Heat pipe with Nano enhanced-PCM for electronic cooling application

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Highlights

• Thermal conductivity of nano enhanced-PCM is enhanced compared to pure Tricosane.

• Thermal performance of heat pipe using nano enhanced-PCM is presented.

• Temperature variations of evaporator with nano enhanced-PCM are reported.

• Maximum of 30% of the input power is stored in the nano enhanced-PCM.

• PCM with 1 vol% Al_2O_3 nanoparticle is found to be optimum for maximum heat transfer.

Abstract

In this study, the thermal performance of a heat pipe using nano enhanced Phase Change Material (PCM) as an energy storage medium for electronic cooling application is studied. The PCM is placed around the adiabatic section of the heat pipe in which heat is absorbed and released depending on the power inputs at the evaporator and fan speeds at the condenser. Experiments are performed to obtain the evaporator, condenser and PCM temperature distributions during the charge, discharge and simultaneous charge/discharge processes. In the present study, Water, Tricosane and nano enhanced Tricosane are used as energy storage materials. The nano enhanced PCMs are prepared by mixing different volume percentage (0.5%, 1% and 2%) of Al_2O_3 nanoparticles with Tricosane. Thermal conductivity of nano enhanced PCM is measured and found to be enhanced to a maximum of 32% compared to pure Tricosane. The effects of PCM filling volumes, fan speeds and heating power on the performance of cooling module are also investigated. From this study it is found that the evaporator temperature of heat pipe with nano enhanced PCM is decreased about 25.75%, which can save 53% of the fan power compared with the traditional heat pipe. Also found that the nano enhanced PCM can store

almost 30% of the energy supplied at the evaporator leading to the reduction in fan power consumption.

1. Introduction

Phase change materials (PCM) are gained greater importance in the field of power electronics as an effective cooling media due to its high heat storing ability. Development of various advanced equipment's in the fields of power electronics, communications, computers and aviation have resulted in a need for effective thermal control, as most of the equipment used in these areas dissipate heat in a periodic or transient manner. Small and smart equipment's that use compact devices consume high power, and require better materials that can have relatively better thermal properties. In this context, PCM has been widely used as a coolant material in electronic cooling applications. Kandasami et al. [1] developed a novel PCM based thermal management system for an electronic device and studied the effect of parameter such as heat input, inclination angle, and various melting/freezing times under cyclic steady conditions. Further, finned heat sinks and hybrid heat sinks with PCM materials are also used in the electronic cooling applications [2-4]. Moreover, heat storage unit filled with the PCM of n-eicosane [5] is also used in cooling of mobile electronic devices such as Personal Digital Assistants (PDAs) and wearable computers.

Thermal energy storage systems are classified into three types - Latent Heat Thermal Energy Storage system (LHTES), Sensible Heat Thermal Energy Storage System (SHTES) and Chemical Energy Storage Systems (CESS). LHTES system offers the possibility of storing

higher amounts of energy per unit mass of storage material in comparison to SHTES. Broad applications of LHTES systems in different areas include building heating and hot water, solar systems, drying equipment, refrigeration and waste recovery [6-12]. In all these applications PCM materials are widely used as energy storage materials. Generally, the heat transfer process in the PCM is slow due to its poor thermal conductivity. Hence, different techniques have been used to improve the heat transfer process in the PCM by using fins, heat sinks, hybrid heat sinks and heat spreaders [13, 14]. However, fins or extended surfaces can transfer heat only to a short distance which strongly depends on the thermal conductivity of the materials. Hence, efforts were made to use high thermal conductivity devices such as heat pipes that capable of transferring large amount of heat through a small cross-sectional area to relatively long distances with extremely small temperature differences [15]. A number of experimental and numerical studies have been carried out to investigate the effects of employing heat pipes to aid melting and solidification in LHTES systems [16]. Weng et al. [17] proved that the use of Tricosane as PCM in the heat pipe module, can reduce fan power consumption and average heater temperature in comparison to the same with no thermal storage. Though heat pipe-PCM module is effective in electronic cooling, its heat transfer rate is poor, which led researchers to look for other alternatives. It is known that the thermal conductivity of the metal is much higher (**Table 1**) than PCMs and therefore, adding nano sized metallic particles into the PCM is a better initiative to enhance its thermal conductivity.

Recently, PCM with a suspension of solid particles have been used in electronic cooling applications to enhance the heat transfer by adding micro particles as well as nano-particles into PCM. The micro particles suspended in the PCM are called as micro enhanced PCM (Me-PCMs) and nano particles suspended in the PCM are called as nano enhanced PCMs (Ne-PCMs).

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Table 1 : Thermo-physical properties of copper, Tricosane and Al₂o₃ nanoparticles

Properties	Materials		
	Electrolyte copper	Tricosane	Al$_2$O$_3$
Thermal Conductivity (W/m-K)	401	0.140	30
Specific Heat (kJ/kg K)	0.3844	2.89	0.88
Latent heat (kJ/kg)	207	209	-
Melting point in (^{o} K)	1357.6	320	1233.8

Experimental investigation of Huibinet al. [18] showed that the heat transfer coefficient of the heat sink is enhanced with the use of paraffin wax absorbed with expanded graphite. In this context, copper, aluminum, nickel, stainless steel and carbon fiber in various forms such as fins, honeycomb, wool, brush, etc as materials of thermal conductivity promoters have proven to be useful [19]. Alumina (Al$_2$O$_3$) is found to enhance the thermal conductivity of paraffin wax significantly in double pipe heat exchanger [20]. Similarly, Alumina nano-particles with Me-PCM [21], TiO$_2$ nano-particles with Paraffin wax [22] as PCM and CuO nanoparticles with n-Octadecane as PCM [23] shown enhanced performance as PCMs. Zeng et al. [24] noticed that the natural convection is degraded gradually in the presence of Carbon Nanotubes (CNT) in PCM melted in a cylindrical bottom heated cavity. Saha et al. [25] found that the thermal performance of electronic equipment was enhanced with Paraffin Wax and Eicosane as PCMs and 8% of Aluminum pin or plate pins as thermal conductivity enhancer. Chougule et al. [26] conducted a study with a nanofluid (MCNT/water) charged heat pipe utilizing two different energy storage materials (water and paraffin), different fan speeds and heating powers in the PCM cooling module. It is proved that the cooling module with heat pipe and paraffin as energy storage material can save fan power consumption compared to the module without PCM.

It is evident that numbers of studies have been performed to investigate the performance of PCM, heat pipe with PCM and PCM with solid particles as energy storage material and their combined effect on heat dissipation in electronic cooling. From the literatures [20-23], it is clear that the thermal conductivity of PCM is enhanced by adding nanoparticles which is favorable for the heat transfer enhancement of heat pipe - PCM module. Also the addition of nanoparticles into the PCM is expected to store more amount of heat compared to the traditional PCM. However, the combination of both heat pipes with Ne-PCMs has not been reported in the open literatures. Hence, the present study aimed at determining the performance of heat pipe cooling module with PCM and with dispersion of Al_2O_3 nano-particles suitable for electronic cooling applications. The charge, discharge, and simultaneous charge/discharge processes for the heat pipe-cooling module with PCM and PCM with Al_2O_3 nano-particle are tested under different fan voltage and heating power. Also the effectiveness of the cooling module is estimated and compared to the cases with and without PCM and with Ne-PCM both during charging and discharging processes.

2. Experimental details

2.1 Preparation of Ne-PCM

Ne-PCM is prepared by the well-established standard sonication process as reported in literatures [27, 28]. In this study Tricosane is used as a PCM due to the anti-corrosion behavior and higher thermal energy storage capacity compared to other PCM materials such as Paraffin wax and Eicosane. A commonly available Al_2O_3 nanoparticle which is capable of storing high amount of heat compared to other nanoparticle (See **Table 2**) is selected as a nanomaterial. The Ne-PCM is prepared by dispersing Al_2O_3 nano-particles (50 nm) in analytical grade Tricosane (Alfa-Aesar) with a purity of 99% using Ultrasonic Homogenizer (UP400S). The nanoparticle/PCM mixture is

Table 2. Heat capacity of common materials.

S. No	Material	Heat capacity (J/kg K)
1	Aluminium Oxide	880
2	Copper	385
3	brass	380
4	Sand	290
5	Silver	240
6	Iron	444
7	Gold	129

subjected to an intensive sonication process for about 30 min to make a homogeneous mixture after which is heated to a temperature just above melting point of Tricosane. The nanoparticles suspended in the PCM uniformly distributed which is confirmed using Scanning Electron Microscope (Fig 1). In this study, Ne-PCM is prepared with volume percentages of 0.5, 1 and 2% of Al_2O_3. The thermal conductivities of both pure PCM and Ne-PCM are measured at different temperatures using KD2 Pro Thermal Properties Analyser (Decagon Devices, Inc., USA). The principle of this device is based on the transient hot wire method. It consists of a microcontroller and a needle sensor. The sensor made of stainless steel with a length and diameter of 60 and 1.3 mm respectively. The uncertainty limit of this device is ±5% for a full range of reading and the readings are stood with ASTM D5334 [29] and IEEE 442 [30] standards. Further, to validate the measured data, thermal conductivity of Ne-PCM is compared with Hamilton and Crosser model [31] which is given as

$$k_{n,pcm} = k_{pcm} \left[\frac{k_{np} + 2k_{pcm} - \phi(k_{pcm} - k_{np})}{k_{np} + 2k_{pcm} + \phi(k_{pcm} - k_{np})} \right] \tag{1}$$

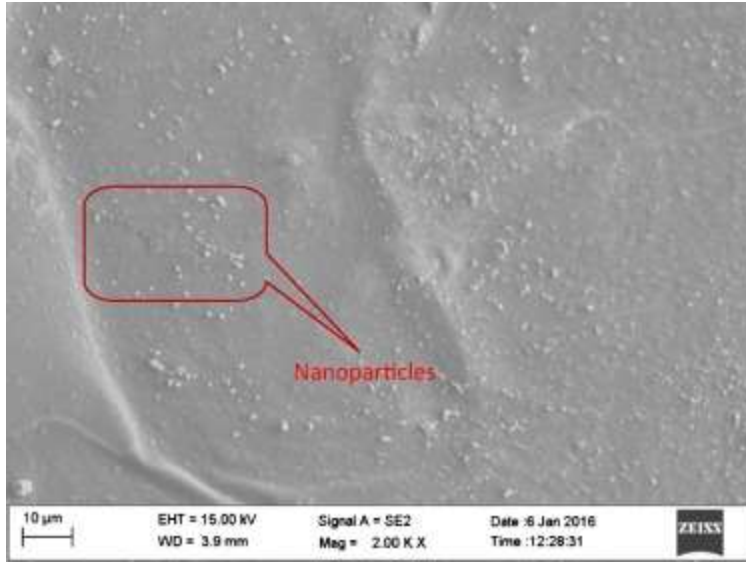In this model the nanoparticles are assumed as cylindrical shape.

Fig. 1. SEM view of distribution of nanoparticles in PCM.

2.2 Test set-up and details

Fig. 2 shows the schematic view of the experimental set-up to study the cooling performance of heat pipe-PCM module. The experimental set-up consists of a copper-water heat pipe, a heat sink, an energy storage tank, cooling fan, heater, power supply, computer, and a data logger (Agilent) unit. Temperatures at different parts of the heat pipe and PCM are measured using OMEGA T-Type thermocouples with an accuracy of ±0.2 ^{o}C as shown in Fig 3. The heat pipe is made of Cu with a length of 190 mm, outer diameter of 7.8 mm and an inner diameter of the tube is 6.8 mm. The cooling module is divided into 3 major components namely evaporator, storage tank and the heat sink. The length of the evaporator (50 mm), adiabatic (80 mm) and condenser section (60 mm) are fixed based on heat transfer limitations of heat pipe in such a way to maximize the heat transfer performance of heat pipe. Heat is supplied to the evaporator section of the cooling module. Storage tank is fabricated around the adiabatic section of heat pipe where PCM absorbs and releases heat. The maximum volume of PCM that can be accommodated in the energy storage tank is 140 cc. The condenser section of the heat pipe is attached to a heat sink
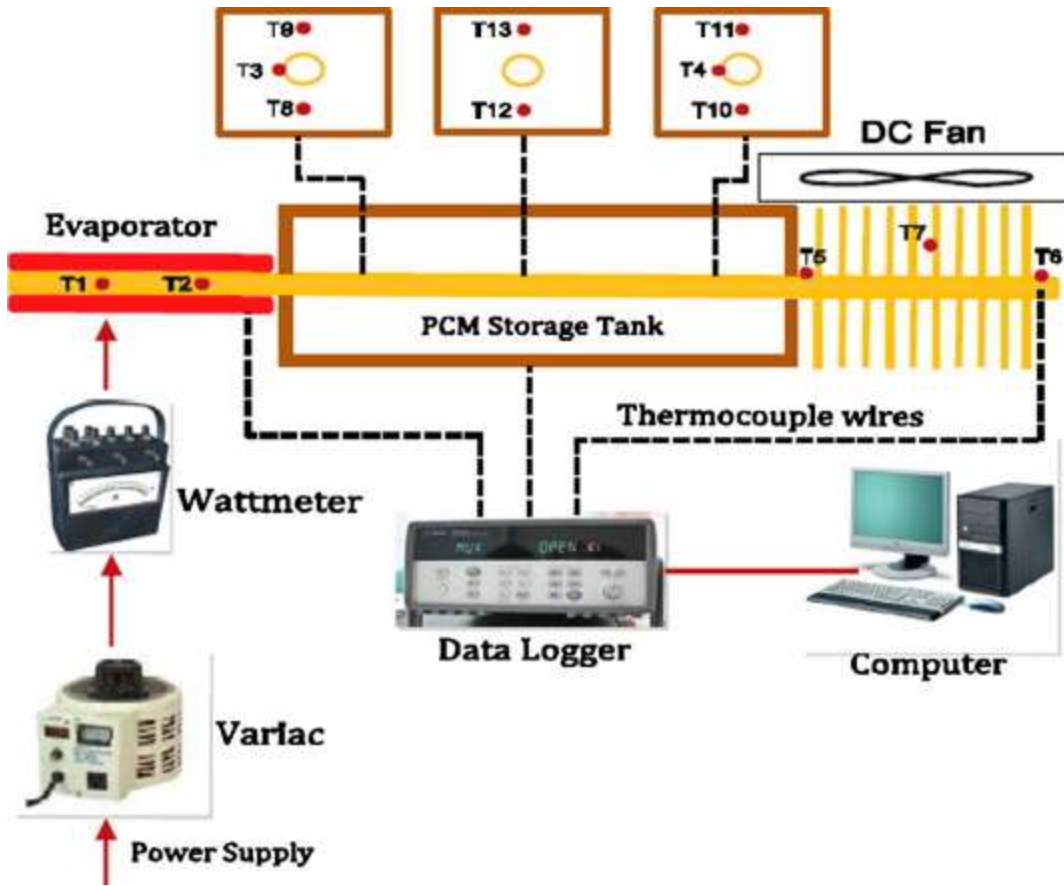
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Fig. 2. Schematic of the experimental set up of heat pipe – PCM module.
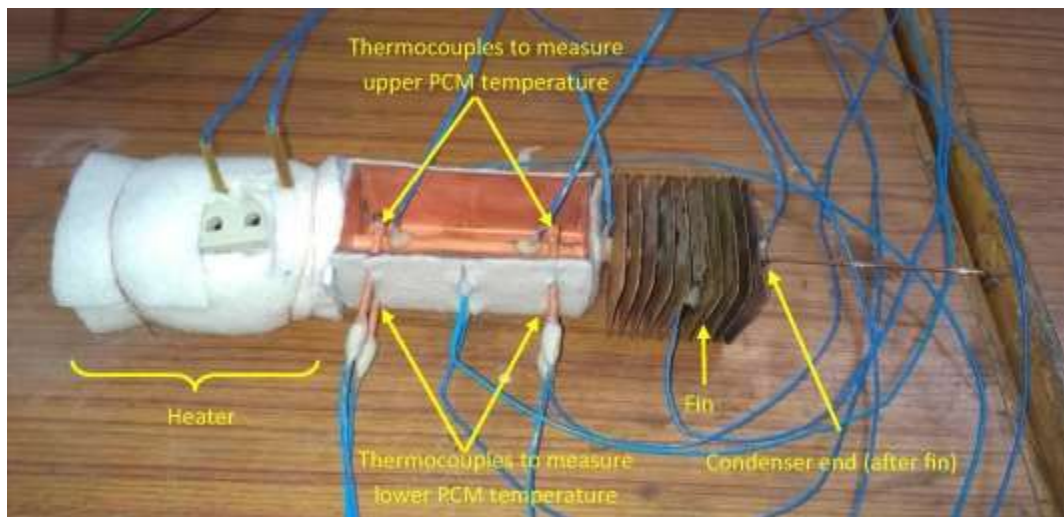

Fig. 3. Experimental set up of heat pipe – PCM module and thermocouple positions.

where ten copper fins with a height of 50 mm, width of 60 mm and a thickness of 0.2 mm are welded over to form a heat sink. The total cooling area of the heat sink is 0.00120 m^2.

In this experiment, heat is supplied to the evaporator section of the heat pipe by adjusting the variable transformer which is absorbed by both PCM and the storage tank. The energy stored in PCM is estimated as

$$Q = m\, C_p(T_e - T_i) \tag{2}$$

where T_i and T_e are the initial and final temperature of the PCM respectively

$$T_i = \frac{1}{6}\sum_{n=1}^{6} T_{n,i} \tag{3}$$

$$T_e = \frac{1}{6}\sum_{n=1}^{6} T_{n,e} \tag{4}$$

The uncertainty present in the estimation of stored energy is calculated as

$$\frac{\Delta Q}{Q} = \sqrt{\left(\frac{\Delta m}{m}\right)^2 + \left(\frac{\Delta(\Delta T)}{\Delta T}\right)^2} \tag{5}$$

Table 3 shows the uncertainty of energy storage in the PCMs at different heat inputs and found that the maximum uncertainty is less than 2 percent.

Table 3. Uncertainty in heat storage estimation.

S. No	Heat input (W)	Uncertainty (%)				
		Water	Tricosane	Tricosane with 0.5% Al$_2$O$_3$	Tricosane with 1% Al$_2$O$_3$	Tricosane with 2% Al$_2$O$_3$
1	13	1.71	1.74	1.26	1.27	1.19
2	18	1.55	1.7	1.16	1.14	1.14
3	23	1.51	1.67	1.12	1.05	1.11

3. Results and discussion

The cooling performance of the heat pipe - PCM module is investigated by varying different parameters such as heat inputs (13, 18 and 23 W), fan voltages (3.4 and 5 V), PCM (W/O PCM, Water, Tricosane, Tricosane with Al_2O_3 nano-particles) and filling volumes (100, 115 and 130 cc). The effects of nanoparticle concentration on the thermal conductivity of PCM and parameters such as energy storing capacity of heat pipe –PCM module are discussed.

3.1 Effect of nanoparticle concentration on the thermal conductivity of PCM

Fig 4 shows the measured thermal conductivity of PCM (both solid and fluid state) with and without nanoparticle at different temperatures along with the thermal conductivity estimated using Hamilton and Crosser model. The PCM is at solid phase up to a temperature of 47 ^{o}C after that it gets converted to liquid phase. It is observed that the addition of nanoparticles in the PCM enhances the thermal conductivity. It is also seen that the thermal conductivity of Ne-PCM increases with increase in volume concentration of nanoparticles irrespective of phases (solid or liquid). However, variation of thermal conductivity enhancement between the volume concentrations of 0.5 to 2 is insignificant. At solid phase, the maximum enhancement in thermal conductivity of PCM with 2 vol% of alumina nanoparticle is 12% compared to pure Tricosane. However, at liquid phase, the maximum enhancement in thermal conductivity of Ne-PCM with 2 vol% of alumina nanoparticle is 32% compared to pure Tricosane. The enhancement in thermal conductivity of Ne-PCM between the volume concentrations of 0.5 to 2 is about 3.29% which is insignificant compared to the uncertainty of the KD2 Pro device. Therefore, further increase in nanoparticle concentration does not improve the thermal conductivity of PCM. Though there is

an enormous enhancement in measured thermal conductivity, the Hamilton and Crosser model under predicts the measured thermal conductivity.
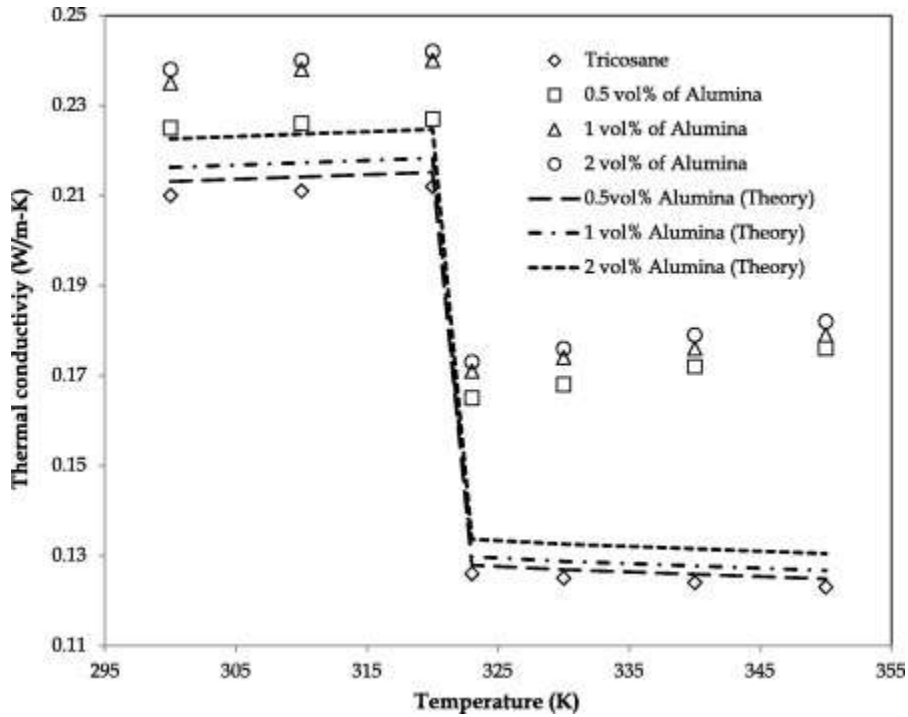

Fig. 4. Thermal conductivity of Ne – PCM at different temperatures.

3.2 Effect of PCM materials on the cooling performance of heat pipe-PCM module

Fig. 5 shows the transient temperature response during charging and discharging processes at various heat inputs for different energy storage materials with the PCM quantity of 100 cc. It is seen that the evaporator temperature increases with heat input for all energy storage materials and the same temperature decreases when the supply of heat is turned off. A similar temperature profile is also reported in the previous study using Tricosane as PCM [17]. In the present study, the reference temperature is taken 85 ^{o}C since it is the junction temperature of the electronic device of current application. It is observed that the time taken to reach 85 ^{o}C while
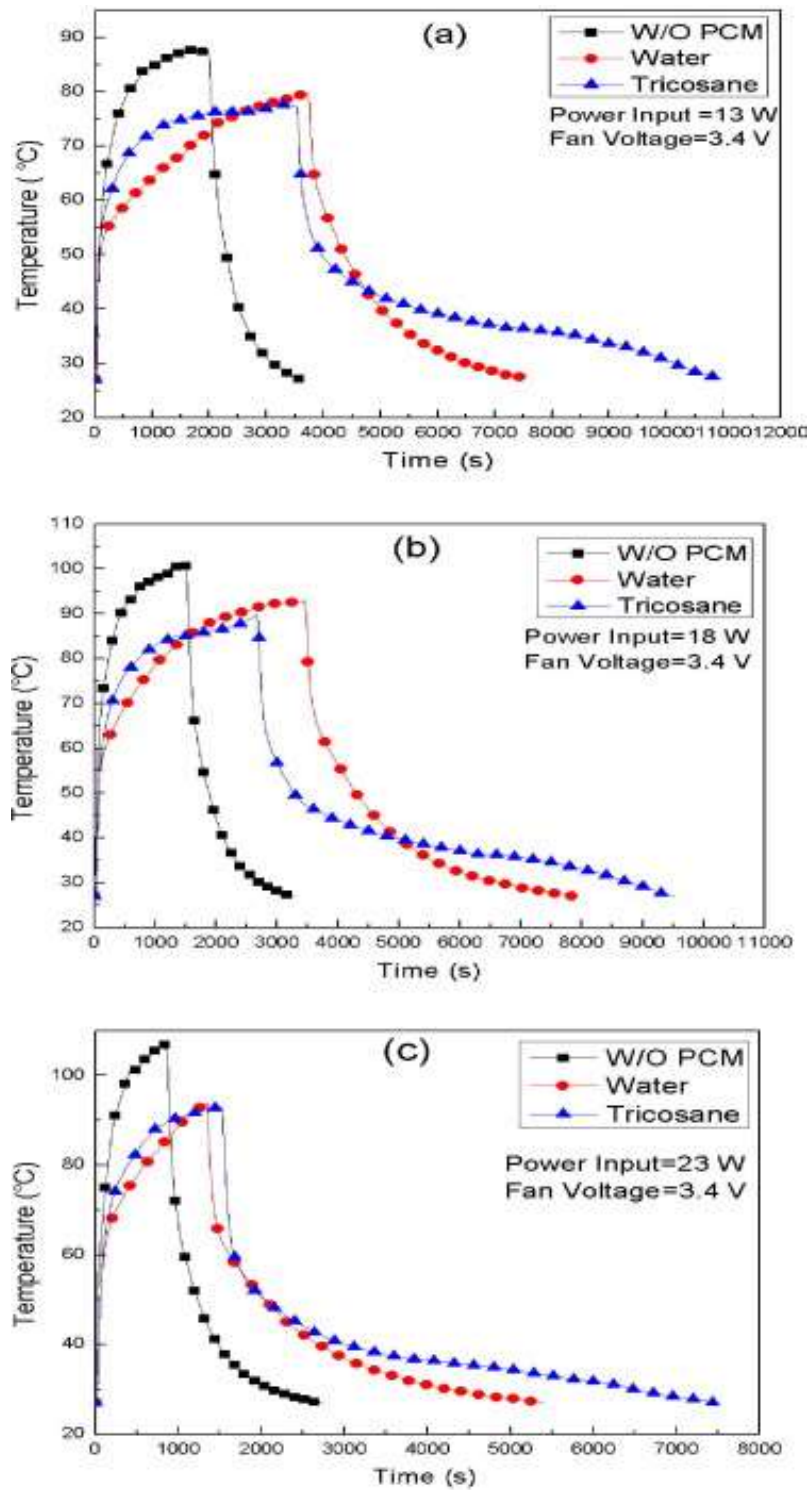
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Fig. 5. Temperature variations during charging at different heating powers of (a) 13 W, (b) 18 W, (c) 23 W and discharging at a fan voltage of 3.4 V.

heating is 1020, 330 and 185 s for 13, 18, and 23 W respectively when no PCM was used. When Tricosane and water are used as the PCM at 13 W, the maximum temperature of evaporator is 77 ^{o}C. Also time taken to reach the reference temperature is 3030 and 2790 s for Tricosane and water beyond that which it reached a steady state. While using water as a storing media, the time taken to reach 85 ^{o}C is 1530 and 840 s for 18 and 23 W respectively. Similarly, 1410 and 570 s are taken to reach 85 ^{o}C at 18 and 23 W respectively for Tricosane. It reveals that, at lower heating powers, the energy absorbed by PCM is as more as heat is stored in the form of latent heat. Further, it is understood that the heat absorbing characteristics of Tricosane is slow compared to water during charging process and this is mainly due to low thermal conductivity of Tricosane.

During discharge process, for without PCM, the evaporator needs about 1620 s to decrease from 85 to 27 ^{o}C at 13 W when the fan voltage is 3.4 V. In contrast, water and Tricosane need 3690 and 7440 s respectively for the same temperature drop. Similarly at 18 W, it takes 1710, 4350 and 6810 s to decrease from 85 to 27 ^{o}C when the fan voltage is 3.4 V for without PCM, water and Tricosane respectively. At 23 W, complete cooling process takes place at 1800, 4020 and 5940 s respectively for without PCM, water and Tricosane. From these results, it is understood that the discharge time is long for Tricosane owing to poor thermal conductivity and phase change process. In the discharging process, energy stored in the form of latent heat is released and solidification takes place.

3.3 Effect of nanoparticle concentration on the performance of PCM materials

The performance enhancement of the Ne-PCM is explained with the use of recorded temperature variations of the evaporator. The temperature variations of evaporator at different heat inputs without PCM, with Tricosane and Tricosane with 0.5, 1 and 2 vol% of Al_2O_3 are
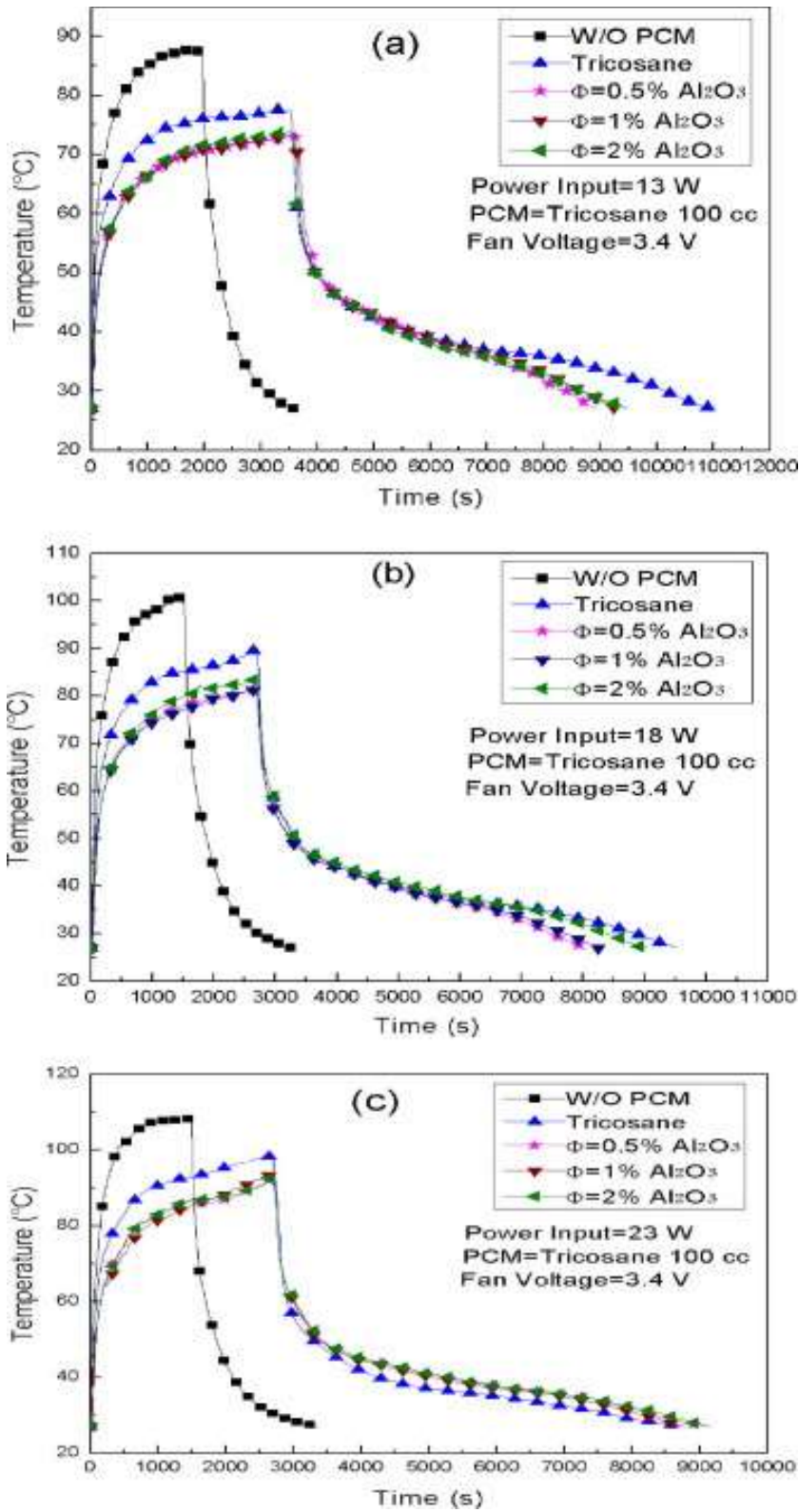
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Fig. 6. Temperature variations of PCM and Ne – PCM at different volume percentages of Al$_2$O$_3$ during charging and discharging at different heating powers (a) 13 W, (b) 18 W, (c) 23 W at fan voltage of 3.4 V.

presented in Fig 6. After 1500 s, the evaporator temperature of traditional heat pipe is 87.3 ^{o}C and the same for traditional heat pipe with PCM is 75.1 ^{o}C at 13 W. Therefore, introduction of PCM into traditional heat pipe reduces the temperature by 14%. Similarly, 15% and 16% of reduction in wall temperature at the evaporator is observed when compared to the traditional heat pipe at 18 and 23 W respectively. Further, the addition of nanoparticles into the PCM reduces the evaporator temperature of heat pipe to 70.6, 69 and 69.9 ^{o}C respectively for 0.5, 1 and 2 vol% of Al_2O_3 nanoparticles. When compared to the traditional heat pipe, the evaporator temperature of 0.5, 1 and 2 vol% of nanoparticles in the PCM is decreased by 19, 21 and 20% respectively. For the same nanoparticle at vol% of 0.5, 1 and 2% and the heat input of 18 W, the temperature at the evaporator is reduced by 22, 23 and 20% respectively. At 23 W, the temperature at the evaporator is reduced by 23, 25 and 23% respectively for 0.5,1 and 2 vol% of Al_2O_3 nanoparticles in the PCM. These results clearly indicate that the addition of nano-particles in the PCM reduces the evaporator temperature and thus enhances the performance of PCM. The addition of nano-particles in Tricosane enhances the thermal conductivity of the PCM, leading to the performance enhancement of heat pipe-PCM module. Further, the maximum reduction in evaporator temperature is found at 1% volume of Al_2O_3 in Tricosane for all heat inputs. This shows that there is an optimum vol% of Al_2O_3 for the maximum enhancement of heat transfer and adding further nano-particles in PCM does not improve the PCM performance. This negative effect attributed to the fact that viscosity of Ne-PCM increases significantly as nanoparticle concentration increased. A similar observation is also found in the previous studies [33, 33]. The increase in viscosity reduces the buoyancy and leads to the slower melting process since the melting process is dominated by natural convection. Hence, the performance of Ne-PCM at 2 vol% is deteriorating. Further, addition of nano-particles into the Tricosane reduces the discharge

time considerably at 13 W heat input. As the heat input increases, difference in discharge time between the Tricosane, Tricosane with nano-particles decreases, and the same completely diminishes at 23 W. The reason for this variation is not clear and further experimentation is needed to explain.

In most of the electronic cooling applications, charging and discharging takes place simultaneously and a steady heat transfer takes place through heat pipes. Whenever an excess heat is generated in the electronic component that heat will be stored in the PCM and released slowly through the heat pipe during off peak period. In order to replicate the same actual application of heat pipe-PCM module, both the charging and discharging time is fixed as 5 min. First, heat input of 13 W is applied for 5 min then it is raised to 23 W. Again, after 5 min heat input is brought back to 13 W while the fan is running at 3.4 V. Figure 7 (a) to (d) show the charging and discharging of Tricosane (PCM), and Tricosane with different volume concentrations of Al_2O_3 nano-particles at a fan voltage of 3.4 V. Also it shows the temperature at the evaporator, fin as well as the PCM at just above and below the heat pipe as mentioned in the Fig 3. From the results, it is seen that the temperature of PCM changes follows the same trend of evaporator. This shows that the PCM and Ne-PCM can charge the energy during peak heating and discharge the heat of both heat pipe and heat sink without affecting the regular operation of cooling module. This operation serves as better thermal management concept for electronics.
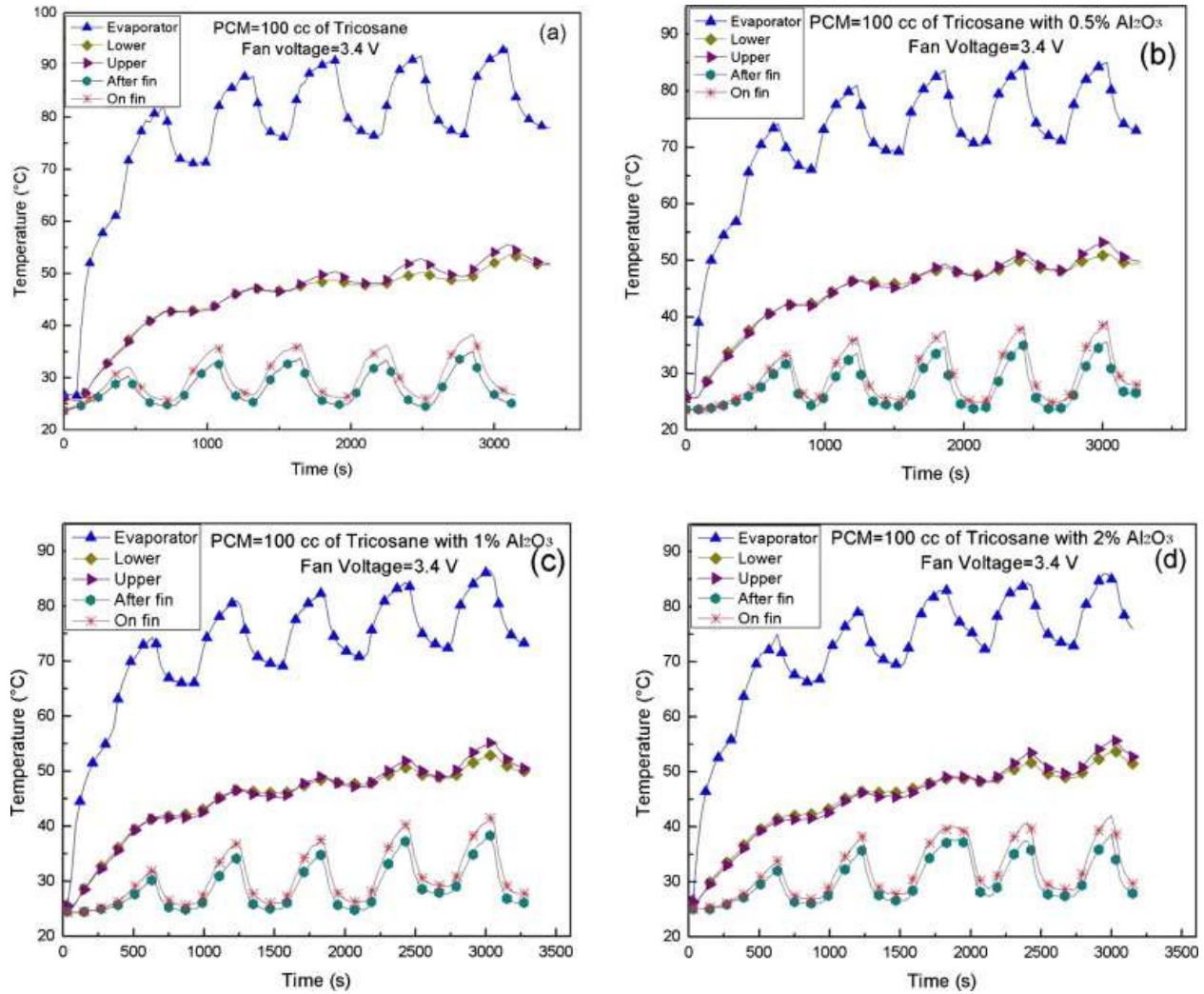
Fig. 7. Temperature variations of evaporator, PCM and fin during simultaneous charging and discharging process: (a) Tricosane and Tricosane with (b) 0.5 vol% (c) 1 vol% and (d) 2 vol% of Al$_2$O$_3$ nano-particles.

3.4 Effect of nanoparticle concentration on the performance of heat pipe –PCM module

In order to explain the effectiveness of heat pipe - PCM module using Ne-PCM, the lowest and highest temperature at the evaporator of heat pipe is presented in Fig 8 (a). It is seen that the lowest and highest temperature is 79.8 and 98.9 $^{\circ}$C when no PCM is used at a fan voltage of 3.4 V. At a same power level and fan voltage, with the use of Tricosane as PCM, the lowest and highest heater temperature is 76.7 and 93.3 $^{\circ}$C. These results indicate that the Tricosane can
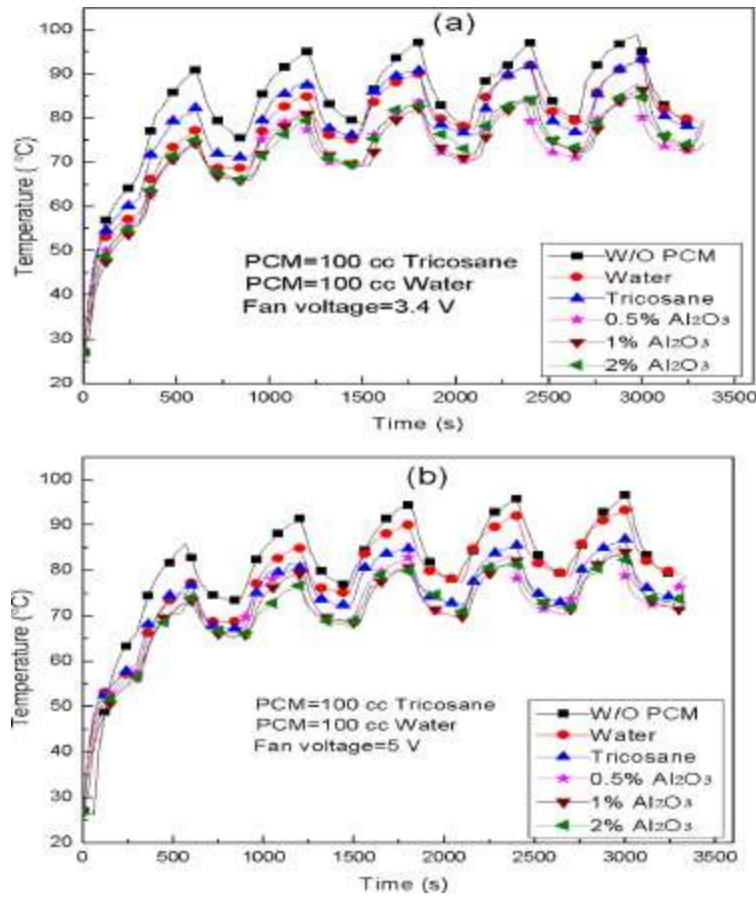
Fig. 8. Evaporator temperature progress of heat pipe – PCM module during simultaneous charge and discharge process at a fan voltage of (a) 3.4 V and (b) 5 V.

effectively reduce the temperature rise. Further, it is found that the lowest and highest temperature of evaporator when 0.5, 1 and 2 vol% of Al_2O_3 nano-particles added with the Tricosane is 70.9, 72.7, 72.9 $^{\circ}$C and 85.1, 86.5, 87.8 $^{\circ}$C respectively at the fan voltage of 3.4 V for the same heating power. The differences in temperature are estimated as 19.1, 16.6, 14.2, 13.8 and 14.9 $^{\circ}$C respectively when no PCM, Tricosane, Tricosane with 0.5, 1 and 2 vol% are used. It is interesting to note that the difference in temperature decreases up to a concentration of 1 vol% of Al_2O_3 and increases for 2 vol% of Al_2O_3. This result clearly indicates that the use of nano-particles with Tricosane can effectively reduce the heater temperature. Further, it is noticed that there is an optimum volume concentration (1%) for the maximum heat transfer

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enhancement. The cyclic temperature variations during simultaneous charging and discharging process at a fan voltage of 5 V are presented in Fig. 8(b) and it showed a similar trend of Fig 8(a).

Fig. 9 shows the lowest and the highest temperature at the evaporator of the cooling module when no PCM was used at 5 V, with pure Tricosane at 5 V and Tricosane with 1% Al_2O_3 at 3.4 V. It is found that the evaporator temperature decrease to 96.6 ^{o}C and 79.1 ^{o}C respectively as the fan voltage changes from 3.4 to 5 V. The temperature difference is 17.5 ^{o}C. When Tricosane is the energy storage material, the lowest and highest heater temperature is 87 and 73.1 ^{o}C respectively, and the temperature difference is 13.9 ^{o}C. These results match with 1% volume of Ne-PCM at a fan voltage of 3.4 V. At this voltage, for the same heating power and temperature change, the power consumption is 0.23 W (I = 0.07 A). For a similar performance with PCM, the required power consumption is 0.5 W with a fan voltage of 5 V (I = 0.1 A). Based on these experimental results, a saving of almost 53% of electronic power utilization is observed with 1 vol% Al_2O_3 enhanced Tricosane compared to the ordinary Tricosane.
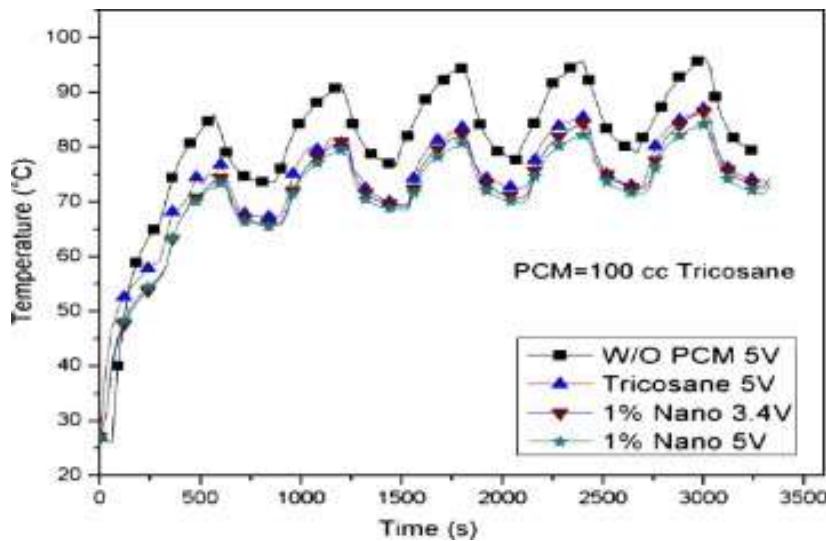

Fig. 9. Comparison of evaporator temperature progress of heat pipe – PCM module during simultaneous charge and discharge process.

3.5 Effect of nanoparticle concentration on the energy storage capacity of different PCM materials

The energy stored in the PCMs at different input power is calculated using Equation. 2 and presented in Table 4. It shows that the energy stored in the PCM is increasing as the heat input increases for all cases. Also found that the energy stored by Tricosane as PCM is higher than the energy stored by the water. Further, it is noticed that the energy storage is increasing as the concentration of nanoparticle in the Tricosane increases from 0.5 to 1% and then decreases for 2% at 13 and 18W. Contrary, energy storage is increasing for the volume concentration of 2% at 23W. The reason for this variation is not known and further experiment is needed to explain this behavior. Moreover, it is noticed that the PCM with 2% Al_2O_3 stores almost 30% of heating power supplied at the evaporator. Therefore, as the energy storage in the PCM increases the energy transferred through the heat sink is decreasing and leading to saving of fan power consumption. This proves that the PCM can absorb heat energy at a higher rate and discharge lower amount to the heat pipe and heat sink. Hence, the goal of thermal management is reached effectively.

Table 4 Energy stored in different PCMs at various heat inputs

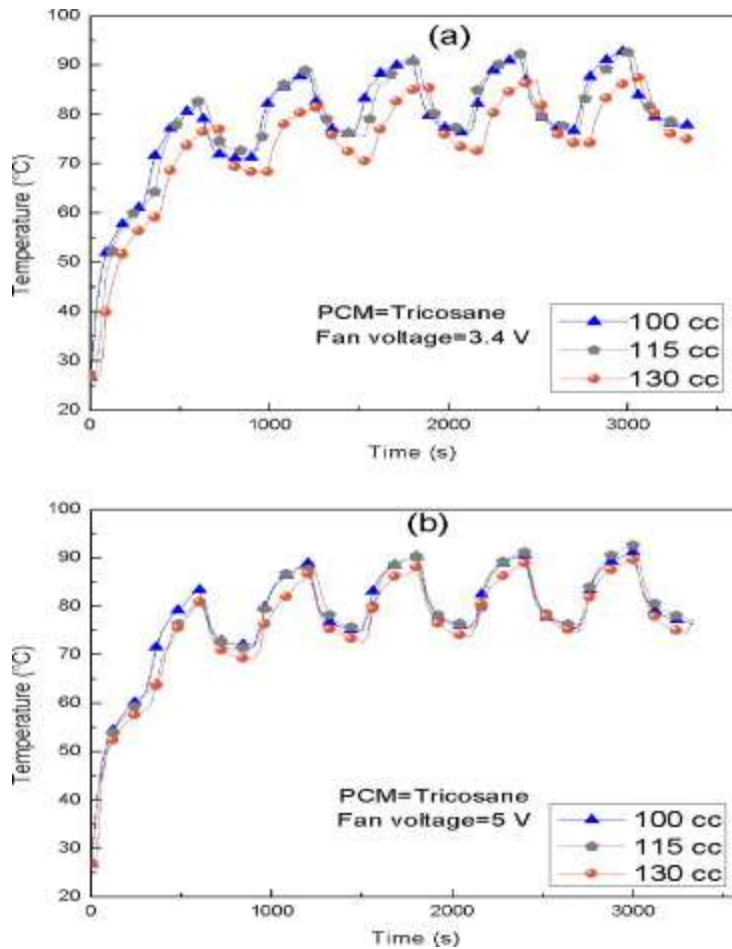| S. No	Heat input (W)	Energy stored in the PCM (W)				
		Water	Tricosane	Tricosane with 0.5% Al_2O_3	Tricosane with 1% Al_2O_3	Tricosane with 2% Al_2O_3
1	13	4.17	4.54	4.61	5.24	4.67
2	18	4.87	4.97	5.76	6.71	6.54
3	23	5.10	5.8	7.02	8.16	8.81

Fig. 10. Evaporator temperature progress of the heat pipe – PCM module for different PCM volumes during the charge and discharge process of Tricosane at a fan voltage of (a) 3.4 V and (b) at 5 V.

3.6 Effect of PCM quantity on the performance of heat pipe – PCM module

Finally, to improve the performance of heat pipe - PCM module, the charging volume of PCM material is varied from 100 to 130 cc and the performance is studied. Figure 10 (a) and (b) show the temperature variations in evaporator for different charge volumes and fan voltages in simultaneous charge and discharge process. From this analysis, it is found that the performance of heat pipe – PCM module is similar for both 100 and 115 cc at 3.4 V. Also, it is

seen that the lowest and highest heater temperatures are 75.6 and 90 $^{\circ}$C, respectively for 115 cc charge volume. The temperature difference for 115 cc is 14 $^{\circ}$C that is 2.6 $^{\circ}$C less than that obtained in the 100 cc. Similarly, for the charge volume of 130 cc, nearly 4 $^{\circ}$C drop in temperature is found when compared to 100 cc charge volume. These results clearly indicate that the increase of charge volume reduces the difference in temperature and enhances the heat pipe-PCM module performance. Though there is a significant variation in the effect of heat transfer on PCM volume at 3.4 V, no variation is observed at 5 V. This may be due to the higher amount of continuous heat rejection in the condenser due to higher fan speeds.

4. Conclusions

The thermal performance of the cooling module with pure Tricosane and Tricosane with various concentration of Al_2O_3 nano-particles are estimated by using the recorded temperature variations at different heating powers. The effect of PCM material, PCM quantity, heat input, fan voltage and nano-particles concentration on the performance of cooling module is also studied. From the analysis, it is found that the evaporator temperature is decreased about 25.75% when PCM (Tricosane) is replaced with 1% volume of Ne - PCM as energy storage material. Based on the experimental results, Tricosane with Al_2O_3 nano-particles as PCM can save 53% the fan power consumption. The maximum energy stored in Tricosane is found to be 30% of the input power for the heat pipe-PCM module that uses Al_2O_3 nano-particles with 2 volume percentage. The thermal performance of the heat pipe-cooling module is found to increase with the increase in concentration of Al_2O_3 nano-particles in Tricosane. The performance decreases when the Al_2O_3 concentration exceeds 1 volume percentage. Finally, it can be concluded that using proper

suspension of nanoparticle in conventional phase change materials has great potential of improving the traditional energy storage systems.

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Nomenclature

C_p specific heat of PCM (J/kg K)

k thermal conductivity (W/m K)

T temperature (^{o}C)

ΔT change in temperature (^{o}C)

Δm change in mass (kg)

m mass of PCM (kg)

Q energy stored (W)

ΔQ change in energy storage (W)

ϕ volume fraction

Subscripts

np   nanoparticles

pcm   phase change material

n,pcm   nano enhanced PCM