

Experimental Study of Thermal Energy Storage Characteristics using Heat Pipe with Nano-Enhanced Phase Change Materials

Jogi Krishna¹, P.S. Kishore¹, A. Brusly Solomon²

¹Department of Mechanical Engineering, Andhra University, Visakhapatnam 530003, India

²Centre for Research in Material Science and Thermal Management, School of Mechanical Sciences, Karunya University, Coimbatore 641114, India

Abstract. The paper presents experimental investigations to evaluate thermal performance of heat pipe using Nano Enhanced Phase Change Material (NEPCM) as an energy storage material (ESM) for electronic cooling applications. Water, Tricosane and nano enhanced Tricosane are used as energy storage materials, operating at different heating powers (13W, 18W and 23W) and fan speeds (3.4V and 5V) in the PCM cooling module. Three different volume percentages (0.5%, 1% and 2%) of Nano particles (Al_2O_3) are mixed with Tricosane which is the primary PCM. This experiment is conducted to study the temperature distributions of evaporator, condenser and PCM during the heating as well as cooling. The cooling module with heat pipe and nano enhanced Tricosane as energy storage material found to save higher fan power consumption compared to the cooling module that utilities only a heat pipe.

1. Introduction

In the recent past there has been vast development in various electronic applications for consumer needs. These equipments use micro electronic equipment subjected to large amounts of power, resulting in heat generation. Storage and dissipation of heat at a faster rate has become a mandatory requirement in such equipment. Small and smart equipment that uses compact devices, consume high power and require better materials that can have relatively better thermal properties. In electronic cooling, an energy storage technology plays a key role in utilizing alternative energy solutions. The four main classifications of energy storage include chemical, electrical, mechanical and thermal systems. Categorization of systems that store thermal energy can be of 3 types – Latent Heat Thermal Energy Storage systems (LHTES), Sensible Heat Thermal Energy Storage Systems (SHTES) and Chemical Energy Storage Systems (CESS). Among these systems, the first one, i.e., LHTES is proven better over the other two systems, since it allows energy storage at a steady temperature, where the phase change occurs.

The ability of storing heat energy in Phase Change Materials (PCM) is very high and hence PCM has found its place as an important raw material for cooling application equipment. Baby et al. [1] explored the thermal characteristics of phase change material based heat sinks for electronic equipment cooling, using n-eicosane as the phase change material (PCM). 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. Mills et al. [2] increased thermal conductivity of paraffin wax by two orders of magnitude by impregnating porous graphite matrices with the paraffin. Hamdani et al. [3] succeeded to enhance thermal conductivity by mixing paraffin wax and alumina (Al_2O_3) particles. Ho et al. [4] used a hybrid water-based suspension of Al_2O_3 nano-particles and microencapsulated phase change material (n-eicosane) particles (MEPCM) as a functional forced convection fluid. Khodadadi et al. [5] enhanced thermal conductivity of phase change materials (PCM) through dispersion of nano-particles. Nabeel et al. [6] experimented the melting of n-octadecane with CuO nano-particle suspensions in a square enclosure.

Efforts were made to use high thermal conductivity devices, such as heat pipes, that are capable of transferring large amounts of heat through a small cross-sectional area to relatively long distances, with extremely small temperature differences. Shukla [7] gave an overview of heat pipes used in different space missions. There has been a large amount of work done to understand and enumerate the use of heat pipes in PCM based applications, particularly in LHTES systems. Liu et al. [8] have studied the dynamic characteristics of heat storage device with heat pipe during charging process. Paraffin is taken as phase change material (PCM) and water is used as heat transfer fluid (HTF). R134a is taken as working medium of heat pipe. Tiari et al. [9] has worked on the behaviour of LHTES systems with the help of a finned heat pipe. Liu et al. [10] experimented with the heat exchangers to study the effective use of heat pipes in heating/cooling modes that occur simultaneously. Weng et al. [11] has effectively utilized PCM in a heat pipe to establish its potential in electronic cooling applications. Sahu et al. [12] worked with paraffin as ESM used in nano-fluid (Micro Carbon Nano Tubes/water) charged heat pipe.

It is evident that the above studies have been reported to establish the effective use of PCMs in the heat pipes in the areas of electronics cooling. Jogi Krishna et al. [13] experimentally investigated the thermal performance of heat pipe with Nano enhanced-PCM and their hybrid effect on heat dissipation process. Present study reports the heat pipe module with Nano enhanced-PCM as Energy Storage Material (ESM) for electronics cooling. The study compares the thermal performance of heat pipe module with Water, Tricosane and addition of Al_2O_3 to Tricosane (Ne-PCM) as energy storage materials. The Nano particles are proven to increase the thermal conductivity of PCM and hence help to store relatively more heat which is favourable for the functioning of the heat pipe – PCM module.

2. Experimental Test set-up and details

The schematic view of the experimental set-up showed Fig. 1, 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. The temperature at different parts of the heat pipe and PCM are measured using OMEGA T-Type thermocouples with an accuracy of $\pm 0.2^\circ\text{C}$ as shown in Fig. 2. The heat pipe is made of Cu tube with a length of 190 mm, outer diameter of 7.8 mm and an inner diameter of 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 according to heat transfer based design to optimized heat transfer through the heat pipe. The thermo physical properties of heat pipe, fins, PCM and Nanoparticles (Al_2O_3) are shown in table -1.

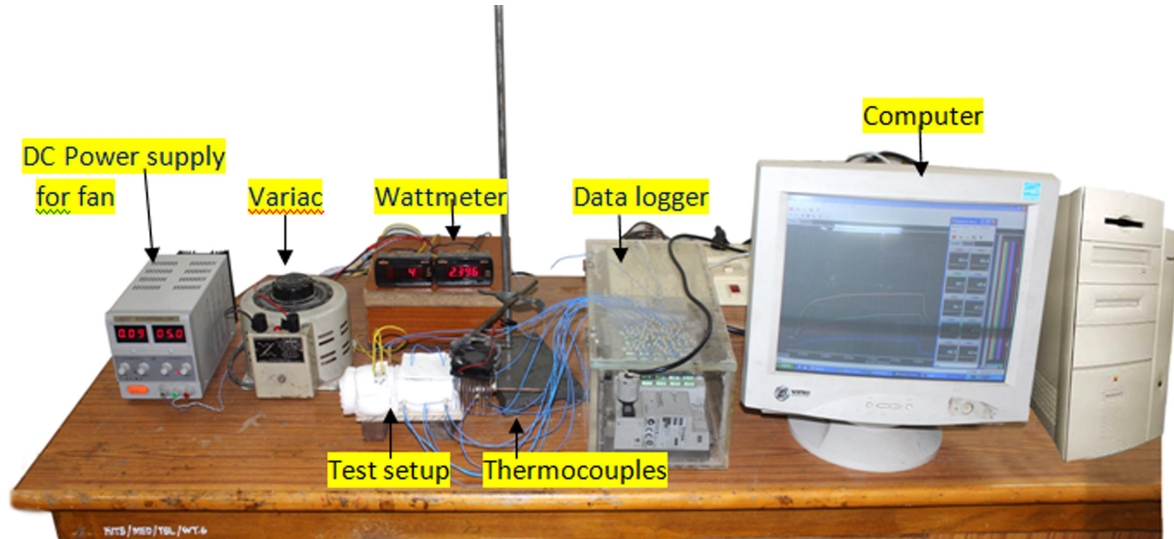


Figure 1. Schematic of the experimental set up of heat pipe – PCM module.

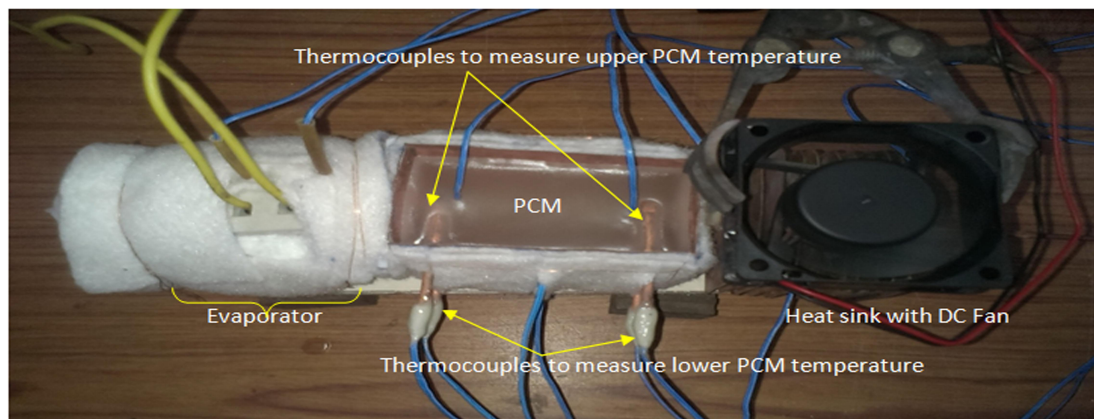


Figure 2. Experimental set up of heat pipe –PCM module and Thermocouple positions

Table 1. The thermo physical properties of heat pipe, fins, PCM and Nanoparticles (Al_2O_3)

| Properties | Materials | | |
|--|--|-----------------|---|
| | Electrolyte copper (Heat pipe & Fins) | Tricosane (PCM) | Al_2O_3 (Nanoparticles) |
| Thermal conductivity, k (W/m K) | 401 | 0.14 | 30 |
| Specific heat, c_p (kJ/kg K) | 0.3844 | 2.89 | 0.88 |
| Latent heat, h_{fg} (kJ/kg) | 207 | 209 | --- |
| Melting point in (K) | 1357.6 | 320 | 1233.8 |
| Density, ρ (Kg/m^3) | 8978 | 786 | 3600 |
| Dynamic viscosity, μ (Kg/m-s) | ---- | 0.1 | 0.1 |

3. Preparation of Nano enhanced-PCM

A commonly available Al_2O_3 nanoparticle which is capable of storing high amount of heat compared to other nanoparticle is selected as a nanomaterial. The Nano enhanced-PCM is prepared by dispersing Al_2O_3 nanoparticles (50 nm) in analytical grade Tricosane (Alfa-Aesar) with a purity of 99% using Ultrasonic Homogenizer (UP400S). The nanoparticle/PCM mixture is 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.

Energy stored in PCM (Q_{ESM}): The energy storage in the PCM is related to the mass and the temperature difference between initial and final temperature of PCM in the storage tank. It can be shown as

$$Q_{ESM} = m_{ESM} C_{P,ESM} (T_e - T_i) \quad (1)$$

Where

$$T_i = \frac{1}{6} \sum_{n=1}^6 T_{n,i} \quad (2)$$

$$T_e = \frac{1}{6} \sum_{n=1}^6 T_{n,e} \quad (3)$$

4. RESULTS And DISCUSSIONS

In this study, the tests are performed under various operating conditions, namely, heating powers (13 W, 18 W, and 23 W), fan voltages (3.4V and 5 V), and different ESM (water, Tricosane and Nano enhanced Tricosane). The filling volume in energy storage tank is kept constant at 100 cc in all the test runs and the temperature distributions in PCM are evaluated during experimental study. The results obtained from this study are elaborated below.

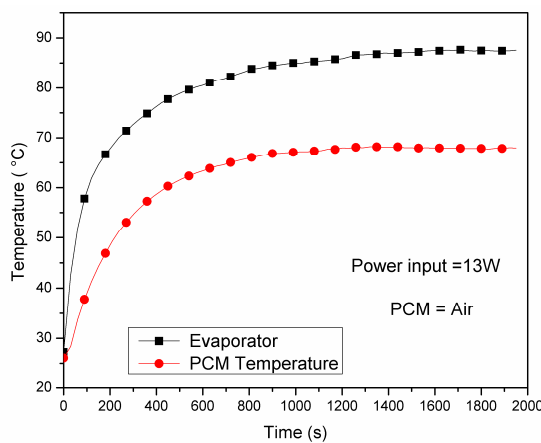


Figure 3(a)

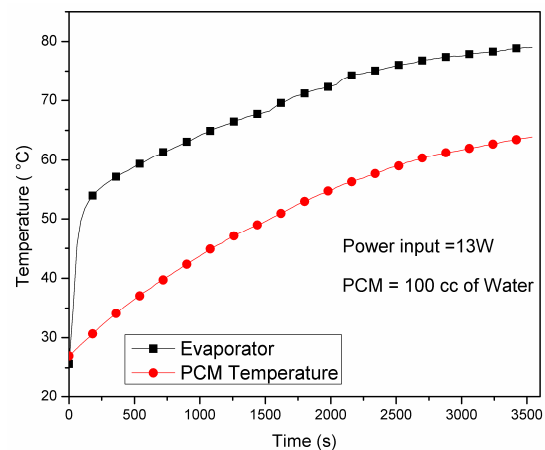


Figure 3(b)

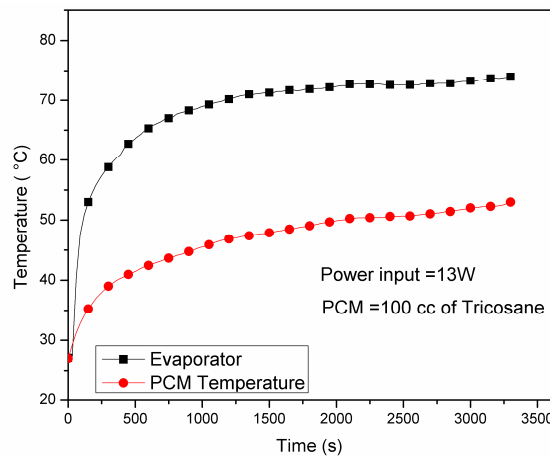


Figure 3(c)

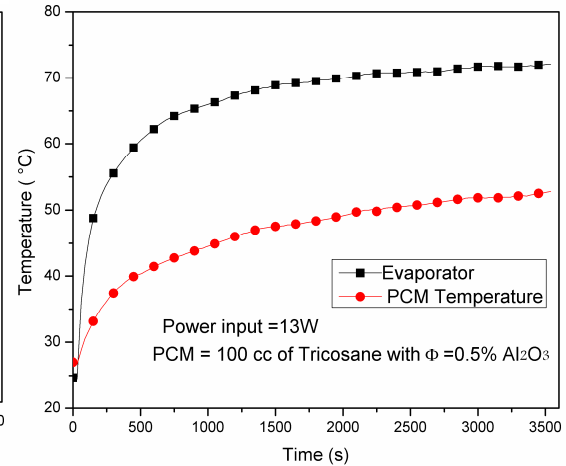


Figure 3(d)

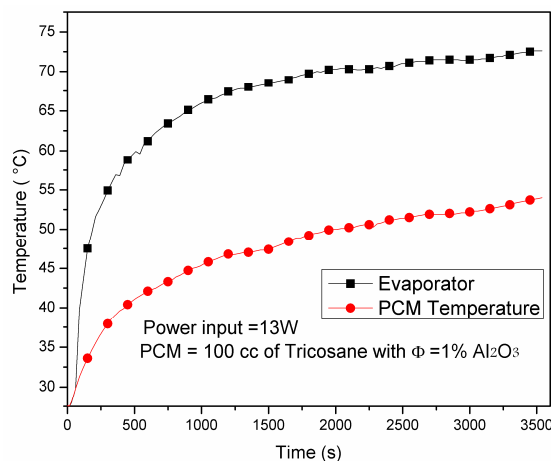


Figure 3(e)

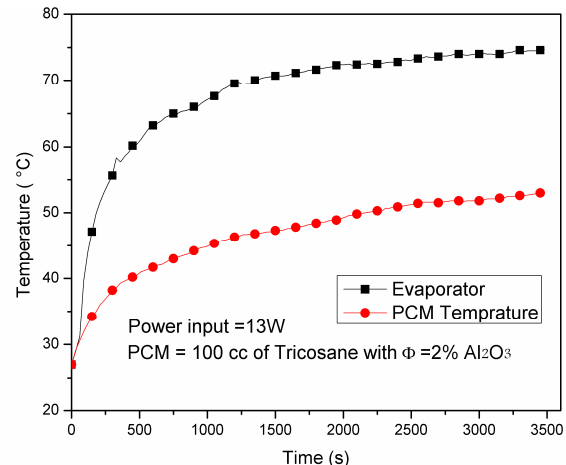


Figure 3(f)

Fig.3: Temperature variations of Evaporator and ESM (different PCMs) during charging at a heating power of 13W.

Phase Change Material Charging Process

The temperature distributions are clearly depicted in the figures 3(a)-(f). Fig 3(a) refers to a traditional heat pipe, in which no energy storage material used in energy storage tank. At a heater power of 13 W, test results show that evaporator temperature increases to 87.9 °C and air temperature in energy storage tank is also observed to be increased to 68 °C in the time span of 2000 s. The heat energy is then stored in the tank as sensible heat, which is discharged when the heat source is detached. Fig. 3(b) depicts transient temperature distribution when water is used as ESM in the same operational conditions. The corresponding values of temperatures of evaporator and ESM are found to be 80 °C and 63 °C respectively, exhibiting better thermal conductive behaviour of water compared to air. Fig. 3(c) shows Tricosane, the PCM as the ESM. Since it can store more heat energy in the form of latent heat during the phase change process, from solid to liquid state at 47 °C, it is found to exhibit excellent thermal behaviour compared to the previous ESMs. This is observed from the experimental values of

temperatures of evaporator and ESM (76°C and 53°C). Also the percentage of energy stored in the ESM (as calculated using Eq. 2) is observed to have improved.

Fig 3(d) to 3(f) represent the transient temperature distribution of heat pipe cooling module with Nano-enhanced Tricosane by addition of 0.5%, 1% and 2% volume fractions of Al_2O_3 to Tricosane respectively. Resulting in evaporator temperatures of 74°C , 72°C and 73°C and ESM temperatures of 54°C , 56°C and 55°C corresponding to 0.5%, 1% and 2% volume fractions of Al_2O_3 in Tricosane. It is observed that the percentage of energy stored in nano enhanced PCM increased up to 1% volume of Al_2O_3 in Tricosane and then decreased at 2% volume of Al_2O_3 . Also reduction in evaporator temperature is found optimal at 1% volume fraction of Ne-PCM, at every heat input. The viscosity of Ne-PCM is said to have negative impact at 2% volume fraction, showing insignificant improvement in PCM performance [14]. 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 deterioration in the performance of Ne-PCM at 2% volume is resulted.

The above graphs show the performance of various ESMs at an input of 13 W and over a period of 3000 seconds. Experiments conducted by varying the input powers to 18 W and 23 W, with all the ESMs have also shown the same trend strengthening the fact that the performance is optimal at 1% volume fraction of Al_2O_3 in Tricosane. At 18W heating power the transient temperature distribution of heat pipe cooling module with air, Water, Tricosane, Tricosane with 0.5%, 1% and 2% volume of Al_2O_3 as ESM in the EST are estimated. The evaporator temperatures at 18W are 100.7°C , 92.5°C , 88°C , 83°C , 81°C and 84°C and respective energy storage material temperatures are 72.5°C , 68°C , 54°C , 58°C , 56°C and 54°C . Similarly at 23W heating power 105°C , 93°C , 88°C , 85°C , 83°C and 86°C are the evaporator and 78°C , 68°C , 55°C , 58°C , 62°C and 60°C are the energy storage material temperatures respectively.

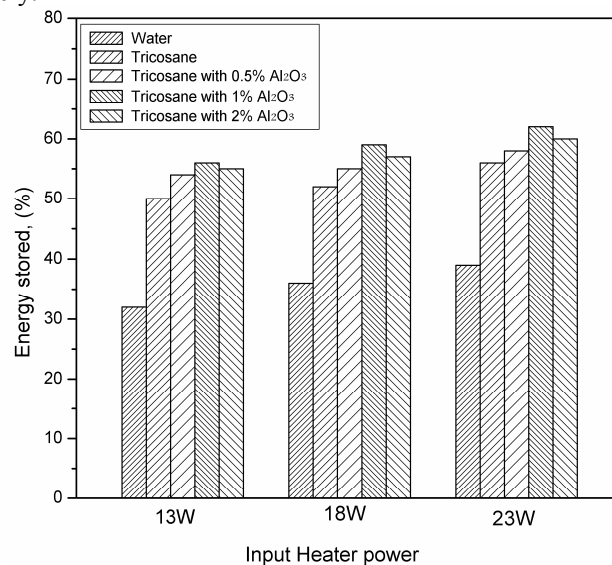


Figure 4: The percentage of energy stored in the PCM at different heating powers of 13W, 18W and 23W.

Figure 4 shows the comparative energy storage particulars of various ESMs for above three different heating powers. The amount of energy stored in water and Tricosane as ESM is found to be lower compared to nano enhanced Tricosane with 1% volume of Al_2O_3 . In all the three cases of ESM, it is noticed that the thermal performance of heat pipe module increases with the increase in the Al_2O_3 nano-particles concentration up to 1% in Tricosane. However, with the increase in the concentration level of Al_2O_3 nano-particles in Tricosane from 1 vol% to 2 vol%, the thermal performance decreases.

Similar results were obtained by previous researcher as well [12]. This indicates that the rise in the concentration of added nano-particles reduces the thermal efficiency of heat pipe.

The maximum energy stored in is found to be 63% of the input power for the cooling heat pipe module that uses Tricosane with 1vol.% of Al_2O_3 . The enhancement in energy storage of heat pipe cooling module Tricosane with 1 vol.% of Al_2O_3 as ESM compared to Tricosane as ESM is found to be 10% at 13 W. While, for the 23 W heating power, the enhancement in energy storage of heat pipe cooling module with Tricosane with 1 vol.% of Al_2O_3 as ESM compared to Tricosane as ESM is found to be 13%. This indicates that enhancement in energy storage of nano-fluid used heat pipe cooling module increases with increase in input power from 13W to 23 W. It may be noted that at higher input power (23 W) heat transfer rate of nano enhanced PCM increases due to increase in thermal conductivity with temperature.

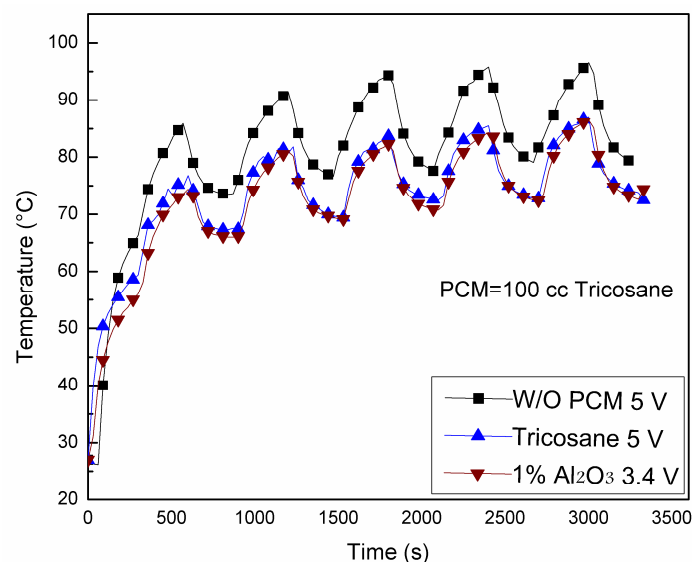


Figure.5. Comparison of evaporator temperature progress of heat pipe-PCM module during simultaneous charge and discharge process

Figure 5 shows the simultaneous heating and cooling effects and the corresponding transient temperature variation in different ESM (Tricosane and Tricosane with 1vol% of Al_2O_3) for various fan voltages (3.4V and 5V) with heating powers of 13W and 23 W, respectively. It is noticed that the Tricosane as ESM with 23W heating power and 5V fan on cooling sides of heat sink stores same amount of energy when Tricosane with 1vol% of Al_2O_3 is used as ESM with 13W heating power and 3.4V fan on cooling sides of heat sink. This indicates that water as ESM needs higher heating power (23 W) and higher fan voltage (5V) to store same amount of energy compared to PCM as ESM. It is observed that utilizing Tricosane with 1vol% of Al_2O_3 (PCM) as ESM can have considerable reduction in fan voltage thereby saving 53% in heating power in the form of fan power consumption. This means that the PCM can absorb the heat energy at higher rate and discharge lower amount of heat energy to the heat pipe and heat sink to reach the goal of energy management.

5. Conclusions

The Present study experimentally investigated the thermal performance of heat pipe with nano enhanced PCM as Energy storage materials for electronic cooling. The effect of different ESMs (water, Tricosane and Tricosane with 0.5%, 1% and 2% volume fractions of Al_2O_3), PCM quantity, heat inputs (13W, 18W and 23W) and fan voltages (3.4V and 5V) on the performance of cooling module is studied. The thermal performance of the heat pipe-cooling module is found to increase with

the increase in volume fraction of Al_2O_3 nano-particles up to 1%, beyond that its performance decreases. Tricosane with 1% concentration of Al_2O_3 nano-particles as PCM can save 53% of the fan power consumption. It can be stated that using proper suspension of nanoparticle in conventional phase change materials, has great potential of improving the traditional energy storage systems.

References

- [1] Baby R, Balaji C, "Thermal management of electronics using phase change material based pin fin heat sinks", *Journal of Physics, Conference Series.*, 395, 012134, 2012.
- [2] Mills A, Farid M, Selman J.R., Al-Hallaj S, "Thermal conductivity enhancement of phase change materials using a graphite matrix", *Appl Therm Eng.*, 26, 1652–1661, 2006.
- [3] Hamdani, Thaib R, Irwansyah, Dailami, Mahlia T.M.I, "Experimental Investigation on Melting Heat Transfer of Paraffin Wax- Al_2O_3 Storage System", *Int J Appl Eng Research.*, 9, pp. 17903-17910, 2014.
- [4] Ho C.J, Huang J.B, Tsai P.S, Yang Y.M, "Preparation and properties of hybrid water-based suspension of Al_2O_3 nanoparticles and MEPCM particles as functional forced convection fluid", *Int Commun Heat Mass Transfer.*, 37: 490–494, 2010.
- [5] Khodadadi J.M, Hosseinzadeh S.F, "Nanoparticle-enhanced phase change materials (NEPCM) with great potential for improved thermal energy storage", *Int Commun Heat Mass Transfer.*, 34: 534–543, 2007.
- [6] Nabeel S. Dhaidan, Khodadadi J.M, Al-Hattab Tahseen A, Al-Mashat Saad M, "Experimental and numerical investigation of melting of phase change material/nanoparticle suspensions in a square container subjected to a constant heat flux", *Int J Heat Mass Transf.*, 66, 672–683, 2013.
- [7] Shukla K. N, "Heat Pipe for Aerospace Applications—An Overview", *Journal of Electronics Cooling and Thermal Control.*, 5, 1- 14, 2015.
- [8] Liu Xu, Fang Guiyin, Chen Zhi, "Dynamic charging characteristics modeling of heat storage device with heat pipe", *Applied Thermal Engineering.*, 31, 2902-2908, 2011.
- [9] Tiari Saeed, Qiu Songgang, Mahdavi Mahboobe, "Numerical study of finned heat pipe-assisted thermal energy storage system with high temperature phase change material", *Energy Convers and Manage.*, 89, 833–842, 2015.
- [10] Liu Zhongliang, Wang Zengyi, Ma Chongfang, "An experimental study on heat transfer characteristics of heat pipe heat exchanger with latent heat storage Part I: Charging only and discharging only modes", *Energy Convers and Manage.*, 47, 944–966, 2006.
- [11] Che Weng-Ying, Pin Cho-Hung, Chung Chang- Chih, Li Chen- Sih, "Heat pipe with PCM for electronic cooling", *Appl Energy.*, 88, 1825–1833, 2011.
- [12] Sahu S.K, Chougule Sandesh S, "Thermal Performance of Nanofluid Charged Heat Pipe With Phase Change Material for Electronics Cooling", *Journal of electronic packaging.*, 137: 021004-7, 2015.
- [13] Krishna Jogi, Kishore P.S, Brusly Solomon A, "Heat pipe with nano enhanced-PCM for electronic cooling application", *Experimental Thermal and Fluid Science.*, 81, 84–92, 2017.
- [14] C.J. Ho, J.Y. Gao, "Preparation and thermo-physical properties of nano-particle in-paraffin emulsion as phase change material", *Int. Commun. Heat Mass Transf.*, 36 (5), 467–470, 2009.