Heat Transfer Enhancement of High Temperature Thermal Energy Storage using Open Cell Metal Foam & Paraffin Wax

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Abstract— An energy storage system challenges Phase Change material (PCM) to enhance the storage performance. Since most of PCMs stands to relatively low thermal conductivity, this in turn reduces the systems performance. In this study a compound metal foam/nano particles enhancement technique was used to improve the charging and discharging ability of the paraffin wax. The influence of open cell metal foam structure and nano particle volume fraction on the instantaneous evolution of the solid-liquid interfaces, distribution of temperature gradients in compound PCM were investigated.

Key words: Heat Transfer, Thermal Energy, Cell Metal Foam, Paraffin Wax

I. Introduction

Studied the effects of geometrical parameters like pore-size and thickness of ligaments of the Paraffin- Graphite foam, to enhance the thermal properties like thermal diffusivity and the storage capacity and compared with pure paraffin wax by increasing the mass ratio.[2] Investigated the behavior of pure-NaNO3 phase change material, PCM with copper metal foam and expanded graphite to enhance the heat transfer capability in high temperature thermal energy storage systems and found that heat transfer can be significantly enhanced by metal foams moderately by expanded graphite, thereby reducing the charging and discharging period.[3] They investigated the melting process of paraffin wax with seven high porosity copper metal foam samples experimentally and numerically. [4] They prepared stable Bio-based PCMs with xGnP, (Exfoliated graphite Nano platelets) by using the vacuum impregnation method to enhance thermal performance.[5] The Energy storage properties of the nano composite PCMs are characterized and compared the performance of carbon nano fillers of various sizes and shapes in enhancement of thermal conductivity of paraffin-based nano composite PCMs.[6] Experimentally investigated the melting and solidification processes in Triplex Tube Heat Exchanger (TTHX) with internal and external fins at different mass flow rates of the PCM.[7] Studied the effects of pore size and porosity by developing a three dimensional finite element model, considering both the Metal and PCM domains, and suggested an optimal pore size and porosity.[8]Studied the heat transfer characteristics of the copper foam ligament and paraffin wax. Found the evolvement of solid–liquid interface and temperature variation during the melting process and compared with the numerical results by the two-temperature energy model.[9] Investigated experimentally an appropriate concentration of paraffin wax in paraffin wax–water nanoemulsions, and found that the energy stored per unit time per unit heat exchanger volume was the highest for paraffin wax–water emulsion containing 10% paraffin wax, exceeding those of water and pure paraffin wax by 11% and 23% respectively.

Studied the performance of a paraffin wax filled with aluminum metal foam, experimentally in a shell and tube arrangement with different porosity (95% and 77%) and found good agreements with simulation results.

II. EXPERIMENTAL SETUP & TEST PROCEDURES

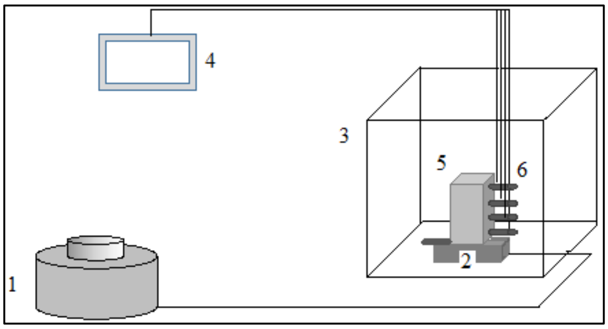


Fig. 1: Schematic Diagram of the Experimental Setup, 1) Variac 2) Heating Element 3) Enclouser 4) Digital Temperature Indicator 5) Container 6) Thermocouples

Fig.1 shows a schematic diagram of the test section. A power variac with digital indicator is used to control and measure the heat input, the enclosure made of synthetic fiber glass of dimensions 400x400x400mm^3. The heater was well insulated with over 30mm thick glass wool and 30mm thick asbestos fabric which provides sufficient thermal insulation to control the heat loss from the source to surroundings. Heating element of 30mmx30mm was left on heat source without insulation to provide constant heat input to the containers filled with compound PCMs through the base plate.

Experimentation consists of four models like pure paraffin wax (PCM), Nano mixed PCM, Paraffin wax with metal foam. Nano-PCM embedded with metal foam. In nano-PCM, Silver coated Copper Nano powder mixed with paraffin wax by ultrasonic stirring process maintained at constant heat input conditions in4%weight ratio. AnAl6101 open cell metal foam of 40ppihavingfrontal area 85×30mm^{2}and thickness 12mm was attached 50mmAl square base plate of thickness 4mm by braze welding.

PCM properties vary with material purity and its previous melting/solidification cycles. The volume change during the melting process of phase change material is up to 10%.Based on the volumetric expansion, the PCM container was designed to 50mm square cross section and 100mm height made with fiber glass. Base plates were attached to containers bottom which ensures a perfect leak proof during melting process.Fig.2 shows an arrangement of four containers filled with PCM compounds. Four probe thermocouples were placed between the heating element and the base plate of the container to measure the average base surface temperature(T_b). Four k-type thermocouples were inserted in equal distances along the length of the container through the insulation, to measure the temperatures T_1, T_2, T_3, and T4of the PCM during phase change process. Experiments were conducted at a 40W heat input. Temperatures were recorded in regular intervals during charging and discharging processes.

Physical characteristics of paraffin wax (PCM)	
Melting temperature	48–54(°C)
Specific heat capacity	2.4(kJ/kg °C)
Latent heat	195 (kJ/kg)
Density	0.88 (g/cm^3)

Table 1:

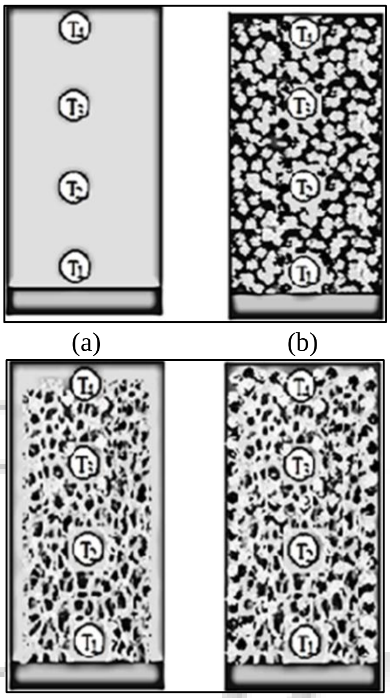


Fig. 2: Arrangement of the Containers. (a) Pure PCM, (b) Nano-PCM, (c) PCM with Metal foam, (d) Nano-PCM with Metal Foam

III. EXPERIMENTAL RESULTS & DISCUSSION

In this study four separate charging processes are tested to examine the heat transfer mechanism during transient phase change phenomena in different PCM compounds. They are (a) melting of pure paraffin wax (b) melting of PCM mixed with Nano, (c) melting of PCM in metal foam, (d) melting of nano-PCM embedded with metal foam. The discharging process is that where paraffin wax is cooled from liquid phase to solid phase without insulation by natural convection.

Properties of Al-6101 Metal Foam, 40PPI	
Compression Strength	2.530 MPa
Tensile Strength	1.240 MPa
Shear Strength	1.310 MPa
ModulusElasticity (Compression)	103.08 MPa
Modulus of Elasticity (Tension)	101.84 MPa
Shear Modulus	199.95 MPa
Specific Heat	0.895 (J/g°C)
Bulk Thermal Conductivity	5.8 w/m°C
Melting Point	660 °C

Table 1:

Properties of Silver coated Copper Nano powder	
Physical Appearance	Dry powder
Powder Mesh Size	325
Morphology	Dendritic
Tap Density	2.5-3.5 g/cc
Color	Tan, dark brown
Silver content	10%

Table 2:

A. *Charging Process*

Since base plates were attached to the containers, heated from the bottom surface, solid paraffin wax at the lower part of containers will first absorb the heat from the base plate at the initial stage of the heating process. Part of the input heat is used to increase the temperature of base plate, and then conducted upwards. All containers were well insulated with asbestos fabric to minimize the convection heat transfer. A heat gradient exists inside the PCMs, with highest temperature being at the bottom and the lowest being at the top. Obviously the heating process is a transient heat transfer problem. The charging process in all four models depends on the physical nature of the composition. The thermal conductivity of the composition plays a vital role in charging process. If the thermal conductivity is not sufficient, the heat cannot be transferred to the top of the container quickly.

Since this is transient heat related, the temperature difference between the base plate and different positions T_1-T_4 are used to compare the heat transfer performance for different containers for a given input heat flux. Higher the temperature difference lowers the heat transfer rate for a given heat input. The temperature difference is defined as

$$\Delta T_i = T_b - T_i$$

Where subscript i represents1, 2, 3, and 4, the temperatures of the compound PCM during phase change at different positions along the length, from base plate to top of the containers.

Fig. 3: Paraffin Wax (PCM)

Fig. 4: Silver Coated Copper Nano Powder

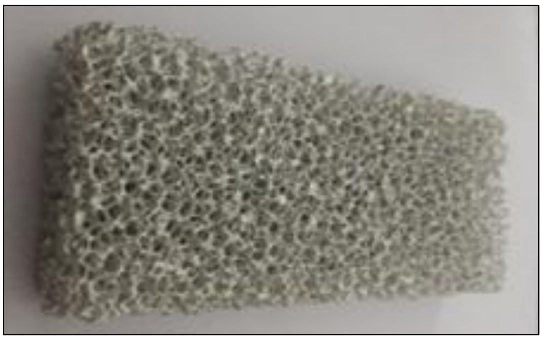


Fig. 5: Al-6101 Metal Foam, 40PPI

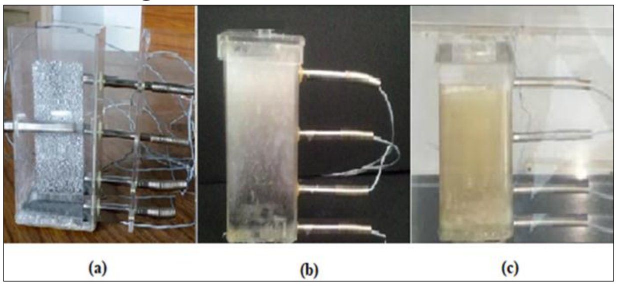
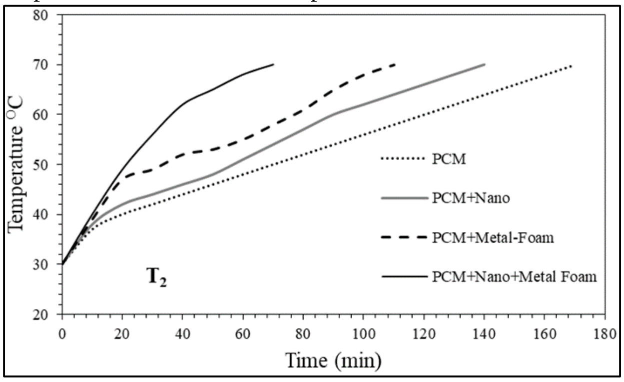
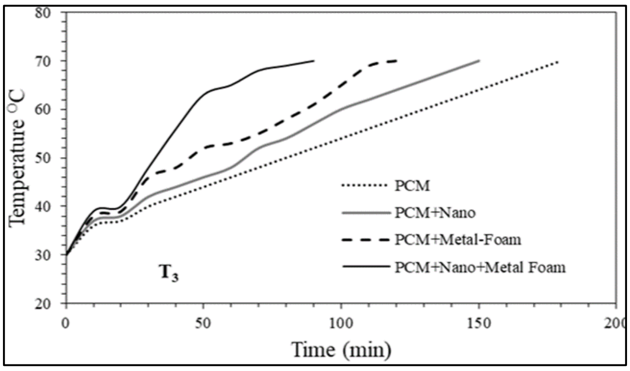


Fig. 1 (A): Metal Foam inside the Container (B) Nano-PCM inside the Container (C) Pure PCM during Solidification

The excellent structure of open cell metal foam has a continuous material and high thermal conductivity struts to conduct the heat across PCMs composites.in Fig. 6, the temperatures of T_2 and T_3inside all the containers with different PCM compounds were plotted. While melting pure PCM takes around 170 minutes to change into complete liquid phase, the duration to phase transfer decreases with respect to the composition embedded with PCM. It was observed that nano-PCM mixed with metal foam accelerates the melting process in 60 minutes.Fig.7 shows the curves of temperature difference ΔT_2 and ΔT_3 inside the containers during heating process, which indicates the temperature difference of base plate to the respective locations in a container. If the temperature difference is less means the charging process was quick enough to melt all the PCM. It was clear that the difference is almost same while melting started. It was found that the temperature difference decreases very rapidly in nano-PCM embedded with metal foam compare with other PCM compounds.

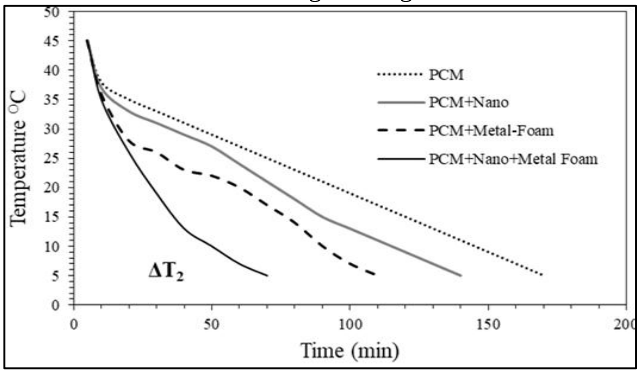


(a)

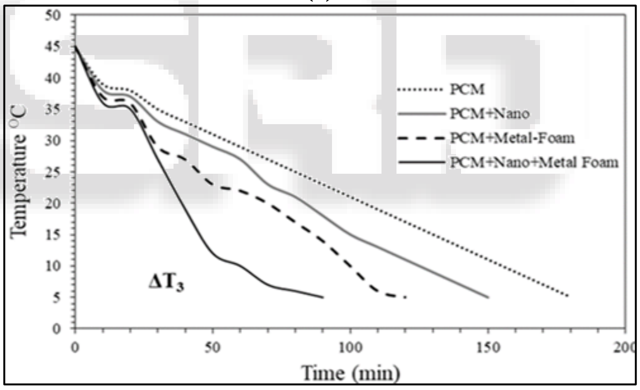


(b)

Fig. 6: Temperature Comparison of T_2 and T_3 inside the Container during Melting Process



(a)



(b)

Fig. 7: Temperature comparison of T_2 and T_3 inside the container during melting process

B. Discharging Process

In this investigation, the cooling circuit was no provided to study discharging process test but a simple natural convection cooling process is attempted without insulation. The container loses its sensible and latent heat at a very low rate for a long period of time. The test results are shown in Fig. 8, Similar to the charging process metal foams can enhance the discharging process. It is expected that the discharging process can be further enhanced if forced convection (active cooling) is employed.

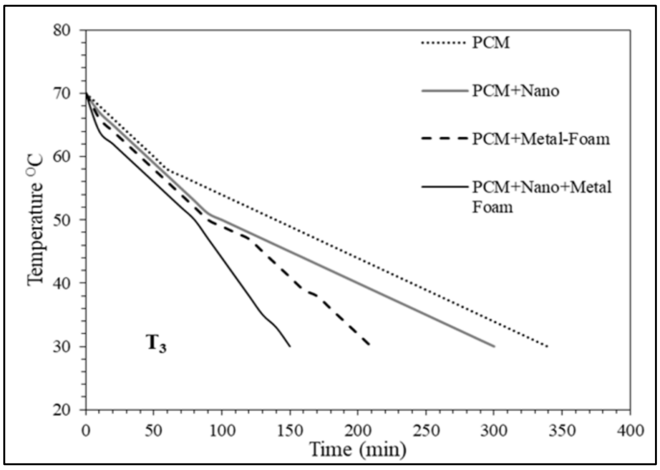


Fig. 8: Temperature distribution of T_3 Inside all the Containers during Solidification Process

IV. CONCLUSIONS

In this paper the feasibility of using metal foams and nano-PCM combinedly to enhance the heat transfer capability in thermal energy storage systems is investigated. The results show that heat transfer can be enhanced by the use of these open cell metal foams, thereby reducing the temperature difference among the PCM compounds, and the charging/discharging periods can be dramatically shortened. Metal foam structures and nano embedded with PCM can significantly enhance the heat transfer in the solid region.

REFERENCES

[1] Yajuan Zhong, QuanguiGuo, SizhongLi, JingliShi, LangLiu, "Heat transfer enhancement of paraffin wax using graphite foam for thermal energy storage," Solar EnergyMaterials&SolarCells, vol. 94, pp. 1011-1014, 2010.

[2] C.Y. Zhao, Z.G.Wu, "Heat transfer enhancement of high temperature thermal energy storage using metal foams and expanded graphite," Solar Energy Materials & SolarCells, vol. 95, pp. 636-643, 2011.

[3] W.Q. Li, Z.G. Qu, Y.L. He, W.Q. Tao, "Experimental and numerical studies on melting phase change heat transfer in open-cell metallic foams filled with paraffin," Applied Thermal Engineering, vol. 37, pp. 1-9, 2012.

[4] Su-GwangJeong,OkyoungChung,SeulgiYu,SughwanKim,SuminKim, "Improvement of the thermal properties of Bio-based PCM using exfoliated graphite nanoplatelets," Solar EnergyMaterials&SolarCells, vol. 117, pp. 87-92, 2013.

[5] Li-Wu Fan , Xin Fang , Xiao Wanga, Yi Zeng, Yu-Qi Xiao, Zi-Tao Yu , Xu Xuc, Ya-Cai Hua,, "Effects of various carbon nanofillers on the thermal conductivity and energy storage properties of paraffin-based nanocomposite phase change materials," Applied Energy, vol. 110, pp. 163-172, 2013.

[6] Abduljalil A. Al-Abidi, Sohif Mat, K. Sopian, M.Y. Sulaiman,Abdulrahman. Th. Mohammad, "Experimental study of melting and solidification of PCM in a triplextube triplextube heat exchanger with fins," Energy and Buildings, vol. 68, pp. 33-41, 2014.

[7] Sriharsha S. Sundarram, Wei Li, "The effect of pore size and porosity on thermal management performance of phase change material infiltrated microcellular metal foams," Applied Thermal Engineering, vol. 64, pp. 147-154, 2014.

[8] P. Zhang, Z.N. Meng, H. Zhu, Y.L. Wang, S.P. Peng, "Melting heat transfer characteristics of a composite phase change material fabricated by paraffin and metal foam," Applied Energy, 2015.

[9] B. Sivapalan, M. Neelesh Chandran, S. Manikandan, M.K. Saranprabhu, S. Pavithra, K.S. Rajan, "Paraffin wax–water nanoemulsion: A superior thermal energy storage medium providing higher rate of thermal energy storage per unit heatexchanger volume than water and paraffin wax," Energy Conversion and Management, vol. 162, pp. 109-117, 2018.

[10] Aditya Atal, Yuping Wang, Mayur Harsha, Subrata Sengupta, "Effect of porosity of conducting matrix on a phase change energy storage device," International Journal of Heat and Mass Transfer, vol. 93, pp. 9-16, 2016.

