ISSN: 2754-4966

Journal of Nanosciences Research & Reports

Research Article

Open Access

A Review on Shape Stabilized Phase Change Material for Thermal Energy Storage Applications

Anas Islam[1*], AK Pandey[1], R Saidur[1,2], Aman Yadav[3] and Kamal Sharma[4]

[1]Research Centre for Nanomaterials and Energy Technology (RCNMET), School of Engineering and Technology, Sunway University, No 5, Jalan University, Bandar Sunway, Petaling Jaya, 47500 Selangor Darul Ehsan, Malaysia

[2]School of Engineering, Lancaster University, Lancaster, LA1 4YW, UK

[3]College of Engineering, University Malaysia Pahang, Lebuhraya Tun Razak, Gambang, Kuantan 26300, Pahang, Malaysia

[4]Institute of Engineering and Technology, GLA University, Mathura, UP 281406, India

ABSTRACT

Thermal energy storage (TES) using solar energy is one of the most prominent techniques to store the energy and reduce to gap between energy demand and supply. There are many useful applications that can be fuelled by TES. Phase change materials (PCM) as TES materials are of great importance as far as the energy storage applications are concerned. However, there are various bottleneck problems with pure PCM like liquid phase leakage, low thermal conductivity, supercooling etc. To overcome this deficit, highly porous foam is used to improve the leakage problem of PCMs during phase transition. Additionally, nanoparticles and nucleating agent are the most commonly employed in-practice approaches to get rid of the issue of low thermal conductivity and supercooling, respectively. In addition, even after being subjected to multiple heat cycles, foam-stabilized PCM composites showed remarkable stability without being degraded. This paper discusses the major foams that has been incorporated with different PCMs along with their critical outcomes. This paper also discusses the significant uses of foam stable PCMs reported by several researchers. As a result of its high latent heat, good thermal conductivity, balanced chemical compatibility, and high thermal stability, the foam-stable PCM composite is a viable choice for thermal-energy management systems.

Corresponding author

Anas Islam, Research Centre for Nanomaterials and Energy Technology (RCNMET), School of Engineering and Technology, Sunway University, No 5, Jalan University, Bandar Sunway, Petaling Jaya, 47500 Selangor Darul Ehsan, Malaysia.

Received: November 06, 2024; **Accepted:** November 14, 2024; **Published:** November 29, 2024

Keywords: FSPCM, Porous Materials, Foam Stabilization, Thermal Management, TES

Introduction

Nowadays the whole world is witnessing the technical advancement at an exponential rate, with such a huge jump in the demand of energy especially from the last decade and growing greenhouse concern has prompted the scientist to look for some alternate sources of energy [1]. The other prominent reason to look for the alternate energy resources is the fast depletion of conventional energy sources such as natural gas, oil, coal, or nuclear [2]. Among the available alternate energy resources, the renewable resources of energy are the most promising ones since it is capable enough to meet global energy demand as well as a perfect answer to attain a low-carbon future [3]. Solar energy holds a dominating position as far as thermal energy storage is concerned compared to other sources of renewable energy like biomass and wind. In current era, TES is the need of the hour for the continuous energy supply in a vast number of applications like buildings, power generation [4]. Figure 1 shows the potential application areas where TES is being used.

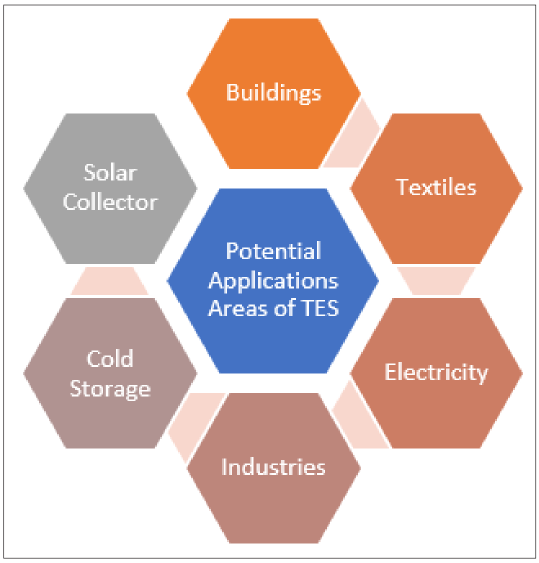

Figure 1: Major Applications of TES

Phase change materials (PCM) are extensively used in TES, latent heat from melting and freezing can be stored in a quantity far greater than that of sensible thermal storage alone [5]. Since pristine PCMs witness several types of problems such as the leakage of liquid phase, low thermal conductivity, supercooling etc therefore it is recommended to enhance the property of PCM prior to its use [6]. There are various methods to resolve these issues with the PCM e.g., addition of nano particles and nucleating agents to improve its heat transfer rate and avoid supercooling respectively, encapsulation to protect the PCM from external environment pure PCMs, use of FSPCM to improve the thermal conductivity of PCM [7]. This article will summarize the recent advancements and challenges of foam stable phase change materials (FSPCM).

Overview of FSPCM

In order to overcome the problem of low thermal conductivity in PCM, porous materials and metallic foams are used [8]. The liquid PCMs are poured over or embedded into the foams and allowed to solidify, thereby the surface area gets increased as a result of which the heat transfer rate will also get enhanced. The rate at which heat transfers through foam depends on its PPI i.e., the number of pores per linear inch, fibre length, porosity (the ratio between total volume vs actual volume occupied by the foam), relative density, fibre thickness, surface area per unit of volume and pore density [9]. Figure 2 shows the various types of foams that are commonly used by researchers.

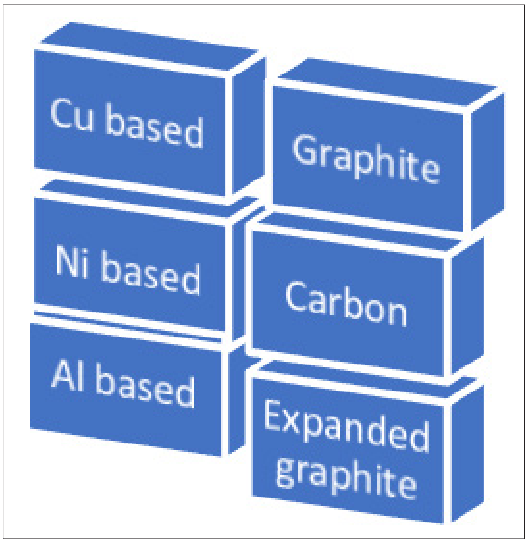

Figure 2: Various Types of Foams/Porous Material

Recent Progress and Challenges in FSPCM

Impregnation of PCM into a foam/ metal foam (MF) is a commonly adapted technique for preparing the FSPCM. It might not be convenient to immerse the MF into the liquid PCM directly without impregnation due to the presence of trapped air molecules in the porous structure, thus it would lead to creation of voids hence the strength of FOCM might get reduced. Finally, these air bubble trapped inside the micro-pores of a composite PCM will lead poor heat transfer and a lower PCM loading ratio. To avoid the formation of air bubbles the process of vacuum impregnation is carried out. The air bubble in the PCM is be removed with the use of a vacuum [10]. Figure 3 depicts method of making FSPCM with the use of a vacuum, metal foam, and paraffin.

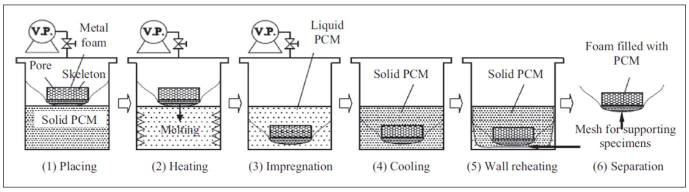

Figure 3: Vacuum Impregnation for the Preparation of FPCM [8].

In the course of making shape stabilized PCM composite Warzoha et al. compared vacuum impregnation to direct submersion infiltration by measuring the impregnation ratio (mass of impregnated PCM to mass of the perfectly impregnated case) [11]. The results showed that vacuum impregnation was far more effective than simple submersion, resulting in an almost 100% impregnation ratio for composite PCMs of paraffin and carbon foam. It has also been shown to be particularly successful in creating FSPCM [8-11].

Due to the porous structure, Cu foams have a large surface area relative to their volume. Among metals, copper has high thermal conductivity stands out as a top option for use in heat transmission. For the best heat conduction, PCMs are being combined with copper foam of varied pore sizes and densities [12]. In order to increase heat transfer, employed paraffin wax RT58 as PCM, which contains metal foams imbedded within it [13]. Bottom surfaces of the test samples have been heated at a constant flux of heat. The authors discovered that by incorporating metal foam, the overall heat transfer rate can be increased by a factor of three to ten [14]. The thermal characteristics of a copper foam/paraffin composite were examined experimentally by the authors. It was shown that PCM temperatures could be lowered by using copper foam/paraffin composites as they considerably improved the heat transfer rate. Figure 4 shows the aluminum foam that was prepared by and copper foam prepared by along with the geometrical dimensions of both foam and their respective plates [15, 16]. He came out with the results that copper foam, while similar in morphology to aluminium foam, has superior thermal performance.

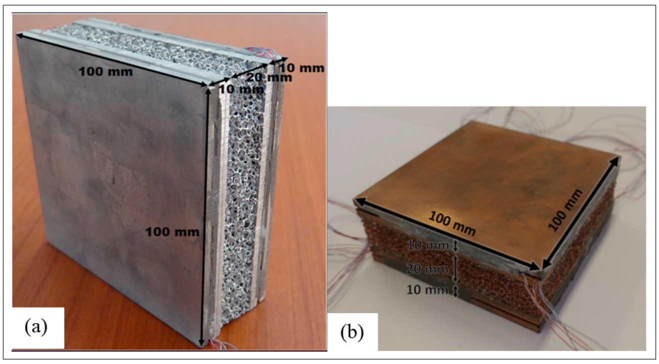

Figure 4: Prepared Samples of (a) Al-foam and (b) Cu-foam

Using numerical methods, compared two PCM-based cold thermal energy storage systems. Comparing two units, one with a bio-PCM and while the other with aluminium foam, concluded that the one with Al foam shows minimal free convection in both the cooling charging and discharging processes [17].

Despite of low thermal conductivity (89 W/m-K) of Nickel, its relatively higher melting point (1455 °C) makes nickel foam a good candidate to be employed to acquire heat transmission rate. A significant improvement by almost three times higher than pure paraffin in the heat transfer of the paraffin/nickel foam composite was observed. Deviations in the peak melting temperatures by

0.55 °C and 0.40 °C of Paraffin/nickel foam composite and paraffin/copper foam composite respectively with a pore size of 25PPI were also recorded as compared to pure paraffin due to the presence of the porous metal foam [8]. In order to enhance the properties of the nickel foam (NF) skeletons, employed reduced graphene oxide (rGO) nanosheets adorned with Ni nanoparticles (Ni@rGO) impregnated with acidic graphene oxide solution and then thermally reduced. NF/Ni@rGO supported CPCMs are superior to their bare Ni-Foam supported counterparts in terms of form stability, heat storage density, and recycling potential [18].

Expanded graphite is among the most popular carbon - containing foam for heat transfer because of its lower density. Relatively minimal density and exceptionally conductive expanded graphite is used to improve the thermal conductivity and heat transfer of phase change materials (PCMs). Expanded graphite (EG) has a low density because it is extremely porous (porosity >99%) [19]. Chriaa et al. (20) used Hexadecane as PCM, and expanded graphite (EG) was added to analyze the performance of expanded graphite on the phase change materials composites [20]. This composite consists of 75% PCM, and 15% expanded graphene rest were the supporting materials. He claimed that EG has a positive impact on the thermal conductivity (TC) of PCM composite thereby increasing the TC 1.24 W/m. Some of the important studies related to FSPCM are summarized in Table 1.

Table 1: Some Crucial Findings on Different Foam Stable PCM

Ref No.	Foam used	Method	Application Focused	Findings
[8]	Ni, Cu	Vacuum impregnation	Thermal charecterization	Thermal Conductivity (TC) of the FSPCM were enhanced
[21]	PW/HGF composite PCM	chemical vapor deposition (CVD)	Solar/thermal energy conversion	TC of PW/HGF is 87% higher than PW/GF and 744% higher than pure PW
[22]	Salts binaly/EGF	solution impregnation (SI) method	---	TC was enhanced by 4.9–6.9 time
[23]	Bi-Sn-In alloy/Ag/copper foam	---	Thermal management electronic device	FSPCM demonstrated excellent endothermic and exothermic properties
[24]	GNF/PCM	---	transient thermal response of PCM	base temperature of GNF/PCM enhanced 1.6 times

As a result of the improved thermal conductivity of PCM, the rate of heat transfer is improved. However, in most cases the specific heat of FSPCM gets lower thus it might not suitable for applications that need heat storage. When FSPCMs are employed for electronic cooling, they lower the base temperature, this limits FSPCM potential usefulness over longer cycles by decreasing its latent heat.

The rate of charging and discharging of thermal energy gets enhanced in FPCMs, the larger surface area aids in the passage of heat by conduction. Within PCM, temperature distributions become more even, because liquid PCM mobility is impeded, hence free convection heat transmission is reduced [25-30].

Conclusions

The current article reviewed the recent progress in foam stable phase change materials. Commonly used metallic (Al, Cu and Ni) and carbon based (C, Gr and Ex. Gr) foams were summarized to show their effect on the overall characteristics of PCM including the thermophysical properties. The following conclusions could be drawn based on the current study:

- The most important use of foam-stable PCMs is to enhance the thermal conductivity and heat transfer rate (k).
- In terms of thermal distribution, composite PCMs showed the most consistency.
- The time required to store and retrieve energy was reduced by a significant ratio due to the increment in the thermal charging and discharging speeds.
- FSPCMs are used to reduce the interface temperatures of electronic devices and Li-ion batteries therefore they are preferred to use in electronic devices.

References

1. S Ali, SP Deshmukh (2019) An overview: Applications of thermal energy storage using phase change materials. Materials Today: Proceedings 26: 1231-1237.
2. A Islam, SP Dwivedi, VK Dwivedi (2021) Effect of friction stir process parameters on tensile strength of eggshell and SiC-reinforced aluminium-based composite. World Journal of Engineering 18: 157-166.
3. MR M Cruz, DZ Fitiwi, SF Santos, JPS Catalão (2018) A comprehensive survey of flexibility options for supporting the low-carbon energy future. Renewable and Sustainable Energy Reviews 97: 338-353.
4. CA Ikutegbe, MM Farid (2020) Application of phase change material foam composites in the built environment: A critical review. Renewable and Sustainable Energy Reviews 131: 110008.
5. Shuai Zhang, Daili Feng, Lei Shi, Li Wang, Yingai Jin, et al. (2021) A review of phase change heat transfer in shape-stabilized phase change materials (ss-PCMs) based on porous supports for thermal energy storage. Renewable and Sustainable Energy Reviews 135: 110127.
6. VV Tyagi, K Chopra, RK Sharma, AK Pandey, SK Tyagi, et al. (2022) A comprehensive review on phase change materials for heat storage applications: Development, characterization, thermal and chemical stability. Solar Energy Materials and Solar Cells 234: 111392.
7. Md H Zahir, SA Mohamed, R Saidur, FA Al-Sulaimann (2019) Supercooling of phase-change materials and the techniques used to mitigate the phenomenon. Appl Energy 240: 793-817.
8. X Xiao, P Zhang, M Li (2013) Preparation and thermal characterization of paraffin/metal foam composite phase change material. Appl Energy 112: 1357-1366.
9. Wei Cui, Tianyu Si, Xiangxuan Li, Xinyi Li, Lin Lu, et al. (2022) Heat transfer enhancement of phase change materials embedded with metal foam for thermal energy storage: A review. Renewable and Sustainable Energy Reviews 169: 112912.
10. P Zhang, X Xiao, ZW Ma (2016) A review of the composite

phase change materials: Fabrication, characterization, mathematical modeling and application to performance enhancement. Appl Energy 165: 472-510.
11. R Warzoha, O Sanusi, B McManus, AS Fleischer (2013) Development of Methods to Fully Saturate Carbon Foam with Paraffin Wax Phase Change Material for Energy Storage. J Sol Energy Eng 135: 021006.
12. T ur Rehman, HM Ali, MM Janjua, U Sajjad, WM Yan (2019) A critical review on heat transfer augmentation of phase change materials embedded with porous materials/foams. International Journal of Heat and Mass Transfer 135: 649-673.
13. W Zhao, DM France, W Yu, T Kim, D Singh (2014) Phase change material with graphite foam for applications in high-temperature latent heat storage systems of concentrated solar power plants. Renew Energy 69: 134-146.
14. J Zhao, Y Guo, F Feng, Q Tong, W Qv, et al. (2011) Microstructure and thermal properties of a paraffin/expanded graphite phase-change composite for thermal storage. Renew Energy 36: 1339-1342.
15. A Diani, M Campanale (2019) Transient melting of paraffin waxes embedded in aluminum foams: Experimental results and modelling. International Journal of Thermal Sciences 144: 119-128.
16. A Diani, L Rossetto (2021) Melting of pcms embedded in copper foams: An experimental study. Materials 14: 1-13.
17. M Caliano, N Bianco, G Graditi, L Mongibello (2019) Analysis of a phase change material-based unit and of an aluminum foam/phase change material composite-based unit for cold thermal energy storage by numerical simulation. Appl Energy 256: 113921.
18. R Yang, X Huang, G Zhao, Z Liu, G. Wang (2023) Ni@rGO into nickel foam for composite polyethylene glycol and erythritol phase change materials. Chemical Engineering Journal 451: 138900.
19. J Lopez, Z Acem, E Palomo Del Barrio (2010) KNO3/NaNO3 - Graphite materials for thermal energy storage at high temperature: Part II. - Phase transition properties. Appl Therm Eng 30: 1586-1593.
20. I Chriaa, M Karkri, A Trigui, I Jedidi, M Abdelmouleh, et al. (2021) The performances of expanded graphite on the phase change materials composites for thermal energy storage. Polymer 212: 123128.
21. Jie Yang, Guo Qiang Qi, Yang Liu, Rui-Ying Bao, Zheng Ying Liu, et al. (2016) Hybrid graphene aerogels/phase change material composites: Thermal conductivity, shape-stabilization and light-to-thermal energy storage. Carbon N Y 100: 693-702.
22. L Zhong, X Zhang, Y Luan, G Wang, Y Feng, et al. (2014) Preparation and thermal properties of porous heterogeneous composite phase change materials based on molten salts/expanded graphite. Solar Energy 107: 63-73.
23. K Chen, J Ding, W Wang, J Lu (2023) Shape-stable Bi-Sn-In alloy/Ag/copper foam composite phase change material for thermal storage and management. Chemical Engineering Journal 454: 140087.
24. K Chintakrinda, RD Weinstein, AS Fleischer (2011) A direct comparison of three different material enhancement methods on the transient thermal response of paraffin phase change material exposed to high heat fluxes. International Journal of Thermal Sciences 50: 1639-1647.
25. T Kim, DM France, W Yu, W Zhao, D Singh (2014) Heat transfer analysis of a latent heat thermal energy storage system using graphite foam for concentrated solar power. Solar Energy 103: 438-447.
26. X Huang, Y Lin, G Alva, G Fang (2017) Thermal properties and thermal conductivity enhancement of composite phase change materials using myristyl alcohol/metal foam for solar thermal storage. Solar Energy Materials and Solar Cells 170: 68-76.
27. A Hussain, IH Abidi, CY Tso, KC Chan, Z Luo, et al. (2018) Thermal management of lithium ion batteries using graphene coated nickel foam saturated with phase change materials. International Journal of Thermal Sciences 124: 23-35.
28. A Hussain, CY Tso, CYH Chao (2016) Experimental investigation of a passive thermal management system for high-powered lithium ion batteries using nickel foam-paraffin composite. Energy 115: 209-218.
29. Z Wang, Z Zhang, L Jia, L Yang (2015) Paraffin and paraffin/aluminum foam composite phase change material heat storage experimental study based on thermal management of Li-ion battery. Appl Therm Eng 78: 428-436.
30. S Feng, Y Zhang, M Shi, T Wen, TJ Lu (2015) Unidirectional freezing of phase change materials saturated in open-cell metal foams. Appl Therm Eng 88: 315-321.