Advanced phase change materials applications in thermal management field: A topical review

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Abstract

Due to their high latent heat stowing ability and steady thermal phase change behavior, phase change materials (PCMs) are studied for energy storage materials in the thermal management field. Pure PCMs have innately low thermal conductivity, which is improved by using different techniques, including the use of metal foams, nanoparticles, a mixture of different PCMs, encapsulation of PCM, and the finned structures. These modified PCMs are researched for various applications such as thermal control of electronic devices, thermoelectric generators (TEGs), smart textiles, heat exchangers, building thermal management and solar photovoltaic modules. It is observed that the utilization of PCMs is a promising option for performance enhancement of these applications. The utilization of PCMs have proven to overcome the decrement that was in terms of thermal and electrical effectiveness and indicated better results.

Keywords: Thermal Management, Phase Change Material, Thermoelectric Generator, Finned-Heat Sink, Photovoltaic Module

1. Introduction:

Excessive temperature generation with the advancement of electronic industry, reduces the overall performance and reliability of electronic devices, PV panels and batteries[1,2]. Thermal optimization using phase change materials-based systems have been refined in order to avoid premature failure and maintain reliability of equipment[3,4]. PCMs with high latent heat storage capability and optimal thermal stability and reasonable melting/freezing temperatures have encouraged research in the thermal control applications such as thermal management of electronic devices[5,6], thermoelectric generators[7,8], photovoltaic panels[9–11], buildings air conditioning[12,13], spacecrafts[14,15], and heat exchangers[16,17] as presented in figure 1. Since PCM's low thermal conductivity makes its use difficult, particularly at higher temperatures, researchers are working to improve its thermal conductivity, thermal stability, and thermal energy storage ability by incorporating thermal conductivity enhancers such as plate and pin fins[18] [19], nanoparticles[20][21], porous metal foams[22], and microencapsulation[23]. PCMs are used in various types of heat sinks for thermal behavior characterization and performance improvement of electronic devices[24]. Similarly, PCM's heat-storage properties have allowed it to be used in applications such as thermoelectric generators and PV panels where PCM accumulates thermal energy and improves cooling performance and results in enhanced electricity generation[25,26].Fadl et al. [27] observed the PCM melt fraction, heat absorption, and temperature distribution during the melting of RT-44HC PCM in a horizontal rectangular cavity.Hayat et al. [28] investigated a dual system of cooling integrated with RT-35HC PCM-based heat sink, heat pipe, copper foam and fan at various thermal loads.Prieto et al. [29] using the CFD porosity model analyzed the thermal performance of RT-60 PCM filled heat exchanger with water as heat transfer fluid. Results showed that the higher PCM thickness and vertical model increased the charging and discharging time of PCM.Prasad et al. [30] investigated heat sinks integrated with RT-35HC and RT-44HC PCMs at constant and intermittent thermal loads.

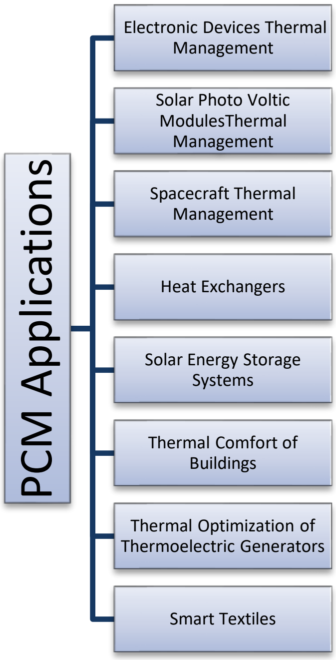

Figure 2. Various Applications of Phase Change Materials

2. Recent studies on advancements in PCMs:

The addition of nanoparticles has substantial effect on enhancement in thermal properties of PCM, a lot of research has been done to analyze thermal behavior of these nano PCMs. In order to improve the efficiency of a solar absorption unit, Singh et al. [31] investigated thermal attributes of a dualistic eutectic graphene nanoplatelets with PCM. Using a regular synthesis procedure, nanoparticles were applied to the pure PCM in amounts ranging from 1% to 5%. As compared to pure PCM, nano PCM's thermal conductivity and specific heat increased by 104% and 80%, respectively. The addition of iron and copper nanoparticles to the hydrated salt PCM was studied by Gupta et al. [32] to determine thermal properties such as melting and freezing rate. In the PCM, nanoparticles were added in 0.5 wt.%. According to findings, the incorporation of copper and iron nanoparticles, the PCM melting rate increased by 5.6% and 7.8%, and the freezing rate increased by 30% and 35%, respectively. The effect of copper metal foam and copper nanoparticles composite on the thermal characteristics of PCM was studied by Senobar et al. [33]. For drawing conclusions, nanoparticles and metal foam together and separately employed. As compared to pure PCM, attained findings showed that combining metal foam with nano PCM increased melting rate and thermal conductivity by 65%, and 24% correspondingly, on stable temperature sources, and on stable heat flux solidification rate by 12%.Sun et al. [34] conducted an experimental study in which coconut shell charcoal and graphite nanoparticles were introduced into a paraffin for thermal evaluation using the melting process. Yan et al.[35] studied the heat load application on mini-channel heat sink made with aluminum oxide/water nanofluid. The findings showed that 10% nanoparticles at 500 Reynolds number reduced thermal resistance by 10.88%. Furthermore, ceiling's microencapsulated PCM in ceiling of heat sink improved thermal control, and PCM melted quicker at lower Reynolds numbers. For thermal energy storage applications, Kant et al. [21] investigated the inclusion of different concentrations of graphene nanoparticles in PCM. It was shown that the nano particles addition improved rate of melting and PCMs thermal conductivity but slowed heat transfer by convection and increased viscosity. Ren [36] studied the pin fin heat sink with micro encapsulated PCM and expanded graphite for thermal control of electronic devices. It was revealed that as compared to simple pin fins heat sink case, expanded graphite composite with micro encapsulated PCM was analyzed to be superior option for longer running times and higher heat loads. Mayilvelnathan and Arasu [37] studied melting/freezing performance of the shell and tube TES system by dispersing 1 wt% graphene nanoparticles in erythritol PCM. At various temperatures and flow speeds, therminol oil was used as heat transfer fluid HTF. Rabady and Malkawi [38] investigated the effect of adding graphite nanoparticles and carbon nano tubes to sodium thiosulfate pentahydrate PCM for thermal conductivity augmentation. It was reported that by adding 7% carbon nano tubes and graphite nanoparticles to PCM increased thermal conductivity by 249.61% and155.33% respectively. Mhiri et al. [39] investigated the graphite nanoparticles enriched paraffin wax (RT60) infused into carbon foam for TES applications. By findings, nano enriched PCM with carbon foam led to 9-fold increase in thermal conductivity and a 42% increase in melting rate as compared to pure paraffin.

Table 1. Summary of various studies on thermal conductivity improvement of PCMs

References	PCM type	Base Media	Type of study	Key findings
[40]	Paraffin wax	square pin fins	Experimental	Operation time enhancement ratio 3 was achieved.
[41]	RT-44HC	Expanded graphite	Experimental	32 times improvement in thermal conductivity.
[42]	RT-35HC	Copper foam	Experimental	11 times reduction in Melting time.
[43]	Paraffin RT-35	Plate fins	Experimental	Operation time enhancement ratio of 3.3 was achieved.
[44]	Paraffin wax, RT-44 and RT-35HC	Triangular pin fins	Experimental	Temperature reduction of 10 °C was obtained.

[45]	Paraffin wax, n-eicosane, RT-54, RT-44, , SP-31 and RT-35HC	Square and rectangular pin fins	Experimental	2.5 enhancement ratio of Operation time and temperature reduction of 8 ^{o}C was detected.
[46]	Paraffin wax, RT-54, RT-44, RT-35HC, SP-31 and n-eicosane	Triangular and circular, rectangular pin fins	Experimental	4 enhancement ratio of Operation time was attained and temperature reduction of 10 ^{o}C was achieved.
[47]	Plastic paraffin	Finned copper slab and PCM silicon, graphite, matrix	Experimental	With fins critical time enhanced by 6.5 times for heat sink.
[48]	Composite PCM (Copper nanoparticles enriched paraffin wax)	Solar collector	Experimental	Thermal conductivity enhanced by 46%.
[39]	Composite PCM (graphite nanoparticles enriched paraffin wax)	Carbon foam	Experimental and Numerical	42% melting rate enhancement by composite PCM infused in carbon foam.
[49]	RT35HC Paraffin	Copper foam and Iron nickel foam	Experimental	7.9 enhancement ratio in operation time by copper foam.

3. PCM use in thermal management of electronic equipment:

Electronic components used in computer or other equipment usually gets heat up due to increased data processing loads and compactness. This increased heat generation is the reason of premature failure and reduced performance of electronic devices. To, solve this issue, extensive studies have been done using PCM based heat sinks with the introduction of nanoparticles and porous metal foams in PCMs[50].Wu et al. [51] prepared composite PCM by paraffin wax with 20% expanded graphite and compared it with aluminum substrate and ribbed radiator for the thermal optimization of electronic devices. Rehman et al. [52] investigated the increase in thermal conductivity of different PCMs in terms of charging and discharging periods using copper foam-based heat sink. PCM volume fractions were defined as 0.68 and 0.83. At 0.8W/m^2, the maximum temperature drop was found to be 25% for RT-35HC-copper foam. For the SPT of 40 ^{o}C and 60 ^{o}C, the maximum enhancement ratios for the RT-35HC and RT-44 with copper foam were 8 and 7.7 respectively. Wang et al. [53] studied the heat sink performance with composite PCM of paraffin and porous copper fibers (figure 3 presented below). Results concluded that the addition of porous copper fiber improved HT at high thermal loads and protected the heat source from sudden high thermal loads. thermal conductivity enhancement was prominent at smaller porosity and longer temperature stability was realized using higher porosity of copper fiber.

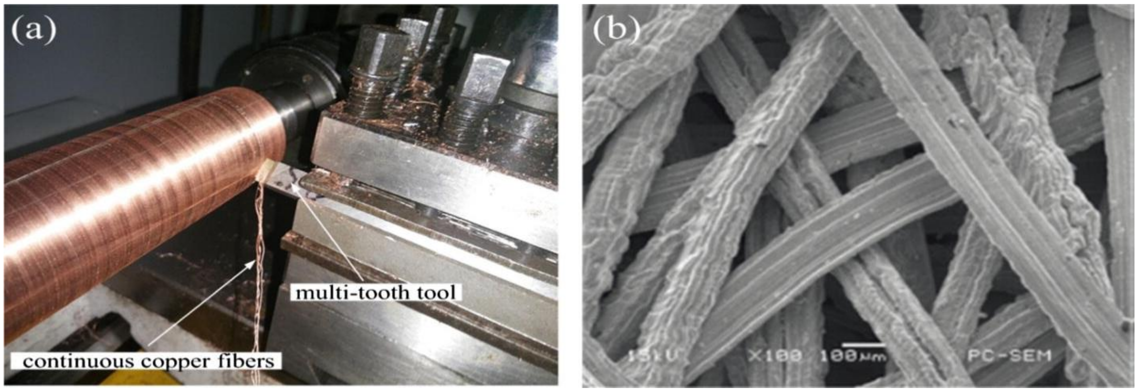

Figure 4. (a) fabrication of copper fibers (b) The SEM image of a porous copper fiber[53].

PT-37 and n-eicosane PCMs were studied for passive cooling of tablet PCs by Ahmed [54]. Experimentations was carried out with PCMs encased in varying sizes of aluminium foil at various heating levels and orientations. Gharbi et al. [47] investigated the thermal properties of PCM-based heat sinks with silicone matrix, graphite matrix, and copper fins for electronic equipment cooling. , according to the findings, heat sink critical time doubled by the use of PCM. Several configurations of PCM embedded in micro-channel heat sinks were numerically investigated by Hasan and Tbena [55]. According to results, the addition of PCM reduced the sink temperature more than without PCM case. The authors concluded that a PCM with a reasonable melting temperature compatible with the application temperature should be used. Pakrouh et al. [56] used numerical simulation and Taguchi method to refine the PCM (RT-44) based pin fin heat sinks. Debich et al. [57] heat sinks numerically studied with and without PCMs. Evaluation was made by varying PCM volume fraction, heat sink geometry, input power ranges, and PCM types. The results showed that n-eicosane performed better in terms of thermal management than other PCMs, and increasing the volume fraction of PCM in the heat sink induced a delay in the latent heating process, thereby improving thermal management efficiency as displayed in figure 5.

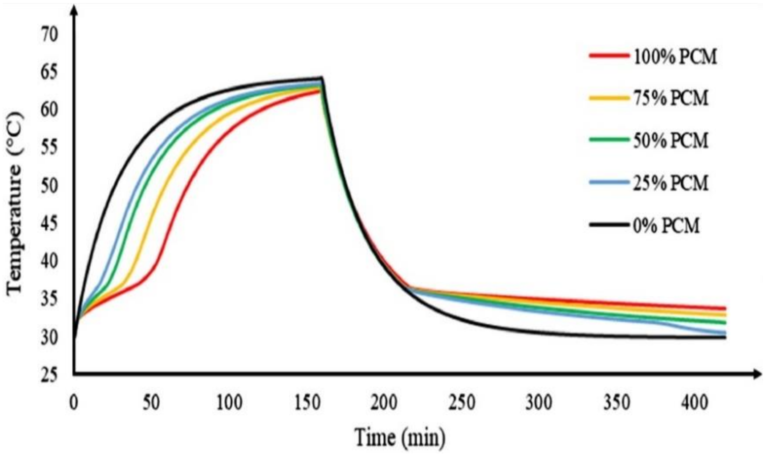

Figure 6. Temperature variations for different volume fraction of three PCMs[57].

4. PCM usage in Thermal Energy Harvesting:

A thermoelectric generator (TEG) is a solid-state system that converts thermal energy to electricity or the other way around. A thermoelectric generator involves a temperature differential on both sides (hot and cold side) to produce electrical energy. PCM and heat sinks have been used in experiments to improve the thermal performance of TEGs[58,59]. Jaworski et al. [60] studied the TEG fixed with PCM filled container with copper fins for radiative heating and passive cooling. Results showed that the PCM stabilized the TEG temperature and assisted in electricity generation during both melting and solidification periods. Author proposed the use of rubber to create the PCM container to prevent leakage of high melting temperature PCMs.The effect of copper nanoparticles in paraffin wax for solar energy harvesting and water heating was experimentally examined by Lin and Al-Kayiem [48]. Thermal conductivity of PCM enhanced by 46% with 2 wt% copper nanoparticles in compared to pure PCM. The addition of copper nanoparticles reduced the supercooling effect improved the thermal stability of PCM. Besides, the introduction of copper nanoparticles in paraffin wax improved the performance of solar collector. Karthick and Suresh [61] investigated solar TEG using d-mannitol PCM and aluminium oxide NPs on the TEG's cold side. TEG efficiency was evaluated using a variety of PCM nanoparticle mixtures (SEM and TEM images shown below in figure 7), heat inputs, and thermosyphon passive and natural convection cooling. Sui et al. [62] tested a concentrated solar TEG with PCM encased in heat exchangers of various geometries. The PCM was found to be useful for thermal control of the TEG's cold end, as the PCM energy storage reduced cold end temperature fluctuations and increased power generating time. Shittu et al. [63] Investigated the intermittent heating load influence on solar TEG numerically using a PCM located at the top of the solar TEG and changing the fin number and PCM height. Selvam et al. [64] studied the thermal and electrical performance of the TEG with the heat sink surrounding the OM32 PCM.

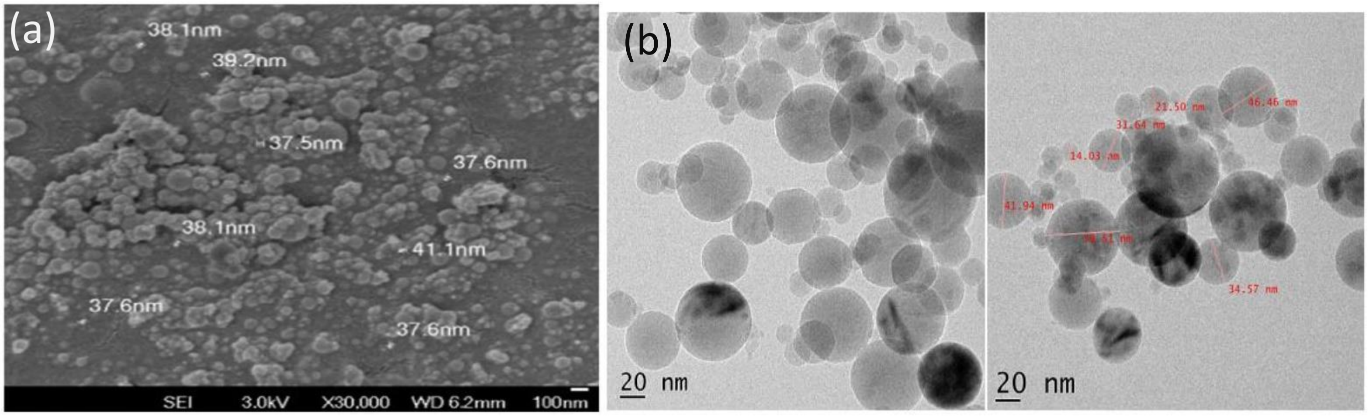

Figure 8. (a) SEM image of Alumina nanoparticle (b) TEM image of Alumina nanoparticles[61].

4. PCM use in Photovoltaic Modules:

Photovoltaic (PV) panels are a viable idea for generating electricity from solar energy, but only 15-20% of solar radiation is converted into electricity. Solar energy heats the PV module, causing complete damage to the panel as a result of the continuous heating. To solve this issue, studies have been done using nanofluids and nano enhanced PCMs[65]. Adibpour et al. [66] investigated the sun tracking PV panels with and without PCM under real outdoor conditions for thermal control and electric power enhancement. During the bright time of day, the maximum and average temperature differences between the PCM-PV panel and the reference PV panel were 16.3 °C and 9.1°C correspondingly. Similarly, as opposed to a reference PV panel, the average and maximal efficiency of PV panels with PCM increased by 4.6% and 6.8% correspondingly. as showed in figure 9.

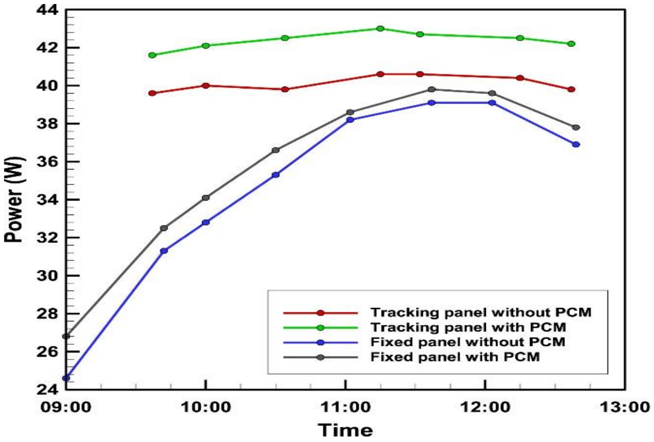

Figure 10. Power profile of fixed and tracking PV panels with and with PCM[66].

With a comparison PV panel, Simón-Allue et al. [67] compared a PCM filled PV panel with glazed and unglazed surfaces, polymeric and aluminum-based heat absorbers. Li et al. [68] tested the efficiency of a traditional PV system and a PCM-PV system with a thermal collector. In comparison to the reference PV system, the PCM-PV system increased the temperature differential and electricity production by 23^{o}C and 5.18%, respectively, as depicted in figure 12. The addition of a PCM to a PV panel increased power generation and allowed the energy stored in the PCM to be used to warm water for domestic use.Using the RT42 PCM and an inclined rectangular box with internal and external fins, Sathe and Dhoble [69] numerically performed the thermal analysis PV panel. The thickness of the PCM sheet and the inclinations of the rectangular boxes were

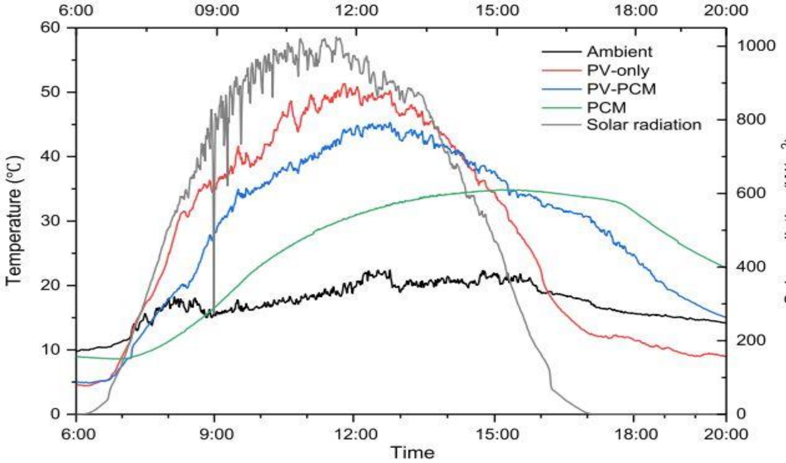

Figure 11. Temperature variations of PV-only, PV-PCM and PCM[68].

changed. Rabie et al. [70] conducted an experimental and theoretical analysis for thermal control of PV systems using PCM. According to results, the inclination angles of 0^{o} and 45^{o}, as well as the increased over height ratio, reported better cooling effect and consistent temperature distribution due to improved natural convection in the PCM cavity.Khanna et al. [71] analyzed the thermal properties of a finned PCM-PV unit for various solar concentration levels.

Conclusion:

PCMs have a broad range of properties that have sparked the interest of researchers in various thermal cooling and storage applications. Following an analysis of recent research on PCMs and improvements, the following key points are summarized:

- The addition of NPs to PCMs improves stability, reduces the tendency for supercooling, and improves thermal conductivity.
- Because of higher latent heat carrying ability, PCMs are used in the thermal regulation of electronic equipment, thermoelectric generators, and photovoltaic panels.
- Passive cooling with finned heat sinks based on PCM has a lot of potential for dealing with high thermal loads and intermittent heat loads. The thermal properties of PCM saturated in metal foams has improved its viability for permanent, intermittent, and shock loads.
- Numerous studies have shown the baseline temperature reduction, enhancement in operation time, improvements in reliability and functionality of electronic devices being achieved by PCM, nano- PCMs and metal foam composites PCMs.
- Thermoelectric generator research has shown that using PCMs, nano enhanced PCMs, and finned heat sinks, enhanced temperature difference of the hot and cold sides of the TEG, better thermal control, uniform temperature distribution, and continuous power production, and higher TEG performance are attained.
- At high temperatures, the overall efficiency of a photovoltaic panel is weakened; however, PV panels with PCM have shown improved electrical and thermal output. Thermal efficiency of PCM-based cooling is more actively enhanced by nanoparticles-based heat transfer fluid addition to the PV panel.

Nomenclature			
Abbreviations			
PCM	Phase Change Material	TM	Thermal Management
NP	Nanoparticles	MF	Metallic foam
TEG	Thermoelectric Generator	HS	Heat sink
HT	Heat Transfer	PV	Photovoltaic
SPT	Set Point Temperature		
TES	Thermal energy storage		
Symbols			
T	Temperature (℃)	P	Power output (W)
V	Voltage (V)	Q	Heat Flux (W/m^2)

References

[1] S.L. Tariq, H.M. Ali, M.A. Akram, M.M. Janjua, Experimental investigation on graphene based nanoparticles enhanced phase change materials (GbNePCMs) for thermal management of electronic equipment, J. Energy Storage. 30 (2020) 101497. https://doi.org/10.1016/j.est.2020.101497.

[2] W. Li, F. Wang, W. Cheng, X. Chen, Q. Zhao, Study of using enhanced heat-transfer flexible phase change material film in thermal management of compact electronic device, Energy Convers. Manag. 210 (2020) 112680. https://doi.org/10.1016/j.enconman.2020.112680.

[3] H.M. Ali, Applications of combined/hybrid use of heat pipe and phase change materials in energy storage and cooling systems: A recent review, J. Energy Storage. 26 (2019) 100986. https://doi.org/10.1016/j.est.2019.100986.

[4] S.A. Atouei, A. Rezania, A.A. Ranjbar, L.A. Rosendahl, Protection and thermal management of thermoelectric generator system using phase change materials: An experimental investigation, Energy. 156 (2018) 311–318. https://doi.org/https://doi.org/10.1016/j.energy.2018.05.109.

[5] S. Motahar, M. Jahangiri, Transient heat transfer analysis of a phase change material heat sink using experimental data and artificial neural network, Appl. Therm. Eng. 167 (2020) 114817. https://doi.org/https://doi.org/10.1016/j.applthermaleng.2019.114817.

[6] A. Ghanbarpour, M.J. Hosseini, A.A. Ranjbar, M. Rahimi, R. Bahrampoury, M. Ghanbarpour, Evaluation of heat sink performance using PCM and vapor chamber/heat pipe, Renew. Energy. 163 (2021) 698–719. https://doi.org/10.1016/j.renene.2020.08.154.

[7] X. Luo, Q. Guo, Z. Tao, Y. Liang, Z. Liu, Modified phase change materials used for thermal management of a novel solar thermoelectric generator, Energy Convers. Manag. 208 (2020) 112459. https://doi.org/10.1016/j.enconman.2019.112459.

[8] Y. Tu, W. Zhu, T. Lu, Y. Deng, A novel thermoelectric harvester based on high-performance phase change material for space application, Appl. Energy. 206 (2017) 1194–1202. https://doi.org/10.1016/j.apenergy.2017.10.030.

[9] H.M. Ali, Recent advancements in PV cooling and efficiency enhancement integrating phase change materials based systems – A comprehensive review, Sol. Energy. 197 (2020) 163–198. https://doi.org/10.1016/j.solener.2019.11.075.

[10] A.R. Abdulmunem, P.M. Samin, H.A. Rahman, H.A. Hussien, I.I. Mazali, Enhancing PV Cell's electrical efficiency using phase change material with copper foam matrix and multi-walled carbon nanotubes as passive cooling method, Renew. Energy. 160 (2020) 663–675. https://doi.org/10.1016/j.renene.2020.07.037.

[11] M.H. Jahangir, S.M.E. Razavi, A. Kasaeian, H. Sarrafha, Comparative study on thermal performance of an air based photovoltaic/thermal system integrated with different

phase change materials, Sol. Energy. 208 (2020) 1078–1090. https://doi.org/10.1016/j.solener.2020.08.056.

[12] D.K. Bhamare, M.K. Rathod, J. Banerjee, Selection of phase change material and establishment of thermophysical properties of phase change material integrated with roof of a building using Measure of Key Response index: Proposal of a new parameter, J. Energy Storage. 32 (2020) 101812. https://doi.org/10.1016/j.est.2020.101812.

[13] B. Pandey, R. Banerjee, A. Sharma, Coupled EnergyPlus and CFD analysis of PCM for thermal management of buildings, Energy Build. (2020) 110598. https://doi.org/10.1016/j.enbuild.2020.110598.

[14] C.R. Raj, S. Suresh, R.R. Bhavsar, V.K. Singh, K.A. Govind, Influence of fin configurations in the heat transfer effectiveness of Solid solid PCM based thermal control module for satellite avionics: Numerical simulations, J. Energy Storage. 29 (2020) 101332. https://doi.org/https://doi.org/10.1016/j.enconman.2018.10.055.

[15] Y. Guo, H. Yang, W. Fu, L. Bai, J. Miao, Temperature control of star sensor baffle using 3D printing and PCM thermal energy storage technology, Int. J. Heat Mass Transf. 165 (2021) 120644. https://doi.org/10.1016/j.ijheatmasstransfer.2020.120644.

[16] S. Pakalka, K. Valančius, G. Streckienė, Experimental comparison of the operation of PCM-based copper heat exchangers with different configurations, Appl. Therm. Eng. 172 (2020) 115138. https://doi.org/10.1016/j.applthermaleng.2020.115138.

[17] X. Chen, X. Li, X. Xia, C. Sun, R. Liu, Thermal storage analysis of a foam-filled PCM heat exchanger subjected to fluctuating flow conditions, Energy. (2020) 119259. https://doi.org/10.1016/j.energy.2020.119259.

[18] S.S. Haghighi, H.R. Goshayeshi, M.R. Safaei, Natural convection heat transfer enhancement in new designs of plate-fin based heat sinks, Int. J. Heat Mass Transf. 125 (2018) 640–647. https://doi.org/10.1016/j.ijheatmasstransfer.2018.04.122.

[19] H.M. Ali, A. Arshad, Experimental investigation of n-eicosane based circular pin-fin heat sinks for passive cooling of electronic devices, Int. J. Heat Mass Transf. 112 (2017) 649–661. https://doi.org/10.1016/j.ijheatmasstransfer.2017.05.004.

[20] S.L. Tariq, H.M. Ali, M.A. Akram, M.M. Janjua, Experimental investigation on graphene based nanoparticles enhanced phase change materials (GbNePCMs) for thermal management of electronic equipment, J. Energy Storage. 30 (2020) 101497. https://doi.org/https://doi.org/10.1016/j.est.2020.101497.

[21] K. Kant, A. Shukla, A. Sharma, P. Henry Biwole, Heat transfer study of phase change materials with graphene nano particle for thermal energy storage, Sol. Energy. 146 (2017) 453–463. https://doi.org/10.1016/j.solener.2017.03.013.

[22] M.M. El Idi, M. Karkri, Heating and cooling conditions effects on the kinetic of phase change of PCM embedded in metal foam, Case Stud. Therm. Eng. 21 (2020) 100716. https://doi.org/https://doi.org/10.1016/j.csite.2020.100716.

[23] C. Liu, P. Du, B. Fang, Z. Li, B. Chen, Z. Rao, Experimental study on a functional microencapsulated phase change material for thermal management, Int. Commun. Heat Mass Transf. 118 (2020) 104876. https://doi.org/10.1016/j.icheatmasstransfer.2020.104876.

[24] A. Arshad, H.M. Ali, W.-M. Yan, A.K. Hussein, M. Ahmadlouydarab, An experimental study of enhanced heat sinks for thermal management using n-eicosane as phase change material, Appl. Therm. Eng. 132 (2018) 52–66. https://doi.org/https://doi.org/10.1016/j.applthermaleng.2017.12.066.

[25] T.T.K. Tuoi, N. Van Toan, T. Ono, Theoretical and experimental investigation of a thermoelectric generator (TEG) integrated with a phase change material (PCM) for harvesting energy from ambient temperature changes, Energy Reports. 6 (2020) 2022–2029. https://doi.org/10.1016/j.egyr.2020.07.023.

[26] F. Rajaee, M.A.V. Rad, A. Kasaeian, O. Mahian, W.-M. Yan, Experimental analysis of a photovoltaic/thermoelectric generator using cobalt oxide nanofluid and phase change material heat sink, Energy Convers. Manag. 212 (2020) 112780. https://doi.org/10.1016/j.enconman.2020.112780.

[27] M. Fadl, P.C. Eames, An experimental investigations of the melting of RT44HC inside a horizontal rectangular test cell subject to uniform wall heat flux, Int. J. Heat Mass Transf. 140 (2019) 731–742. https://doi.org/10.1016/j.ijheatmasstransfer.2019.06.047.

[28] M.A. Hayat, H.M. Ali, M.M. Janjua, W. Pao, C. Li, M. Alizadeh, Phase change material/heat pipe and Copper foam-based heat sinks for thermal management of electronic systems, J. Energy Storage. 32 (2020) 101971. https://doi.org/10.1016/j.est.2020.101971.

[29] M.M. Prieto, I. Suárez, B. González, Analysis of the thermal performance of flat plate PCM heat exchangers for heating systems, Appl. Therm. Eng. 116 (2017) 11–23.

[30] J. Sunku Prasad, R. Anandalakshmi, P. Muthukumar, Numerical investigation on conventional and PCM heat sinks under constant and variable heat flux conditions, Clean Technol. Environ. Policy. 87 (2020) 454–462. https://doi.org/10.1007/s10098-020-01829-8.

[31] R.P. Singh, J.Y. Sze, S.C. Kaushik, D. Rakshit, A. Romagnoli, Thermal performance enhancement of eutectic PCM laden with functionalised graphene nanoplatelets for an efficient solar absorption cooling storage system, J. Energy Storage. (2020) 102092. https://doi.org/10.1016/j.est.2020.102092.

[32] N. Gupta, A. Kumar, S.K. Dhawan, H. Dhasmana, A. Kumar, V. Kumar, A. Verma, V.K. Jain, Metal nanoparticles enhanced thermophysical properties of phase change material for thermal energy storage, Mater. Today Proc. 32 (2020) 463–467. https://doi.org/10.1016/j.matpr.2020.02.164.

[33] H. Senobar, M. Aramesh, B. Shabani, Nanoparticles and metal foams for heat transfer enhancement of phase change materials: A comparative experimental study, J. Energy Storage. 32 (2020) 101911. https://doi.org/10.1016/j.est.2020.101911.

[34] X. Sun, L. Liu, Y. Mo, J. Li, C. Li, Enhanced thermal energy storage of a paraffin-based phase change material (PCM) using nano carbons, Appl. Therm. Eng. 181 (2020) 115992. https://doi.org/10.1016/j.applthermaleng.2020.115992.

[35] W.-M. Yan, C.J. Ho, Y.-T. Tseng, C. Qin, S. Rashidi, Numerical study on convective heat transfer of nanofluid in a minichannel heat sink with micro-encapsulated PCM-cooled ceiling, Int. J. Heat Mass Transf. 153 (2020) 119589. https://doi.org/10.1016/j.ijheatmasstransfer.2020.119589.

[36] Q. Ren, P. Guo, J. Zhu, Thermal management of electronic devices using pin-fin based cascade microencapsulated PCM/expanded graphite composite, Int. J. Heat Mass Transf. 149 (2020) 119199. https://doi.org/10.1016/j.ijheatmasstransfer.2019.119199.

[37] V. Mayilvelnathan, A. Valan Arasu, Experimental investigation on thermal behavior of graphene dispersed erythritol PCM in a shell and helical tube latent energy storage system, Int. J. Therm. Sci. 155 (2020) 106446. https://doi.org/10.1016/j.ijthermalsci.2020.106446.

[38] R.I. Rabady, D.S. Malkawi, Thermal conductivity enhancement of sodium thiosulfate pentahydrate by adding carbon nano-tubes/graphite nano-particles, J. Energy Storage. 27 (2020) 101166. https://doi.org/10.1016/j.est.2019.101166.

[39] H. Mhiri, A. Jemni, H. Sammouda, Numerical and experimental investigations of melting process of composite material (nanoPCM/carbon foam) used for thermal energy storage, J. Energy Storage. 29 (2020) 101167. https://doi.org/10.1016/j.est.2019.101167.

[40] A. Arshad, H.M. Ali, M. Ali, S. Manzoor, Thermal performance of phase change material (PCM) based pin-finned heat sinks for electronics devices: Effect of pin thickness and PCM volume fraction, Appl. Therm. Eng. 112 (2017) 143–155. https://doi.org/10.1016/j.applthermaleng.2016.10.090.

[41] Z. Ling, J. Chen, T. Xu, X. Fang, X. Gao, Z. Zhang, Thermal conductivity of an organic phase change material/expanded graphite composite across the phase change temperature range and a novel thermal conductivity model, Energy Convers. Manag. 102 (2015) 202–208. https://doi.org/10.1016/j.enconman.2014.11.040.

[42] M. Martinelli, F. Bentivoglio, A. Caron-Soupart, R. Couturier, J.-F. Fourmigue, P. Marty, Experimental study of a phase change thermal energy storage with copper foam,

Appl. Therm. Eng. 101 (2016) 247–261. https://doi.org/10.1016/j.applthermaleng.2016.02.095.

[43] M.H. Joneidi, M. Rahimi, R. Pakrouh, R. Bahrampoury, Experimental analysis of Transient melting process in a horizontal cavity with different configurations of fins, Renew. Energy. 145 (2020) 2451–2462. https://doi.org/10.1016/j.renene.2019.07.114.

[44] H. Usman, H.M. Ali, A. Arshad, M.J. Ashraf, S. Khushnood, M.M. Janjua, S.N. Kazi, An experimental study of PCM based finned and un-finned heat sinks for passive cooling of electronics, Heat Mass Transf. 54 (2018) 3587–3598. https://doi.org/10.1007/s00231-018-2389-0.

[45] M.J. Ashraf, H.M. Ali, H. Usman, A. Arshad, Experimental passive electronics cooling: Parametric investigation of pin-fin geometries and efficient phase change materials, Int. J. Heat Mass Transf. 115 (2017) 251–263. https://doi.org/10.1016/j.ijheatmasstransfer.2017.07.114.

[46] H.M. Ali, M.J. Ashraf, A. Giovannelli, M. Irfan, T. Bin Irshad, H.M. Hamid, F. Hassan, A. Arshad, Thermal management of electronics: An experimental analysis of triangular, rectangular and circular pin-fin heat sinks for various PCMs, Int. J. Heat Mass Transf. 123 (2018) 272–284. https://doi.org/10.1016/j.ijheatmasstransfer.2018.02.044.

[47] S. Gharbi, S. Harmand, S. Ben Jabrallah, Experimental comparison between different configurations of PCM based heat sinks for cooling electronic components, Appl. Therm. Eng. 87 (2015) 454–462. https://doi.org/10.1016/j.applthermaleng.2015.05.024.

[48] S.C. Lin, H.H. Al-Kayiem, Evaluation of copper nanoparticles – Paraffin wax compositions for solar thermal energy storage, Sol. Energy. 132 (2016) 267–278. https://doi.org/10.1016/j.solener.2016.03.004.

[49] T.- Rehman, H.M. Ali, Experimental study on the thermal behavior of RT-35HC paraffin within copper and Iron-Nickel open cell foams: Energy storage for thermal management of electronics, Int. J. Heat Mass Transf. 146 (2020) 118852. https://doi.org/10.1016/j.ijheatmasstransfer.2019.118852.

[50] Z. He, Y. Yan, Z. Zhang, Thermal management and temperature uniformity enhancement of electronic devices by micro heat sinks: A review, Energy. 216 (2021) 119223. https://doi.org/10.1016/j.energy.2020.119223.

[51] W. Wu, G. Zhang, X. Ke, X. Yang, Z. Wang, C. Liu, Preparation and thermal conductivity enhancement of composite phase change materials for electronic thermal management, Energy Convers. Manag. 101 (2015) 278–284. https://doi.org/10.1016/j.enconman.2015.05.050.

[52] T.- Rehman, H.M. Ali, A. Saieed, W. Pao, M. Ali, Copper foam/PCMs based heat sinks: An experimental study for electronic cooling systems, Int. J. Heat Mass Transf. 127 (2018) 381–393. https://doi.org/10.1016/j.ijheatmasstransfer.2018.07.120.

[53] H. Wang, F. Wang, Z. Li, Y. Tang, B. Yu, W. Yuan, Experimental investigation on the thermal performance of a heat sink filled with porous metal fiber sintered felt/paraffin composite phase change material, Appl. Energy. 176 (2016) 221–232. https://doi.org/10.1016/j.apenergy.2016.05.050.

[54] T. Ahmed, M. Bhouri, D. Groulx, M.A. White, Passive thermal management of tablet PCs using phase change materials: Continuous operation, Int. J. Therm. Sci. 134 (2018) 101–115. https://doi.org/10.1016/j.ijthermalsci.2018.08.010.

[55] M.I. Hasan, H.L. Tbena, Using of phase change materials to enhance the thermal performance of micro channel heat sink, Eng. Sci. Technol. an Int. J. 21 (2018) 517–526. https://doi.org/10.1016/j.jestch.2018.03.017.

[56] R. Pakrouh, M.J. Hosseini, A.A. Ranjbar, R. Bahrampoury, A numerical method for PCM-based pin fin heat sinks optimization, Energy Convers. Manag. 103 (2015) 542–552.

[57] B. Debich, A. El Hami, A. Yaich, W. Gafsi, L. Walha, M. Haddar, Design optimization of PCM-based finned heat sinks for mechatronic components: A numerical investigation and parametric study, J. Energy Storage. 32 (2020) 101960. https://doi.org/10.1016/j.est.2020.101960.

[58] K. Huang, Y. Yan, G. Wang, B. Li, Improving transient performance of thermoelectric generator by integrating phase change material, Energy. 219 (2021) 119648. https://doi.org/10.1016/j.energy.2020.119648.

[59] Y.-S. Byon, J.-W. Jeong, Phase change material-integrated thermoelectric energy harvesting block as an independent power source for sensors in buildings, Renew. Sustain. Energy Rev. 128 (2020) 109921. https://doi.org/10.1016/j.rser.2020.109921.

[60] M. Jaworski, M. Bednarczyk, M. Czachor, Experimental investigation of thermoelectric generator (TEG) with PCM module, Appl. Therm. Eng. 96 (2016) 527–533. https://doi.org/10.1016/j.applthermaleng.2015.12.005.

[61] K. Karthick, S. Suresh, Effect of adding alumina nanoparticle in D-Mannitol for reversible solar thermoelectric power generation: An experimental study, Sol. Energy Mater. Sol. Cells. 219 (2021) 110781. https://doi.org/10.1016/j.solmat.2020.110781.

[62] X. Sui, W. Li, Y. Zhang, Y. Wu, Theoretical and Experimental Evaluation of a Thermoelectric Generator Using Concentration and Thermal Energy Storage, IEEE Access. 8 (2020) 87820–87828. https://doi.org/10.1109/ACCESS.2020.2993288.

[63] S. Shittu, G. Li, Q. Xuan, X. Xiao, X. Zhao, X. Ma, Y.G. Akhlaghi, Transient and non-uniform heat flux effect on solar thermoelectric generator with phase change material, Appl. Therm. Eng. 173 (2020) 115206. https://doi.org/10.1016/j.applthermaleng.2020.115206.

[64] C. Selvam, S. Manikandan, N.V. Krishna, R. Lamba, S.C. Kaushik, O. Mahian, Enhanced thermal performance of a thermoelectric generator with phase change materials, Int. Commun. Heat Mass Transf. 114 (2020) 104561. https://doi.org/10.1016/j.icheatmasstransfer.2020.104561.

[65] D. Du, J. Darkwa, G. Kokogiannakis, Thermal management systems for Photovoltaics (PV) installations: A critical review, Sol. Energy. 97 (2013) 238–254. https://doi.org/10.1016/j.solener.2013.08.018.

[66] S. Adibpour, A. Raisi, B. Ghasemi, A.R. Sajadi, G. Rosengarten, Experimental investigation of the performance of a sun tracking photovoltaic panel with Phase Change Material, Renew. Energy. 165 (2021) 321–333. https://doi.org/10.1016/j.renene.2020.11.022.

[67] R. Simón-Allué, I. Guedea, R. Villén, G. Brun, Experimental study of Phase Change Material influence on different models of Photovoltaic-Thermal collectors, Sol. Energy. 190 (2019) 1–9. https://doi.org/10.1016/j.solener.2019.08.005.

[68] Z. Li, T. Ma, J. Zhao, A. Song, Y. Cheng, Experimental study and performance analysis on solar photovoltaic panel integrated with phase change material, Energy. 178 (2019) 471–486. https://doi.org/10.1016/j.energy.2019.04.166.

[69] T. Sathe, A.S. Dhoble, Thermal analysis of an inclined heat sink with finned PCM container for solar applications, Int. J. Heat Mass Transf. 144 (2019) 118679. https://doi.org/https://doi.org/10.1016/j.ijheatmasstransfer.2019.118679.

[70] R. Rabie, M. Emam, S. Ookawara, M. Ahmed, Thermal management of concentrator photovoltaic systems using new configurations of phase change material heat sinks, Sol. Energy. 183 (2019) 632–652. https://doi.org/10.1016/j.solener.2019.03.061.

[71] S. Khanna, K.S. Reddy, T.K. Mallick, Optimization of finned solar photovoltaic phase change material (finned pv pcm) system, Int. J. Therm. Sci. 130 (2018) 313–322. https://doi.org/10.1016/j.ijthermalsci.2018.04.033.