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Review

A review of phase change materials (PCMs) in electronic device cooling applications

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ABSTRACT

The portable electronic devices in everyday life have been getting increasingly compact day by day, and with the advancement in wireless technology, they are expected to facilitate multitasking. In this context, efficient heat dissipation to maintain consistent thermal performance has become quite a challenge. Phase change materials (PCMs) have emerged as a viable option to eliminate problems regarding the thermal management of compact electronics. This review looks into the different types of PCMs investigated by researchers so far, especially in the case of cooling compact electronic devices. It also discusses the parameters critical to its efficiency and implementation, encapsulation, etc. The merit of internal fins, nanomaterials, and metal foams as thermal conductivity enhancers along with shortcomings in the current literature have also been noted in this review.

1. Introduction

The compact electronic devices used in everyday life are getting smaller, slicker, and more lightweight in design. This inevitably makes their internal geometry more complex, and assembly strictly limited in volume. Therefore, proper and consistent heat dissipation in these devices is becoming more challenging. In addition, the evolution of wireless technologies has notably increased the bandwidth, capacity, and utility of portable electronic devices, and will continue to do so in the coming future. Thus, while the scope of multi-tasking with compact electronics has expanded, the loads on the processors in these devices have also become highly variable and more likely to experience temporary power surges. Hence, without an appropriate thermal management system in place, temperature rise would result in performance deterioration, critical failure of components [1,2], and discomfort in interaction with the device [3-5]. The criticality of temperature management in electronics may be emphasized by the fact that over 55% of electronic device failures are associated with high temperatures [6,7]. Moreover, the electronic device failure rate may decrease by 4% if the component temperature can be lowered by just 1°C. On the other hand, the failure rate may increase by 100% if the device temperature rises by 10–20°C [8]. To make things worse, factors like noise, maintenance, additional cost, and power consumption [9] make conventional thermal management systems unsuitable for implementation in compact electronics [10,11]. Phase change material (PCM) comes into play for the thermal management of compact mobile electronics on account of being compact, static, and passive [12-14], which helps minimize throttling due to transient loads. Owing to the fact that passive heat sinks do not consume any additional power and have no moving component, PCM-based passive heat sinks have grabbed the attention of researchers as a reliable solution for quite a while now [15]. PCMs have been acknowledged as competent candidates by many researchers to regulate the thermal performance of a wide range of systems [16-18] including thermal protection systems [19-21], energy storage systems [16, 22, 23], and electronic cooling systems [24, 25]. They are substances that can absorb and subsequently release a sufficient amount of energy during phase transition to facilitate effective heating and cooling. Generally, PCMs have relatively high latent heat capacity. Between sensible heat and latent heat, the latter is the more efficient way to store thermal energy since it provides significantly higher energy storage density along with a lower difference in temperature during heat absorption and release [16]. There is a broad variety of PCMs that switches between solid and liquid phases at a wide range of operating temperatures. Such characteristics make them lucrative to implement in a number of applications. Figure 1 illustrates the heat absorption and emission process of a phase change material.

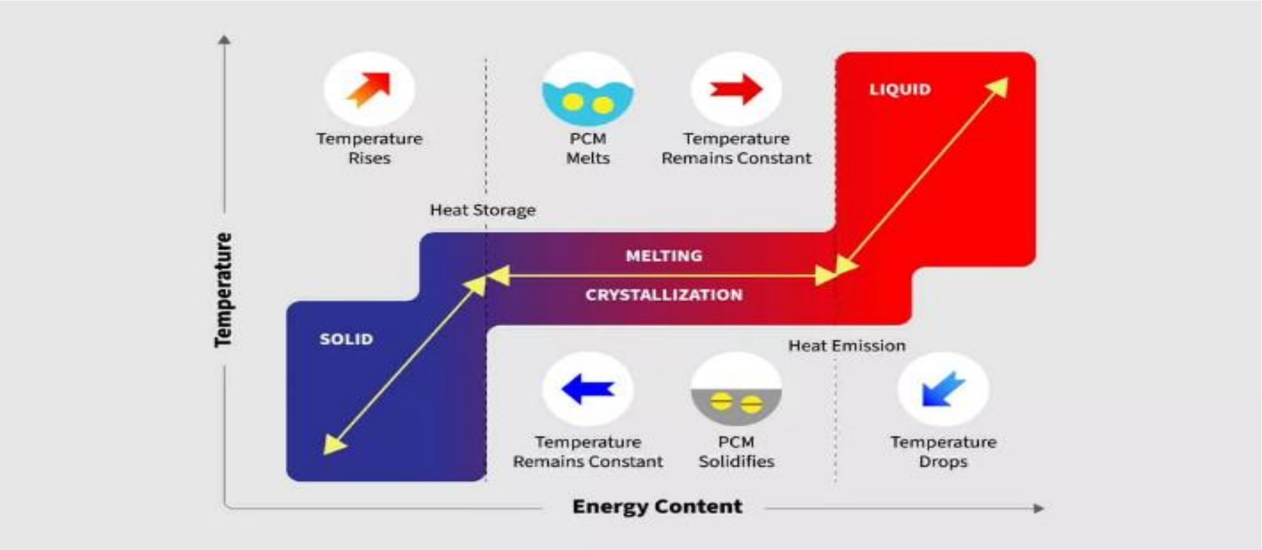

Figure 1. Heat absorption and emission process of a phase change material

In fact, passive cooling systems using PCMs have been dubbed the next-generation electronic cooling system by some researchers [27]. Research showed that PCM-based passive thermal systems could achieve significant improvement in thermal control provided that the temperature control set points and the fluctuation range of the ambient temperature were enveloped by the phase change range of the PCM [28]. Over the past few years, researchers have been extensively investigating phase change heat storage to attain an alternative solution to existing thermal management problems [29-31]. On account of their relatively high latent heat capacity, PCMs have the ability to delay the elevation of temperature and store it for a certain duration, which is called effective thermal control time [32, 33]. This is an indication that the application of PCM can effectively regulate the temperature of electronics within the desired range. Commonly used PCMs, such as – paraffin waxes, are cheap and possess a moderate level of thermal storage density. However, they have low thermal conductivity and consequently require a large surface area for adequate heat transfer. On the other hand, hydrated salts as PCMs can provide larger energy storage density and higher thermal conductivity but they go through supercooling and phase separation during the transition, which means that their application needs to be combined with some appropriate nucleating and thickening agents [16]. Classification of phase change materials is shown in Figure 2.

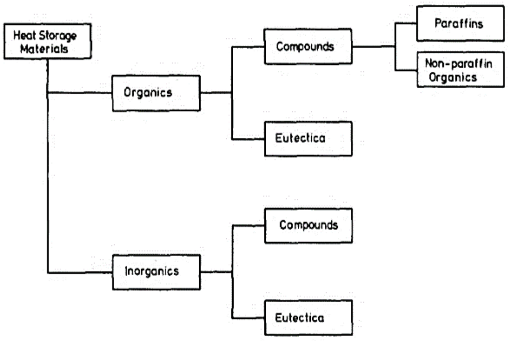

Figure 2. Classification of phase change materials [26]

2. Encapsulation of PCMs

Encapsulation of phase change materials (PCMs) is an essential process that provides several benefits in a thermal management system. For an ideal encapsulated PCM system with satisfactory storage efficiency, the shell layer needs to possess good mechanical property, should protect inner PCM from leakage, and occupy only a small fraction of the system volume. So, the core (PCM) to shell ratio is important in successful encapsulation. Among the advantages of PCM encapsulation are larger heat transfer area, reduced reactivity with the surroundings, and precise volumetric control at the outset of phase transition [16]. More than two hundred materials melting from 10°C to 90°C have been identified by Lane [34, 35], to be potentially used for encapsulation of PCMs. In order to prevent leakage of melted PCMs and simultaneously control the volume fluctuations during the occurrence of phase change, the microencapsulation technique is employed [36, 37]. Such a microencapsulation method called the Pickering emulsion templating method has emerged as a promising method to fabricate microencapsulated phase change materials (microPCMs) [38]. Stabilization of Pickering emulsions by solid particles has been recognized as a more stable and eco-friendly option than conventional emulsions [39, 40]. Not only that, but it has also shown compatibility with a variety of polymeric shell materials. Stabilizers such as– Fe_3O_4 [41], TiC [42], TiO_2 [43], BN [44], SiO_2 nanoparticles [45], have already been used to produce microPCMs. Multiple studies have reported an encapsulation ratio between 62.5% to 72.0% and commented that the emulsification efficiency was limited by the Pickering particle used, to a great extent. Zhang et al. [46] achieved a slightly better encapsulation ratio (78%) and latent heat of 186.8 J/g, using double-walled shells (polystyrene/ graphene oxide). These approaches have brought about several advantages of micro- or nano-encapsulated PCMs, namely, better encapsulation ratio, enhanced thermal conductivity, and improved protection against leakages. Zhu et al. [47] prepared microPCMs composited with silicone rubber, in the shape of a sheet and studied its capability to delay temperature rise against scenarios where processor demands are high, e.g., gaming and multitasking. The internal structure of the PCM/ rubber composites was also observed by them. It was reported that the shell of the microencapsulation remained intact without any visible oil stains, which implies that those microcapsules possess the mechanical strength to survive sheer force and heating at the time of its composition. The analysis of the life cycle of the encapsulated PCMs showed that it could be expected to be the same as that of the service life of the device, meaning it would not be necessary to be replaced during the device's lifetime. For the microencapsulation of organic phase change materials (OPCMs), polymeric nanoparticles have also been utilized. Lignin nanoparticles [48], Cellulose nanocrystals (CNCs) [49] have been employed as Pickering stabilizers to achieve an encapsulation ratio between 81.4% and 83.5%. Moreover, Nanochitin has been proved to be a super-efficient choice for a Pickering stabilizer due to its effectiveness at ultra-low concentrations [50-52], compared with CNCs and lignin. In their investigation, [47, 51] studied the physiochemical properties of regenerated nanochitin (RCh) and the corresponding Pickering emulsions. It was mentioned that usage of RCh also concurs with the sustainability requirement [47]. Encapsulated paraffin wax (PW) in polyurea (PU) shells and used RCh as a stabilizer to prepare microPCMs with high payload and phase transition enthalpy. Morphological analysis, thermal storage capacity, thermal reliability, and stability were subsequently analyzed. In addition, those microPCMs were blended with silicone rubber and attached to the central processing unit (CPU) within a mobile phone, which could potentially avoid any drastic temperature rise during operation. Figure 3 demonstrates a schematic diagram illustrating the preparation and implementation of the RCh/PU microPCMs [47].

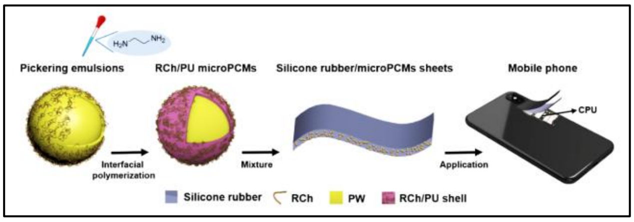

Figure 3. Schematic diagram illustrating the preparation and implementation of the RCh/PU microPCMs [47]

In conclusion, the RCh/PU microPCMs showed significant effectiveness in cooling of compact electronic devices, particularly in case of delaying spike in temperature during heavy loading (>80% CPU utilization), and hence, it possesses massive potential in the passive thermal management of such devices. Tomizawa et al. [53] fabricated a microencapsulated PCM sheet with a thickness between 1.60~2.45 mm to embed in mobile devices. It was claimed that the development of a sufficiently thin PCM sheet or film would successfully solve the problems in phase change thermal management of compact electronics.

3. PCM: Variety, Performance, and Applications

Understandably, researchers have been exploring the application of a wide variety of PCMs to be employed in compact electronic devices. Hydrocarbon like n-eicosane has been used in conjunction with finned heat sinks for thermal control of portable electronic devices [54]. The effect of power levels and orientation have also been studied. An experimental study of multiwall carbon nanotube/paraffin as heat sink revealed that nano-PCM module can enhance thermal control of electronic chipset by reducing the cooling time up to 6.0% [55]. Jieshan He et al. [56] made a composite PCM to conduct battery thermal management and observed that PCM could control the maximum temperature below 48.0 °C. Analytical modeling and optimization of the Li-ion battery pack by Parhizi et al. [57] have revealed that the thermal conductivity of PCMs has a substantial impact on the cell core temperature. A numerical and experimental study by Huang et al. [58] proposed and investigated various flexible form-stable composite PCMs (CPCMs) and embedded them in a Li-ion battery pack. The experimental results showed a temperature drop of 18 °C at a 10 °C discharge rate, which allowed the battery pack to operate safely for a longer duration without exceeding the critical upper-temperature limit. The study found flexible CPCM for low power levels and low ambient temperatures; and another one for high power levels, fluctuating heat fluxes, and high ambient temperatures. Addressing the problem of space limitation, complex irregular internal geometry, and proper contact with internal components, Wanwan et al. [59] managed to develop a flexible PCM (FPCM) of 0.4 mm thickness [60, 61]. Subsequently, the researchers conducted experimental studies on small-type compact electronic devices and confirmed the stability of shape, thermophysical properties, and durability. The developed FPCM film achieved overall thermal conductivity of 1.68 W/m·K and reduced the temperature of the chip by 11°C at 2.5 W operating power. Despite that, the FPCM was unable to provide proper heat flow along the in-plane direction inside the device. Therefore, graphene film with transverse thermal conductivity of 1500 W/m·K was used to increase the heat diffusion area along the in-plane direction. The results showed improvement in heat diffusion along with 32.4% extension in thermal control time at 3.2 W. Figure 4 and Figure 5 demonstrate FPCM film developed by Wanwan et al. [59] and Heat diffusion FPCM film composited with a graphene sheet.

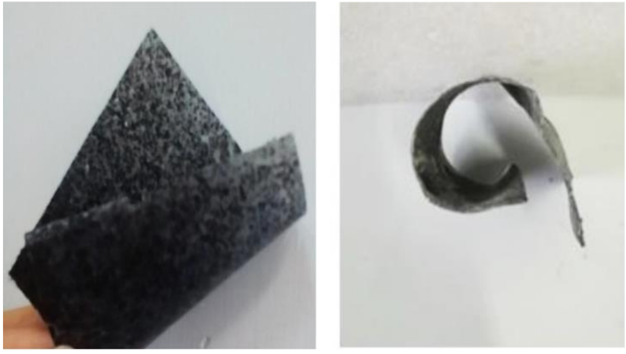

Figure 4. FPCM film developed by Wanwan et al. [59]

Figure 5. Heat diffusion FPCM film composited with graphene sheet [59]

4. Thermal conductivity enhancement

A critical issue that restricts the application of PCMs is the thermal conductivity property. Because of low thermal conductivity, especially in organic PCMs (0.1~0.4 W/m·K), the heat transfer rate within a PCM block remains limited. Thus, the latent heat capacity of PCMs can only be partially utilized. Inability to melt sufficiently during heat absorption causes them to become thermal insulators, which is severely damaging to the heat dissipation of the electronic device [62]. For PCM cooling to become suitable for electronic cooling applications, it is necessary to combine it with materials that would boost its thermal conductivity and consequently result in better heat conduction. Such materials are known as thermal conductivity enhancers (TCEs). As a result, researchers have leaned towards composite PCMs manufactured with TCEs such as internal fins, metallic foams [63], carbon-based matrix [64], nanomaterials, etc. to counteract the challenges with thermal conductivity. To optimize the problem regarding thermal conductivity, researchers have explored thermal conductivity enhancement techniques. In PCM composited with carbon foam support structures, the calculations showed that controlled temperature could drop by 59°C provided that the thermal conductivity of the carbon foam was increased by 50% [65]. The incorporation of inorganic nanoparticles into paraffin wax achieved a maximum 16% increment in its thermal conductivity, with 0.3% added weight [66]. For organic PCMs, the fabrication of the carbon nanotube/Cu-foam hybrid resulted in an enhancement of thermal conductivity of the paraffin matrix by a factor of 3.1 [67]. In high-power Li-ion battery modules, an integrated copper microfibrous–metal cooling tube structure was developed to increase heat transfer [26]. The study found that the battery cell temperature could be much lower than the threshold and the heat transfer could reach about 58.0 W/m·K. Nevertheless, the corresponding volume of the structure was 0.57L, which is considered oversized for compact electronics. In the study of the melting performance of PCMs in a thermal storage system, Xu et al. [68] used porous metallic media in an effort to increase the thermal response of PCMs. The study found silicon carbide to be a suitable practical choice because it has relatively high thermal conductivity, is chemically inert, and inexpensive. Wei & Malen [69] explored the advantages of spatially dependent reinforcements to enhance thermal conductivity on the charge and discharge rates of PCMs. The combination of copper fibers with PCM-based heat sinks also showed massive potential for thermal conductivity enhancement of the PCMs [70]. Usage of PCM boards displayed high thermal storage capacity and improved thermal conductivity, indicating its suitability in electronic cooling applications [71]. Various passive cooling methods were enlisted and evaluated in a review by Sahoo et al. [72].

4.1 Internal fins as TCE

The numerical study by Shatikian et al. [73, 74] revealed the melting characteristics of a PCM-based passive thermal system containing internal fins. The effect of various parameters including different fin dimensions, the thickness of PCM layers, and heat flux was investigated. Another numerical study by Wang et al. [75] explored some key factors affecting the thermal performance of PCM-based multi-fin heat sinks and reported that such heat sinks would be favorable for maintaining stable operational temperature in electronic devices. However, while researchers such as Fok et al. [76] and Kalbasi et al. [77] concur that PCM-based systems with internal fins are potentially pragmatic solutions for electronic device cooling, its proper implementation is still subject to optimizations in terms of the quantity of PCMs, number of fins, power level of the heat source, etc. In order to improve the thermal conductivity of passive thermal management systems, Hafiz et al. [78] used pin-fins in an n-eicosane-based circular heat sink. The study found definitive evidence of positive thermal control performance. Having said that, the optimal thickness was found to be 3 mm, which is still unsuitable for compact electronics. Theoretical and numerical study of Gallium-based PCM heat sink with copper fin structures were conducted to determine the ability of such systems to cope with ultra-high thermal shocks. The findings suggested that copper could be used under ultra-high thermal shock conditions. However, its effectiveness was critically dependent on factors such as the geometric dimension of the fin and the number of fins within the limit [79]. Several investigations focused on the efficiency of pin fins for PCM (paraffin wax, n-eicosane) based heat sinks while varying the fin thickness, volumetric fraction, and heat flux [80- 84]. It has been shown that pin-fins can serve as thermal conductivity enhancers (TCE) at a constant volume fraction [85]; the number of fins and volumetric fraction were crucial in such cases [86]. Moreover, research efforts have been made to determine heat sink matrix performance under different heat inputs. Srikanth et al. [87] conducted a numerical and experimental study to optimize a PCM-based composite pin-fin matrix heat sink in order to extend the thermal operation time during heating and reduce the duration of the discharging cycle. Numerous studies explored the effectiveness of pin-fins as TCE in PCM-based thermal systems and found positive outcomes. Nevertheless, research also showed that the number of fins, PCM quantity, power rating of the heat input [88, 89], the volumetric fraction of fins, and convection [90] were decisive factors in these scenarios, both for constant and sporadic thermal loading. A comparative study of pure PCM, PCM in a graphite matrix, and PCM in silicone matrix in pin-fin heat sinks discovered that the graphite matrix packed with PCM dominates over other patterns [91]. Hafiz et al. [92] assessed the effects of various parameters on the passive cooling of electronic devices. The study was conducted within a power level of 5W to 8W, with three different pin-fin configurations (circular, rectangular, and triangular cross-sections) and six different phase change materials (paraffin wax, RT-54, RT-44, RT-35HC, SP-31, and n-eicosane); at a constant volumetric fraction of both pin-fins (9.0%) and PCMs (90.0%). The outcomes suggested that pin-fins with triangular cross-sections were dominant over others, followed by rectangular and circular ones, respectively. Heat sinks with different pin-fin configurations have been shown in Figure 6.

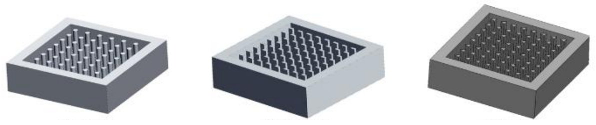
(a)Circular pin-fins (b)Rectangular pin-fins (c)Triangular pin-fins

Figure 6. Heat sinks with different pin-fin configurations [92]

It may be noted that although PCM with pin fins results in better performance, about 70% of the studies have used plate fins simply because of the ease of manufacturing. Also, 57% of internal fin-related studies used eicosane as the phase change material [72]. As discussed above, a considerable number of research have been conducted on phase change material-based thermal systems. There are findings that can potentially provide a better performance, for example, the development of thin PCM sheets. But the current progress is yet to match the high degree of compactness and equally complicated internal geometry of the compact devices so that they would be assembled perfectly with other internal parts.

4.2 Nanomaterials as TCE

Metallic fins do improve the thermal performance of the passive cooling systems, but they also add to the weight of the system while reducing the volume of PCM. Understandably, it somewhat negates its beneficial effect. Highly conductive nanoparticles added at a small volume fraction may work as an excellent thermal conductivity enhancer (TCE) and be a great contender for electronic device cooling applications. Composite PCMs with different nanoparticles at varied mass concentrations have been assessed in many studies. Dispersion of copper oxide nanoparticles at different mass loading showed that there is a linear relationship between the thermal conductivity and mass loading of nanoparticles [93]. Similarly, composite PCMs made with nano-graphite (NG)/ paraffin demonstrated a gradual increase in thermal conductivity along with the NG content [94]. It has been found that for a fixed power level, the base temperature of the device decreases when the nanoparticle loading is increased. However, for higher power levels, the effect of nanoparticle loading becomes immaterial. In addition, more nanoparticle also means reduced melting duration due to lower volume of the PCM. Nonetheless, these observations may vary depending on the size, shape, and type of PCMs. Hence, the current research findings are still not sufficient to draw any conclusive remark regarding the performance and applicability of nano-enhanced PCMs. More thorough research is essential to establish relationships between base temperature, melting period, power level, particle loading level, etc. [72].

4.3 Metal foams as TCE

The applicability of metallic foams with PCMs has grabbed the attention of researchers in recent years mainly due to significantly better thermal conductivity and lightweight. Combining the ability of PCM to store thermal energy with the ability of metal foams to transport heat away from the electronic chips and distribute it uniformly throughout the PCM has become the key objective to them. With internal fins, despite the improvement in thermal performance, non-uniform heat transfer and the added weight of the fins are still an issue. With nanoparticles, there are issues with particle loading at higher power levels, and PCM–nanoparticle compatibility is also a problem in many cases. Metal foam composite PCMs can circumvent these issues and still provide desired results. In comparison with conventional PCMs (paraffin, acid, and hydrous salt), most alloys provide certain advantages such as relatively high thermal conductivity, lower volume expansion, higher volume latent heat and accurate phase change temperature, etc [95]. Tian and Zhao [96] numerically investigated the implementation of metallic foams with PCMs and their effect on heat transfer enhancement in the system. Their study stated that for a variety of metal foam samples, the heat transfer rate can be further improved by using metal foams with relatively small porosities and larger pore densities. Porosity, pore density, interstitial heat transfer, and thermal conductivity dictate the suitability of metal foams composited with PCMs. The use of metal foams reduces the time lag of the response from the PCM which in turn provides better resistance to overheating of the device. Experimental studies on paraffin/ expanded graphite (EG) composites with a variable mass fraction of EG revealed that EG composites at a 10% mass fraction could potentially be the most promising option for passive thermal storage systems [97]. Other studies revealed that the addition of EG had no effect on the thermal properties of the paraffin/EG composite PCM while the charging duration for the composite was shorter compared with pure paraffin PCM [98]. Wang et al. [99] conducted an experimental study to obtain enhanced heat transfer performance at different power levels by fabricating a composite PCM embedded in a porous metal matrix. It has been suggested to include low melting point liquid metals as a new category of PCM. Regarding this, a cooling system with gallium-PCM is said to be a feasible choice in such systems [100, 101]. Embedding PCM in carbon foam to achieve enhanced heat transfer has been stated as the most promising enhancement technique by some authors [102]. Fabrication and testing of a low melting point alloy (LMPA) by Zhao et al. [95] showed comparative performance of the prepared PCM with traditional organic PCM (paraffin, RT-60). The comparison showed up to 50 times better thermal conductivity in LMPA as well as 2.11 times higher thermal energy storage capacity per unit volume. Its performance held up, particularly at lower heat flux (3000–5000 Wm-2), but not so much at higher heat flux (~7000 Wm-2), possibly due to heat leakage at higher flux. To remedy that, the researchers added Poco foam to the LMPA and reported satisfactory performance even at higher heat flux. About two-third of the studies with metal foams have used eicosane as the PCM. Also, two-third of the metal foams were made of aluminum while the rest were made of copper [72]. Copper foam as a thermal conductivity enhancer has shown to make internal heat transfer in paraffin PCMs more uniform and reduce the heat storage duration of paraffin wax [103]. It should be noted that although copper and carbon foam have been used as foam materials, a comprehensive study regarding its corrosion behavior is required before its stable application.

5. Conclusion

Since electronic and wireless technology have been focused on becoming increasingly compact, portable, and capable of multitasking, the challenge of dissipating excess heat due to additional power consumption is only getting more critical day by day. Due to its high latent heat capacity, phase change materials have emerged as a promising solution in establishing an efficient passive thermal cooling system. The main points of focus have been to regulate temperature of electronic devices such that it concurs with the phase change range of PCMs and to extend the effective thermal control time for consistent heat dissipation. A variety of PCMs by themselves and along with incorporating other organic and inorganic materials have been evaluated and found promising results. Moreover, the encapsulation process, which determines the efficiency and longevity of PCMs, has also been discussed. As volumetric restrictions and complex internal geometry have limited the application of PCM-based systems, some studies devoted to developing flexible PCM sheet/ film have been discussed above. The addition of composite materials such as- graphene matrix seemed to enhance thermal performance in flexible PCM sheets. Finally, approaches towards the enhancement of thermal conductivity via three different approaches (internal fins, nanoparticles, and metal foams) have been discussed. It is evident that phase change materials in electronic device cooling have been the center of attention in numerous analytical and experimental studies. That said, more exhaustive research is still required to understand and establish a correlation between its influencing factors, to investigate pure and hybrid PCMs under realistic loading conditions i.e., transient intermittent loading and higher heat flux conditions, and also to obtain a better understanding of the materials, their properties, and interaction with the thermal system and its surroundings.

Ethical issue

The author is aware of and complies with best practices in publication ethics, specifically with regard to authorship (avoidance of guest authorship), dual submission, manipulation of figures, competing interests, and compliance with policies on research ethics. The author adheres to publication requirements that the submitted work is original and has not been published elsewhere.

Data availability statement

Data sharing is not applicable to this article as no datasets were generated or analyzed during the current study.

Conflict of interest

The author declares no potential conflict of interest.

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