Thermal performance of heat sink using nano-enhanced phase change material (NePCM) for cooling of electronic components

Anuj Kumar *, Rohit Kothari, Santosh Kumar Sahu, Shailesh Ishwarlal Kundalwal

Department of Mechanical Engineering, Indian Institute of Technology Indore, Indore 453552, Madhya Pradesh, India

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- Heat sink
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ABSTRACT

Present experimental study reports the thermal performance of nano-enhanced phase change material (NePCM) based thermal energy storage system for cooling of electronic components. The NePCM based heat sink (HS) cooling is a passive cooling technique that can eliminate the fan-based conventional cooling technique. A plate heater was used to impersonate the heat generated by microelectronics. Here, copper oxide (CuO), paraffin wax, and aluminum are considered as nanoparticle, phase change material (PCM), and HS material, respectively. Different HS configurations such as HS with no fin (HSNF), HS with rectangular plate fins (HSRPF), HS with square pin fins (HSSPF), and HS with circular pin fins (HSCPF) are studied for a fixed volume fraction of fin material. The performance of various HS configurations are analyzed for different nanoparticle concentration ($\phi=0.5-3.0$), and heat flux values ($q^\prime=1.5-3.0\text{ kW/m}^2$). For $\phi=3.0$, thermal conductivity and viscosity of NePCM are found to increase by 150% and 100%, respectively. The HSSPF involving PCM/NePCM exhibits better thermal performance compared to other HS configurations. The maximum reduction in temperature is found to be 13 °C and 15 °C for HSSPF involving PCM and NePCM ($\phi=0.5$), respectively. The highest enhancement ratio of 5.0 is obtained for HSSPF at $q^\prime=2.0\text{ kW/m}^2$ for SPT of 65 °C. The addition of CuO nanoparticle beyond $\phi=0.5$ decreases the HS performance considerably.

1. Introduction

Electronic devices such as cellular phones, laptops, light-emitting diode (LED), digital cameras, notebooks, personal digital assistants (PDA), control systems in missiles, and battery modules of electric vehicles are currently designed with enhanced processing speed and higher compactness. Because of miniaturization and higher power density, the heat generation due to electronic circuitry increases. Higher heat generation results in a rise in the working temperature of electronic components beyond the critical limits. It is argued that the failure rate of the electronic components increases significantly due to the enhancement in working temperature [1,2]. Therefore, an efficient cooling technique is required to prevent failures and maintain the long-term reliability of the electronic devices.

Several active cooling techniques are adopted to maintain the allowable temperature limit of the electronic components [3–5]. The active cooling systems are considered to be inefficient because of larger volume occupancy, noisy operation, continuous maintenance, and additional power consumption. This has motivated the researchers to develop innovative passive cooling techniques that can prevent the overheating of electronic devices. The utilization of phase change material (PCM) for thermal management of electronic components has gained attention due to the higher value of latent heat of fusion. The PCM absorbs heat during melting operation and releases it to the surroundings during solidification, and maintains the uniform and safe temperature limit of the electronic devices. Although PCM (Organic) possesses very good properties such as high specific heat, density, latent heat of fusion, low or no sub-cooling effect, non-corrosive, non-toxicity, and chemical inertness, but it faces challenges of lower value of thermal conductivity.

Various thermal conductivity enhancers (TCEs) such as fins, metallic/nonmetallic foams, and nanoparticles are used to enhance the thermal conductivity of PCM. Metallic foams (copper, and Iron-Nickel) impregnated with PCM were investigated by Rehman et al. [6] under various heating conditions. A maximum 17% reduction in heat sink (HS) base temperature is achieved for copper foam-PCM composite in comparison to HS with no PCM. Kothari et al. [7] reported the thermal performance of various PCM based HS configurations such as HSNF, HS involving two plate fins, HSNF involving metal foam, and HS involving two fins and metal foam. It is reported that two fins MF-PCM based HS performs better than others in terms of enhancement ratio. In addition to

* Corresponding author.
E-mail address: phd1801103004@iiti.ac.in (A. Kumar).

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this, various studies have been made to analyze the heat transfer characteristics of PCM based system incorporating different HS designs integrated with PCM [9–18] for electronic cooling. Baby and Balaji [8] experimentally studied the thermal performance of plate fins and pin fins heat sinks. They reported that HS with pin fins performs better than HS with plate fins. A novel cooling module was proposed by Lv et al. [12] that employs serpentine composite PCM plates for battery thermal management. The new design is found to reduce the weight of the module by 70% and increases the energy density of the battery module by 12.8%. Ali and Arshad [13] carried out an experimental investigation to predict the effect of pin fin thickness and reported that HS with 3 mm fin thickness enhances the thermal efficacy. In another experimental study, Arshad et al. [14] reported the effect of pin fin thickness and found that HS with 2 mm thick fin provides the best thermal performance. Ashraf et al. [16] carried out an experimental investigation to optimize the PCM based circular and square pin fins HS considering a 9% volume fraction of TCE arranged in a staggered and inline fashion. It was reported that inline configuration results in better thermal performance. The thermal performance of different PCMs such as n-eicosane, SP-31, RT-35HC, RT-44, RT-54, and paraffin wax filled inside circular, rectangular and triangular pin fins HSs has been experimentally carried out by Ali et al. [17]. The study reports RT-44 HC as the better choice of PCM for 60 °C set point temperature (SPT). Kothari et al. [19] proposed an analytical model to predict temperature variation, solidification time, and solid fraction by heat balance integral method in a rectangular system with plate fins. In another study, Kothari et al. [20] proposed a model to analyze the melting and solidification behavior of PCM in the annulus. It has been reported that there exist particular fractions of TCE and PCM to obtain the optimum latent heat phase duration. In addition, studies [21–23] have been made to investigate the optimum quantity of TCEs and HS configuration to achieve higher thermal performance. Saha et al. [21] reported that an 8% volume fraction of TCEs has the best

Table 1
Summary of literature review on PCM and NePCM based HS.

<table>
<thead>
<tr>
<th>Source</th>
<th>Methods/Heat input</th>
<th>HS size (mm²)</th>
<th>PCM (M.P., °C)/Nanoparticle (wt%)</th>
<th>Observations</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ho et al. [32]</td>
<td>Experimental (40 °C)</td>
<td>HS with no fins</td>
<td>n-octadecane (25.1–26.5)</td>
<td>Increasing the nanoparticle in n-octadecane degrade the natural convection</td>
</tr>
<tr>
<td>Fazanbehnia et al. [33]</td>
<td>Experimental (2–6 kW/m²)</td>
<td>HS with plate fins</td>
<td>Al₂O₃ (5.0, 10.0)</td>
<td>Effect of NePCM is more pronounced after latent phase finished</td>
</tr>
<tr>
<td>Tariq et al. [34]</td>
<td>Experimental (0.86–2.4 kW/m²)</td>
<td>HS with no fins</td>
<td>RT-44 HC (44)</td>
<td>Graphene based composite PCM shows enhancement in operation time compared to pure PCM</td>
</tr>
<tr>
<td>Motahar et al. [35]</td>
<td>Experimental (0.74–1.98 kW/m²)</td>
<td>HS with triangular plate fins</td>
<td>RT-42 HC (64)</td>
<td>Adding carbon nanofibers and TiO₂ to RT-42 HC does not improve the thermal performance</td>
</tr>
<tr>
<td>Bayat et al. [36]</td>
<td>Numerical (1.0–30 kW/m²)</td>
<td>HS with plate fins</td>
<td>TiO₂ (2, 4)</td>
<td>PCM is in solid state, temperature does not change considerably by adding nanoparticle</td>
</tr>
<tr>
<td>Sharma et al. [39]</td>
<td>Experimental (0.8 W)</td>
<td>Without and with micro-fin</td>
<td>Al₂O₃ (2, 4, 6)</td>
<td>NePCM for finned HS is not giving encouraging performance</td>
</tr>
<tr>
<td>Alimohammadi et al. [40]</td>
<td>Experimental (1 to 5 kW/m²)</td>
<td>HS with 4 plate fins</td>
<td>Mn(No₃)₂ (37)</td>
<td>Greater reduction in HS base temperature with PCM and NePCM was found compared to HS without fins in both forced and free convection</td>
</tr>
<tr>
<td>Joseph and Sajith [41]</td>
<td>Experimental (2.835–11.338 kW/m²)</td>
<td>HS with 4 plate fins</td>
<td>Paraffin wax (58–62)</td>
<td>Higher energy saving for HS with PCM-GF composite than HS with and without PCM.</td>
</tr>
<tr>
<td>Kohari et al. [42]</td>
<td>Experimental (2 kW/m²)</td>
<td>Without and with 2 plate fin</td>
<td>Al₂O₃ (0.5, 4 and 6 wt %)</td>
<td>Addition of small amount of nanoparticles in the PCM decreases the melting time</td>
</tr>
<tr>
<td>Present Study</td>
<td>Experimental (1.5–3 kW/m²)</td>
<td>Pin fin HS</td>
<td>Paraffin wax (58–62)</td>
<td>Addition of CuO beyond 0.5 decreases the thermal performance</td>
</tr>
</tbody>
</table>
thermal performance. Baby and Balaji [22] carried optimization by employing an artificial neural network algorithm for plate-fin HS filled with PCM and reported that a 15% volume fraction of plate fins could provide better thermal performance. Arshad et al. [23] studied various types of square pin fin based HS with varying thickness (1, 2, and 3 mm) at 9% TCE volume fraction. The authors reported that HS with 2 mm thick fins transfer heat to the PCM more uniformly. The application of composite PCM in battery thermal management for long-term cycles was studied by Lv et al. [24]. It is reported that the cycling life of the battery module with PCM increases by 65.3% compared to module without PCM. A novel polymer PCM (PoPCM) was designed and synthesized by Xiao et al. [25] to take care of the issues pertaining to leakage of PCM after melting. The solid-solid PCM (PoPCM) is found to be the best alternative for battery thermal management.

It may be noted that although the fins and MFs increase the thermal conductivity of PCM system and enhance the thermal performance of HSs, they increase the size and weight of the system [26]. Therefore, efforts have been made to use metallic [27–30] and non-metallic [31] nanoparticles to enhance the thermal conductivity of PCM system, keeping the system light weight as well. Studies have been made to analyze the melting behavior of Al$_2$O$_3$/n-octadecane based NePCM in a square differentially heated vertical cavity [32]. It was reported that enhancement in thermal conductivity by mixing Al$_2$O$_3$ could be counterpoised due to far higher enhancement in viscosity, leading to a reduction in heat transfer. Farzanehnia et al. [33] carried out an experimental investigation by seeding multiwall carbon nanotube (MWCNT) in PCM under free and forced convective heat transfer conditions. The use of NePCM increases the operating time under free

<table>
<thead>
<tr>
<th></th>
<th>Support systems</th>
<th>4</th>
<th>Data acquisition system</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>NePCM filled HS assembly</td>
<td>5</td>
<td>Laptop</td>
</tr>
<tr>
<td>3</td>
<td>DC power source</td>
<td>6</td>
<td>Thermocouples</td>
</tr>
</tbody>
</table>

Fig. 1. Experimental setup (a) Schematic view (b) Photographic view.
convective heat transfer. However, under forced convective heat transfer, the use of NePCM produces undesirable results as compared to pure PCM. Tariq et al. [34] used RT-44HC/graphene nanoparticles (GNPs) and RT-64HC/GNPs based NePCM. In their studies, it was reported that RT-44HC/GNPs and RT-64HC/GNPs based NePCM are suitable for lower and higher heating loads, respectively. The effect of carbon nano fibers (CNFs) and TiO$_2$ based NePCM on HS performance was investigated by Motahar et al. [35]. They reported that HS with pure PCM delayed the operating time by 110% for set point temperature (SPT) of 35°C. While the addition of CNFs, reduces the operating time by 15% for 35°C SPT.

In addition, studies have been reported in the literature to analyze NePCM in finned heat sinks. Bayat et al. [36] performed a numerical simulation of plate-fin HS by adding Al$_2$O$_3$ and CuO nanoparticles at 2%, 4%, and 6% mass fraction. It is reported that the addition of nanoparticles in pure PCM at a small percentage (2%) improves the HS performance. Bondareva et al. [37] carried out a numerical study on the finned HS with NePCM and reported that the optimum volume concentration of nanoparticles is a function of fin height. Babazadeh et al. [38] carried out numerical simulation to study the heat release rate for HS with fins associated with NePCM. The optimum nanoparticle diameter was found to be 40 nm by considering the effect of fouling in heat release unit. Experimental and numerical investigations performed by various researchers on NePCM based HSs [32–36,39–42] have been summarized in Table 1.

It is evident from the literature that several studies have been made to analyze thermal performance of PCM based HSs for thermal management of electronic components. These include different HS configurations such as HS with no fin, pin fins of various cross-section (circular, square, and triangular) [13–18], and rectangular plate fins [8], arranged with different arrays (inline/staggered) [18]. These studies also discuss the effect of PCM type, fin thickness, fin number and optimum value of fin material for enhancement of thermal performance. Numerous studies have also been made to analyze the thermal performance of various NePCM based HSs with and without fins. It may be noted that the thermal performance of NePCM based HSs depends on nanoparticle properties (concentration, size, and type) [35,36], fin parameters (height, number, cross-section, arrangement, thickness), set point temperature, and heat load [13–18]. It is observed the heat load and SPT requirement are different for different applications. Limited experimental studies are available that address the thermal performance of HSs with different values of SPT and heat load. Also, studies pertaining to the thermal performance of HSs with circular pin fins (HSCPF) and HS with square pin fins (HSSPF) filled with NePCM have not been reported in the literature (Table 1). In addition to this, limited studies have been made that consider the CuO nanoparticle in a PCM based HS thermal energy storage system for cooling of electronic components (Table 1). Therefore, in the present experimental study, efforts have been made to analyze the thermal performance of different HS configurations such as HS with no fin (HSNF), HS with rectangular plate fins (HSRPF), HS with square pin fins (HSSPF), and HS with circular pin fins (HSCPF) with paraffin wax and CuO based NePCM for a varied range of nanoparticle concentration ($\phi=0.5,1.0$, and 3.0), and different heat loads ($q''=1.5,2.0,2.5$, and 3.0 kW/m$^2$) with two different values of SPT.
The main objectives of the present study are as follows.

- To synthesize NePCM and analyze the thermophysical properties of NePCM (latent heat, specific heat, density, thermal conductivity, and viscosity) for different nanoparticle concentrations.

- To study the base temperature of unfinned HS assembly with and without PCM.

- To analyze the thermal performance of various HS configurations with pure PCM and NePCM.

- To investigate the effect of different values of heat flux, nanoparticle concentration, and SPT on HS base temperature, operating time, enhancement ratio, latent heating phase duration, and thermal conductance.

2. Experimental setup and procedure

The schematic and photographic view of the experimental test facility is presented in Fig. 1(a-b). It comprises various units such as HS support system, NePCM based HS assembly, DC power source, Digital data acquisition system (DDAS), laptop, and thermocouples. Here, the DC power supply unit (L3260, Aplab, India) having voltage and the current range of 0–32 V and 0–5 A, respectively, is employed to provide

![Fig. 3. Position of thermocouple (a) isometric view (b) top view.](image-url)
the required input heat flux to the HS assembly. Calibrated K-type thermocouples are employed to record the temperature at the base and inside the PCM. The HS assembly is insulated by employing 25 mm thick ceramic glass wool to minimize the heat loss to the surrounding. Plate heater (Sunrise products, India) of thickness 4 mm, made up of coil type nichrome wire wound on mica sheet is employed to imitate the heat dissipated by the electronic chips of the electronic devices. The DDAS ceramic glass wool is used to record the temperature at various dissipated by the electronic chips of the electronic devices. The DDAS (34972A, Agilent, USA) is used to record the temperature at various locations of HS in an interval of 10 s. Paraffin wax (Sigma Aldrich, USA) having a melting range of 58–62 °C is considered as PCM in the present study. Most of the researcher has selected n-eicosane as PCM which has a melting temperature of 36.5 °C. It may be noted that countries near the equator including India where the temperature in the summer crosses 45 °C; hence use of n-eicosane as PCM is not suitable for thermal management of electronics. CuO nanoparticle employed in the present study has an average size of 30–50 nm, 99.9% purity, and 10 m²/g specific areas and is manufactured by Nano lab India.

2.1. Heat sink assembly and thermocouple position

The present experimental study aims to investigate the thermal characteristics of four different configurations of HS such as HSNF, HSRPF (4 fins), HSCPF (132 fins), and HSSPF (225 fins). Taking a cue from other studies; we have considered a 9% volume fraction [8,9,13,43] and inline configuration [18] of fins for all the cases. Highly conductive thermal paste (OT-201, OMEGATHERM, Omega India) is employed between the HS base and plate heater to reduce the contact thermal resistance. The photographic view of HSs used in the present investigation is shown in Fig. 2(a-d). HSs are having dimensions of 100 × 100 mm² base, and 25 mm height is used. Circular pin fins of diameter 2.95 mm and height 20 mm and square pin fins of dimensions 2 × 2 × 20 mm³ are fabricated by wire electrical discharge machining (ELPULS 15, Ecocut, Electronica India) from an aluminum slab of dimension 101 × 101 × 25 mm³. The plate fins of dimensions 100 × 20 × 2.5 mm² are fabricated by a CNC milling machine (Emcomill E350, Emco group, Austria). Aluminum 6061 is chosen as an HS material due to its lightweight and higher thermal conductivity. The plate heater having a dimension of 100 × 100 mm² and a thickness of 4 mm is used to provide uniform heat flux from the bottom surface of the HS. All four sides and top surface of the HS are covered with a 5 mm thick transparent Plexiglas sheet which also acts as an insulator. There is a 2 mm gap left between the top surface of PCM/NePCM and the bottom surface of plexiglas sheet to compensate for the volume expansion of PCM after melting. The dimensions of the material used are listed in Table 2.

High precision and pre-calibrated 24 thermocouples (K-type) are attached at various locations of the HS assembly to measure the temperature during melting of PCM/NePCM (Fig. 3a-b). Thermocouples B₁ to B₈ are fixed on the base of the HS to measure the base temperature. In order to fix the thermocouples, groves of 1.5 mm depth are made that are located 45 mm from HS sidewalls. Thermocouples W₁ to W₄ are fixed on the center of the outer wall of the HS. Thermocouples T₁ to T₉ are inserted 25 mm inside the PCM/NePCM to analyze the spatial distribution of temperature inside the HS. The locations of thermocouples T₁-T₉ from HS bottom surface are shown in Fig. 3(a-b). Thermocouples T₉ and T₁₀ are attached on the upper wall of HS, and below the heater, respectively. Thermocouples T₃₁ to T₃₄ are placed on the six outer surfaces of the insulation wall to measure the heat loss during the experiment. Also, a thermocouple is left to the atmosphere to measure the ambient temperature. Based on the temperature values (T₁₁-T₁₆), the heat loss to the surroundings is calculated, and the maximum value is found to be 6.27% of the input heat flux value (3.0 kW/m²).

2.2. Preparation of NePCM and experimental procedure

NePCM is obtained by adding CuO nanoparticles at different mass fractions inside the pure PCM. The thermophysical properties of PCM and CuO nanoparticles are summarized in Table 3 [15,44,45]. Initially, the amount of solid PCM and CuO nanoparticles is measured by digital
analytical balance (PGB 301, Wensar weighing scale, Chennai India). The total amount of PCM and CuO nanoparticles is taken as 136.5 g. After weighing PCM and CuO nanoparticles, the PCM is melted by placing it on a hot plate at a constant temperature of 80°C. CuO nanoparticles are dispersed step by step into liquefied paraffin wax and simultaneously stirred on the magnetic stirrer (REMI, 2MLH, India) for 2 h at 500 rpm. Subsequently, an ultrasonic vibrator (USBT-6, RICO Scientific Industries, India) is then used to sonicate the mixture at a constant frequency for 4 h to ensure uniform distribution of nanoparticles in the PCM. The temperature of the ultrasonic vibrator should be maintained above the melting point to avoid PCM solidification. Fig. 4 presents the step by step process involved in the preparation of NePCM. NePCM obtained is allowed to solidify at room temperature and used for further analysis.

Initially, solid PCM/NePCM is melted and poured inside the HS cavity. Thermocouples are then fixed at required positions in the PCM/NePCM based HS assembly, and subsequently, PCM/NePCM is allowed to solidify at room temperature. The plate heater is fixed at the bottom surface of the HS. Heat flux is supplied from the DC source by controlling the current and voltage as per ohm’s law. The HS is kept in a horizontal position throughout the experiments for all the cases. Spirit level is utilized to check the horizontal position of the HS assembly. All the experiments were performed at an ambient temperature of 30°C and repeated three times to reduce the experimental errors.

3. Characterization and thermophysical properties of TCE, PCM/NePCM

3.1. SEM analysis of TCE and NePCM

In this study, Aluminum-6061 and CuO are used as TCEs. In order to estimate the metallurgical composition of Aluminum-6061, Energy Dispersive X-ray Spectroscopy (EDX) analysis is performed by Field-Emission Scanning Electron Microscope (FE-SEM, Supra55 Zeiss, Germany). Fig. 5 depicts the peak of the elements present in the material. It can be noticed from Fig. 5 that Aluminum-6061 used in the present study is nearly pure aluminum [46]. Here, SEM analysis is also carried out for NePCM to estimate the nanoparticle distribution inside the pure PCM. Fig. 6 shows the uniform distribution of CuO nanoparticles inside pure PCM, and no agglomeration is noticed.

<table>
<thead>
<tr>
<th>NePCM</th>
<th>Latent heat (kJ/kg)</th>
<th>Thermal conductivity (W/mK)</th>
<th>Decrease in latent heat (%)</th>
<th>Increase in thermal conductivity (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>φ = 0.0</td>
<td>153.21</td>
<td>0.23</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>φ = 0.5</td>
<td>146.46</td>
<td>0.36</td>
<td>4.40</td>
<td>56.52</td>
</tr>
<tr>
<td>φ = 1.0</td>
<td>131.09</td>
<td>0.406</td>
<td>14.43</td>
<td>76.52</td>
</tr>
<tr>
<td>φ = 3.0</td>
<td>115.28</td>
<td>0.576</td>
<td>24.75</td>
<td>150</td>
</tr>
</tbody>
</table>

Fig. 6. SEM image of paraffin wax/CuO based NePCM.

Fig. 7. Heating curve of pure PCM and NePCM.

Table 4

Variation in latent heat of fusion and thermal conductivity of NePCMs compared to pure PCM.

Fig. 8. Variation of thermal conductivity of PCM and NePCM with temperature.

NePCM based HS assembly, and subsequently, PCM/NePCM is allowed to solidify at room temperature. The plate heater is fixed at the bottom surface of the HS. Heat flux is supplied from the DC source by controlling the current and voltage as per ohm’s law. The HS is kept in a horizontal position throughout the experiments for all the cases. Spirit level is utilized to check the horizontal position of the HS assembly. All the experiments were performed at an ambient temperature of 30°C and repeated three times to reduce the experimental errors.
3.2. DSC analysis of PCM/NePCM

The melting point and latent heat of fusion for PCM/NePCM with different mass fractions of CuO are obtained with the help of Differential Scanning Calorimetry (DSC 8000, Perkin-Elmer, USA). The DSC analysis is performed for temperatures varying between 25 °C and 80 °C with a heating rate of 10 °C/min. Fig. 7 depicts the heating curve for PCM/NePCM at different mass fractions of CuO. It can be noticed that the mixing of CuO nanoparticles inside pure PCM does not affect the melting temperature of PCM significantly. However, the addition of CuO nanoparticles inside pure PCM reduces the latent heat of fusion. The decrease in latent heat of fusion and an increase in thermal conductivity due to the introduction of CuO nanoparticles inside the pure PCM are presented in Table 4. The reduction in the latent heat value is found to be 4.40, 14.43, and 24.75% for nanoparticle loadings of 0.5, 1, and 3, respectively than pure PCM. The changes in latent heat of NePCM are insignificant up to nanoparticle loadings of 0.5. However, with the increase in nanoparticle loading (1 and 3%) the change in latent heat of NePCM becomes significant. This is because the addition of nanoparticles decreases the amount of PCM, and therefore less amount of energy is absorbed during the phase change process by NePCM compared to pure PCM.

3.3. Thermophysical properties of PCM/NePCM

3.3.1. Thermal conductivity of PCM/NePCM

Here, the thermal conductivity of PCM and NePCM in the solid phase is measured for a temperature range varying between 30 and 50 °C with an interval of 5 °C by utilizing TEMPOS thermal properties analyzer (TPA KS-3, Meter group, USA). It may be noted that thermal conductivity value measured for temperature below the melting point of PCM/NePCM to avoid the possible natural convection effect in the mushy zone during melting. The measurement is repeated five times to avoid any discrepancies in the result and the average value is presented here. The maximum deviation in the measurement of thermal conductivity is

Table 5
Variation of thermophysical properties with addition of CuO.

<table>
<thead>
<tr>
<th>Properties</th>
<th>∅=0.0</th>
<th>∅=0.5</th>
<th>∅=1.0</th>
<th>∅=3.0</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density (kg/m³)</td>
<td>880</td>
<td>905.6</td>
<td>931.2</td>
<td>1033.6</td>
</tr>
<tr>
<td>% change</td>
<td>–</td>
<td>2.91</td>
<td>5.82</td>
<td>17.45</td>
</tr>
<tr>
<td>Specific heat (J/kgK)</td>
<td>2800</td>
<td>2725.497</td>
<td>2655.09</td>
<td>2408.34</td>
</tr>
<tr>
<td>% change</td>
<td>–</td>
<td>2.66</td>
<td>5.17</td>
<td>13.98</td>
</tr>
<tr>
<td>Viscosity (Pa.s)</td>
<td>0.0235</td>
<td>0.0284</td>
<td>0.0366</td>
<td>0.0470</td>
</tr>
<tr>
<td>% change</td>
<td>–</td>
<td>21</td>
<td>56</td>
<td>100</td>
</tr>
</tbody>
</table>

Fig. 9. Comparison of experimental results with the existing studies (a) Without PCM (b) With PCM.

Fig. 10. Baseline comparison (a) Time temperature variation of base temperature of HS with and without PCM (b) Time temperature variation of wall of HS with and without PCM.
found to be ±10%. The variation of thermal conductivity values with temperature for various nanoparticle loading is shown in Fig. 8. The thermal conductivity increases with an increase in nanoparticle mass fraction and remains almost independent of temperature between 30 °C to 45 °C. The maximum increment in thermal conductivity is found to be 150% at $\phi = 3.0$ (Table 4). However, as the temperature reaches close to the melting point, the thermal conductivity decreases considerably.

### 3.3.2. Density, specific heat and viscosity of NePCM

Here, density, specific heat, and viscosity are obtained using standard formulae and correlations for heat transfer analysis of NePCM based HS assembly. It is assumed that the CuO nanoparticle is distributed uniformly within the pure PCM. In such a case, the effective thermal properties such as density and specific heat of NePCM can be estimated using the mixture rule as below [47,48].

$$\rho_{\text{NePCM}} = \phi \rho_{np} + (1 - \phi) \rho_{PCM} \quad (1)$$

$$\left(\rho c_p\right)_{\text{NePCM}} = \phi \left(\rho c_p\right)_{np} + (1 - \phi) \left(\rho c_p\right)_{PCM} \quad (2)$$

The viscosity of NePCM is obtained using the correlation provided by Vajjha et al. [49]. It may be noted that the correlation is valid for $\phi$ lies between 0.01 and 0.06.

$$\mu_{\text{NePCM}} = 0.9197 e^{22.853\phi} \mu_{PCM} \quad (3)$$

where $\phi$ represents the volume fraction of nanoparticles and can be obtained using the following expression [50].

$$\phi = \frac{W_{np}}{W_{np} + W_{PCM}} \quad (4)$$

where, $W_{np}$ and $W_{PCM}$ represent the weight of the nanoparticle and the weight of the PCM, respectively. Here, $\rho_{np}$ and $\rho_{PCM}$ represent the density of nanoparticle and PCM, respectively. Table 5 presents the variation of density, specific heat and viscosity of NePCM at $\phi = 0.0, 0.5, 1.0$ and 3.0. The density of NePCM increases while specific heat decreases with an increase in $\phi$. The density of NePCM increases by 18% and specific heat decreases by 14% at $\phi = 0.5$ and $\phi = 3.0$. Also, viscosity increase by 56% and 100% at $\phi = 1.0$ and $\phi = 3.0$, respectively.

### 4. Uncertainty in measurement and data reduction

Pre-calibrated Chromel-Alumel K-type thermocouples are used to record the temperature at different positions of HS assembly. The thermocouples are calibrated for the temperature range of 0-100 °C.
The calibration is performed using a constant temperature bath with standard mercury in a glass thermometer (temperature range from 0 to 200 °C and 0.1 °C resolution). The maximum deviation in the measurement of temperature is found to be ±0.1 °C. A DC power supply (Aplab L3260, 0-32 V/0-60A, India) is used to provide the required electrical power to the plate heater. The readings of current and voltage measurements displayed by DC power source are verified using a standard digital multimeter (Mecco 206). The uncertainty involved during the measurement of voltage and current is found to be ±0.1 V and ±0.1 A, respectively. The error analysis method suggested by Coleman and Steele is utilized here to evaluate the uncertainty in power input [52, 53]. The uncertainty associated with the power is found to be ±4.12% at a power level of 25 W (2.5 kW/m² heat flux). Eq. (5) is utilized to estimate the uncertainty in the power measurement.

\[
\frac{\Delta P}{P} = \pm \sqrt{\left(\frac{\partial I}{I}\right)^2 + \left(\frac{\partial V}{V}\right)^2}
\]

where, \(I\) and \(V\) represent current and voltage, respectively whereas \(\partial I\) and \(\partial V\) denote the uncertainty involved in the current and voltage measurement.

Various parameters are used to investigate the thermal performance of PCM/NePCM based HS assembly. These include nanoparticle mass fraction (\(\varnothing\)), enhancement ratio in operating time (\(\xi\)) of the HS with the addition of TCEs, and thermal conductance (G). Here, fins and CuO are collectively considered as TCEs. These parameters are defined below.

Nanoparticle mass fraction is defined as the ratio of the mass of CuO particle to the mass of PCM.

\[
\varnothing = \frac{m_{CuO}}{m_{PCM}}
\]

(6)

The value of \(\xi\) for HS involving TCE is estimated as the ratio of time required to reach the SPT value of PCM/NePCM based HS involving TCE and HS NF with no PCM [13].

\[
\xi = \frac{t_{cr \text{ With TCEs and PCM}}}{t_{cr \text{ Without TCEs and PCM}}}
\]

(7)

Thermal conductance of the NePCM based HS is expressed as the total amount of heat transfer from the HS surface and is obtained by the following expression [13].

\[
G = \frac{P}{T_{\text{max}} - T_{\text{amb}}}
\]

(8)

where \(P\) is the heat input to the HS assembly, and \(T_{\text{max}}\) represents the maximum temperature after the charging phase.
Fig. 13. Comparison of time temperature distribution of different HS configurations for 2.0 kW/m² at (a) pure PCM (b) Φ = 0.5 NePCM.

5. Validations

For validation, present test results are compared with the experimental results of Arshad et al. [14], Mahmoud et al. [54], Kothari et al. [55], Huang et al. [56], and Zhao et al. [57]. Results are compared for both HS without and with PCM subjected to different heat flux values. These studies utilize paraffin wax as PCM and the melting temperature is found to be 56–58 °C [14], and 58–62 °C [55]. In addition to this, Lauric acid with a melting temperature range of 42–44 °C and stearic acid having a melting temperature of 68.77 °C are used as PCM by Huang et al. [56] and Zhao et al. [57], respectively. The heat flux value is varied between 1.3 and 3.0 kW/m² in these studies [14,54–57]. The initial temperature is considered as 20–30 °C [14,54–57].

In the present investigation, HS is having an overall dimension 100 × 100 × 25 mm³ and paraffin wax having melting temperature 58–62 °C is considered as PCM. Present test results obtained from HS without PCM and HS with PCM are compared with the available experimental results (Fig. 9 a-b). Fig. 9 (a-b) reveals that the variation of base temperature in the present study follows a similar pattern as reported by other researchers [14,54–57]. The deviation in the results might be due to the variation in their HS configuration, type of PCM used, variation in heat flux values, and initial heating condition. Based on the qualitative and quantitative agreement, the present test facility is assumed to be validated and used for further analysis.

6. Results and discussion

6.1. Performance of HS with and without PCM

The performance of HS is evaluated by comparing the variation of the base and wall temperature of the HS with and without PCM. Fig. 10 (a-b) compares the transient temperature variation at the base and side wall of HSNF with and without PCM at \( q'' = 1.5 \) kW/m². The average temperature of thermocouples \( (B_1, B_2, and B_3) \) are considered as the base temperature while, the average temperature of thermocouples \( (W_1, W_2, W_3, and W_4) \) are considered as the side wall temperature of the HS. The base temperature of the HS without PCM takes 910, 1230, and 1600 s to attain a temperature of 60, 70, and 80 °C, respectively, while in the case of PCM based HS the base temperature increases up to 60, 70, and 80 °C in 2420, 6060 and 7610 s, respectively. Similar behavior can be seen in temperature variation of side wall of the HS (Fig. 10b). Time taken by HS (without PCM) to attain a wall temperature of 40, 50, and 55 °C is found to be 1120, 2120, and 2700 s, respectively, while the time taken by the side wall of HS filled with PCM to achieve the temperature of 40, 50, and 55 °C is found to be 1810, 4610 and 7500 s, respectively. This shows the rise in temperature in the case of HS without PCM is steady and faster, which is extremely undesirable for thermal management of electronic devices for long-term reliability. For PCM based HS the rise in temperature can be identified in three regions such as sensible heating phase (region 1), the latent heating phase (region 2), and the sensible heating phase post melting (region 3). During heating, the temperature rises sharply (region 1), remains nearly constant (region 2), and again increases at a faster rate (region 3). It can be inferred from Fig. 10(a-b) that PCM based HS can be used for controlling and maintaining the temperature below the critical limit, which may increase the performance and reliability of the electronic components.

6.2. Effect of mass fraction of CuO nanoparticle

Fig. 11(a-d) illustrates the transient temperature variation of NePCM based HS configurations for different mass fraction of CuO (0.0, 0.5, 1.0, 3.0) at constant \( q'' =1.5 \) kW/m². For all the configurations (HSNF, HSCPF, HSSPF, and HSRPF), the HS involving pure PCM exhibits better performance compared to NePCM based HSs irrespective of nanoparticle concentration. However, at lower nanoparticle concentration (\( \Phi =0.5 \)) NePCM reflects comparable thermal performance to pure PCM. Adding CuO at higher nanoparticle concentrations into the pure PCM increases the thermal conductivity. In spite of that, NePCM based HSs unable to dissipate more heat compared to pure PCM. This might be due to the various reasons like increase in thermal contact resistance between HS surface and NePCM due to combined properties of PCM and nanoparticle [58], weak convection heat transfer rate in NePCM due to enormous increase in viscosity, especially at higher concentration [32], reduction in latent heat of fusion compared to pure PCM (Table 4). It may be noted that at 3.0 mass fractions the viscosity of NePCM is increased by two times. Sharma et al. [39] also reported experimentally
that the variation in transient temperature for unfinned and micro finned HS involving PCM/NePCM is found to be negligible. In another study, Motahar et al. [35] reported that HS temperature increases with NePCM involving carbon nano fiber (CNF) as nanoparticle. They also reported that adding CNF at a higher concentration causes greater HS temperature.

6.3. Effect of heat flux

Transient temperature variations of various HSs at $q''=1.5-3.0$ kW/m$^2$ for $\varnothing=0.5$ are presented in the Fig. 12 (a-d). The average temperature recorded by thermocouples B$_1$-B$_3$ is used to plot the average response temperature at each $q''$. The PCM melting rate increases with an increase in heat flux values. With the increase in input heat flux, the latent heating phase duration decreases, leading to an increase in HS base temperature. This is undesirable for PCM based cooling. During the initial period, the PCM undergoes pre sensible heating phase followed by latent heating phase. After completion of latent heating phase the PCM undergoes the post sensible heating phase. For HSNF, at $q''=1.5$ kW/m$^2$, the duration of sensible and latent heating phase is found to be 0 to 3530 s and 3530 to 5050 s, respectively with a base temperature of 69 °C at the end of latent heating phase. While for other heat flux values $q''=2$, 2.5 and 3.0 kW/m$^2$, the duration of latent heating phase continue from 2210 to 3560 s, 1920 to 3250 s, and 1410 to 1980 s, respectively with the corresponding heat sink base temperature of 76, 76.8, and 78 °C, respectively at the end of latent heating phase. With the completion of the latent heating phase, the post melting sensible heating phase continues and the base temperature increases rapidly. Similar behavior can be seen in the case of other HS designs (Fig. 12 a-c). A sharp increase in temperature can be seen even in the latent heating phase for HS with fins. This might be due to the presence of the number of fins and pitch of the fins [23]. It should be noted that PCM based HS assembly is not encouraged to operate after completion of the latent heating phase as the temperature of the base increases rapidly after post melting.

6.4. Effect of heat sink configurations

Fig. 13 (a-b) compares the time-temperature distribution of different configurations of HSs for pure PCM and NePCM at $\varnothing=0.5$ subjected to $q''=2.0$ kW/m$^2$. At 9% volume fraction of fins, HSSPF has the highest heat transfer efficacy in terms of lowering the base temperature followed by HSCPF, HSRPF, and HSNF (Fig. 13 a). Similarity can be seen at $\varnothing=0.5$. After the latent heating phase, the difference in base temperature variation between HSCPF and HSSPF is insignificant. This reveals convection current in HSCPF filled with pure PCM is dominant and enhances the heat transfer rate. The lower base temperature in the case of
HSSPF before melting may be due to the higher number of fins. With an increase in fin numbers, the heat transfer area increases and leads to enhance the heat transfer to the PCM/NePCM and keep the base temperature at the lower limit. The surface area per unit volume of square pin fin, circular pin fin, and rectangular plate fin HS are found to be 1.84, 1.27, and 0.8, respectively. Moreover, in the case of HSSPF, fins are thin and closely spaced, which also gives higher fin effectiveness. Maximum temperature reduction of 13°C and 15°C is observed for HSSPF filled with pure PCM and NePCM at φ=0.5. At a given volume fraction of TCE, HS involving square pin fins provide better thermal performance compared to HS with rectangular fins and HS with circular pin fins.

6.5. Uniformity of temperature inside the HS

In order to investigate the temperature uniformity within the HS, the spatial temperature variation for each HS configuration is estimated and shown in Fig. 14(a-d). Tests are conducted for \( q'' = 2.0 \text{ kW/m}^2 \) and \( \phi = 0.5 \). The average temperature of thermocouples \( T_1 \) to \( T_8 \) recorded after 2000, 3000, and 4000 s is used for the analysis. It is observed that the temperature gradient in the case of HSNF and HSRPF are higher compared to HSCPF and HSSPF, which clearly indicates the non-uniform temperature distribution in HSNF and HSRPF. In the case of HSCPF and HSSPF, the temperature remains almost constant as we move towards the vertical direction from the bottom surface of the HS. The non-uniformity in temperature can only be seen at 20 mm of height since PCM remains solid at this height even after 4000 s of heating. Uniform temperature distribution in the case of square and circular pin fin HS is because of the higher number of fins which allow the uniform melting of PCM/NePCM from all directions and maintains the uniform temperature gradient inside the HS.

6.6. Comparison of latent heating phase and thermal conductance (G)

Heat transfer performance of PCM integrated HS can be studied in more detail by comparing the latent heating phase duration of various configurations of HS. In a view of this, the variation of latent heating phase duration for various HS configurations and varied range of input heat flux are shown in Fig. 15 (a). The latent heating phase completion time of HSSPF is found to be higher compared to other configurations. Maximum latent heating phase completion time of 2930 s is obtained for HSSPF at \( q''=1.5 \text{ kW/m}^2 \). Latent heating phase duration decreases with the increase in input heat flux values. This is because of the heat storage rate increases at higher heat flux values. Higher latent heating phase completion time in the case of HSSPF is mainly due to the higher fins surface area, which allows the uniform melting of PCM from all the directions and counterbalances the low thermal conductivity of PCM.

Fig. 15 (b) presents the thermal conductance (G) of various HS configurations filled with pure PCM, for heat flux values varying between 1.5 and 3.0 kW/m². The thermal conductance values of PCM base HS assembly have been estimated by using Eq. (8). Thermal conductance basically represents the heat transfer rate per unit temperature difference through the surface of the HS in a steady regime. It is found that that HSSPF embedded with pure PCM gives higher thermal conductance values followed by HSCPF, HSRPF, and HSNF. The thermal conductance values increase with the increase in heat fluxes.

6.7. Enhancement in operating time

Fig. 16(a-d) presents the enhancement in operating time to attain various critical SPTs for different HS configurations integrated with pure PCM and \( \phi = 0.5 \) NePCM. Critical SPT represents the maximum operating temperature beyond which the performance and reliability of the electronic devices decreases. Here, the temperature of 65 and 75°C are selected as critical SPTs and Eq. (7) is used to obtain the enhancement ratio. It can be noticed that at \( q''=1.5 \text{ kW/m}^2 \), HSCPF has the highest enhancement ratio for SPT of 65°C. While for \( q''=2.0, 2.5, \) and \( 3.0 \text{ kW/m}^2 \), HSSPF exhibits the highest enhancement ratio. For SPT of 75°C, at \( q''=1.5 \text{ kW/m}^2 \), HSRPF exhibits the highest enhancement ratio when HS is filled with pure PCM (Fig. 16c). While for \( \phi = 0.5 \) NePCM, HSCPF provides the highest enhancement ratio (Fig. 16d). For other heat flux values, HSSPF provides the highest enhancement ratio. The highest enhancement ratio for HSCPF and HSRPF at \( q''=1.5 \text{ kW/m}^2 \) is mainly due to the variation in latent heating phase completion time. For SPT of 65°C and \( q''=1.5 \text{ kW/m}^2 \) the maximum value of enhancement ratio is found to be 5.4, and 5.2 for \( \phi = 0.0 \) and \( \phi = 0.5 \), respectively. While for SPT of 75°C and \( q''=1.5 \text{ kW/m}^2 \), the maximum value of enhancement ratio is found to be 6.5 and 4.65 for \( \phi = 0 \) and \( \phi = 0.5 \), respectively.
lower heat flux (1.5 kW/m²) HSRPF and HSCPF exhibit the highest value of enhancement ratio for pure PCM and NePCM. While as the heat flux value increases (q′′=2.0, 2.5 and 3.0 kW/m²), HSSPF provides highest enhancement ratio. An enhancement ratio of 5.0 is obtained for HSSPF at 2.0 kW/m² heat flux value for SPT of 65 °C.

7. Conclusions

In the present experimental investigation, various configurations of HS such as HSNF, HSCPF, HSSPF, and HSRPF embedded with different mass fractions of NePCM composite are studied to stretch the operating time of electronic devices. Constant volume fractions (9.0%) of fins have been used to ensure an equal quantity of PCM/NePCM. Tests are conducted for various heat flux values ranging from 1.5–3.0 kW/m² and various mass fraction of CuO (∅ = 0.0–3.0). The important conclusions drawn from the study are presented below.

- It is observed that PCM integrated HS extends the operating time for electronic devices compared to HS without PCM.
- The addition of copper oxide nanoparticles inside the pure PCM reduces the value of latent heat of fusion while increasing the thermal conductivity and viscosity. The maximum reduction in latent heat of fusion is found to be 24.75% at ∅=3.0. At the same time, the maximum enhancement in thermal conductivity and viscosity is found to be 150% and 100%, respectively.
- Based on various parameters such as duration of latent heat phase completion time, thermal conductance, enhancement ratio, and temperature uniformity, HSSPF is found to be superior compared to other HS configuration. However, as the melting of PCM/NePCM completes, the difference in temperature variation for HSSPF and HSCPF is insignificant. The maximum temperature reduction of 13 °C and 15 °C is observed for HSSPF filled with pure PCM and NePCM at ∅=0.5. At higher heat flux values highest enhancement ratio is obtained for HSSPF. An enhancement ratio of 5.0 is obtained at 2.0 kW/m² of heat flux value for SPT of 65 °C.
- The addition of CuO nanoparticle beyond ∅=0.5 decreases the HS performance drastically since HS base temperature increases sharply due to an enormous increase in viscosity.

CRediT authorship contribution statement

Anuj Kumar: Conceptualization, Methodology, Software, Validation, Formal analysis, Data curation, Writing - original draft. Rohit Kothari: Conceptualization, experimental set up and heat sink design, Analysis. Santosh K. Sahu: Resources, Funding acquisition, Visualization and Supervision, review & editing, Project administration. Shailesh Ishwarlal Kundalwal: Funding acquisition, Supervision, review & editing, Project administration.

Declaration of competing interest

The authors declare that they have no known competing financial interest or personal relationships that could have appeared to influence the work reported in this paper.
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