[ \rho_{np} = \varphi \rho_n + (1-\varphi)\rho_p \]  \hspace{1cm} (1)

\[ (\rho c_p)_{np} = \varphi(\rho c_p)_n + (1-\varphi)(\rho c_p)_p \]  \hspace{1cm} (2)

It may be noted from Table 3 that the specific heat capacity decreases with the addition of nanoparticles and the percentage reduction in specific heat increases with the increase in nanoparticle loading. This is due to low specific heat of Al\textsubscript{2}O\textsubscript{3} nanoparticle compared to pure PCM.
1.3.2 SEM Analysis Of NePCM

Scanning Electron Microscopy was done on all samples of NePCM to confirm uniform dispersion of nanoparticles. Fig. 5 represents the FESEM image of NePCM taken on the Supra 55 Zeiss Field Emission Scanning Electron Microscope. Uniform dispersion of Al$_2$O$_3$ nanoparticles can be seen in the figure. It may be noted that the use of magnetic stirrer and ultrasonicator result in uniform dispersion of nanoparticles in the phase change material.

![FIGURE 5: FESEM IMAGE OF NEPCM](image)

1.4 Image processing and analysis

The melt fraction was calculated with the help of images captured from one side of the heatsink (front side). The images captured were initially cropped to the required region. After cropping and resizing them to appropriate size, they were enhanced. Photo enhancement made the solid-liquid interface clearly visible, and the melted portion was easily distinguishable from the solid wax. Then with the help of MATLAB, the enhanced images were converted into binary images. Fig. 6 represents all the steps involved to obtain the binary image and inturn the melt fraction of PCM. A binary image is a digital image whose pixels have only two possible intensity values (0 and 1). They are normally displayed as black and white, black corresponding the pixel having 0 value and white corresponding 1 value. Due to the photo enhancement, the melted portions were appropriately designated with the 0 value pixel (black pixels) and the melt fraction was calculated by the number of pixels corresponding to the 0 value (black pixels) divided by the total number of pixels of the image.

\[
\text{Melt fraction} = \frac{\text{Number of black pixels}}{\text{Total number of pixels}}
\]  

(3)

1.5 Results and Discussion

1.5.1 Comparison Of Present Results With The Existing Studies

Fig. 7 shown the comparison of present results for pure PCM inside the unfinned heat sink with the existing studies of Arshad et al. [4] and Mahmoud et al. [12]. The studies of Arshad et al. [4] and Mahmoud et al. [12] were based on thermal management of electronic devices using PCM based heat sink with and without fins. However, the main objective of the present study is to investigate the melting of NePCM in finned heat sink. It has been found that results of the present investigation shows a similar pattern as obtained in the existing investigations for pure PCM filled in an unfinned heat sink case.

![FIGURE 6: STEPS INVOLVED IN IMAGE PROCESSING TO OBTAIN THE MELT FRACTION FOR UNFINNED HEATSINK](image)

![FIGURE 7: COMPARISON OF PRESENT INVESTIGATION WITH EXISTING STUDIES](image)

1.5.2 Propagation Of Melt Front And Variation Of Melt Fraction With Time

In order to better understand the melting phenomena of PCM, the Solid-liquid interface progression is visualized with the help of digital camera (Sony RX10M2) at equal time intervals of 5 minute for different configurations of heat sinks and are shown in Figs. 8-9. For the sake of brevity, the sequential photographs of melting process are shown only for the pure PCM and constant heat flux of 2.0 kW/m$^2$. Paraffin wax exists in opaque white color in solid phase and become transparent in liquid phase. Hence, in all the photographs, the liquid and solid phases are represented by black and white colors, respectively.

![FIGURE 8-9: SEQUENTIAL PHOTOGRAHPS OF MELTING PROCESS](image)
The images are taken till the entire PCM is melted. Figs. 8 and 9 shows the propagation of melt front in case of unfinned and two finned heat sinks, respectively. It can be seen from Fig. 8 that PCM starts to melt from the bottom of the heat sink and the melting of the PCM is horizontally layer by layer. While, from Fig. 9 shows that PCM starts to melt at the proximity of the fins and the melting of the PCM is not layer by layer that is unlikely to that of the unfinned heat sink. It may be noted from the figures that initially the liquid PCM layer thickness is increasing with the smaller rate because the heat transfer is conduction dominated and buoyancy force are not able to overcome the viscous force. Due to this reason, the solid-liquid interface remain parallel to the heated surface for unfinned heat sink and to the fin and heated surface for finned heat sinks during the initial stage of melting. However, as the time progresses, the thickness of liquid layer increases and the effect of viscous force is overcome by the buoyancy force. Due to this reason, a counter clockwise convection current starts between hot and cold liquid PCM. This increase in convection current increases the melting rate and changes the solid-liquid interface profile. solid-liquid interface is in linear shape during the initial stage of melting due to conduction dominated heat transfer mechanism. However, as the melting progresses, the impact of natural convection increases and wavy interface shape is obtained. It may be attributed to the fact that three dimensional Benard convection cells are formed in the liquid PCM [25]. Fig. 9 shows the melting photographs of the PCM inside two finned heat sinks. The interface shape is always remain symmetric on both the sides of the fin, which is attributed to the fact equal circulation of buoyant flows in both halves of the heat sink.

Figs. 10 and 11 shows the variation of melt fraction with time for different weight fractions (φ) of \( \text{Al}_2\text{O}_3 \) nanoparticles dispersed in paraffin wax filled in unfinned and two finned heat sinks, respectively. While, Figs. 12 and 13 shows the total melting time of PCM filled in heat sinks with unfinned and two finned heat sinks, respectively. In case of the unfinned heat sink, the melting starts early for NePCM compared to PCM due to increased thermal conductivity. NePCM having \( \phi = 0.5\% \) melts faster compared to NePCM (\( \phi = 4 \& 6\% \)). Highest melting time of 125 min was recorded for the PCM based heat sink and lowest melting time of 106 min was recorded for NePCM (\( \phi = 0.5\% \)). Maximum reduction of 15.23% in melting time was observed after the addition of 0.5% \( \text{Al}_2\text{O}_3 \) nanoparticles. However, a further increase in nanoparticle loading causes an increase in melting time. A similar pattern is observed in the case of two finned heat sink. The lowest melting time of 84 mins is observed for NePCM with \( \phi = 0.5\% \). Melting time is found to increase in order of \( \phi = 0.5\%, 4\% \) and 6%. Maximum reduction of 19.23% in melting time was recorded after the addition of 0.5% \( \text{Al}_2\text{O}_3 \) nanoparticles in case of two finned heat sink. Also, Melt fraction at a given time is found to decrease for NePCM (\( \phi = 4\% \)) compared to NePCM (\( \phi = 0.5\% \)). Increase in melting time with nanoparticle loading is due to the increase in the viscosity and agglomeration.

**FIGURE 8:** PROGRESSION OF MELT FRONT OF PURE PCM (\( \phi = 0 \)) IN UNFINNED HEATSINK

**FIGURE 9:** PROGRESSION OF MELT FRONT OF PURE PCM (\( \phi = 0 \)) IN TWO FINNED HEATSINK

### 1.5.3 Effect Of Nanoparticle Loading On Heat Sink Base Temperature

Variation of the base temperature of the heat sinks with time for different weight fractions of nanoparticles is shown in Figs. 14 and 15. More the time required to attain SPT better is the performance and thermal management of the system. Air-based heat sink reaches the 80°C mark far early compared to PCM and NePCM based heat sinks. PCM based heat sink requires maximum time to reach SPT (80°C). Hence its performance is best, followed by NePCM (\( \phi = 0.5\% \)) based heat sink. Further increment in the nanoparticle loading results in a reduction of the thermal performance. Although the thermal conductivity of paraffin wax increases with \( \text{Al}_2\text{O}_3 \) nanoparticles but the specific and latent heat decreases, which in turn leads to higher temperature of the system.
FIGURE 10: VARIATION OF MELT FRACTION OF NePCMs WITH TIME IN UNFINNED HEAT SINK

FIGURE 11: VARIATION OF MELT FRACTION OF NePCMs WITH TIME IN TWO FINNED HEAT SINK

FIGURE 12: MELTING TIME OF NePCMs IN UNFINNED HEAT SINK

FIGURE 13: MELTING TIME OF NePCMs IN TWO FINNED HEAT SINK

FIGURE 14: VARIATION OF BASE TEMPERATURE WITH TIME FOR UNFINNED HEAT SINK

FIGURE 15: VARIATION OF BASE TEMPERATURE WITH TIME FOR 2 FINNED HEAT SINK
CONCLUSIONS

Passive cooling thermal management technique using heat sinks filled with Al₂O₃ nanoparticle dispersed paraffin wax has been implemented in this experiment. The effect of the addition of Al₂O₃ nanoparticle for various weight fractions (φ = 0%, 0.5%, 4%, and 6%) in the paraffin wax filled in storage units with different dimensions on the thermal performance of the system has been analyzed. Experiments are performed for constant heat flux value of 2 kW/m². Melting process is observed photographically, and thermocouples were used to determine the temperature distribution of the base of the heat sinks. Photographs are captured at regular time intervals to obtain the melt front location.

The key finding obtained from the present investigation are as follows

i. Latent heat decreases with increase in the nanoparticle loading, maximum decrement being 28.65% for NePCM (φ = 6%) as compared to pure paraffin wax.

ii. Addition of nanoparticles results in the reduction in melting time, the maximum reduction being 15.23% and 19.23% for NePCM (φ = 0.5%) in unfinned and two finned heat sink.

iii. Melting time increases with the further addition of Al₂O₃ nanoparticles. However, it is still less compared to pure PCM. A similar pattern is followed for two finned heatsinks.

iv. The addition of small amounts of nanoparticles will be essential as nano-enhanced PCM based heatsink will perform better in power spikes condition because the total melting time decreases with φ = 0.5%.

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