ChemTech

International Journal of ChemTech Research
CODEN (USA): IJCRGG, ISSN: 0974-4290, ISSN(Online):2455-9555
Vol.9, No.05 pp 563-570, 2016

Natural heat transfer enhancement methods in phase change material based thermal energy storage

Ramalingam Senthil[1]*, Marimuthu Cheralathan

Department of Mechanical Engineering, SRM University, Kattankulathur, Tamil Nadu, India

Abstract : Thermal energy storage (TES) using latent heat storage (LHS) material has received a greater attention due to its large energy density and isothermal operation characteristics. The major drawback of Phase Change Materials (PCMs) is their unacceptable low thermal conductivity. The effects of naturally available heat transfer improvement methods for the melting and solidification behavior of PCM are discussed. The primary techniques are the eccentricity, inclination, multi-tubes, fins, nanoparticles, porous structures such as foam, graphite, mesh, etc. The heat transfer methods decide whether the heat transfer in PCM should be convective or conductive dominated heat transfer.
Keywords: phase change material, eccentricity, inclined storage, natural convection, thermal conductivity enhancement.

Introduction

Solar water heating is one of the classic techniques used to convert solar energy into thermal energy. The demand of solar water heater has been increasing nowadays due to a reduction in fossil fuel resources and increasing awareness of renewable energy benefits. TES plays a vital role in making solar water heater competent enough with conventional water heaters. LHS using PCM is preferred to sensible heat storage for SWH as it has high TES density and isothermal operating capacity. PCMs classified into organic, inorganic and eutectics based on their compositions. Organic PCMs are suitable for low-temperature applications like SWH due to its no phase segregation, limited sub-cooling and noncorrosive properties. The lower thermal conductivity of PCM requires performance enhancement.

The heat transfer rate can be improved by optimizing the geometry through inclination and eccentric arrangement, thereby aiding natural convection and by improving the thermal conductivity of PCM using metal foam, nanoparticles, fins, foils, heat pipes, expanded graphite, micro and macro encapsulations, etc. Heat transfer rate can be increased by enlarging the convection dominated zone by making small changes in the geometry of the system. The most studied natural thermal performance enhancement techniques are the eccentricity, inclination and multi-tubes inside the PCM container. Such methods are less complicated heat transfer mechanisms and lesser cost.

I. Eccentricity

Eccentricity improves the melting rate by increasing the natural convection zone and achieved by lowering the HTF tube in a concentric tube storage unit. Enhancing the heat transfer rate without adding any extra thermal conductivity enhancer and it may lead to a considerable reduction in the storage unit cost.

Numerical simulation of convection-dominated melting of a PCM in a cylindrical annulus heated isothermally from the inside wall and the enhancements in Rayleigh number increased the heat transfer rate[1]. Melting of PCM in the bottom section was ineffective due to density variation in PCM. Numerical simulation of melting of PCM inside concentric and eccentric horizontal annulus was carried out using the fluent software[2]. Heat conduction to the PCM was dominant at the beginning of melting for all zones through contact melting. After a few minutes, natural convection becomes dominant the top half of hot cylinder while heat conduction remains dominant in the bottom of the hot cylinder. Thus, the melting rate in top half was observed faster than the lower half of the cylinder. The melting rate increased sharply when inner cylinder tube moved down of the center due to dominant natural convection heat transfer in the molten area of PCM. The thermal conductivity enhancement of n-octadecane as PCM through dispersion of CuO nanoparticles was investigated and melting of nano-enhanced PCM (NePCM) can be expedited through using an eccentric shell and tube arrangement by lowering the center of the internal cylinder or tube to increase the area, volume and amount of NePCM that is exposed to the effect of the buoyancy-driven convection[3]. An eccentricity of e = 0.5 was observed with 18.7% saving in charging time than the concentric tube. The melting of paraffin wax with four different heat transfer tube configurations having eccentricity (e) of 0, 10, 20 and 30 mm inside the PCM as shown in Fig 1. The inner tube was moved eccentrically towards down to the center to enhance natural convection currents inside. The lowest melting time was observed for the eccentric geometry of e = 30 mm due to increased convective heat transfer coefficient[4].

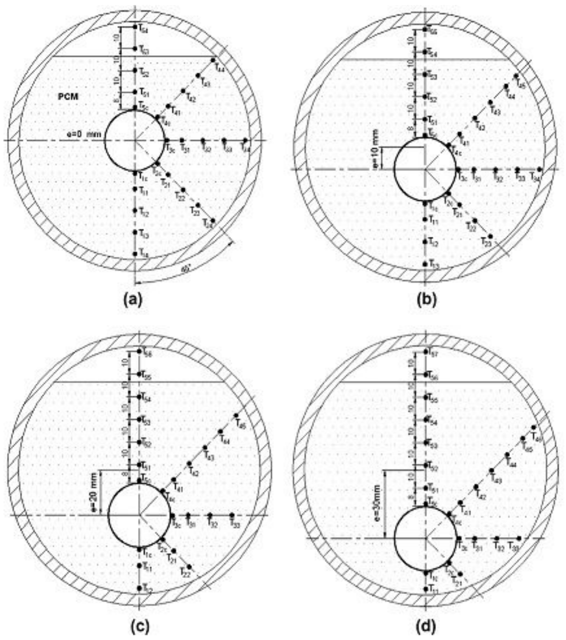

Figure 1: Heat transfer tube arrangements (a) e= 0 mm, (b) e= 10 mm, (c) e= 20 mm, (d) e= 30 mm. [3]

Expansion of convection zone was easier with eccentricity. The eccentric geometry with e = 30 mm decreased the total melting time by 67%. The influence of the eccentricity of the inner tube (e) on the solidification time, six different orientations of the inner heat transfer tube: one concentric (e = 0, i.e. the inner tube and the outer shell have the same center) and five eccentric (e =- 30, - 20, - 10, 10 and 20 mm) were analyzed and the moving the inner HTF tube upward or downward according to the center of the outer shell increases the total solidification time [5]. The concentric geometry was preferred for complete solidification.

II. Orientation and Multitubes

Like eccentricity, orientation also plays a major role in determining the performance of storage unit. The orientation decides whether the system should be dominated by conduction or convective heat transfer. The enhancement of melting/solidification characteristics of paraffin as PCM was achieved by tilting 5° of the outer surface of the storage container[6]. A 30% decrease in the total melting time was achieved through inclination.

Thermal behavior of PCM in a quadrant cavity at various inclinations from 0° to 360° was investigated numerically using enthalpy-porosity approach[7].

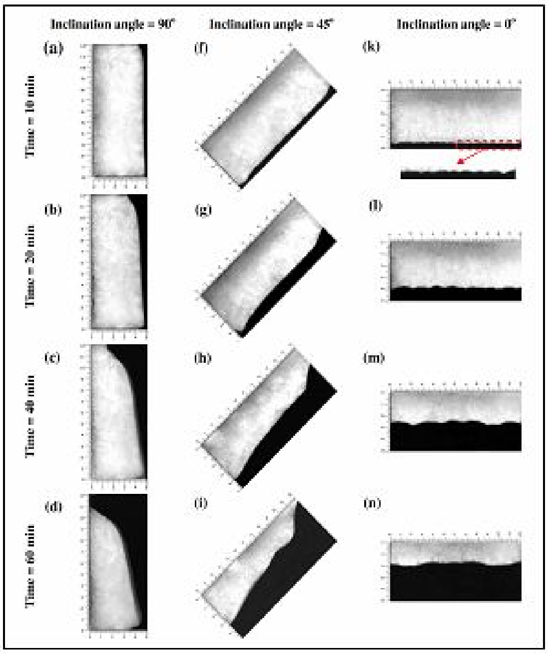

Figure 2: Melting process of PCM for different inclination angles [7]

Inclination angles dramatically affected the convection currents in PCM. Paraffin with a melting interval of 26-28 °C was used. Five inclination angles of 0, 45, 135, 180, and 225° were considered. The melting rate was affected to a greater extent at inclination angles 180 and 225°. Natural convection was found to be weaker for 45° than for other angles. This is because the heat is transferred from top to bottom. 225° inclination took the shortest time for complete melting.

A three-dimensional melting process in a vertical cylindrical enclosure for inclination angles of 5° and 10° was investigated and the modest tilting of the enclosure significantly enhances the convection currents in the PCM [8]. The dynamic thermal PCM melting in a rectangular enclosure at various inclination angles (0°, 45°, 90°) was experimentally investigated with lauric acid as a PCM[9]. The melting process of PCM in a rectangular enclosure for inclination angles of 0°, 45°, 90° at various times are shown in Fig. 2. The inclination has a significant effect on natural convection and melting time of the PCM. The total melting time for the 45° and 0° inclined enclosures was 35% and 53% less than the vertical enclosure. The melting time in the horizontal enclosure is less than half of that in the vertical enclosure. The system orientation had a minimal effect on the solidification rates for nearly all case studies due to conduction-dominated heat transfer[10]. Natural convection within the PCM strongly depends on the location of the hot surface relative to the solid PCM. Therefore, system orientation may alter the melting rates. Liquid fraction for horizontal orientation is higher than that of vertical orientation.

Comparison of the thermal behavior of a horizontal and vertical shell and tube energy storage was done and for the horizontal configuration, during charging convective heat transfer was dominant in the upper part of cylinder and less significant in the lower part while it was observed to be uniform for the vertical configuration [11].

The horizontal configuration had superior thermal performance than a vertical configuration in the case of charging. But the orientation had less impact on the thermal performance during discharging due to conduction dominated heat transfer. A comparison has been made between concentric and multi-tube heat exchanger by to understand the effect of the multi-tube configuration shown in Fig. 3 on the thermal performance[12]. The melting rate increased when the number of tube increased from 1 to 4 and the melting time decreased up to 29% for the four tubes heat exchanger. HTF inlet temperature and mass flow rate had a greater impact on the multi-tube heat exchanger than that of concentric tube.

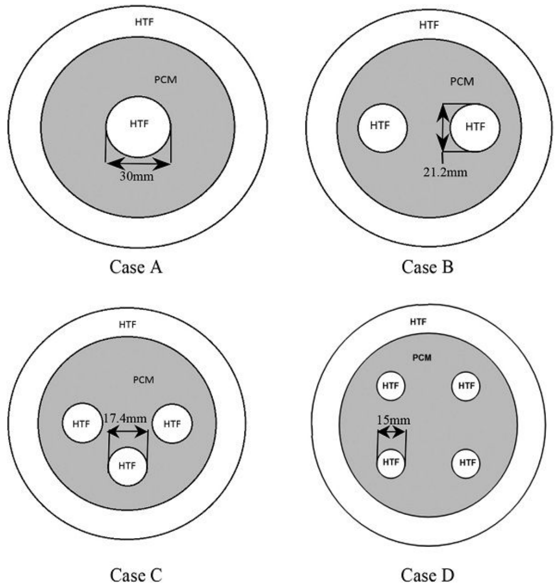

Figure 3: Physical configuration of Multi-tube heat exchanger [12]

Thermal conductivity enhancement techniques

Thermal conductivity can be enhanced by employing fins, foils, heat pipes, porous structures like metal foam, graphite, expanded graphite, dispersing nanoparticles etc.

I. Metal foam and Expanded Metal Mesh

Metal foam consists of a metal which contains abundant pores. Metal foams are divided into two types. Closed cell foam in which the pores are sealed and the open cell foam, which is made up of an interconnected network that aids the flow of liquid PCM. Open cell foam is used as the thermal conductivity enhancer due to its desirable properties such as large surface area density, high thermal conductivity, good connectivity between ligament and PCM, high porosity, good mechanical strength[13].

The heat transfer characteristics of a paraffin/metal foam composite PCM in a rectangular cavity numerically and experimentally investigated and the copper foam enhanced the thermal conductivity of PCM [14]. It was observed that the temperature of copper foam was higher than that of paraffin in the solid region because of conduction dominated heat transfer. However, the temperature difference between copper foam and paraffin was small due to the heat transfer enhancement by natural convection in the liquid paraffin.

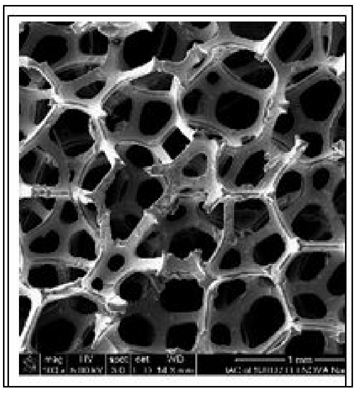

Figure 4: SEM image of Metal foam [28]

Copper foams with 5, 10, 40 Pores per Inch (PPI) with the uniform porosity of 0.94 were investigated to enhance the heat transfer characteristics of paraffin wax [16]. PPI did not have any effect on the performance. Paraffin without foam started to melt earlier than the paraffin with foam. But when the paraffin with foam started melting, it was faster and the heat was uniformly distributed in the PCM. The use of metal foam reduced the melting time of PCM by 20% and also enhanced the heat transfer rate with suppressing the generation of a void during solidification. The Expanded Metal Mesh (EMM) made of aluminium with 90% porosity was employed to improve the melting rate[17]. EMM is 96% cheaper than metal foam per unit volume. The EMM was arranged in the perpendicular configuration. The melting time was just reduced by 14% due to suppression of natural convection by the perpendicular model. Parallel configuration of metal mesh without interlayer gap reduced the melting rate by 81%.

II. Expanded Graphite

The effect of expanded and exfoliated graphite to improve the thermal conductivity of PCM was done and the mass percentage of the paraffin used was 77%. The mechanical strength of the composite was observed to be maintained up to this percentage. Thermal conductivity was increased up to 24 %[18]. Expanded graphite was suggested for a cost effective storage unit. The Expanded Natural Graphite (ENG) was suggested to be the best configuration for LHS among fins, graphite and ENG[19]. The thermal conductivity of ENG/PCM composite was about 100 times greater than that of PCM alone.

III. Fins

Fins are nothing but extended surfaces used to increase the heat transfer rate by reducing the thermal resistance of the PCM. Fins are economical and easy to implement. Fins can be axial or radial in the case of shell and tube geometry. Heat transfer rate can be increased significantly by optimizing the geometry of fins like length, spacing and thickness. Fins can be added to the external and internal side of the HTF tube. External fins reduce the thermal resistance of PCM, whereas internal fins lessen the resistance of heat transfer fluid especially in the case of air.

The melting process of RT 82 in a Triplex tube heat exchanger using Fluent simulation was carried out and the three cases such as triplex tube heat exchanger with internal, external and internal-external fin were studied [20]. No significant effect was observed among the three types of fin on the melting rate. Fins reduced the melting time up to 43.3%. The increase in fin length reduces the melting time. Figure 5 illustrates the triplex tube heat exchanger with fins. As the number of fin increases, melting time decreases. Triplex tube heat exchanger with 8 fins reduced the melting time up to 34.7 %.Fin length had a strong impact on the melting rate than that of fin thickness. It was suggested to increase the fin length and decrease the fin thickness to improve the melting rate [21].

The solidification behavior of PCM in a triplex tube heat exchanger with and without internal and external fins was analyzed and fins reduced up to 35 % of solidification time [22]. The increase in number of fins reduced the solidification time. The effect of fin length was more than that of fin thickness on the solidification rate. Increasing the number of heat pipe enhanced the melting rate in a heat pipe assisted TES [23]. The geometry of fins attached to the heat pipe had a strong impact on the thermal performance. The increase in fin length provided the uniform temperature distribution within the PCM. Number of fins did not have any impact on the performance of the system.

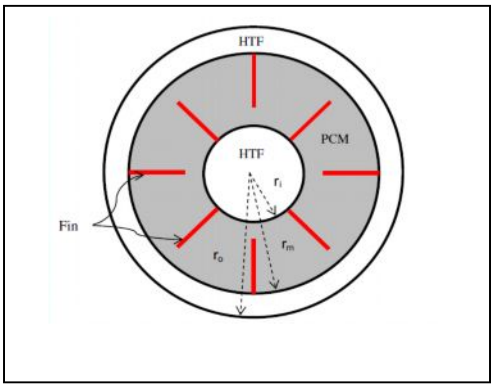

Figure 5: Schematic of Triplex tube heat exchanger with fins [20]

The effect of longitudinal fins on the performance of shell and tube heat exchanger was studied[24]. Stearic acid with phase transition range of 55.7-64.1 °C was used. Three longitudinal fins made of brass were equally spaced at an angular interval of 120°. Melting time was reduced up to 24.52% and the solidification time decreased to 43.6%. Fins did not have a greater effect on melting due to suppression of convective currents. When nanoparticles are dispersed in PCM, it creates two effects. One is the improvement in the magnitude of thermal conductivity and the other one is the reduction in the latent heat. Conduction heat transfer is dominant in the nano enhanced PCM due to its higher thermal conductivity. The effects of multi-walled carbon nano tubes, graphite and graphene on the heat transfer of PCM were studied[25]. Stearic acid with melting temperature of 71 °C was selected as the PCM. Poly vinyl pyrrolidone was used as a dispersion stabilizer. Transient hot-wire method was utilized to measure the thermal conductivity of carbon enhanced PCM. An enthalpy-based lattice Boltzmann method simulation was used by The effect of dispersion of Cu nanoparticles on melting of ice in annuli was studied and the top of the hot cylinder was dominated by natural convection and the bottom was dominated by conduction heat transfer. At any volume fraction of nanoparticles, lower melting time was observed when the heat transfer tube shifted from the center to the bottom. The effect of volume fraction of nanoparticles was more significant for the centre position of heat transfer tube[26].

The paraffin-based nano-fluids were examined to investigate the use of nano-enhanced PCMs for TES applications[27]. The effect of multi-walled carbon nanotubes on the latent heat of fusion was observed. The enhancement in thermal conductivity due to the nanoparticles was not significant enough to outweigh the reduction in latent heat of fusion. The results suggested that the use of nano particle is not an effective way to enhance the storage performance.

Conclusions

The conductivity and convective heat transfer coefficient enhancement during the phase change process of PCM were discussed. Both aspects are opposite in nature; effective in the sensible and latent heat dominated region respectively. The salient points of natural heat transfer enhancement techniques are discussed below:

- The eccentricity of HTF tube below the horizontal axis improves the natural convection zone and enhanced melting process is observed. The solidification has no much variation between concentric and eccentric HTF tube.
- The tilting of an orientation of PCM container improves the melt fraction considerably with improvement in convection dominated melting process. However, the system orientation has less effect during the solidification process.

The thermal conductivity enhancement techniques in the PCM are metal foam, expanded metal mesh, expanded graphite, the addition of fins and nanoparticles to the PCM. The addition of nanoparticles normally reduces the latent heat of the PCM even though thermal conductivity improved.

References:

1. Ng KW, Gong ZX, Mujumdar AS. Heat transfer in free convection-dominated melting of phase change material in horizontal annulus. Int. Comm. Heat Mass Transfer, 1998, 25 (5); 631-640.
2. 2. Ahmad Ali Rabienataj Darzi, Mousa Farhadi, Kurosh Sedighi. Numerical study of melting inside concentric and eccentric horizontal annulus, Applied Mathematical Modeling, 2012, 36; 4080–4086.
3. Nabeel SD, Khodadadi JM, Tahseen A. Al-Hattab, Saad M. Al-Mashat. Experimental and numerical investigation of melting of NePCM inside an annular container under a constant heat flux including the effect of eccentricity. International Journal of Heat and Mass Transfer, 2013, 67; 455–468.
4. Yusuf MY, Mete Avci, Orhan Aydin, Mithat Akgun. Effect of eccentricity on melting behavior of paraffin in a horizontal tube-in-shell storage unit: An experimental study. Solar Energy, 2014, 101; 291–298.
5. Mustafa Yusuf Yazici, Mete Avci, Orhan Aydin, Mithat Akgun. On the effect of eccentricity of a horizontal tube-in-shell storage unit on solidification of a PCM. Applied Thermal Engineering, 2014, 64; 1-9.
6. Mithat Akgun, Orhan Aydın, Kamil Kaygusuz. Experimental study on melting/ solidification characteristics of a paraffin as PCM. Energy Conversion and Management, 2007, 48: 669–678.

7. Wei-Biao Ye, Dong-Sheng Zhu, Nan Wang. Effect of the inclination angles on TES in a quadrantal cavity. J Therm Anal Calorim, 2012,110:1487–1492.
8. Nourouddin Sharifi , Christopher W. Robak , Theodore L. Bergman , Amir Faghri. Three dimensional PCM melting in a vertical cylindrical enclosure including the effects of tilting. International Journal of Heat and Mass Transfer, 2013, 65: 798–806.
9. Babak Kamkari, Hossein Shokouhmand , Frank Bruno. Experimental investigation of the effect of inclination angle on convection-driven melting of phase change material in a rectangular enclosure. International Journal of Heat and Mass Transfer, 2014, 72;186–200.
10. Michael J. Allen, Nourouddin Sharifi, Amir Faghri, Theodore L. Bergman. Effect of inclination angle during melting and solidification of a phase change material using a combined heat pipe-metal foam or foil configuration. International Journal of Heat and Mass Transfer, 2015, 80;767–780.
11. Saeid Seddegh, XiaolinWang, Alan D. Henderson. A comparative study of thermal behaviour of a horizontal and vertical shell and tube energy storage using phase change materials. Applied Thermal Engineering, 2016, 93;348–358.
12. Esapour M, Hosseini MJ, Ranjbar AA, Pahamli Y, Bahrampoury R. Phase change in multi-tube heat exchangers. Renewable Energy, 2016, 85;1017-1025.
13. Li WQ, Qu ZG, He YL, Tao WQ. Experimental and Numerical Studies on Melting Phase Change Heat Transfer in Open-cell Metallic Foams Filled with Paraffin. Applied Thermal Engineering, 2012, 37;1-9.
14. Xiao X, Zhang P, Li M. Effective thermal conductivity of open-cell metal foams impregnated with pure paraffin for latent heat storage. International Journal of Thermal Sciences, 2014, 81;94-105.
15. Peng Zhang, Zhaonan Meng, Hua Zhu, Yanling Wang, Shiping Peng. Experimental and numerical study of heat transfer characteristics of a paraffin/metal foam composite PCM. Energy Procedia, 2015, 75; 3091 – 3097.
16. Simone Mancin, Andrea Diani, Luca Doretti, Kamel Hooman, Luisa Rossetto. Experimental analysis of phase change phenomenon of paraffin waxes embedded in copper foams. International Journal of Thermal Sciences, 2015, 90; 79-89.
17. Ahmad Mustaffar, Adam Harvey, David Reay. Melting of phase change material assisted by expanded metal mesh. Applied Thermal Engineering, 2015, 90; 1052-1060.
18. Ahmet Sari. Form-stable paraffin/high density polyethylene composites as solid–liquid phase change material for thermal energy storage: preparation and thermal properties. Energy Conversion and Management, 2004, 45; 2033–2042.
19. Kevin Merlin, Didier Delaunay, Jérôme Soto, Luc Traonvouez. Heat transfer enhancement in latent heat thermal storage systems: Comparative study of different solutions and thermal contact investigation between the exchanger and the PCM. Applied Energy, 2016, 166; 107–116.
20. Sohif Mat , Abduljalil A. Al-Abidi, Sopian K, Sulaiman MY, Abdulrahman Th Mohammada. Enhance heat transfer for PCM melting in triplex tube with internal–external fins. Energy Conversion and Management, 2013, 74; 223–236.
21. Abduljalil A. Al-Abidi , Sohif Mat , Sopian K, Sulaiman MY, Abdulrahman Th. Mohammada. Internal and external fin heat transfer enhancement technique for latent heat thermal energy storage in triplex tube heat exchangers. Applied Thermal Engineering, 2013, 53; 147-156.
22. Abduljalil A. Al-Abidi , Sohif Mat , Sopian K, Sulaiman MY, Abdulrahman Th Mohammada. Numerical study of PCM solidification in a triplex tube heat exchanger with internal and external fins. International Journal of Heat and Mass Transfer,2013, 61; 684–695.
23. Saeed Tiari, Songgang Qiu , Mahboobe Mahdavi. Numerical study of finned heat pipe-assisted thermal energy storage system with high temperature phase change material. Energy Conversion and Management, 2015, 89; 833–842.
24. Manish K. Rathod, Jyotirmay Banerjee. Thermal performance enhancement of shell and tube Latent Heat Storage Unit using longitudinal fins. Applied Thermal Engineering, 2015, 75; 1084-1092.
25. Da Hee Choi, Juhyuk Lee, Hiki Hong, Yong Tae Kang.Thermal conductivity and heat transfer performance enhancement of phase change materials (PCM) containing carbon additives for heat storage application. International journal of refrigeration, 2014, 42; 112 -120.
26. Mahmoud Jourabian, Mousa Farhadi, Kurosh Sedighi. On the expedited melting of phase change material (PCM) through dispersion of nanoparticles in the thermal storage unit. Computers and Mathematics with Applications, 2014, 67; 1358–1372.

27. Aitor Zabalegui, Dhananjay Lokapur, Hohyun Lee. Nanofluid PCMs for thermal energy storage: Latent heat reduction mechanisms and a numerical study of effective thermal storage performance. International Journal of Heat and Mass Transfer, 2014, 78; 1145–1154.
28. B.Janarthanan and Suresh Sagadevan; Thermal Energy Storage using Phase Change Materials and their Applications: A Review;2015, Vol.8, No.6, pp 250-256.
29. Akshay Ahuja, M. Ramachandran; Review on Phase Change Material as thermal energy storage for cooling; International Journal of ChemTech Research; 2016, Vol.9, No.04 pp 192-196.
30. Vasishta D. Bhatt, Kuldip Gohil, Arunabh Mishra; Thermal Energy Storage Capacity of some Phase changing Materials and Ionic Liquids; International Journal of ChemTech Research; 2010, Vol.2, No.3, pp 1771-1779.

*****