


REVIEWS

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# A comprehensive review on thermal management of electronic devices

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## Abstract

In the field of electronics thermal management (TM), there has already been a lot of work done to create cooling options that guarantee steady-state performance. However, electronic devices (EDs) are progressively utilized in applications that involve time-varying workloads. Therefore, the TM systems could dissipate the heat generated by EDs; however, there seemed to be a necessity for a design that would contain temperature rise within an acceptable range for limiting hot spots and managing thermal transients induced by higher-frequency operating cycles. Heat dissipation issues become more significant when miniaturization in electronics increases. More effective TM often results in enhanced reliability as well as a longer life expectancy for devices. Hence, this paper explicates the TM of EDs, the comparison of cooling methods, the comparison of convections for TM on EDs, the heat source (HS) mounted on the substrate board, and optimization techniques to optimize the size and position of HSs mounted on the substrate board. This paper also analyzes the TM technologies on different EDs from 2014 to 2023 and the comparison of the thermal conductance of EDs with two types of phase change materials (PCMs) and pin-fin heat pipes (HPs).

**Keywords:** Thermal management, Electronic devices, Cooling methods, Heat sources, Optimization methods

## Introduction

In the last decades, more interesting advancements have been made in the field of electronic devices (EDs), and they will lead to a revolution in people's lives in the future [1]. Since electronics have become more integrated with daily lives, there is an increasing demand for transience—the ability for technology to interact with nature without leaving a permanent mark [2]. EDs are small devices or a group of small devices designed to control the flow of electric current for their use in various applications. The purpose of electronic components comprises motion control and information processing [3]. In particular, the physical entities that influence electrons when connected to an electrical circuit are named EDs [4]. In recent years, the EDs' working performance has been growing along with mounting amalgamation levels of components. Poor heat dissipation leads to continuing heat accumulation as well as raised temperatures, which are deleterious to the EDs' efficacy and reliability. Therefore, an effective thermal management (TM) system is vital to electronics [5]. Excess heat will be generated by EDs and circuits. TM

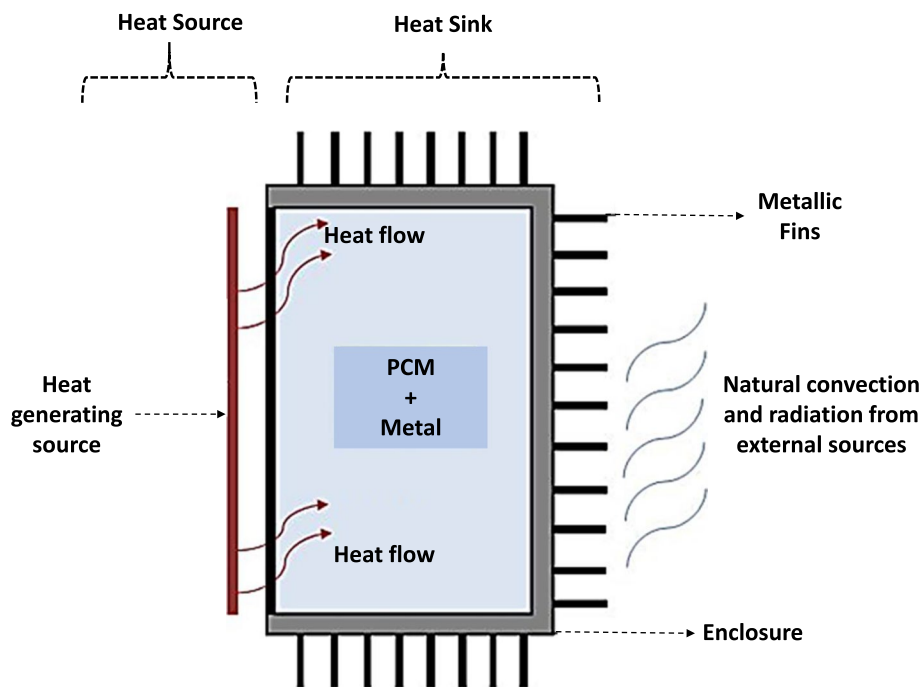
systems are required for EDs to ensure the full safety of EDs as well as circuits [6]. The key part of TM is the material that makes up the vital electronic components. In the TM of electronic components, their temperature should be retained below their respective permissible maximal temperature all the time throughout normal operating hours [7]. For instance, TM in an ED segment through a fixed PCM module is elucidated in Fig. 1.

Designing a cost-efficient TM system with higher safety and reliability for power electronics under the hood is crucial [8]. In the meantime, by providing effective TM for the modules, the temperature necessities and the electronic module’s total cost could be reduced [9]. Some benefits of TM on electric vehicles are as follows [10]:

- Thermal simulations allow engineers to design the cooling system.
- Optimize the design for the reasons of decreasing power consumption, weight, size, reliability, and cost.
- Verifying the thermal design to ensure there are no issues when the equipment is built.

There are mainly four electronics-based sectors: automotive, consumer electronics, computers, and telecommunications. Among the four electronic devices, automotive electronics had the largest market size of million dollars in most years. Figure 2 explicates the graphical representation of TM technologies on different EDs from 2014 to 2023. The predicted use of EDs will have having gradually increasing pattern.

The phase change materials (PCM) are receiving enormous attention for the cooling of the electronics due to their high value of both heat capacity and latent heat of fusion leading to improved thermal energy storage. The PCM is in solid form at the initial stage, then



**Fig. 1** Thermal management in an electronic device segment through a fixed PCM module

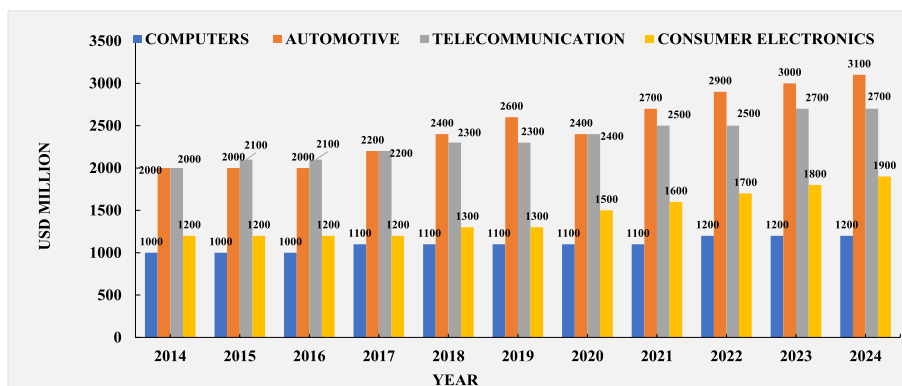


Fig. 2 Graphical representation of thermal management technologies on different electronic devices from 2014 to 2024

starts melting and becomes liquid with the increase in temperature of the electronic components. The PCM again changes its phase from liquid to solid after the removal of heat from the components and a drop in their temperature. This feature of phase interchangeability and reversibility without getting vaporized is an important characteristic of PCM. Hence, the use of PCM is gaining interest in the domain of electronic cooling, battery thermal management, building cooling, solar power generation systems, etc. [11, 12].

Several phase change materials (PCMs) are available in the market having a wide range of thermal conductivity, latent heat, heat capacity, and melting temperature. The classification of the PCMs (Fig. 3) depends on their melting temperature and ease of application. The different types of PCM include paraffin wax, non-paraffin organics, hydrated salts, and metals. Paraffin wax is the preferred candidate for electronic applications due to its properties like high latent heat value, a wide range of melting points, non-corrosive, chemically inert, and negligible volumetric change during the phase change. Hydrated salts are generally used for large energy storage applications, as they are much cheaper; however, the component design using the hydrated salts must take into account the effect of corrosion; hence, a limited number of cycles are available for the same. During the melting of the PCMs, the sensible heat causes the initial temperature rise of the

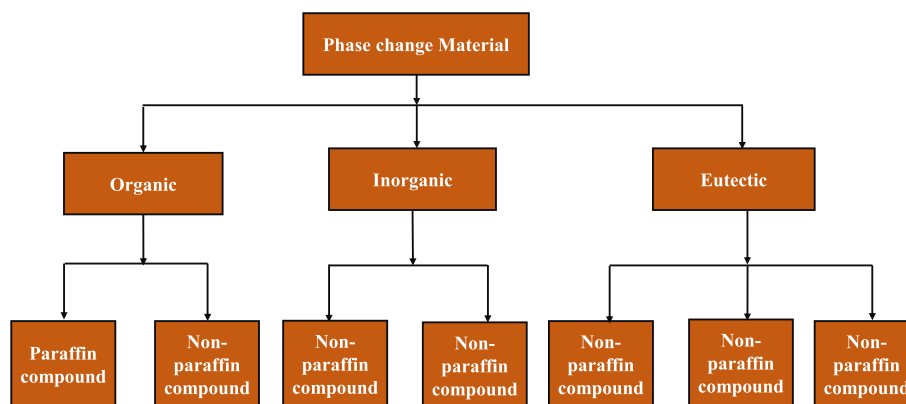


Fig. 3 Different categories of phase change materials

PCMs; the energy is then stored in the form of latent heat after reaching the PCM melting point temperature. The total of the sensible heat and latent heat leads to the total energy stored in the PCMs. Hence, the PCMs is extensively used for electronic cooling applications, as it stores the thermal energy apart from cooling the system. Figure 4 shows the contribution of various environmental factors to electronic device failure.

Environmental elements like temperature, vibration, humidity, and dust are among the many causes of electrical equipment failure. According to studies, temperature causes over 55% of failures in electrical devices, which is the biggest percentage contributor. The second most important issue, vibration, accounts for about 45% of failures, followed by humidity (19%) and dust (8%), respectively. In order to ensure the reliability and increase the lifespan of electronic equipment, it is essential to take these environmental elements into account while developing and using them.

Developments in the electronics industry have resulted in an augmented requirement for innovative TM technologies for enhancing system performance and reliability by eliminating the higher heat flux produced in EDs [11]. However, there were some problems in the TM of EDs, like reduced form factors, enhanced consumer demands, and reaching stringent standards and needs [12].

The structure of the present work is as follows: Introduction section contains the introduction; Thermal management techniques section is TM of EDs, cooling methods, various heat sources on the substrate board, and explanation of different optimization techniques to fix the size and position of HS mounted on the substrate board. The future scope for further research is reported.

### Thermal management techniques

Thermal management techniques for electronic devices are crucial to prevent overheating, extend the lifespan of components, and ensure reliable performance. This section briefly overviews various thermal management techniques and methods for various electronic devices.

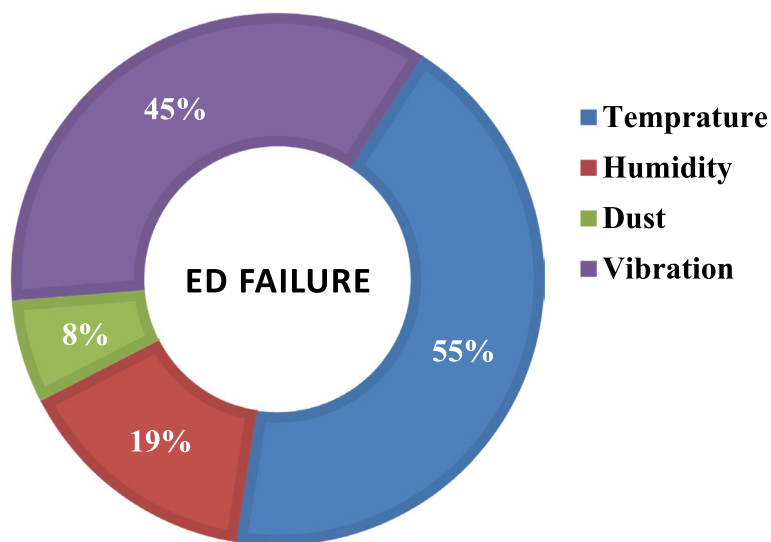


Fig. 4 Various factors affecting electronic failures

### Thermal management of electronic devices

TM has the capability of controlling the system's temperature and noise level by employing technology grounded in thermodynamics and heat transfer (HT) [13]. Intelligent thermal designs could be utilized by engineers to prevent heat-related failures, increasing the system's life expectancy, and reducing energy consumption, time-to-market, and emitted noise, along with cost [14]. In this connection, much effort has been put into the field of electronics thermal management. Adeel et al. [15] explained the TM of EDs with PCM-filled pin-fin heat sinks (PFHSs). Point temperatures were set at 45 °C and 65 °C for evaluating the thermal performance concerning various parameters. The comparison results revealed that the heat sink base temperature for the 3 mm diameter of the PFHS was superior to the 2 mm<sup>2</sup> PFHS. However, the main limitations of TM are its maintenance costs and time.

Qinlong et al. [16] elucidated the TM of EDs utilizing the pin-fin-centered cascade micro-encapsulated (ME) phase change material (PCM)/expanded graphite (EG) composite. As per the analysis, the heat absorption was enriched by the cascade MEPCM-EG composite via the solid-liquid stage change in the heat sink's top half area. However, the MEPCM's melting speed was uneven, thus inhibiting the latent heat's effective use to control the temperature rise. Arshad et al. [17] examined the PCM-centric round PFHSs for the TM of electronics with the pin-fin diameter effect. Analysis displayed that higher numbers of enhancement ratios were attained for critical SPTs of 60 °C and 70 °C in 3 mm pin diameter PFHS when analogized with 2 mm and 4 mm round PFHS.

In another study, Tauseef et al. [18] reported the energy storage of TM in electronics with RT-35HC paraffin. The results depicted that the highest base temperature decrease of 22% for PCM volume fraction 0.8 was shown by the copper foam-centric sink. The copper foam with 97% porosity was contrasted with other copper foams with low porosity (95%). For HT enhancement, metallic foams coated with graphene-like materials were analyzed only partially.

Jun et al. [19] described the TM of EDs with melamine foam-supported, form-stable PCMs. The analysis revealed that outstanding cyclic shape memory properties and thermal stability were exhibited by the MF-PW20 PCM. This excellent property supports the growth of devices. However, potential applications in the TM of devices were within limited space.

Muhammad et al. [20] scrutinized the PCM, HP, and copper foam-centric heat sinks for the TM of EDs. Experimental results showed that the maximum temperature reduction was attained at 47%, 51%, and 54% at heat fluxes of 2, 2.5, and 3 kW, respectively, for the hybrid cooling. The hybrid system with active as well as passive cooling was not assessed for enhancing the heat sink arrangement.

Enhance reliability, and prevent EDs, the higher heat generation has adverse impacts on the user's health along with reliability as well as performance, which creates the requirement for TM in all electronic products [21]. TM products reduce the heat produced by the regular operation of electronics, to enhance their reliability and prevent premature failure [22]. The work of TM on the list of different EDs with its findings and limitations is depicted in Table 1.

Thermal management is also important for wearable devices. Users experience discomfort due to the temperature 45 °C if the temperature of the wearable device reaches

**Table 1** Analysis of thermal management on distinct electronic devices

Ref.	Electronic Device	Outcome	Limitation
Benjamin et al. [23]	Tablet computer	The latent heat thermal energy storage (LHTES) module displayed that the comfort limit was reached on the front surface after 19.2 min, hence, the LHTES enhanced the safer operating time by 30%.	Outcomes were not transferable to all situations.
Tousif et al. [24]	Tablet computer	Analysis showed that the CM-centric thermal energy storage (TES) unit's employment was proved and confirmed as the best option for TM of tablet PCs.	The results presented were limited to PT-37-centric TES units.
Lun et al. [25]	Air conditioning	As per the analysis, prototype A2 provided 15.5 W cooling power, which was adequate for maintaining indoor occupants at a thermal neutral sensation when the indoor temperature set-point was augmented to 26.1 C.	Only fewer than young Asian male participants were tested for every single prototype in every single condition.
Ziya et al. [26]	Wearables	Results specified that dip-coating with the AgNW (silver nanowires) dispersion 3 times had led to the optimal loading amount of Ag NWs	Preparation approaches were limited.
Revna et al. [27]	Liquid crystal display (LCD) TV	Results depicted that the applied power supply with 10 mm height has a 34% higher power density concerning its counterpart having 13.5 mm in height.	The power card design for LCD was limited.

45 °C. In this connection, Raihana et al. [28] explained the TM of wearables along with implantable healthcare EDs. Here, the significance of internal as well as external functional properties in TM, together with their impacts on device performance, was applied. The analysis demonstrated long operation times along with better overall performance at safer operating temperatures. Here, the limitations were modeling characteristics, unstandardized reporting, inadequate validation procedures, and undefined parameters.

Maher et al. [29] elucidated the experimental and computational fluid dynamics (CFD) study on the dynamic TM in smartphones utilizing graphene-nanosheet coating as an efficient cooling technique. Three-dimensional CFD simulations were developed. As per the outcomes, the maximum temperature of an iPhone with a plastic cover was about 3 °C above the case of an iPhone without any cover. Owing to the limited power given to TM, some EDs could not receive full support.

#### Cooling methods for thermal management of electronic devices

Numerous cooling techniques were suggested from the angles of both the material and the structure's design. Generally, TM is classified as active and passive cooling mechanisms. Active cooling mechanisms offer high cooling capacity. For a module with spatial limitations, the passive cooling system is more practical when analogized with

active cooling [30]. However, for the TM of EDs, there are different cooling techniques available [31].

Sharma et al. [32] described the nano-enhanced PCM for TM of building-integrated concentrated photovoltaics (BICPV). The outcomes exhibited that, when contrasted with utilizing the micro-fins only, the average temperature at the center of the model was cooled down by  $10.7^{\circ}\text{C}$  utilizing micro-fins with PCM and  $12.5^{\circ}\text{C}$  utilizing micro-fins with n-PCM. Even though there was broad knowledge presented on the macro-scaled fin, research on micro-fins remains inadequate.

Xiaohui et al. [33] investigated the TM of a higher-power LED on a TEC. As per the analysis, the  $T_s$  was lowest when the TEC worked at its rated power; also, the  $T_s$  was lower in contrast to  $T_a$  at  $55^{\circ}\text{C}$ . It was found that the outcomes attained were higher with the higher ambient temperature of LED. Hafiz et al. [34] elucidated the study for various PCMs in the TM of electronics. Outcomes suggested that triangular pin-fins were the most efficient pin-fin configuration for HT, both with and without PCM. The heat sink did not enhance the system's performance in terms of electronics. Table 2 shows the various studies that have been done using distinct cooling techniques for the thermal management of electronic devices.

Karimi et al. [42] examined various cooling techniques to maintain the ideal operating temperature while analyzing the thermal problems related to electric car battery packs.

**Table 2** Comparison of cooling methods for thermal management

Ref.	Cooling methods	Findings	Limitations
Chuanwei et al. [35]	HP and thermoelectric cooler (TEC)	The amalgamation of HP and TEC displayed that the battery's surface temperature was reduced.	To obtain the optimum performance, design guidance is necessary.
Weixiong et al. [36]	Heat pip-assisted PCM	The efficiency obtained after increasing velocity was undesirable when the higher temperature endures diminishing at a low rate.	TM with energy allocation was still essential in the integrated thermal system.
Jiaqiang et al. [37]	Liquid cooling	The number of pipes is efficient for cooling the plate.	An intelligent battery thermal system's growth was less realistic.
Lie et al. [38]	Liquid cooling	The location of the inlet and outlet and flow direction have a superior effect on cell temperature distribution.	Pump energy consumption was not reduced as expected.
Nandy et al. [39]	Electric motor	The minimum value was attained at $0.28^{\circ}\text{C/W}$ at the heat load of 150 W.	HP's usage on the motor housing's outer surface was inefficient.
Yongxin et al. [40]	Liquid cooling	Numerical analysis stamped that the maximum temperature $T_{max}$ and change in temperature $\Delta T$ reduced as $\alpha$ increased. Higher alpha enhances the HT between the battery cell and the heat conduction region.	The liquid-cooled system's guidelines for lightweight design were not mentioned properly.
Amin et al. [41]	Heat sink	PCM increases the system usage time and the time was increased further under passive cooling conditions.	Performance could be better if active and passive cooling is preferred.



They discovered that a distributed forced convection cooling strategy is an effective and economical way to maintain constant temperatures and voltage distributions inside the battery pack at a range of discharge rates. They concluded that choosing the right cooling system and battery configuration is essential for preserving battery performance and life cycle after examining the impact of cooling conditions and pack configuration on battery temperature. Synthetic jet actuation for cooling electronics equipment is discussed by [43], and has benefits such as small size, low power consumption, simplicity of use, and low cost. They look at several actuation techniques and assess how well they work using actuation and geometric parameters, flow properties, and jet formation criteria. The authors also outline research gaps and difficulties in the application of synthetic jet cooling for electronics thermal management. They also suggest an empirical correlation for forecasting Nu numbers.

A heat transfer improvement technique for electronic cooling based on micro-scale impinging jet arrays with microstructure heat sinks is examined by [34]. They discuss the effect of generated crossflow on pressure drop and compare the cooling performance of the micro-impinging jet array to traditional large-scale jet impingement cooling. The mechanisms by which various types of microstructure heat sinks affect the rate of heat transfer and pressure drop for the micro-impinging jet array are empirically analyzed and discussed by the authors. They conclude that combining the micro-impinging jet array with a micro-structured surface is the only practical way to effectively remove high chip heat fluxes while maintaining an acceptable pressure drop.

Thermal regulation in electronic components is to keep temperatures constant below the manufacturer's maximum specified service temperature because even a 10 °C rise in temperature can cause a 50% drop in system reliability. Multichip modules have been designed with a variety of heat-removal techniques, such as air-cooling systems, direct cooling, and tiny thermosyphons. The authors summarize analytical, numerical, and experimental work in the past decade to enhance existing schemes and establish new ones for thermal regulation of semiconductor devices, modules, and overall systems [34, 44].

Nowadays, research is being conducted based on AI-driven thermal management for electronic devices, which is a cutting-edge approach that leverages artificial intelligence (AI) and machine learning (ML) algorithms to optimize and control the thermal performance of electronic components. This technology is especially crucial as electronic devices become more powerful and compact, generating increased heat that can negatively impact performance, reliability, and longevity. Artificial driven (AI) thermal management AI algorithms may be used to monitor temperature sensors and adjust cooling solutions in real time. For example, gaming laptops and high-end desktops may use AI to optimize cooling based on the demands of the running applications.

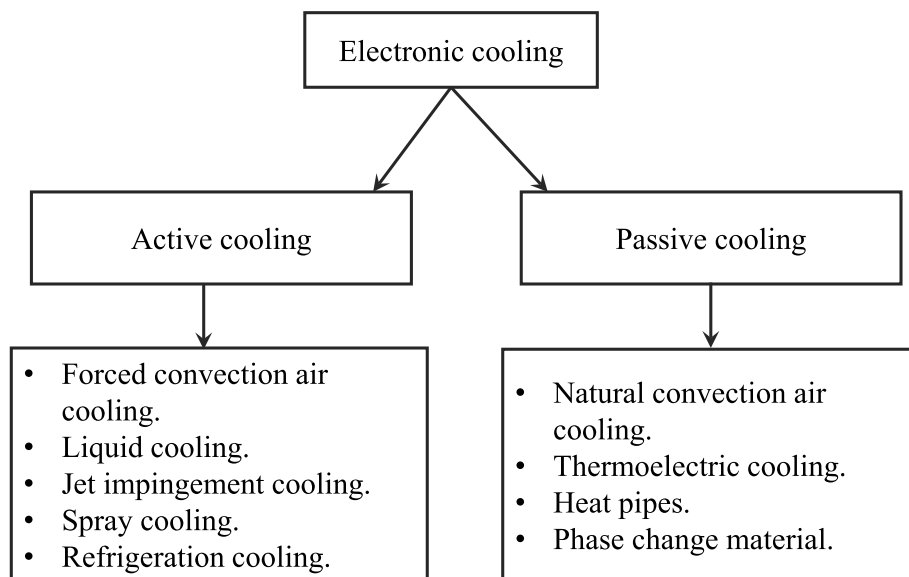
### **Comparison of convection heat management**

In the electronics field, the most commonly utilized HT techniques for cooling are conduction and convection. There are three different types of convection for heat management on electronic devices: forced convection, natural convection, and mixed convection [45, 46].



Peng et al. [47] examined the forced-air convection for the battery TM system with mathematical modeling. The study stated that there was an enormous increase in the internal finned structures as well as temperature; furthermore, in the forced air convection, its temperature was reduced. During the analysis, a higher cycling rate should not be suggested at the higher ambient temperature. Murali et al. [48] elucidated the numerical evaluation of forced convective HT of nanofluids in the microchannel for cooling electronic equipment. After analyzing the properties of nanofluids, results showed that the heat transfer rate enhances as the temperature of the fluid at the inlet increases. Also, the nanoparticles were smaller, and the particle volume fraction was also lower. Fanchen et al. [49] described the natural convection’s lattice Boltzmann for the nanofluid-centric battery TM. After evaluating Rayleigh numbers ( $10^3$  to  $10^6$ ) and nanofluid volume fractions (0 to 6%), they reported that the copper nanoparticles improved cooling performance, which reduced the temperature difference in the battery TM. The heat was not sufficiently dispersed by the vortexes (Fig. 5).

Air continues to be the most widely used coolant in electronic systems due to its low cost, ease of availability, less maintenance, non-contamination, and most importantly, it does not add vibration, noise, and humidity to the system. The method does not have any fluid handling problems. This method is generally free from freezing, boiling, and dripping problems, and is generally preferred for low to medium heat flux levels ( $100\text{--}10000\text{ W/m}^2$ ). This can be used for varied engineering applications like avionics, cooling of computers and data centers, and auto-mobile electronics. Moreover, this takes into account the combined heat transfer modes (conduction, convection, and radiation). However, natural, forced, and mixed convection are the commonly used air-cooling techniques. Most of the consumer-based electronic products and low-end applications of electronics deal with heat dissipation in the form of natural convection and surface radiation. However, natural convection has an edge over radiation due to



**Fig. 5** Different techniques available for electronics cooling

its low operating cost, high system reliability, and noise-free operation. Here, the buoyancy forces due to the density difference cause the fluid movement. Natural convection cooling is characterized by non-dimensional parameters like the Grashof number (Gr) and Rayleigh number (Ra). However, for higher cooling rates of the electronic components, natural convection air cooling is not preferred. As a result, forced convection air cooling is achieved using external means like a fan or blower. Here, the buoyancy forces are negligibly small. The forced convection cooling is characterized by Reynolds number (Re). However, in many air-cooled systems, mixed convection is preferred and has been an area of interest for many researchers. Here, both the external inertia forces and the buoyancy forces are of the same order. Mixed convection cooling is employed in different applications like cooling of heat exchangers, electronic components, avionic packages, and data centers, and can be used for higher heat transfer rates up to  $16,000\text{W}/\text{m}^2$ . The mixed convection cooling is characterized by the non-dimensional parameter Richardson number (Ri). The  $Ri \geq 1$  leads to pure natural convection,  $Ri \leq 1$  indicates the forced convection and  $Ri \approx 1$  identifies the mixed convection heat transfer regime [50]. A summary of convection research for electronic device heat management is shown in Table 3.

#### **Heat sources mounted on the substrate board**

In recent years, the development of electronic techniques has attracted the attention of engineers. Both new types of technique and their production technology are being developed and modernizing existing electronic devices and their components. The creation of new electronic devices leads to an increase in power and capacity combined with the miniaturization of these devices. As a result, several problems become urgent, the solution of which is necessary for the further development of electronics, namely, the development of new materials with improved properties, the efficient use of energy in devices, and the improvement of the cooling system efficiency for heat-loaded elements in the electronic systems [58].

The increasing heat flux demand from the electronic components is posing a greater challenge to the researchers. Ultimately their temperature shoots up. Hence, the role of the thermal management technique is extremely crucial to improve the reliability and performance of the electronic components. There are different factors affecting the failure of an electronic component, but temperature contributes to the highest factor of 55% [59].

Stable-state HT tests are performed using non-identical rectangular HSs, and the maximum temperature in the model equals the position's strong function when fluxes are held constant [53, 54].

Durgam et al. [59] explored the substrate-mounted discrete square HSs in the horizontal channel by utilizing natural convection cooling. Utilizing aluminum, HSs were constructed, which were similar to integrated circuit components. Analysis indicated that multilayer copper-clad boards exhibited no significant enrichment in HT. The multilayer copper-clad board's performance was not expected.

Sarper et al. [60] scrutinized the material selection's thermal aspect for substrate boards armed with higher-heat flux IC chips. Laminar, forced convection air had been included. From the findings, it was clear that in the HT, there was a rise in the thermal conductivity, and failure chances were reduced in the ED. Nevertheless, it was less

**Table 3** Types of convection for thermal management on electronic devices

Ref.	Convection	Findings	Limitations
Peng et al. [51]	Forced air convection	Analysis showed that the maximum temperature on force air convection for the active mode significantly decreased as compared to the passive mode.	With only 4 mm gaps, the analysis's requirements could not be met.
S. Sadrabadi, et al. [52]	Natural convection	According to the results, the plate cubic PFHS had a thermal resistance that was around 12% lower than the plate pin-fin.	If the various types of micro-channel impacts with varied rib forms have been studied, the performance will be improved.
Shahrouz et al. [53]	Mixed convection	The investigation showed that when the nanoparticle volume percentage increased, the Reynolds number, temperature gradients, and heat absorption all decreased in the cavity.	In some cases, mixed convection resulted in limited enhancement of HT.
Masoud et al. [54]	Mixed convection	The results showed that the silicon chip and cavity had the best HT when approached from angles of ( $-45^\circ$ , $0^\circ$ , $-90^\circ$ , $45^\circ$ , and $90^\circ$ )	HT was not directly feasible for some geometries, such as cavities. The HT process requires optimization.
Youfu et al. [55]	Forced air convection	According to analysis, serpentine PCM (S-PCM) increases energy density while consuming just 70% of the energy.	The considerable temperature gradient during analysis could cause issues.
Purusothaman et al. [56]	Natural convection	The results showed that the applied correlations improved the parameters of EDs and produced excellent results with 100% dependability.	Due to the larger volume fraction of nanoparticles, the HT rate will be constrained.
Fatih et al. [57]	Mixed convection	Analysis revealed that when a larger cylinder was used in contrast to a smaller one for the cylinder's clockwise rotation, the average Nusselt number increased by 10%.	In some cases, the process was slow.

reliable. Table 4 explicates the HS types mounted on the substrate board, along with their findings and limitations.

#### Optimization methods for substrate board

The prevailing studies mostly concentrated on heat conduction optimization by designing the higher thermal conductivity material's distribution. Optimization methodologies or techniques are computationally feasible for determining the HS's optimum location [63, 64].

Yue et al. [65] investigated the ANN for predicting mini- or micro-channel saturated flow boiling HT coefficients grounded on universally consolidated data. Totally, from 50 sources, the database was collected. Analysis indicated that the hidden layers (75, 70, 60, 50, 30, 20, and 10) from ANN were found, and the mean absolute error achieved was 14.3%. It was not able to generalize from the limited training data. Investigations conducted by various researchers on heat source optimization for substrate board mounting is presented in Table 5.

**Table 4** Exploration of mounted substrate boards heat source varieties

Ref.	Heat sources	Findings	Limitations
Shankar et al. [61]	3 × 5 aluminum HSs	The numerical results demonstrated a drop in Reynolds number and HSs surface temperature, as well as an increase in thermal conductivity.	Because the current study solely takes into account that specific arrangement, there were few applications offered.
Shankar et al. [62]	9 aluminum square parts	The results showed that the temperature excess values achieved for FR4 and bakelite were high when compared to the copper-clad board.	Correlations were not very useful.
Kia et al. [63]	15 protruding aluminum square HSs	The single-side copper clad was selected, according to experiment results, and simulations showed a variation of less than 5%.	High-temperature applications are constrained.
Naveen et al. [64]	15 aluminum discrete square HSs of 15,155 mm sizes	An analysis revealed that a single-layer copper-clad substrate board could effectively dissipate heat from electronic components for the heat flux values (4000 to 12,000 W/m <sup>2</sup> )	The single-layer copper-clad board was an inappropriate selection for the substrate board.

**Table 5** Investigation of heat source optimization methods for substrate board mounting

Author name	Optimization method	Findings	Limitations
Shintaro et al. [66]	Genetic algorithm and Lagrange multiplier	Analysis revealed that the used technique was the most effective way to optimize size under various settings and characteristics.	The number of operational machines will be constrained in the intermediate season because of the lesser loads.
Tao et al. [67]	Genetic Algorithm II	The results showed that a fluctuation of roughly 85.53% in the skin friction coefficient was achieved with a variance of 17.19% in the HT coefficient.	There was a very stringent space limitation for a battery pack.
T. K. Hotta, et al. [68]	Artificial neural network (ANN) with a genetic algorithm	According to the findings, the combination of ANN and GA was shown to be quick in achieving the HS's global ideal location.	Due to time constraints and available features, geometric parameters were not completely explored.
Yunfei et al. [69]	Genetic algorithm	Observations revealed that multi-objective when compared to other algorithms, the best model displayed a great energy economy.	The performance of the heat sink in terms of heat transfer and hydraulics could not be optimized by a single objective.
Qian et al. [70]	ANN	The employed hybrid modeling technique allowed for the containment of additional effects, such as system health state and current into the battery, and it was also easily expanded to more intricate systems.	Nine buried neurons' experimental data could not be precisely matched.

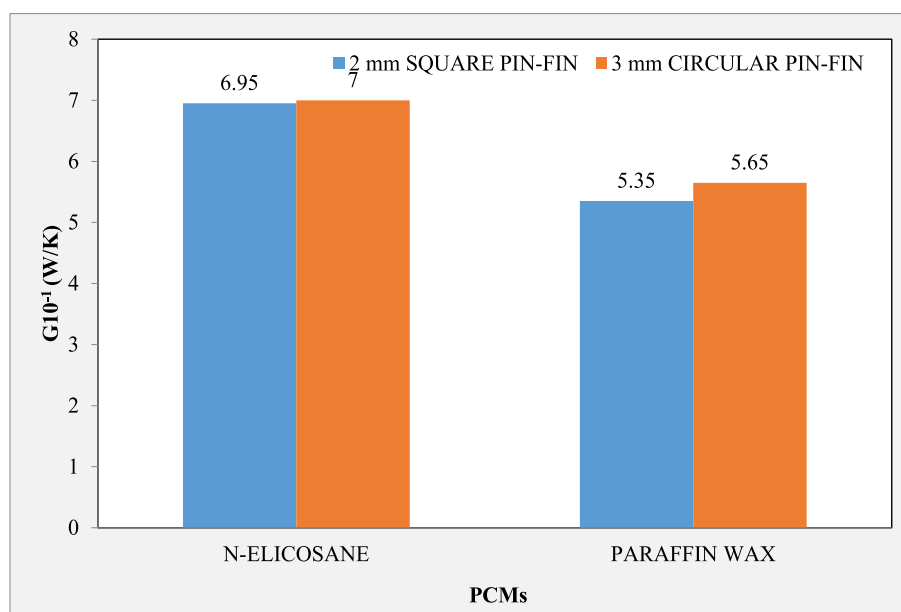
### Conductance of electronic devices with PCM's pin-fin heat pip

Advances in the electronics industry resulted in a considerable increase in power densities, thus leading to the development of small as well as smart products. In these small products, the augmenting requirement for advanced heat dissipation solutions is predicted to drive industry growth soon [71–73].

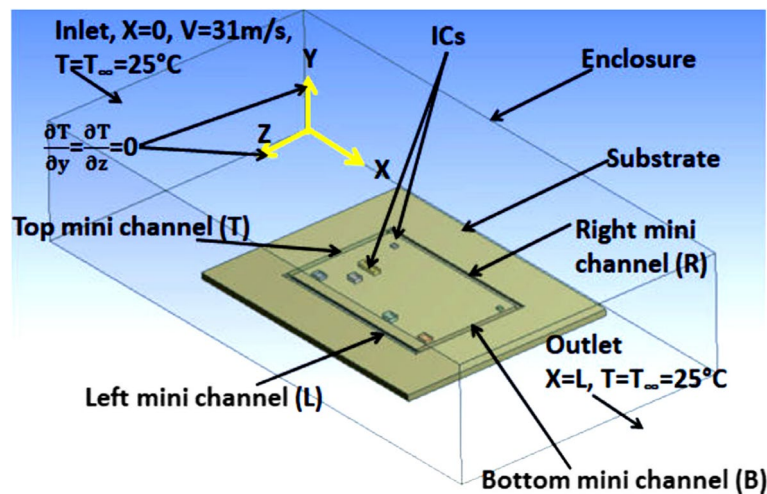
Furthermore, the comparison of the thermal conductance of EDs with PCM pin-fin HPs has been analyzed. Two PCMs considered here are paraffin wax and n-eicosane [15, 74, 75], both of which have various thermophysical properties. Figure 3 graphically represents the comparison of the thermal conductance of EDs with PCMs pin-fin HP.

Figure 6 depicts that for comparing the thermal conductance (one of the thermal properties), 2 mm square pin-fin and 3 mm circular pin-fin configurations were presented. For paraffin wax and n-eicosane, the thermal conductance attained is  $6.95 \times 10^{-1}$  W/K and  $5.69 \times 10^{-1}$ , respectively, in a thick circular PFHS. It was concluded that when comparing both, the 3 mm circular PFHS's best thermal performance is due to the optimal number of fins, fin pitch, and fin thickness [76–78].

Mathew and Hotta [79] carried out numerical analysis under mixed convection for the cooling of IC chips with the phase change material filled inside the mini-channels. Seven asymmetric rectangular IC chips installed on a substrate board (SMPS board) make up the computational models, as shown in Fig. 7. The study revealed that n-eicosane absorbs the heat generated by the IC chips, resulting in a 5.5% decrease in the configuration's maximum temperature. The findings imply that a mini channel with a smaller hydraulic diameter provides a better rate of heat transfer from IC chips and effectively cools them.



**Fig. 6** Graphical representation of the comparison of the thermal conductance of electronic devices with PCM's pin-fin heat pipe



**Fig. 7** The computational model developed by Mathew and Hotta [80, 81]

### Future scope

Previously, TM systems were preferred for larger components and very high heat-producing systems such as those used in power generation, industrial assembly, and transportation. Recently, however, large-scale electronic applications have expanded their scope, integrating electrical systems, electric vehicles, etc., with batteries. It is also used in small electronic devices (ED) such as watches, home appliances, mobile phones, tablets, and robots. All EDs and circuits generate excessive heat. To avoid this problem, TM needed to be more reliable and prevent premature failure. In this review, we thoroughly study the convection of TM on ED and HS mounted on substrates and discover the advantages and disadvantages of using TM for ED cooling methods. Investigators can further broaden their focus on TM in ED by considering the limitations of their investigation.

- A thermal interface material (TIM) is a substance placed between an IC and a heat sink to improve heat transfer and extend the operating cycle of integrated circuits. ICs generate heat during operation, and this heat must be dissipated to avoid IC damage or performance problems. Heat transfer between the IC and heatsink can be impeded by the small gap that the TIM is designed to fill. Improved heat transfer allows for lower IC temperatures, resulting in more reliable and efficient operation.
- Batteries with thermal management systems use phase change materials (PCM) to absorb excess heat generated during charging or discharging, which can keep the battery temperature within a safe operating range. When the battery generates excessive heat, the PCM absorbs the heat and undergoes a phase change (such as from solid to liquid), releasing the stored heat energy again. Using a PCM to control battery temperature more effectively can reduce the risk of damage and deterioration.
- To obtain the desired temperature distribution, artificial neural networks (ANN) can be used to optimize the size and location of the heat source and improve the overall performance of electrical devices. ANN is a machine-learning technology that analyzes complex data to find patterns that can be used to make predictions and decisions. ANN can

analyze the thermal properties of electronic devices in the context of heat sources and select the optimal size and placement of heat sources to obtain the desired temperature distribution. By optimizing the heat source, the device can work more effectively and reliably, improving both performance and durability.

## Conclusions

In electronics, TM utilizes the principles of thermodynamics for controlling the temperature and noise in a circuit. TM considers the materials (coolants or thermal interface materials), tools (heat sinks), and technologies (finite element analysis or CFD) to remove excess heat from the components to the surroundings. There are both needs and opportunities for novel materials to address some TM disputes, with advances in electronics and the emergence of new application areas nowadays. Though the TM challenges facing modern electronics are significant in magnitude as well as scope, a diverse and novel set of cutting-edge materials is rising to meet them. The limitation here was that the size of power dissipation and semiconductor were at different places, and development was required in advanced cooling to reduce cost without sacrificing the efficacy of cooling. So, future researchers should consider this limitation and find a suitable technique for reducing costs.

## Abbreviations

TM	Thermal management
PCM	Phase change material
EE's	Electronics devices
HS	Heat source
HP	Heat pipe
ANN	Artificial neural network
CFD	Computational fluid dynamics
HT	Heat transfer
TES	Thermal energy storage
LHTES	Latent heat thermal energy storage
TEC	Thermoelectric cooler
PFHS's	PCM-filled pin-fin heat sinks
ME	Micro encapsulated
EG	Expanded graphite

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## Authors' contributions

The first draft of the manuscript was written by AM. AK and NA performed the conceptualization of the research idea, participated in the interpretation of the results, and reviewed the edited manuscript. All authors have made a substantial contribution to the manuscript. All authors read and approved the final manuscript.

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## Declarations

### Competing interests

The authors declare no competing interests.

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