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ORIGINAL RESEARCH PAPER

An experimental assessment of nanostructured materials embedded in a PCM-based heat sink for transient thermal management of electronics

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ABSTRACT: In the present paper, an experimental assessment was performed on the transient thermal performance of a heat sink filled by a phase change material (PCM) and PCM embedded with carbon nanofibers (CNFs) and titania (TiO_2) nanoparticles as nanostructured materials. In order to enhance the thermal conductivity of PCM, CNFs and TiO_2 nanoparticles at different loadings (0.5wt. % and 2 wt.% of CNFs and 2 wt.% and 4 wt.% TiO_2) were dispersed by two-step method in to the molten PCM. The thermal conductivity and viscosity measurements showed an enhancement in composite thermal conductivity as well as an increment in viscosity. The heat sink was filled with PCM, PCM/CNF and PCM/TiO_2 and experiments were accomplished by inputting power ranging from 3 W to 8 W. Results showed that filling the heat sink with PCM delayed the time to reach a typical temperature of 35°C by up to 110% for the power level of 8 W, while adding 2 wt.% of CNFs reduced this time by 15% and 4 wt.% of TiO_2 nanoparticles improved by 2%. Generally, dispersion of TiO_2 led to lower heat sink transient temperatures. However, adding 2 wt. % of CNFs and 4 wt. % TiO_2 nanoparticles in to PCM at power level of 8 W raised the steady operation temperature by 11°C and 0.3°C, respectively.

KEYWORDS: *heat sink, nanostructured material, PCM, thermal conductivity, transient operation*

INTRODUCTION

Generated heat by operating electronic devices must be dissipated to improve performance and long-term reliability. Heat dissipation techniques are widely used in thermal management of electronics in both steady and transient operation. Most electronics operate for long periods of time and thus their dissipation mechanism is designed for steady operation. But electronic devices in warming-up period operate transiently, or in some applications never run long enough to reach steady operation. Transient operation of electronics may cause thermal shock or produce thermal stresses that reduce the reliability of electronic devices [1].

A common thermal management technique for transient operation is to use PCMs in electronics, because of their large thermal energy storage capacity in a nearly narrow temperature range. Through this technique, a heat sink as a conventional method for cooling of electronics is filled with a proper PCM and the dissipated heat is absorbed by the PCM. Many researchers have studied experimentally [2-9] and numerically [7-17] the PCM-based heat sinks.

Although PCMs exhibit desirable properties, they possess a low thermal conductivity which reduces the thermal response of the PCM-based heat sinks.

For transient thermal management in electronic devices which use PCM-based heat sinks, inserting a high thermal conductivity matrix in to the PCMs in addition to using fins has been a solution to enhance effective thermal conductivity of PCM. Two types of thermal conductivity enhancers, i.e. porous aluminum matrix and fins, were numerically studied by Nayak et al. [18]. The results showed increasing the thermal conductivity of eicosane as PCM had a significant effect on melting rate and evolution of the solid–liquid interface and heat sink performance. The thermal characteristics of a thermal protection system consisting of carbon foam matrix saturated with phase change material were numerically and experimentally investigated by Mesalhy et al. [19]. The results showed that the effective high thermal conductivity caused a high heat absorption rate through a smaller time interval. Yin et al. [20] investigated the thermal response of a heat sink applied a composite PCM. The composite was prepared by absorbing paraffin into expanded graphite. The experimental results showed that the apparent heat transfer coefficients of the heat sink with the composite PCM are 1.36–2.98 times higher than those of the heat sink without the composite PCM. Baby and Balaji [21] experimentally studied the effect of orientation of a copper porous matrix filled PCM based heat sink. The use of copper matrix compensates the low thermal conductivity of PCM. They found a good performance of porous matrix filled PCM based heat sink and not significant impact of orientation on heat transfer performance.

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Nomenclature

CNF	carbon nanofiber	T	temperature (°C)
k	thermal conductivity (W/m.K)	t	time (min)
PCM	phase change material		**Greek Symbols**
		Φ	nanoparticle volume fraction (%)
		μ	viscosity (mPa.s)

Phase change materials with dispersed nanostructured materials have received considerable attention in recent years [22-25]. The effect of using nanostructured materials on thermal management of electronics have rarely been reported in literatures.

Weinstein et al. [26] experimentally explored the use of graphite nanofibers (herringbone, ribbon, or platelet types) to improve thermal conductivity of PCM for thermal management of electronics using a cubic base. They found that the maximum base temperature decreased as graphite fiber loading levels increased. Also, Thermal performance was fiber structure dependent. Tigner et al. [27] analyzed a platform, an aluminum base with a heater cartridge, for thermal management studies of microelectronics cooling methods.

The platform analysis revealed that application of a PCM reduced the surface temperature of the platform by 12 K over temperatures measured without a cooling other than heat transfer to the ambient. Additionally, the Nano-enhanced Phase Change Materials (NEPCM) performed best with an additional 3 K reduction in surface temperature over the PCM. PCM-based heat sinks which used nanostructured materials for enhancing thermal performance are a novel concept in transient thermal management of electronics that have been rarely studied before. Hence, this paper evaluates a heat sink filled by the PCM embedded with CNFs and TiO_2 nanoparticles for experimental thermal management of electronics.

Thermal conductivity and viscosity of PCM/nanostructured material are measured as these are effective on heat dissipation rate. The transient thermal response of PCM/nanostructured material heat sink is compared to unfilled heat sink as well as PCM-based heat sink.

EXPERIMENTAL METHOD AND PROCEDURE

Experimental setup

The heat sink was made of anodized aluminum 6063 alloy with upward triangular fins. The heat sink was normally cooled by natural convection/radiation. The base dimensions of heat sink was 65×65 mm with height of 40mm.

The height of fin was 30mm whose thickness is 4mm at base and 2mm at tip. A polyamide film (Kapton®) resistance heater made by OMEGA®, USA, with pressure sensitive adhesive backing, was attached to the bottom surface of heat sink to generate heat. The heater was 63.5×63.5mm with thickness of 0.203 mm and electrical resistance of 108.6Ω. The power input to the heater was supplied by a programmable DC power supply unit (GW Instek PSP-405) with 0-40V and 0-5A. Three power inputs of 3W, 5W and 8W were applied to heat sink to investigate the thermal management.

Except the top surface, the other sides of the heat sink were insulated by elastomeric insulation to minimize thermal losses.

The insulated heat sink was put under a transparent acrylic plastic cover. Figure 1 shows the experimental setup with instrumentation.

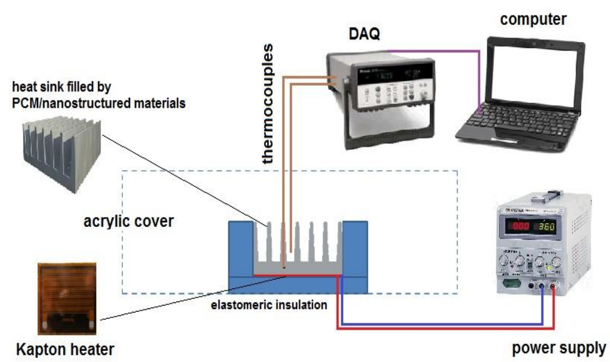

Fig.1. Experimental setup

Heat sink temperature was measured by averaging four thermocouples reading. Each thermocouple was placed in a hole drilled 30mm through the aluminum heat sink and firmly glued by thermally conductive Omega OB-101-1/2. Three more thermocouples were placed in the PCM. Another thermocouple was used to measure the environment temperature.

All thermocouple were T-type (Omega TT-T-30-SLE) and were calibrated using an Isotech Hyperion calibrator and Pt100 sensor in measuring range of 20°C to 80°C prior to the experiments. The thermocouples were connected to a data acquisition system (DAQ) model Agilent 34972A and to a computer to record the temperature readings at every 5 second intervals.

The uncertainty in temperature measurement was ±0.2°C. For the input power, the uncertainty was ±1.0%.

Materials, preparation and thermal properties

The PCM used in this study was paraffin RT42 that was supplied by RUBITHERM® Technologies GmbH, Germany [28].

The most important data of RT42 provided by the supplier are listed in Table 1.

Table 1
Thermal properties of RT42 [28].

property	Typical value
Melting area	38-43°C
Congealing area	43-37°C
Heat storage capacity ± 7.5% (Combination of latent and sensible heat in a temperature range of 35 °C to 50 °C)	174 kJ/kg
Specific heat capacity	2 kJ/kg.K
Solid density	0.88 kg/m3
Liquid density	0.76 kg/m3
Heat conductivity (in both phases)	0.2 W/m.K
Volume expansion	12.5%

Paraffin RT42 with graphite matrix has been previously used in thermal management of battery packs [29]. Also, this paraffin alongside some other PCMs was applied by Mahmoud et al. [30] to investigate thermal management in portable electronic devices.

Titanium (IV) oxide nanopowder (TiO_2 nanoparticles) and Carbon nanofibers (CNF) were purchased from SIGMA-ALDRICH®, Germany, and used as nanostructured materials in this study.

According to data sheet provided by the company, particle size of TiO_2 was ~21 nm with more than 99.5% trace metals basis. Pyrolitically stripped and platelets (conical) CNFs with 98% carbon basis were applied in diameter of 100 nm and length of 20-200 μm.

All materials in this study were used as-received, without further treatment.

Since liquid paraffin may have high dissolved air content, the PCM should be degassed carefully prior to measurements. For this purpose, the PCM was melted under vacuum. PCM/nanostructured materials composites were prepared by a two-step method. TiO_2 nanoparticles and CNFs were added to liquid PCM at a temperature around 60°C.

Then the mixture of PCM/TiO_2 was stirred by a mechanical stirrer at 1000 rpm and sonicated in an ultrasonic bath (VWR, USC2100D, Germany) for 30 minutes. Due to the length reduction issue during stirring, ultrasonic for 20 min was only used to disperse CNFs in liquid paraffin [31].

The thermal conductivity of PCM and PCM/ nanostructured materials composites was measured by a thermal constants analyzer (TPS 2500, Hot Disk AB, Sweden) that is based on the transient plane source (TPS) technique. The measurements were conducted at 20°C (solid state) and 60°C (liquid state).

The viscosity of RT42 and PCM/ nanostructured materials in liquid phase were measured by a viscometer (DV-II + Brookfield programmable viscometer, USA with UL adapter) with a temperature-controlled bath. This equipment is appropriate to liquids with the viscosity in the range 1–2000 cP. The viscosity was measured at spindle rotational speed of 60 rpm.

The uncertainty for thermal conductivity and viscosity was 2% and 4%, respectively [23].

In order to run the experiment, the heat sink was filled with liquid PCM (or PCM/ nanostructured materials) layer-by-layer to ensure absence of internal voids or air bubbles. After one layer was solidified another layer was added. A mass of around 65.00g PCM was poured in the heat sink. Afterward, the heat sink was kept at room temperature of 22˚C for at least 12h to ensure all PCM and heat sink were at the same temperature.

RESULTS AND DISCUSSIONS

Thermal conductivity and viscosity results

Thermal conductivity (k) and viscosity (μ) of PCM and PCM/nanostructured materials are summarized in Table 2.

Table 2
Measured thermal properties of PCM/nanostructured materials.

Materials	Nanoparticle loading (wt. %)	k at 20°C (W/m.K)	k at 60°C (W/m.K)	μ at 60°C (cP)
PCM	-	0.254	0.158	3.64
PCM/TiO_2	2	0.264	0.168	5.69
	4	0.272	0.178	8.46
PCM/CNF	0.5	0.279	0.171	8.87
	2	0.305	0.183	>2000

The thermal conductivity of composites increases by increasing particles loading.

The thermal conductivity enhancement of 4% and 7% is seen for 2wt. % and 4wt.% of TiO_2 nanoparticles, respectively.Also, addition of 0.5 wt.% and 2 wt.% of CNFs to RT42 improves the thermal conductivity by 10% and 20%, respectively.

At the shear rate of $61.15 s^{-1}$ and temperature of 60°C, the RT42 viscosity is 3.64 cP that reaches to 5.69 cP and 8.46 cP for the 2 wt.% and 4 wt.% of TiO_2 nanoparticles, respectively.

At the same shear rate and temperature, the sample viscosity of 0.5 wt. % CNF become 8.87 cP while the viscosity of 2 wt. % CNF increases dramatically that exceeds the upper limit of the viscometer (2000 cP).

Effect of nanostructured materials on transient thermal performance of heat sink

In order to investigate transient thermal response of heat sink filled by PCM and PCM/nanostructured materials, a total of 18 cases were examined in the present study according to the combinations of various power levels (3 W, 5 W an 8 W) and different particle loadings (0.5 wt.% and 2 wt.% for CNF and 2 wt.% and 4 wt.% for TiO_2). The repeatability of temperature measurement was validated by performing melting experiment twice at the power level of 8 W for PCM, PCM/CNF(2 wt.%) and PCM/TiO_2(4 wt.%).

The results showed the measurements are repeatable by around 1% difference. The unfilled heat sink (without any PCM) temperature is depicted in Figure 2 for different power levels. Convection and radiation are the only mechanism of cooling of the heat sink. The rapid grow-up of temperature especially at higher power level can be seen from the thermal response curves. The steady state temperatures of unfilled heat sink are 47.50, 60.00 and 75.5°C at the power levels of 3, 5 and 8 W, respectively.

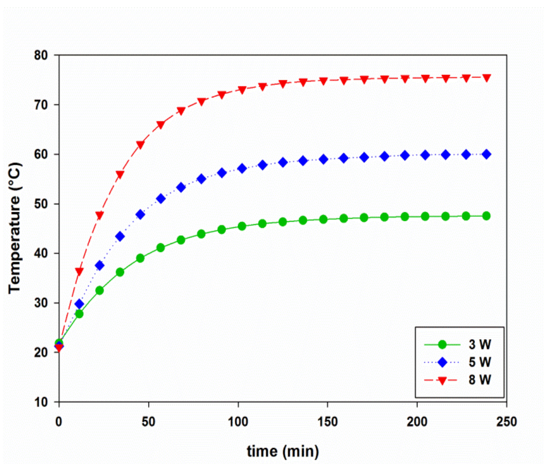

Fig. 2. Temperature-time profile of unfilled heat sink

Transient thermal responses (temperature-time profile) of the heat sink filled with PCM/CNF at various power levels are shown in Figure 3. The heating-up period is around 450, 350 and 250 min for power level of 3, 5 and 8 W.

By supplying power to the heater, heat transmits from the heat sink base to the thermal energy storage medium in three directions, from the two sides of the fins and from the bottom.

At the beginning, all the PCM is in solid state and the dominant heat transfer mechanism in the PCM is pure conduction. The dissipated heat from the heat sink is absorbed and stored by the PCM in the form of sensible heat. The temperature increases almost linearly with time. Then, the temperature of the PCM gradually rises to start melting process. As soon as heat sink temperature becomes equal to or higher than the melting point, the melting process starts. The temperature- rising rates of the PCM are significantly slowed during this period. As the melting process proceeds, the liquid region becomes larger and larger, and thus, natural convection is playing a more and more important role in heat transfer. Because of the higher thermal conductance ability of PCM/CNF composite, a rapid temperature rise of the composite is expected. Previous researches investigators reported this phenomenon for PCMs containing nanostructured materials [32-34].

As it can be seen from Figure 3, the heat sink temperature increases by dispersing CNF to PCM. Adding more CNF causes greater heat sink temperature. Moreover, the heat sink transient temperature depends on heat dissipation rate from the heat sink. Although the PCM/CNF composite possesses a greater thermal conductivity than PCM, the heat sink filled by PCM/CNF composite cannot dissipate heat as well as pure PCM.

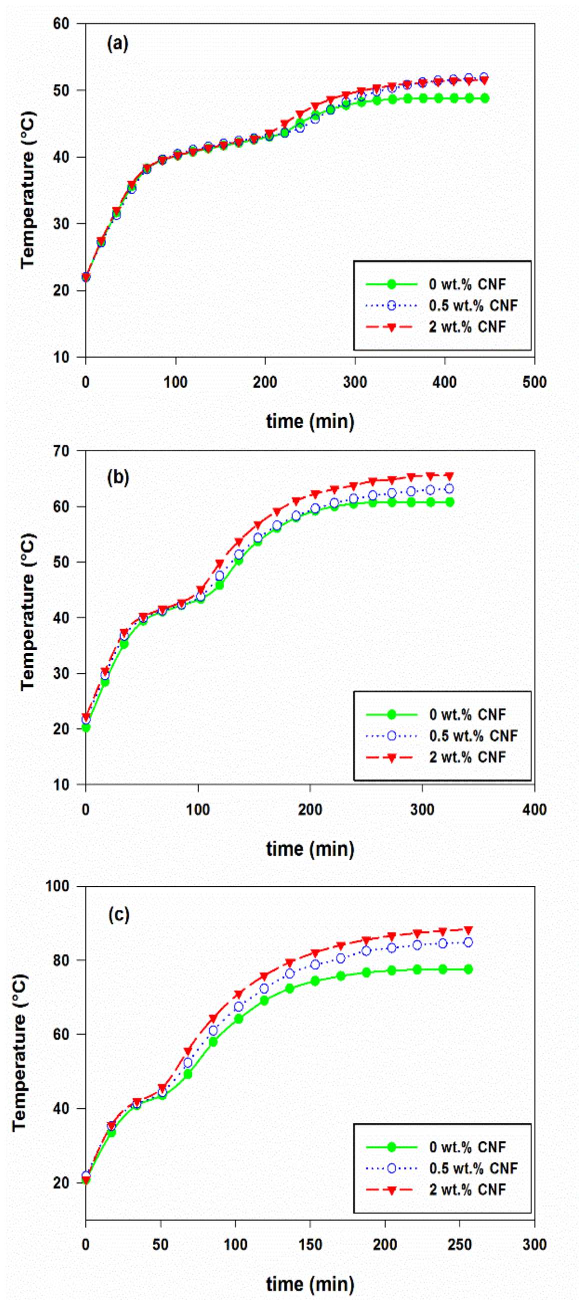

Fig. 3. Temperature-time profile of the PCM/CNF heat sink for power level of (a) 3W (b) 5W (6) 8W

This may be caused by some unexpected reasons like poor dispersion performance of CNFs, great thermal contact resistance between heat sink surface and PCM/CNF due to combined properties of PCM and CNFs [35], no or weak natural convection mechanism in molten PCM/CNF due to large amount of viscosity especially in greater CNF loadings, reduction of latent heat of fusion of PCM/CNF with respect to the PCM [32]. Also, one should bear in mind that higher thermal conductivity results in lower temperature difference in the material, hence lower natural convection heat transfer. In spite of high thermal conductivity of graphite and paraffin composite (4.676 W/m.K), a higher temperature variation with time was reported by Yin et al. [20] for a heat sink connected to a storage unit that works at low power levels. Effect of dispersing TiO_2 nanoparticles in PCM on transient thermal response of heat sink filled by this material was shown in Figure 4.

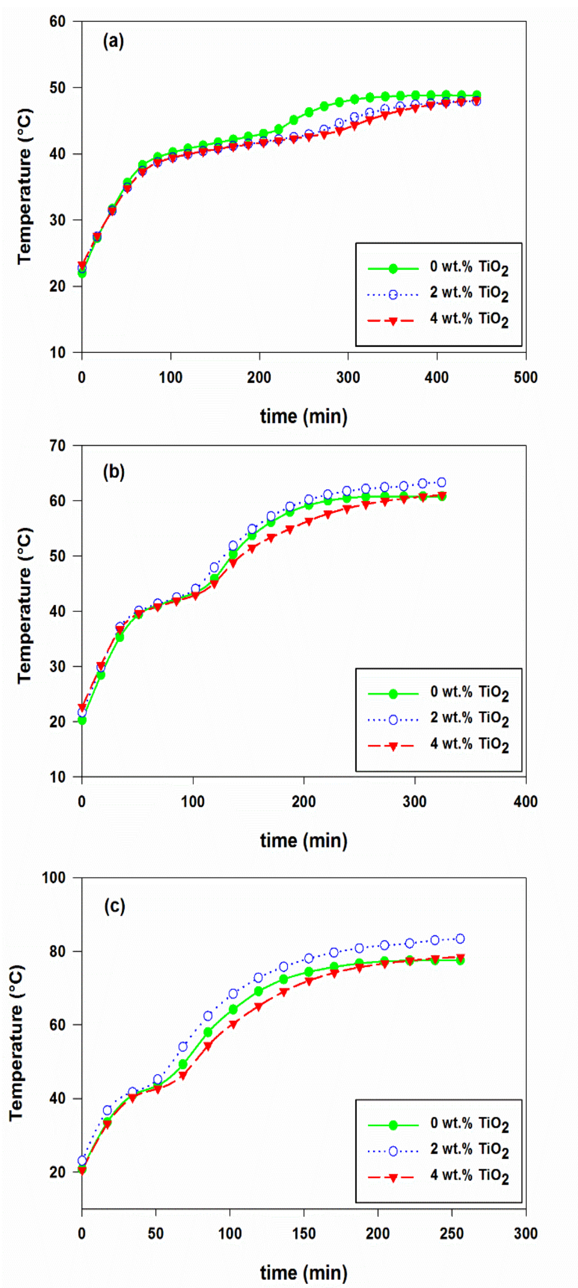

Fig. 4. Temperature-time profile of the PCM/TiO_2 heat sink for power level of (a) 3W (b) 5W (6) 8W

The experiments were run at power levels of 3, 5 and 8 W. Figure 4 shows that the presence of the TiO_2 nanoparticles does not seem to have significant effect at the initial state of heating, as the three curves are almost overlapped for PCM, PCM/TiO_2 (2 wt.%) and PCM/TiO_2(4 wt.%).

The heat sink temperature in the case of heat sink filled by PCM/TiO_2 is generally lower than PCM-based heat sink, except at the power level of 5 W and particle loading of 2 wt.%. that the transient temperature exceeds PCM-based heat sink. Titania nanoparticles are easily dispersed in the liquid PCM and established a good combination with the PCM.

Although the thermal conductivity enhancement of PCM/TiO_2 is not as much as PCM/CNF, the lower viscosity increment by adding TiO_2 nanoparticles causes to keep fluidity of the liquid PCM and to have natural convection in the molten PCM/TiO_2.

This convection is less than that in the case of pure PCM, but the lower thermal contact resistance of PCM/TiO_2 as well as longer time of phase change may have resulted in higher heat dissipation than PCM-based heat sink.

Effect of nanostructured material on time to attain a typical temperature

In order to compare the transient performance of the unfilled heat sink, PCM-based heat sink, PCM/CNF heat sink and PCM/TiO_2 heat sink, the time length required for reaching the heat sink to the typical temperature of 35°C was presented in Figure 5.

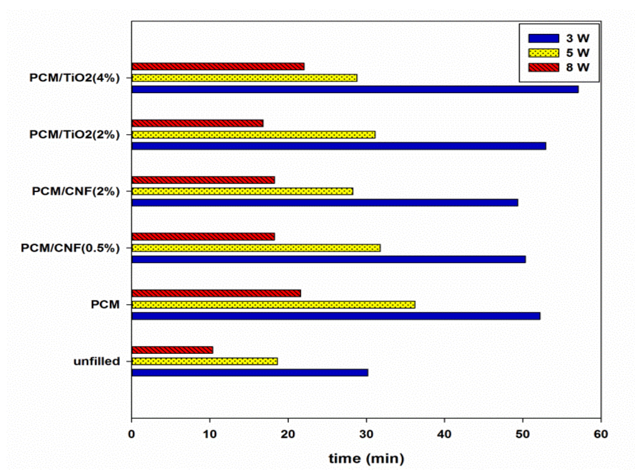

Fig. 5. Comparison of operating times to reach 35°C for various particle loadings and power level

Filling the heat sink with PCM increases the time to reach 35°C by 73%, 95% and 110%, for power level of 3, 5 and 8 W, respectively. Adding CNFs to PCM does not help to make this time longer.

At the CNF loading of 2 wt.%, a reduction of 5%, 22% and 15%, , in the time required to reach 35°C was observed with respect to pure PCM for power level of 3, 5 and 8 W, respectively . A comparison between PCM and PCM/TiO_2 heat sink shows the time to reach 35°C for PCM/TiO_2 (4 wt.%) is longer than that of pure PCM by 10%, 26% and 2% for power level of 3, 5 and 8 W, respectively. There is not much enhancement in time for PCM/TiO_2 (2 wt.%) and even there is decrease in time for power of 5 and 8 W.

Effect of nanostructured material on melting time

The time for melting completion of PCM, PCM/CNF and PCM/TiO_2 at various power levels are compared in Figure 6.

Temperature rise during melting process is so slow, because of storing thermal energy as latent heat of fusion. Increasing the power level causes shortening the melting completion because of the higher heat transfer rate to the PCM.

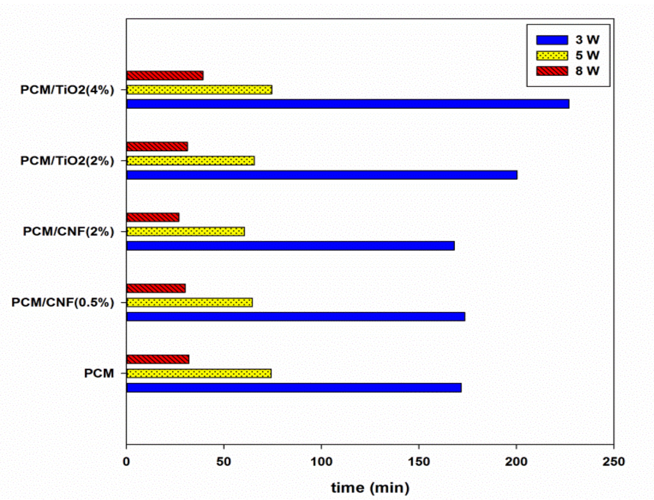

Fig. 6. Melting completion time for PCM, PCM/CNF and PCM/TiO_2

As shown in Figure 6, during melting of the PCM/CNF at loading of 2 wt.%, the time for the melting completion shortens by 2%, 12% and 2% for power level of 3, 5 and 8 W, respectively, as compared to that of pure PCM. The effect of the presence of TiO_2 nanoparticles on the melting time is of great interest. As it can be seen from Figure 6, the greatest enhancement in melting time was observed at the power of 3 W for PCM/TiO_2 composites. By increasing power level, a slight reduction or raise occurs in PCM/TiO_2 melting time. Changing in melting time by adding nanostructured materials might be explained by different molecular interaction between PCM and nanostructured materials.

A comparison between steady operation temperatures

Following the completion melting process, a sharp rise in temperature above the upper limit of the phase transition temperature occurs. Conduction or natural convection heat transfer from heat sink to the molten PCM raises its temperature. After a period of time, heat gain by PCM and heat sink are equal to heat loses and the heat sink reaches to a steady condition with little change in its temperature. The steady temperature for heat sink in various conditions are listed in Table 3.

The steady state operation temperature of heat sink increases by going up the input power level. This temperature slightly rises by filling the heat sink with PCM. Because the PCM reduces the heat transfer ability of the heat sink by covering up its convection surface. Due to reduction in effective surface area, the steady state temperature exceeds the temperature of the unfilled heat sink. Generally, the steady operation temperature of heat sink should not overstep the safe limit.

Table 3
Steady operation temperatures of heat sink.

Power (Watts)	**Unfilled**	**PCM**	**PCM /CNF 0.5wt.%)**	**PCM /CNF (2 wt.%)**	**PCM /TiO_2 (2wt.%)**	**PCM /TiO_2 (4wt.%)**
3	47.5	48.9	51.2	51.0	48.4	48.3
5	60.0	60.8	63.5	65.5	62.5	60.5
8	75.5	77.5	84.5	88.5	78.0	77.8

Embedding nanostructured materials in the PCM-base heat sink raises the steady operation temperature. Adding 0.5 wt.% or 2 wt.% of CNF at power level of 8 W increases the steady operation temperature by8°C and 11°C, respectively. While the dispersing of 2 wt.% or 4 wt.% TiO_2 nanoparticles in to PCM increase its temperature by only 0.5°C and 0.3°C, respectively.

CONCLUSIONS

Transient operation of a finned heat sink filled by a thermal energy storage medium was experimentally assessed in this research. The latent heat thermal energy storage medium was made up of a PCM dispersed with high thermal conductance nanostructured materials (CNFs or TiO_2 nanoparticles). At different loadings (0.5wt.% or 2 wt.% of CNFs, and 2 wt.% or 4 wt.% of TiO_2) and different power levels (3 W, 5 W and 8 W), the relevant conclusions of this assessment are:

- Thermal conductivity measurement proved the enhancement by up to 20% for 2 wt.% of CNFs composite and 7% for 4 wt.% of TiO_2 at 20°C. Simultaneously, a considerable increment in viscosity was measured.
- Transient thermal response of the heat sink showed that the PCM/CNF heat sink operated at higher temperatures than PCM-based heat sink, while the PCM/TiO_2 heat sink temperature was generally lower than PCM-based one.
- Filling the heat sink with PCM promotes the time to reach 35°C by 73%, 95% and 110% for power level of 3, 5 and 8 W, respectively. Adding CNFs to PCM does not make this time longer, but for PCM/TiO_2 (4 wt.%)

this time is longer than pure PCM by 10%, 26% and 2%, for power level of 3, 5 and 8 W, respectively.

- The melting completion time and steady operation temperature generally became better by adding TiO_2 and became worse by adding CNFs.
- The results demonstrated that the thermal conductivity enhancement by embedding nanostructured materials is not the sole way to improve transient thermal performance of a heat sink. Future studies should focus on particle type and shape, dispersion quality, combination efficiency of nanoparticles and PCM in addition to PCM type, heat sink geometry and size, and power levels.

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