International Journal of Engineering

Journal Homepage: www.ije.ir

Experimental and Numerical Investigations on Al_2O_3–Tricosane Based Heat Pipe Thermal Energy Storage

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PAPER INFO

Paper history:
Received 10 November 2017
Received in revised form 23 December 2017
Accepted 04 Janurary 2018

Keywords:
Electronic Cooling Devices
Phase Change Materials
Nanoparticles
Heat Pipe
Thermal Energy Storage

ABSTRACT

The enhancement of operating life cycle of electronic devices necessitates the development of efficient cooling techniques. Therefore, in the present work the effects of employment of Phase Change Material, in the adiabatic section of heat pipe for electronic cooling applications were experimentally and numerically investigated. Tricosane (100 ml) is chosen as PCM in this study, where Al_2O_3 nanoparticles were dispersed in PCM by an ultrasound mechanism with volume fractions of 0.5, 1 and 2%. Transient thermal behavior of the evaporator, energy storage materials and condenser were studied during the charging process with heating powers of 13, 18 and 23W. The performance of system with Tricosane and nanoparticles improved for 1% concentration and reduced for 2% concentration; which concludes for the optimized doping of nanoparticles. In addition, CFD simulation of heat pipe is carried out for the above mentioned opertating conditions. The experimental and simulation results were compared at various operating conditions to establish correlation between them. The numerical results observed to match closely with experimental results. Finally, the thermal performance of heat pipe-PCM module is predicted through CFD simulation for the filling volumes of 115 and 130 ml at 13, 18 and 23 W.

***doi**: 10.5829/ije.2018.31.06c.16*

NOMENCLATURE

c_p	specific heat, J $kg^{-1}K^{-1}$
D	diameter, m
h_{sl}	latent heat of nano PCM, kJ kg^{-1}
k	thermal conductivity, $Wm^{-1}K^{-1}$
L	length, m
W	width, m
Z	height, m
T	temperature, K

Φ	volume fraction
Greek Symbols	
ρ	density (kg/m^3)
μ	dynamic viscosity, kg m^{-1} s^{-1}
Subscripts	
Hp	heat pipe
E	Evaporator
C	Condenser
B	storage tank

1. INTRODUCTION

In this modern civilization, use of electronic devices for longer duration is increasing rapidly consequently increasing the requirement of cooling such devices. It is essential to extract the generated heat from the electronic devices for its hassle free operation. Phase Change Materials (PCM) based cooling system is proven as one of the emerging technologies in the area of cooling electronic devices. PCM based energy storage system helps to slow down the heat transmission, which can reduce the requirement of heat transfer surface in the conditions where the heat transmission is intermittent. Sharma et al. [1] have experimentally shown that organic PCMs exhibit great energy storage density in a marginal melting and freezing temperature differences. Tay et al. [2] studies

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Please cite this article as: J. Krishna, P. S. Kishore, A. Brusly Solomon, V. Kumar Sharma, Experimental and Numerical Investigations on Al_2O_3–Tricosane based Heat Pipe Thermal Energy Storage, International Journal of Engineering (IJE), IJE TRANSACTIONS C: Aspects Vol. 31, No. 6, (June 2018) 980-985

and concluded that the effective thermal conductivity of PCM can be doubled with dynamic melting.

PCMs heat transmission rate is poor because of its low thermal conductivity, which can be improved the use of extended surfaces, hybrid heat sinks, nanoparticles, etc. Sebti et al. [3] investigated the influence of nanoparticles dispersion into concentric annulus on the improvement of heat transfer. The experimental investigation of Arasu et al. [4] on heat transfer improvement of energy storage materials using nano-particles with paraffin wax, suggests it a cheap and widely used Latent Heat Thermal Energy Storage (LHTES) material. The effects of melting temperature and employment of internal fins on the performance of a PCM based heat sink were studied by Li-Wu et al. [5]. Nabeel Dhaidan et al. [6] studied the melting of nano enhanced-PCM, subjected to a constant heat flux, enclosed within a 2D annular capsule formed between two cylindrical shell and tube (concentric and eccentric).

It is also observed in the literature that several researchers have used PCMs in heat pipes. A heat pipe is a system, which is able to transfer high heat fluxes from a heat source to a heat sink with a low thermal resistance using liquid-vapour phase change. M. Ahmadzadehtalatapeh et al., [7] studied the establishment of heat pipe based heat exchangers heat (HPHXs) and a typical climate chamber as a representative of an air conditioning system. E. Azad [8] experimentally examined the performance of the heat pipe solar collector prototype and compared the results with theoretical analysis, thermosyphon using Cerium (IV) oxide nano fluid [9] mixed convection heat transfer in vertical tubes by nanofluid [10] was also studied. For electronic cooling applications, Weng et al. [11] have employed PCM in adiabatic section of the heat pipe. Sahu et al. [12] have used paraffin as energy storage material and Micro Carbon Nano Tubes (MCNT) mixed using water as working fluid in heat pipe.

It is observed from the literature that many researchers have carried out their studies on the effectiveness of PCMs where as very few studies have been carried out on the performance of heat pipe using PCM for electronic cooling applications. The thermal performance of heat pipe with nano enhanced phase change material (NE- PCM) on heat dissipation was experimentally studied in our previous article [13]. In the present study, a numerical investigation is carried out to study the performance of PCM based heat pipe and its validation with experimental results.

2. EXPERIMENTATION

The schematic view of the experimental set-up used to study the cooling performance of heat pipe-PCM module was explained in literature [13]. The heat pipe cooling system is composed of three components viz. evaporator, energy storage tank (adiabatic section) and condenser. Experiments were conducted at different heating power (13, 18 and 23 J/s) and with different energy storage materials (Tricosane and NE Tricosane). For measurements the filling volume of energy storage tank was kept as 100 ml. The temperature distributions of evaporator were obtained during experimental study.

3. NUMERICAL ANALYSIS

3. 1. Physical Model

The physical geometry of the LHTES system is illustrated in Figure. 1. The physical properties of nano-enhanced phase change materials are estimated using the following formulas.

The density can be calculated as [14]:

$$\rho_{npcm} = \phi\rho_{np} + (1-\phi)\rho_{pcm} \tag{1}$$

The specific heat capacity can be calculated as [14]:

$$c_{p,npcm} = \frac{\phi(\rho c_p)_{np} + (1-\phi)(\rho c_p)_{pcm}}{\rho_{npcm}} \tag{2}$$

The density latent heat can be calculated as [14]:

$$h_{s1npcm} = \frac{(1-\phi)(\rho h_{s1})_{pcm}}{\rho_{npcm}} \tag{3}$$

The dynamic viscosity can be calculated as [15]:

$$\mu_{npcm} = 0.983e^{(12.959\phi)}\mu_{pcm} \tag{4}$$

Equation (5) (Halmilton and Crosser) can be used to calculate effective thermal conductivity of the Ne-PCM

$$k_{npcm} = \frac{k_{np} + 2k_{pcm} - 2(k_{pcm} - k_{np})\phi}{k_{np} + 2k_{pcm} + (k_{pcm} - k_{np})\phi} k_{pcm} \tag{5}$$

The governing equations are solved using commercial CFD package of ANSYS FLUENT14.5.

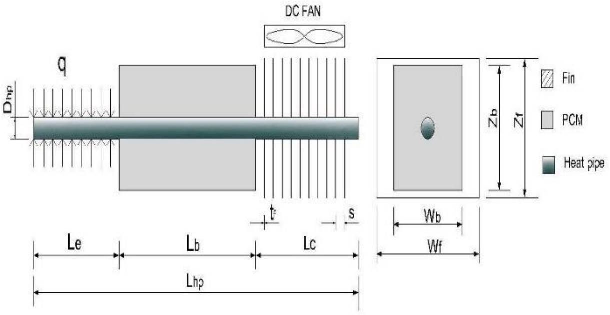


Figure 1. Schematic of the LHTES unit with Evaporator, Energy storage tank and Condenser (consisting of 10 Fins) with DC Fan

Initially, the geometry cleanup is done using ANSYS design modeler and then the computational domain is discretized by structured uniform grid whereas the convective terms are discretized by Second Order Upwind differencing method The PCM momentum equations are solved using PRESSURE BASED method by applying PISO scheme. Also, standard scheme is adopted for pressure interpolation at the cell-faces. The convergence stability is improved by using the relaxation factors of 0.7 and 0.3 for the momentum and pressure respectively. Total time duration used for this simulation is 900s. Each time step completed using 20 iterations. Temperature at each time steps is generated in respective locations such as thermostat positions. Three different mess is gnerated with the maximum edge length of 2 mm, 1.5 mm and 1 mm with number of elements of 81410, 164824 and 249023 respectively. For all above confirugration, the results were observed to be unaffected.

4. RESULTS AND DISCUSSION

Figures 2(a), 2(b) and 2(c) show the comparison between experimental and numerical results at various operating conditions. The temperature profiles of the evaporator with different energy storage materials (Without PCM (W/O PCM), Tricosane, and 0.5, 1 and 2% Al_2O_3 doped Tricosane) at heating power of 13, 18 and 23 J/s (W) were compared. Figure 2 (a) shows the temperature variation at 13 J/s heating power. It can be seen that in 900 s, the evaporator temperature without PCM in the energy storage tank was experimentally and numerically estimated to be 84 and 79˚C. The differences observed between experimental and numerical value was 6%. Tricosane used as storage material in the tank, the temperature variation follows the same trend and 3% variation was observed after 900 s, similarly at 0.5, 1and 2% Al_2O_3 doped Tricosane were used as energy storage materials the observed variations were (69.7 and 67.3˚C) 3.5%, (65.6 and 63.2˚C) 3.7% and (66.3 and 64.2˚C) 3%. A similar temperature profile was reported at heating power of 10W and tricosane used as energy storage material in the tank reported by Weng-Ying et al. [11]. They have experimentally and numerically measured temperatures after 900 s, 68 and 62˚C and the variation was 9%. The transient temperature distribution with Tricosane as energy storage material in the storage tank was observed to be lower than the profile obtained for fluid without PCM. This is due to the fact that Tricosane has high latent heat of energy (as shown in Table 1), because of that it is in solid phase till 47^{0}C then it transformed to liquid phase. Tricosane has the ability to store more heat in the form of LHTES irrespective to its lower thermal conductivity. This is due to the increment of nanoparticles in the Tricosane, which is responsible for increase in the thermal conductivity [13]. It was observed that the maximum reduction in evaporator temperature was 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 did not improve the PCM performance.

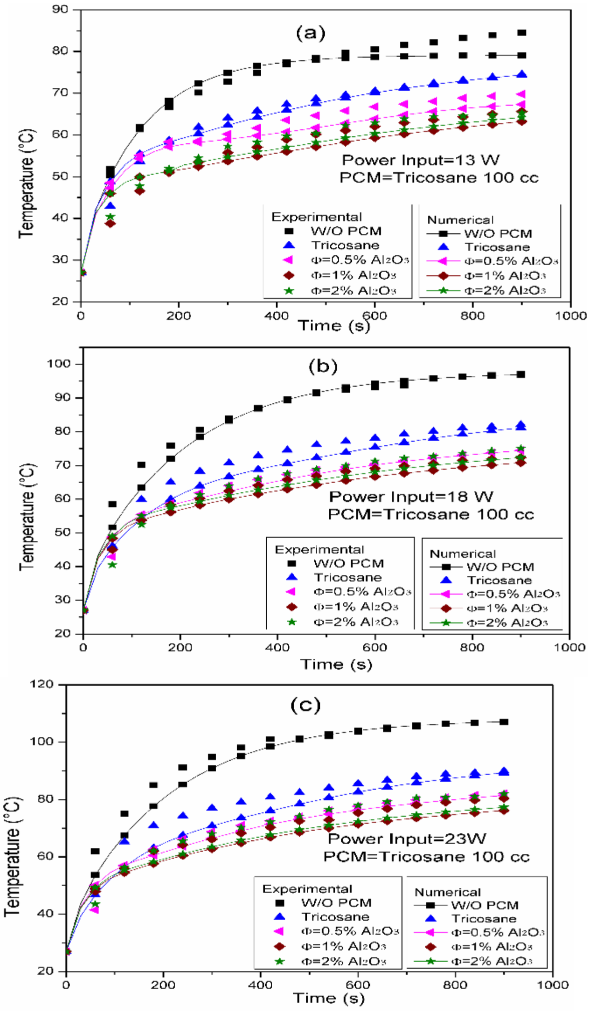


Figure 2. Temperature variations of PCM and Ne – PCM at different volume percentages of Al_2O_3 during charging at different heating powers (a) 13 W, (b) 18 W and (c) 23W

TABLE 1. Thermo physical properties of copper, Tricosane and Al_2O_3

Properties	**Materials**		
	Electrolyte copper	**Tricosane**	**Al_2O_3**
Thermal conductivity (W/mK)	401	0.14	30
Specific heat (kJ/kgK)	0.3844	2.89	0.88
Latent heat (kJ/kg)	207	209	---
Melting point in (K)	1357.6	320	1233.8

The reduction in heat transfer with high vol% is because of the increase in viscosity of PCM with higher concentration of nanoparticle consequently reduces the resistance and slows down the melting (dominated by natural convection). Ho and Gao [16] have reported the similar observation.

It is observed in Figures 2(b) and 2(c) that the experimetnal and simulated temperature profiles at 18 and 23 J/s exhibited similar profile as measured at 13 J/s. Experimentally, the evaporator temperatures observed at 18 J/s for the cases without PCM, with PCM, and with 0.5, 1 and 2% Al_2O_3 based Tricosane were 97.2, 83, 76, 73.6, and 75.4^{0}C, respectively. At the same conditions the numerical values for evaporator temperatures were 96, 81, 74,70 and 72^{0}C. The corresponding variations between experimental and numerical were 1.2, 2.4, 2.7, 5.1 and 4.7%. Similarly, at 23 J/s the experimental values observed to be 107.2, 90.2, 82.2, 80.7 and 81.6 ^{0}C and at the same conditions numerical values were 106, 89, 81, 76.1and 77 ^{0}C, respectively. The variations were 1, 1.1, 1.4, 6 and 6.5%. The differences between experimental and simulation values were due to ignoring the small thermal resistance of one order of magnitude, which makes the total thermal resistance of the heat pipe-PCM module smaller. In addition, the trends of the simulation heater temperature were also lower than data observed for the experimental data. The deviation between simulation and experiment is found to be 6.5%.

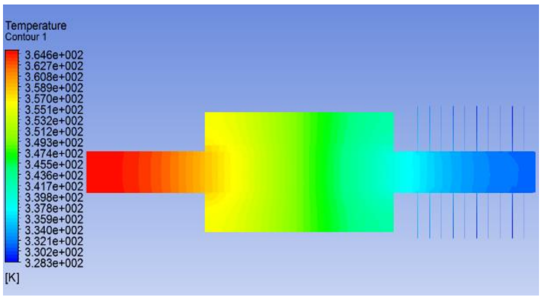
The numerical study was conducted using the procedure and formulation given in Section 3 for all the above mentioned operating conditions i.e. 13, 18, and 23 J/s heating powers as well as for all energy storage materials i.e. without PCM, with PCM, and with 0.5, 1 and 2% Al_2O_3 based Tricosane. Since it was observed from our experimentation that NE-PCM with 1% Al_2O_3 delivered optimize results.

Figures 3(a), 3(b) and 3(c) show the Contours of evaporator temperature (in K) variations of without PCM, with Tricosane and Tricosane with 1% volume fraction of Al_2O_3 during charging at heating power of 18 J/s. Similar effect was observed for 13 and 23 J/s (not shown here). After validaing the simulation method the thermal performance of heat pipe-PCM module with filling volume of 115 and 130 ml was predicted.

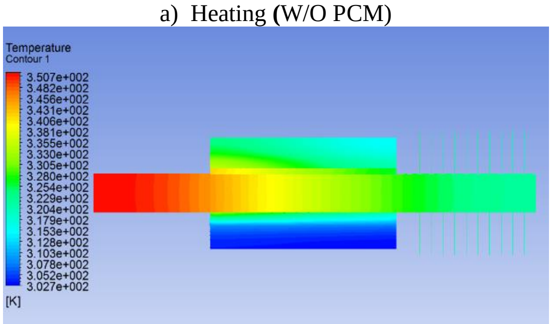
Figures 4(a), 4(b) and 4(c) show the evaluated evaporator temperature profiles for different heating powers (13, 18 and 23W) and PCMs volume of 130 ml during charging process. It can be seen form Figure 4 (a) that for 130 ml filling volume and at 13W heating power for different PCMs (Tricosane, Tricosane with 0.5, 1 and 2 vol% of Al_2O_3). The differences in temperature at 13 W compared to 100 ml were 3.4, 2.3, 2.2 and 2.2°C at 18 W heating power 2, 2, 1.5 and 2.5°C, also at 23 W 3.3, 2.4, 2.1 and 2.2°C, respectively.

It can be concluded from the above observations that increase in PCM volume reduces the evaporator temperature differences and promotes the performance of heat pipe-PCM module at the same heating power.

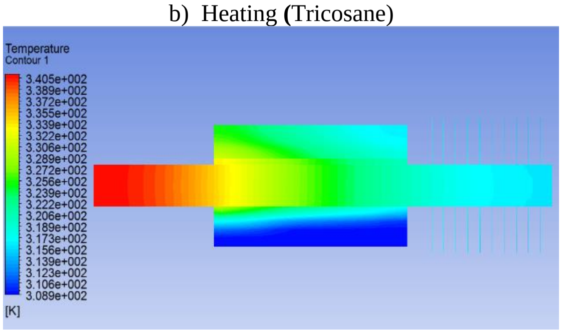
The minor deviations at different time values were attributed to the inevitable experimental losses which cannot be overcome, even though the numerical investigations try to account for such losses. On comparison, very similar results were obtained from experimentation and numerical studies. Also, the trends of experimental and numerical results were similar indicating that the profiles were numerically well solved. However, the small differences between the simulation and experiment in some cases can be explained by the fact of conduction/convention influences during the melting process. The comparison between experimental and numerical data at various conditions clearly exhibited very strong correlation.



a) Heating **(**W/O PCM)



b) Heating **(**Tricosane)



c) Heating **(**Ne–PCM)

Figure 3. Contours of the evaporator temperature variations of W/O PCM, Tricosane and Tricosane with 1vol% Al_2O_3 (Ne-PCM) during charging at heating power of 18 W

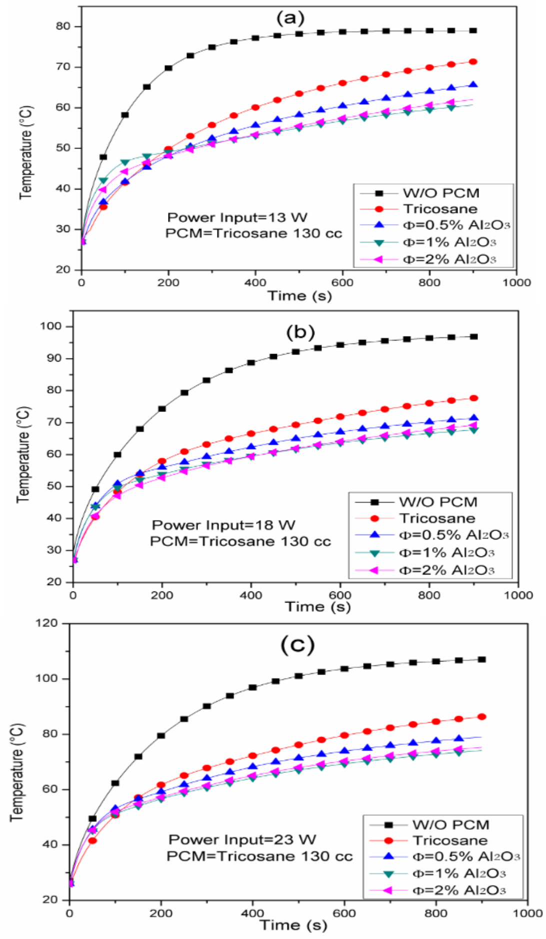


Figure 4. Numerical simulation of the evaporator temperatures for Tricosane (130 cc) and different vol% of Al_2O_3 at various power inputs 13, 18 and 23W

5. CONCLUSIONS

The experimental and numerical studies on performance of heat pipe with and without PCM led to the following conclusions.

- Experimental and numerical studies were conducted for heat pipe performance using Tricosane as a PCM and Tricosane was also doped with 0.5, 1 and 2% volume fraction of Al_2O_3.
- The temperature distribution profile for evaporator was measured for heating powers of 13, 18 and 23 J/s.
- The effect of PCM (with and without nano doping) in evaporator temperature is found significant.
- The concentration of nano particles has positive and negative effect on PCM performances. Therefore, the optimized amount of concentration of nano particles should be applied.
- The evaporator temperatures for 115 and 130 ml PCM volume at 13, 18 and 23 W wre predicted through CFD simulation.
- The increase of PCM volume from 100 to 115 and 130 ml reduces the temperature differences and promote the performance of the heat pipe-PCM module at the same heating power.

Experimental and numerical results were found closely matching.

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PAPER INFO

Paper history:
Received 10 November 2017
Received in revised form 23 December 2017
Accepted 04 Januray 2018

Keywords:
Electronic Cooling Devices
Phase Change Materials
Nanoparticles
Heat Pipe
Thermal Energy Storage

چکیده

افزایش چرخه عمر عملیاتی دستگاه های الکترونیکی، توسعه تکنیک های خنک کننده کارآمد سیتم خنک کننده را ضروری می سازد. بنابراین، در اثر حاضر، اثرات کاربرد مواد تغییر فاز در بخش آدئیوباتیک لوله گرمایی برای کاربردهای خنک کننده های الکتریکی به صورت آزمایشگاهی و عددی مورد بررسی قرار گرفته است. در این مطالعه به عنوان PCM در نظر گرفته شده است که در آن، نانوذرات آلومینیوم در PCM با استفاده از دستگاه همرن مافوق صوت با کسر حجمی 0.5، 1 و 2٪ پراکنده شده اند. رفتار حرارتی گذرا تبخیر کننده، مواد ذخیره سازی انرژی و کندانسور در طول فرایند شارژ با توان های 13، 18 و 23W مورد مطالعه قرار گرفت. عملکرد سیستم با تریکوسن و نانوذرات اکسید الومینیوم با غلظت 1٪ بهبود یافته و برای غلظت 2٪ کاهش داشته است، که نتیجه برای دوپینگ نانوذرات بهینه شده است. علاوه بر این، شبیه سازی CFD لوله گرما برای شرایط ذکر شده فوق انجام گردید. نتایج آزمایش و شبیه سازی در شرایط عملیاتی مختلف برای ایجاد همبستگی بین آنها مقایسه گردید. نتایج عددی مشاهده شده است که با نتایج تجربی انطباف دارد. در نهایت، عملکرد حرارتی ماژول گرما لوله–PCM از طریق شبیه سازی CFD برای حجم پر شدن 115 و 130 میلی لیتر در 13 و 18 و 23 وات است.

doi: *10.5829/ije.2018.31.06c.16*