Journal of Mines, Metals and Fuels, *72(6): 557-579; 2024. DOI: 10.18311/jmmf/2024/45212*

Print ISSN : 0022-2755

Journal of Mines, Metals and Fuels

Contents available at: *www.informaticsjournals.com/index.php/jmmf*

# A Comprehensive Review of Electronic Cooling Technologies in Harsh Field Environments: Obstacles, Progress, and Prospects

**Anant Sidhappa Kurhade[1]*, Nitin Babanrao Kardekar[2], Parimal Sharad Bhambare[3], Shital Yashwant Waware[1], Rahul Shivaji Yadav[4], Prajakta Pawar[1] and Swanand Kirpekar[4]**

*[1]Department of Mechanical Engineering, Dr. D. Y. Patil Institute of Technology Pimpri, Pune - 411018, Maharashtra, India; a.kurhade@gmail.com*

*[2]Department of Mechanical Engineering, Bhivarabai Sawant College of Engineering and Research, Pune - 411041, Maharashtra, India*

*[3]Department of Mechanical and Industrial Engineering, College of Engineering, National University of Science and Technology, Muscat, Oman*

*[4]Department of Mechanical Engineering, Marathwada Mitra Mandal's College of Engineering, Karvenagar, Pune - 411052, Maharashtra, India*

## Abstract

*Electronic cooling is crucial for modern electronic device design, ensuring devices operate at peak performance, reliability, and longevity. This paper offers an in-depth critical review of electronic cooling technologies, covering both established methods and recent innovations. It explores the challenges in electronic cooling, such as effective heat dissipation, thermal management, and reliability concerns. Various cooling strategies are examined, including air cooling, liquid cooling, phase-change cooling, and emerging technologies like thermoelectric cooling and two-phase immersion cooling. The paper also evaluates recent advancements in materials, design, and manufacturing processes that have transformed electronic cooling. Additionally, it discusses the impact of electronic cooling on energy efficiency, environmental sustainability, and cost-effectiveness. Finally, the review highlights future research directions and opportunities for innovation in electronic cooling to meet the increasing demands of high-performance electronic systems. The findings provide valuable insights for thermal design engineers, assisting in optimal IC chip placement on the substrate board to enhance reliability and extend operational lifespan.*

**Keywords:** *Emissions Electronic Cooling, Energy Efficiency, Heat Dissipation, Immersion Cooling, Liquid Cooling, Phase-Change Cooling, Thermal Management, Thermoelectric Cooling, Sustainability*

## 1.0 Introduction

The investigation into effectively handling the thermal aspects of electronic components stands as a significant field of study, drawing the focus of numerous researchers in recent times. Addressing the increasing heat flux demands of electronic components poses a notable challenge, leading to heightened temperatures and potential overheating. Effective thermal management methods are crucial for enhancing the durability and lifespan of electronics. Figure 1 illustrates key factors contributing to electronic component failure, with

**Author for correspondence*

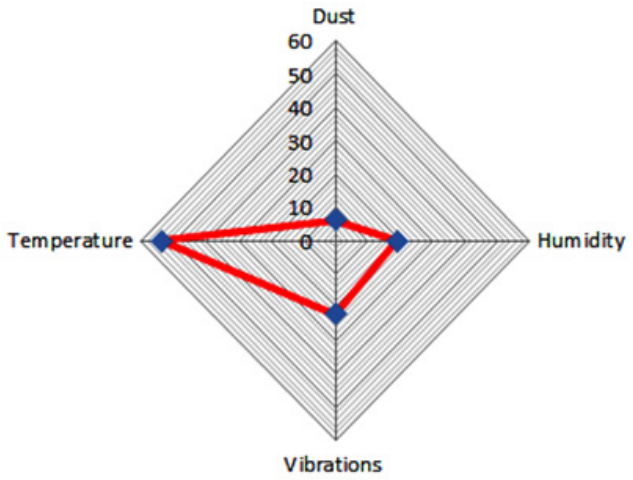



**Figure 1.** Factors affecting the failure of electronic components.

temperature alone responsible for 54% of such failures (Dust 6%, Humidity 19%, and Vibration 22%).

The Integrated Circuit (IC) chips present on Printed Circuit Boards (PCBs) are primarily made of silicon and are highly sensitive to temperature fluctuations. According to the Arrhenius law, for every 20°C rise in chip temperature, their failure rate doubles. Thus, a well-designed thermal approach is essential for prolonging the IC chip lifespan, along with strategic chip arrangement on the PCB to optimize cooling efficiency. As the electronics industry expands rapidly and space optimization remains crucial, electronic component and IC chip dimensions have shrunk. This miniaturization, facilitated by modern technology, intensifies heat generation within a limited space, compromising performance and reliability. Miniaturization increases component density, reducing space for heat dissipation and leading to thermal management challenges due to limited airflow and surface area for heat transfer, exacerbating heat generation in electronic devices. The challenge lies in extending the IC chip lifespan through various cooling methods while keeping temperatures below critical thresholds. This entails balancing increased heat production with effective cooling strategies to enhance chip efficiency and reliability. The review delves into the significant hurdles surrounding electronic cooling, including heat dissipation, thermal management, and reliability concerns. It evaluates the drawbacks of conventional cooling techniques and emphasizes the necessity for innovative solutions to tackle these issues. The review covers traditional and advanced cooling methods such as air, liquid, and phase-change cooling, alongside emerging techniques like thermoelectric and immersion cooling. It highlights recent breakthroughs in materials, designs, and manufacturing, reshaping electronic cooling. Future research directions and innovation opportunities in electronic cooling are outlined, considering their impact on energy efficiency, sustainability, and cost-effectiveness. Additionally, challenges like integrating cooling systems into device design and managing thermal concerns in IoT technologies are discussed. Overall, the review aims to offer insights into the current status of electronic cooling, pinpoint areas for enhancement, and steer future research and development endeavours in this pivotal domain. The main challenges in heat dissipation and thermal regulation for modern electronic devices include managing increased heat from higher power densities, especially in compact designs, and addressing thermal hotspots that can lead to performance and reliability issues. Additionally, there are difficulties in finding materials with better thermal conductivity, balancing energy efficiency, ensuring long-term reliability, minimizing environmental impact, and integrating cooling systems without disrupting device design or increasing costs.

This paper aims to critically review electronic cooling technologies, focusing on both traditional methods and recent innovations. It analyzes challenges such as heat dissipation, thermal management, and reliability while exploring various cooling techniques and their impact on energy efficiency and sustainability. The review also offers insights to help thermal design engineers optimize IC chip placement for enhanced system reliability and longevity.

## 2.0 Electronic Cooling Methods

Various techniques are utilized for cooling electronic components, as depicted in Figure 2. These methods fall into two main categories: active and passive cooling, selected based on specific application needs.

Active cooling involves mechanically assisted systems, requiring external energy for heat dissipation and utilizing fans or blowers for cooling. This approach offers high cooling capacity and enables temperature control below ambient levels. Active cooling methods,

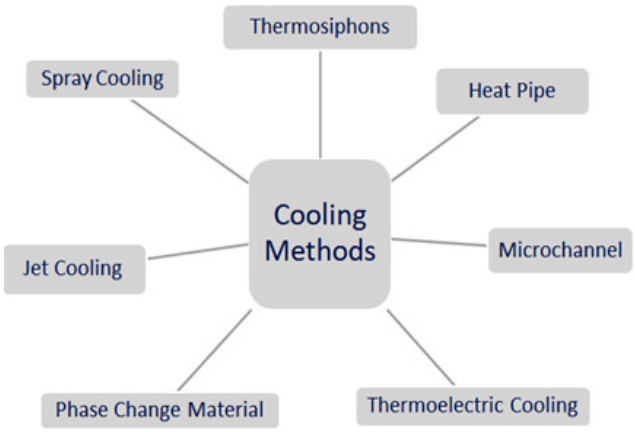



**Figure 2.** Different techniques for cooling electronic components.

such as force convection air cooling, liquid cooling, jet impingement cooling, spray cooling, and refrigeration cooling, play a vital role in dissipating heat from various systems. Force convection air cooling involves using fans or blowers to enhance the natural convection process, efficiently removing heat from surfaces. Liquid cooling utilizes coolant fluid circulated through channels or pipes to absorb and carry away heat, offering high thermal conductivity and precise temperature control. Jet impingement cooling directs high-velocity fluid jets onto surfaces, providing localized cooling and efficient heat transfer. Spray cooling involves spraying coolant directly onto surfaces, rapidly dissipating heat through phase change and evaporation. GaneshKumar *et al.*[1] provide a comprehensive review of the state-of-the-art applications of spray cooling for various fields such as hydrogen vehicles, electronic devices, solar applications, and low-temperature building applications. The review encompasses the current state of research in the field and discusses the potential of spray cooling as a promising heat dissipation technique in these diverse applications. Refrigeration cooling employs refrigerants to absorb and transport heat away from components, ensuring precise temperature regulation. Each of these active cooling methods offers unique advantages, catering to diverse cooling requirements across various industries and applications. Passive cooling is crucial for managing thermal levels at the module level and handling low heat flux rates. It eliminates the need for external power and utilizes heat sinks and fins for natural cooling. Passive cooling methods leverage natural processes and materials to dissipate heat without the need for external power sources. Natural convection air cooling utilizes the buoyancy of warm air to facilitate heat transfer away from surfaces, making it suitable for applications where electricity is limited or unavailable. Thermoelectric cooling systems harness the Peltier effect to create temperature differentials across semiconductor materials, allowing heat to be absorbed and dissipated without moving parts, ideal for compact and low-power cooling needs. Heat pipes employ phase change principles to transfer heat from hot spots to cooler areas through evaporation and condensation of a working fluid, providing efficient and silent cooling solutions. Phase change materials absorb and release heat during phase transitions, offering passive cooling with high thermal storage capacity, making them suitable for applications requiring temperature regulation over extended periods. These passive cooling methods offer energy-efficient and reliable solutions for various industries, from electronics to renewable energy systems. Passive cooling relies on natural processes or materials to dissipate heat without external power sources, while active cooling uses mechanical components and external power to actively remove heat from a system. However, conventional methods struggle to meet the increasing heat flux demands of electronic components. Innovative cooling techniques are necessary to enhance heat removal and maintain temperatures below the safe threshold. Emerging solutions like mini-channels and micro-channels address shrinking component sizes but may increase system complexity. Phase Change Materials (PCMs) offer promise, absorbing heat during melting and releasing it when chips are idle, finding applications in various industries like photovoltaics, solar power, space, waste heat recovery, and pharmaceuticals. Passive cooling dissipates heat naturally without using external power, relying on components like heat sinks and natural convection. Active cooling, on the other hand, uses powered devices like fans or pumps to enhance heat dissipation. Passive cooling is silent and maintenance-free, while active cooling is more effective for high-performance systems.

## 2.1 Air Cooling

Air cooling is a straightforward and widely used method for cooling electronic components, particularly in

applications where fluid-related challenges are not a concern. It effectively operates within low to medium heat flux ranges, avoiding freezing, boiling, and dripping issues commonly associated with fluid-based cooling systems. Its advantages include readily available coolant (air), minimal maintenance requirements, cost-effectiveness, lightweight nature, and immunity to electromagnetic interference. Air cooling is utilized across various engineering fields such as avionics, computer and data centre cooling, and automotive electronics, exploiting all three modes of heat transfer: conduction, convection, and radiation. In air cooling, natural, forced, and mixed convection techniques are commonly employed. Natural convection, suitable for less demanding applications, relies on buoyancy forces driven by fluid density differences. However, when higher cooling rates are needed, forced convection comes into play, employing external mechanical means like fans or blowers to drive the fluid. Mixed convection, where both external inertia and buoyancy forces are significant, is crucial in setups requiring higher heat transfer rates, such as heat exchangers and avionic systems. The balance between buoyancy and inertia forces, represented by the Richardson number, determines the dominance of forced or mixed convection, with optimal mixed convection occurring at a Richardson number around 1.

## 2.2 Phase Change Materials

Phase Change Materials (PCMs) are attracting considerable attention in electronic cooling due to their distinctive features like low thermal conductivity, defined melting points, and latent heat of fusion, enabling thermal energy storage. These materials transition from solid to liquid with rising temperatures and revert to solid when cooled. This reversible phase change, bypassing vaporization, makes PCMs highly desirable for electronic cooling, solar energy, and battery thermal management. PCMs vary in properties such as melting points and thermal conductivity, with selection based on application needs. Common options include salt hydrates and paraffin compounds, storing energy through sensible and latent heat, making them vital in Thermal Energy Storage (TES) for electronic cooling and solar energy applications. PCMs are categorized into organic (e.g., paraffin, fatty acids), inorganic (e.g., salt hydrates, metallics), and eutectic (a combination of organic and inorganic) types based on their chemical composition as shown in Figure 3. The electronics industry's growth and the push for space efficiency have led to shrinking electronic components and IC chips, known as miniaturization. This has increased heat generation per unit volume, reducing performance and reliability. The challenge is to extend the IC chip lifespan using cooling methods while keeping temperatures below critical thresholds. The comprehensive examination of existing literature focuses on the interconnected subjects that are relevant to the current study. Research on heat transfer via natural convection from isolated heat sources. Investigations into heat transfer from discrete heat sources under forced and combined convection conditions. Exploration of the use of phase change materials for cooling electronic components.

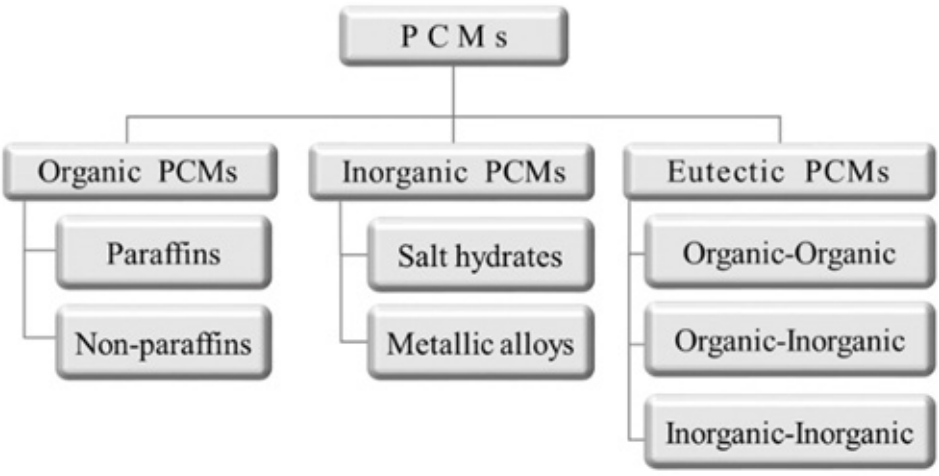



**Figure 3.** Types of phase change materials.

Kurhade *et al.*[2-4,58] explain the material selections and CFD approach towards thermal cooling and CFD Approach for Thermal Management to Enhance the Reliability of IC Chips. Patil *et al.*[1] and Waware *et al.*[6,44,45] explained critical reviews on heat transfer and Heat Transfer Enhancement in Tubular Heat Exchangers with Jet Impingement. Khot Rahul *et al.*[7-11] explain the investigation of Laser Welding Parameters on the Strength of TRIP Steel. Abokersh *et al.*[12] explain the Review of the PCM usage for Solar Domestic Water Heating Systems (SDWHS).

## 3.0 Studies on Heat Transfer via Natural Convection from Isolated Heat Sources

Fujii *et al.*[13] conducted research involving an experiment and a two-dimensional numerical simulation, focusing on protruding Heat Sources (HS) subjected to free convective heat transfer within surrounding air. Heat sources were vertically mounted on a plate, resembling IC packages. They established a relationship between the Nusselt number and a modified Grashof number, effective in predicting IC temperatures for varying spacing and height configurations of the heat source. Optimal temperature conditions were achieved with heat sources optimally spaced at the midpoint height. Chen and Liu[14] and Cui *et al.*[15] numerically explored natural convection around three IC chips mounted in a protruding manner, considering the vertical and horizontal orientations of the substrate board. Heat sources were arranged in inline and staggered configurations for both orientations. Findings indicated that compared to horizontal orientation, vertical orientation led to the highest IC chip temperature. They introduced a correlation incorporating non-dimensional maximum temperature, Rayleigh number, and non-dimensional thermal conductivity. Bessaih and Kadja[16] investigated turbulent flow conjugate heat transfer involving three ceramic heat sources mounted vertically in a two-dimensional setup. Varying spacing between heat sources and disconnecting the power supply of one source were part of the experiment. Increasing the distance between heat sources improved the cooling rate. Disabling one source's power supply reduced thermal interaction among sources, enhancing cooling effectiveness. Aydin and Yang[17] conducted 2D numerical simulations involving four heat sources mounted flush within an enclosure, altering heat source length and Rayleigh number. Conduction prevailed at lower Rayleigh numbers, gradually decreasing as Rayleigh numbers increased, resulting in a temperature decrease. Tou and Zhang[18] numerically investigated a three-dimensional enclosure with nine heat sources mounted vertically and flush. The enclosure was filled with a dielectric fluid, exploring how heat source orientation influenced heat transfer characteristics under natural convection. Altering orientation between 230° and 310° had a negligible cooling effect. Chuang *et al.*[19] performed numerical simulations within a three-dimensional enclosure, focusing on three chips mounted in a protruding manner in five positions. They studied how temperature variations influenced different chip positions under laminar natural convection, finding the upper chip in vertical configuration had the highest maximum temperature. Bhowmik *et al.*[20] conducted experimental studies under transient conditions involving four vertically positioned heat sources flush-mounted within an enclosure. They observed the influence of varying heat flux levels and heat source geometries on temperature changes, proposing a correlation relating Nusselt numbers to Fourier numbers and Rayleigh numbers. Bazylak *et al.*[21] computationally analyzed four heat sources recessed within an enclosure, studying the impacts of spacing and length variations on heat transfer characteristics and dimensionless parameters. Optimal heat transfer rate occurred when spacing equalled heat source length, while different lengths resulted in mixed conduction and convection regimes. Florio and Harnoy[22] employed numerical simulations to study a protruding heat source beneath an oscillating plate, identifying optimal natural convection cooling conditions when the plate amplitude was one-third of clearance spacing and frequency was 2π. Desrayaud *et al.*[23] numerically investigated a protruding heat source between two parallel PCB stacks, manipulating the thermal conductivity and thickness of PCBs. Increasing PCB thermal conductivity and thickness reduced heat source temperatures due to enhanced conduction. Bakkas *et al.*[24] computationally simulated heat sources within single and double domains, finding elevating heat source height increased the Nusselt number with rising Rayleigh number. Double domains exhibited more sophisticated heat transfer characteristics. Koca *et al.*[25] conducted

**Table 1.** Summary of literature pertinent to the cooling of discrete IC chips under natural convection

| Sl. No. | Author(s) | Parameters | Key points |
|---|---|---|---|
| 1 | Fujii *et al.*[13] | Multiple heat sources are arranged in parallel on a vertical plate. | 2D governing equations were solved numerically and validated with the experiment. The geometric parameters and the heat transfer characteristics were studied for the IC package. |
| 2 | Liu *et al.*[35] | Three protruding IC chips. Both Inline and staggered IC chips are arranged under vertical and horizontal board orientation. | The finite element method was used to solve numerically the effect of conjugate heat transfer on various board orientations. The horizontal substrate board has less temperature for the IC chips. |
| 3 | Aydin and Yang[17] | Four flush-mounted heat sources. | 2D numerical simulations carried out under the natural convection. The heat transfer rate has increased with Rayleigh's number. |
| 4 | Bessaih and Kadja[16] | 3 ceramic protruding heat sources. Spacing and power cut OFF were varied. | The finite volume method was used to solve turbulent flow under natural convection. |
| 5 | Chuang *et al.*[19] | Three protruding chips. Vertical, horizontal, staggered, triangular and inverse triangular positions were considered. | The temperature of the chip was the maximum for the vertical arrangement. Better cooling was obtained for the horizontal arrangement |
| 6 | Tou and Zhang[18] | 9 flush-mounted heat sources. Dielectric fluid-filled inside the enclosure. | Developed a correlation for the Nusselt number with different channel inclinations and Rayleigh number. Heat transfer rate is non-uniform in the 9 discrete heat sources. |
| 7 | Bhowmik and Tou[20] | Four flush-mounted heat sources. Water was used as a coolant inside the enclosure. | Heat flux ranges between 1000 - 6000 W/m2. Nusselt number varied in terms of Fourier number and Rayleigh number. |
| 8 | Bazylak *et al.*[21] | 4 Flush-mounted heat sources. Variation of heat source spacing and length. | Heat transfer and Rayleigh number have increased with the spacing and length of the heat sources. |
| 9 | Desrayaud *et al.*[23] | One protruding heat source placed between two parallel PCB stacks. | Studied numerically the heat transfer effect on the thermal conductivity of the substrate board. |
| 10 | Florio and Harnoy[22] | One protruding heat source. Oscillating plate | Better cooling was achieved by the oscillation of the plate placed above the heat source. |
| 11 | Bakkas *et al.*[24] | Four protruding heat sources with simple and double domains. | Studied numerically by varying the height of the heat sources and Rayleigh number. |
| 12 | Koca *et al.*[25] | Combination of flush and protruding heat sources. Triangular enclosure. | Variation in spacing, height, and Rayleigh number. Heat transfer improved with the heat source height and spacing. |
| 13 | Narasimham[89] | Natural convection. Both flush and protrude mounted heat sources. Vertical arrangement. | Attempts have not been made to compare the results of 2D and 3D numerical analysis of natural convection. |

| | | | |
|---|---|---|---|
| 14 | Sudhakar *et al.*[26] | Five protruding heat sources. 5 x 5 array for placing the heat sources. | Temperature decreased with an increase in λ. Nusselt increased with the Grashof number. |
| 15 | Nardini and Paroncini[28] | Four Protruding heat sources. Different arrangement of the heat sources. | Holographic interferometry is used for experimental visualizations. Nusselt number has increased with Rayleigh's number. Better cooling was achieved at a higher Rayleigh number. |
| 16 | Mahdi[90] | Flush-mounted discrete heat source. Vertical arrangement. Non-uniform heat flux. Symmetric and uniform spacing. | Nusselt number has increased with the increase in Rayleigh number. The better cooling rate was obtained at a higher volumetric flow rate of water. |
| 17 | Habib *et al.*[29] | Flush-mounted discrete heat source. Non-uniform and uniform heat flux. Symmetric and uniform spacing. | The non-uniform spacing of the heat sources has shown a better cooling rate in comparison with the uniform spacing of heat sources. |

computational simulations involving heat sources within a triangular enclosure, studying arrangement variations and heat source height and Rayleigh number effects. Optimal heat transfer occurred with protruding heat sources close to inclined walls and increased spacing between sources. Sudhakar *et al.*[26] combined experimental and numerical investigations involving five protruding heat sources in a 5x5 matrix arrangement, varying heat flux levels and heat source spacings. Increased spacing correlated with temperature reduction, influenced by non-dimensional geometric distance parameter (λ). Ahmed *et al.*[27] used mixed convection from a discrete heat source in enclosures with two adjacent moving walls and filled with micropolar nanofluids for their study. Nardini and Paroncini[28] combined experimental and numerical investigations on four horizontally positioned, protruding heat sources, exploring different enclosure configurations and holographic interferometry for visualizations. Findings showed heat transfer varied between conduction and convection-dominated regimes. Habib *et al.*[29] conducted experiments on flush-mounted heat sources with uniform and non-uniform spacings, varying heat inputs and Rayleigh numbers. Randomly spaced heat sources exhibited improved cooling rates. These studies collectively contribute to understanding heat transfer characteristics and optimization strategies in natural convection cooling of electronic components. Coşkun and Çetkin[30] explain an experimental study for battery pack thermal management and electronic cooling and showed cold plates could be used in both electronics cooling and battery thermal management with a control algorithm to switch between sole working fluid and combination modes. Table 1 indicates the summary of relevant literature on the natural convection cooling of discrete IC chips.

## 4.0 Studies on the Examination of Heat Transfer from Isolated Heat Sources under Conditions of Forced and Combined Convection

Choi and Ortega[31] embarked on a numerical exploration to scrutinize how the orientation of channels influences heat transfer from single flush-mounted heat sources. They delved into natural, mixed, and forced convection modes, rotating channels across angles from 0 to 360°. Their study spanned non-dimensional numbers within ranges of $103 \leq Gr \leq 105$ and $0.1 \leq Re \leq 5000$. Notably, they observed substantial variations in the Nusselt number across different channel orientations in natural and mixed convection scenarios, while such effects were less pronounced in forced convection cases. Particularly noteworthy was the highest heat transfer rate observed during mixed convection heat transfer. Du *et al.*[32] conducted a computational investigation employing two-dimensional simulations, focusing on three distinct heat sources vertically affixed within a channel. Their

analysis revolved around mixed convection using the SIMPLER algorithm with the Boussinesq approximation. They underscored the significant impact of heat source spacing on cooling performance, recommending optimal positioning at the channel entrance for enhanced cooling, irrespective of the size and power rating of the heat sources. Ozsunar *et al.*[33,34] conducted a numerical simulation aiming to explore the impact of inclination and non-dimensional parameters (Grashof number and Reynolds number) on mixed convection heat transfer. The study centred on a rectangular channel with uniform heat flux applied to the bottom, open inlet and outlet walls, and an adiabatic upper wall. Results indicated that increased heat transfer correlated with inclination, resulting in higher Nusselt and Grashof numbers. Liu *et al.*[35] and Zhou *et al.*[36] investigated nine heat sources arranged in a protruding manner within a low-speed wind tunnel, focusing on forced and mixed convection heat transfer modes. They found that a center-to-center placement yielded superior outcomes compared to uniformly spaced configurations. Specifically, setting the spacing ratio to 1.8 elevated the maximum temperature by 8.24%, with a corresponding 7.5% increase in the Nusselt number compared to uniform spacing and analytically explored the substrate board's orientation under mixed convection, noting its negligible effect at higher Reynolds numbers and identifying optimal angles for single flush-mounted heat sources. They observed that the orientation significantly influenced the Nusselt number, with peaks at 60° and 70°. Bhowmik and Tou[37] conducted experimental research involving water-filled enclosures housing four flush-mounted heat sources, manipulating flow rate, heat flux, and spatial arrangement to investigate heat transfer characteristics in natural, mixed, and forced convection. They established correlations connecting the Nusselt number to the Grashof and Reynolds numbers, noting a 35% lower computed Nusselt number compared to previous studies. Guimarães and Menon[38] performed numerical simulations involving three flush-mounted heat sources subject to combined free and forced convection, altering Reynolds and Grashof numbers and channel inclination to analyze their impact on heat source temperatures. They found that the Nusselt number significantly improved heat transfer from the sources, particularly at lower Reynolds numbers and inclination angles of 45° and 90°. Aminossadati and Ghasemi[39] and Kargar *et al.*[40] numerically simulated a single flush-mounted heat source within a cavity in a channel, varying its position and the cavity's aspect ratio and Richardson number to observe their effects on heat source temperatures. They found that the highest heat transfer rate occurred at an aspect ratio of two due to increased Richardson numbers from buoyancy-driven flow. Amirouche and Bessaïh[41] conducted numerical simulations on ten protruding heat sources within a vertical channel, studying the effects of non-dimensional parameters and power cycling on heat source temperatures. They found that when some sources were deactivated during simulations, conjugate heat transfer increased temperatures in off conditions, leading to higher cooling rates at elevated Reynolds and Richardson numbers. Ahmed *et al.*[42] and Zarma *et al.*[43] numerically simulated three protruding heat sources within inclined channels under mixed convection, observing enhanced cooling at inclination angles of 45° and 90° with a Richardson number of one, resulting in higher Nusselt numbers. They highlighted the significance of channel inclination at higher velocities for improved heat transfer. Waware *et al.*[44] conducted experimental and numerical studies on seven protruding heat sources under laminar forced convection, exploring the influence of temperature on substrate thermal conductivity at various velocities. They developed an empirical relationship incorporating substrate conductivity, Reynolds number, and heat source spacing, achieving strong agreement between numerical simulations and experimental results. Waware[45] optimized the placement of three flush-mounted heat sources within a square enclosure under forced convection, aiming to minimize the maximum temperature. Using numerical simulations, they employed Artificial Neural Networks (ANN) and a Genetic Algorithm (GA) to identify optimal placements, resulting in significant temperature reductions. Kumar and Phaneendra[46] numerically simulated ten protruding heat sources within a duct under mixed convection, analyzing various configurations for optimal cooling. They observed that closer heat source proximity led to increased system temperatures, suggesting effective cooling strategies involving greater heat source spacing and strategic positioning near inlet and outlet vents. Gasia *et al.*[47] did an experimental evaluation of the use of fins and metal wool as heat transfer enhancement techniques in a latent heat thermal energy storage system.

**Table 2.** Summary of literature pertinent to the cooling of discrete IC chips under forced and mixed convection

| Sl. No. | Author(s) | Parameters | Key points |
|---|---|---|---|
| 1 | Choi and Ortega[31] | Natural, mixed and forced convection. Single Flush-Mounted Heat Source (FMHS). | Channel orientation ranges from 0° to 360°. Mixed convection gave a better rate of cooling. |
| 2 | Du *et al.*[32] | Mixed convection. Three Protruding Symmetric Heat Sources (PMHS). | Numerical analysis using a SIMPLER algorithm. The higher power heat source must be placed at the channel entrance for better cooling. |
| 3 | Queipo and Gil[92] | Muti-Objective Optimization. 36 PMHS. | The thermal and non-thermal objective function of the optimization was formulated using the Arrhenius relation. |
| 4 | Ozsunar *et al.*[34] | Mixed convection heat transfer with uniform heat flux at the heat source bottom. | The bottom wall of the channel was heated to study the mixed convection effect on heat transfer for different Gr, Re, and θ. |
| 5 | Chen and Liu[14] | Forced and mixed convection. 3 x 3 identical PMHS. | Spacing from the centre to centre distance has maximum heat transfer from the heat sources reducing temperature by 27%. |
| 6 | Da Silva *et al.*[93] | Forced convection. FMHS. | Temperature reduced with an increase in Reynolds number. Overall conductance was increased by 25% for $102 \leq Re \leq 104$. |
| 7 | Bhowmik *et al.*[37] | Natural, mixed and forced convection. 4 FMHS. Water coolant. | An experiment study was carried out for the different ranges of $40 \leq Re \leq 2220$ based on heat source lengths ranging from 50 to 2775 mm respectively. |
| 8 | Premachandran and Balaji[94] | Mixed convection. Four identical PMHS. Water and FC70 were used as the coolant. | Numerically investigated using FVM to study the effect of thermal conductivity ratio, spacing ratio, Re and Gr on the heat transfer characteristics. |
| 9 | Guimarães and Menon[38] | Three identical FMHS. Mixed convection. | A better rate of heat transfer was achieved at 45°. |
| 10 | Waware *et al.*[45] | 3 identical FMHS. Forced convection. | Numerically investigated for the velocity 4 m/s. ANN-GA to determine the optimal position of the heat sources. |

| | | | |
|---|---|---|---|
| 11 | Aminossadati and Ghasemi[39] | Mixed convection. Single FMHS. | Studied the effect of heat sources placed at different locations and aspect ratios. A higher heat transfer rate was observed at cavity aspect ratio 2 where Ri is more significant. |
| 12 | Ozsunar *et al.*[33] | Single-chip PMHS. CFD + ANN | The temperature was affected by the Chip material, chip thickness and power input to the chip. |
| 13 | Amirouche and Bessaïh[41] | Ten identical PHMS Mixed convection | Conducted numerical simulations on Ten PMHS with few PMHS under no-power conditions and the remaining under ON. |
| 14 | Sudhakar *et al.*[26] | Five protruding heat sources. 5 x 5 array for placing the heat sources. | Temperature decreased with an increase in λ. Nusselt increased with the Grashof number. |
| 15 | Nardini and Paroncini[28] | Four Protruding heat sources. Different arrangement of the heat sources. | Holographic interferometry is used for experimental visualizations. Nusselt number has increased with Rayleigh's number. Better cooling was achieved at a higher Rayleigh number. |
| 16 | Mahdi[90] | Flush-mounted discrete heat source. Vertical arrangement. Non-uniform heat flux. Symmetric and uniform spacing. | Nusselt number has increased with the increase in Rayleigh number. The better cooling rate was obtained at a higher volumetric flow rate of water. |
| 17 | Habib *et al.*[29] | Flush-mounted discrete heat source. Non-uniform and uniform heat flux. Symmetric and uniform spacing. | The non-uniform spacing of the heat sources has shown a better cooling rate in comparison with the uniform spacing of heat sources. |
| 18 | Ahmed *et al.*[27] | Mixed convection Three identical PMHS | The inclination is dominant for higher Reynolds numbers. Heat transfer is more at 45° for Ri=1. |
| 19 | Waware *et al.*[44] | Forced convection 7 symmetric PMHS and 8 dummy heat sources. | Maximum chip temperature has decreased with an increase in λ. Substrate copper cladding gave the better cooling of heat sources. |
| 20 | Chaurasia *et al.*[95] | Mixed convection 6 PMHS | The ranges of Reynolds number, emissivity, and thermal conductivity of PCB are 115 – 690, 0 - 0.9, and 0.038 - 1.4 W/mK, respectively. |

| | | | |
|---|---|---|---|
| 21 | Xie *et al.*[50] | Single PMHS with PCM-based heat sink Paraffin wax | Numerical study with a heat input of 50000 W/m2. The topology-optimized tree heat sink showed better thermal performance. |
| 22 | Garcia *et al.*[49] | Mixed convection Two identical PMHS | Transient numerical studies were conducted for different parameters, $0°\leq\gamma\leq90°$, and $100 \leq Re \leq 1000$. Studied the buoyancy influence on the different channel inclinations. |
| 23 | Korichi and Laouche[91] | Mixed convection Four identical PMHS | Numerical study on pulsation in the flow under mixed convection. The temperature and flow behaviour were affected due to flow pulsation. |
| 24 | Kumar and Phaneendra[46] | 10 identical PMHS Mixed convection | Numerically investigated the heat flux of 25 x 104 W/m2. High-temperature heat source must be placed at the inlet. |

Kalbasi *et al.*[48] conducted numerical and experimental investigations on 15 protruding heat sources arranged in a grid within a setup, focusing on mixed convection. They utilized Artificial Neural Networks (ANN) to expedite simulations and guide a Genetic Algorithm (GA) in determining optimal heat source placement. Their results emphasized temperature control below critical thresholds through optimal heat flux allocation. García *et al.*[49] numerically simulated an inclined channel containing two protruding heat sources under transient conditions, observing varying buoyancy effects and heat transfer enhancements at different inclinations and Reynolds numbers. They noted increased heat transfer with rising Reynolds numbers, holding the Richardson number constant. Korichi and Laouche *et al.*[91] investigated pulsed flow within a vertical channel housing four protruding heat sources, noting significant heat transfer variations with alterations in airflow amplitude. They emphasized the importance of airflow amplitude for effective electronic component cooling. Xie *et al.*[50] conducted experimental and numerical studies on 15 protruding heat sources. Table 2 shows a summary of relevant literature on the forced and mixed convection cooling of discrete IC chips.

## 5.0 Studies on Exploration of the Use of Phase Change Materials for Cooling Electronic Components

Elmozughi *et al.*[51] and Solomon[52] conducted an analysis using n-octadecane paraffin wax to define the Stefan number, highlighting its constancy as the ratio of sensible heat to latent heat. The study also explored factors influencing the Stefan number such as ratios and geometries. Demirbas[53] extensively examined Phase Change Materials (PCMs), emphasizing their varied applications. Paraffin-based PCMs, cost-effective but with low thermal conductivity, were contrasted with hydrate salts, favoured for their higher melting temperatures and conductivity, particularly in solar applications. Kandasamy *et al.*[54] investigated a mounted heat source (PMHS) with a paraffin wax PCM, observing improved cooling performance with higher power inputs. Their study employed both computational and practical

approaches, with results showing congruence between numerical and experimental outcomes. Faraji and El Qarnia[55] conducted computational simulations with n-eicosane PCM, examining PCM melting and verifying numerical accuracy against existing literature. Results revealed temperature variations among heat sources, attributed to convection and conduction within the PCM. Ye *et al.*[56] simulated paraffin wax in a plate-fin setup to analyze thermal storage, correlating temperature and time non-dimensionally. Paraffin wax showed peak efficiency with a 20°C temperature difference, displaying solid phase dominance during heat release. Mahmoud *et al.*[57] empirically examined various PCMs in heat sinks, noting reduced temperatures and extended operation with PCM integration, particularly with lower melting point PCMs.

El Qarnia *et al.*[59] numerically investigated PCM melting with three heat sources, observing varied temperatures and melt fractions among sources. Kurhade *et al.*[60,61] practically tested heat sinks with different PCMs and configurations, optimizing pin-fin design using neural networks and genetic algorithms. Rathod and Banerjee experimentally studied paraffin wax in a heat exchanger, finding fluid inlet temperature and mass flow rate affected PCM melting and solidification durations. Ali *et al.*[62], Ashraf *et al.*[63], Ali[64], and Arshad *et al.*[65] experimented with various PCM heat sinks, discovering optimized configurations for different PCMs and power inputs and experimented with copper foam and PCM in heat sinks, noting temperature reductions with optimized porosity, PCM volume, and power inputs. Loganathan and Mani[66] optimized PCM selection using fuzzy logic, recommending RT-80 for electronic cooling due to delayed melting. Usman *et al.*[67] experimented with triangular pin-fin heat sinks and PCMs, finding enhanced operation with RT-44 and inline pin-fin arrangement. Zeng *et al* [68] experimented with nano-wire-infused PCMs, noting enhanced thermal conductivity and enthalpy compared to pure PCM. Yavari *et al.*[69] experimented with graphene-infused PCMs, noting increased thermal conductivity at higher graphene concentrations. Rabie *et al.*[70] studied PCM melting in photovoltaic cells, finding optimal cooling with inclined heat sinks and high height ratios. Khademi *et al.*[71] numerically analyzed PCM heat sinks, optimizing fin count, thickness, and volume fraction for extended operation. Buonomo *et al.*[72] numerically studied nanoparticle-infused PCM heat sinks, noting improved melting efficiency and convective heat transfer. Zarma *et al.*[43] simulated nanoparticle-infused PCM in photovoltaic cells, observing enhanced electrical efficiency with Al2O3 nanoparticles. Gharbi[73] simulated copper heat sinks with PCM, finding enhanced performance with longer fins and basic enclosures for low-power inputs. Saha *et al.*[74], and Saha and Dutta[75] experimentally and numerically optimized TCE volume and fin count in PCM heat sinks for electronic cooling. Hasan *et al.*[76] experimented with PCM heat sinks, finding superior performance with salt hydrate and paraffin wax. Salunkhe and Shembekar[77] analyzed PCM behaviours during melting and solidification, discussing microencapsulated PCM challenges. Elmozughi *et al.*[51] simulated PCM energy storage in solar systems, studying PCM phase transitions and expansion effects. Ling *et al.*[78] studied PCM thermal management for batteries, noting optimal melting temperatures and density-thermal conductivity relationships. Kahwaji *et al.*[79] empirically analyzed PCM thermophysical characteristics, recommending alkanes for solar and thermal management systems. Hasan and Tbena[80] simulated micro pin-fin heat sinks with PCMs, noting temperature reductions with n-octadecane and circular fin geometries. Hasan and Tbena[81] simulated a micro-channel heat sink with PCM, observing temperature reductions with PCM placement and melting rates. Karami and Kamkari[82] simulated enclosed PCM setups with pin fins, noting melting time reductions with decreased inclination angles. Song *et al.*[83] combined numerical and practical studies of PCM-cooled battery systems, observing improved battery temperatures and longevity. Thesiya *et al.*[84] did a comprehensive review electronic cooling: A nanomaterial perspective and noted new devices developed through Carbon Nanotubes (CNT) with high thermal conductive nanoparticles, nanofluids, and hybrid materials enhance heat transfer through electronic devices. Singh *et al.*[85] showed the proposed framework in the form of thermal Ragone plots effectively delineates the optimal points for various combinations of heat rate, cut-off point, and aspect ratio, affirming its utility for comprehensive design guidelines for PCM-based composites for electronic cooling applications. Rosli *et al.*[86] presented a numerical investigation of PCM acts as promising elements incorporated in the PVT system that can reduce the temperature of the PVT-PCM system. Table 3 shows summary of relevant literature

**Table 3.** Summary of literature pertinent to the phase change material-based cooling of discrete IC chips

| Sl. No. | Author (s) | Parameters | Key points |
|---|---|---|---|
| 1 | Zhou *et al.*[36] | Three PMHS<br>n-octadecane PCM | Sub-cooling and Stefan number have played a significant role in the melting of PCM. |
| 2 | Demirbas[53] | Different PCMs were analyzed. Paraffin wax and Hydrated salts were widely used | Reviewed different PCMs for various applications. PCM for the solar system is used as Glauber's salt, Calcium chloride hexahydrate and Paraffin wax. |
| 3 | Saha *et al.*[74],<br>Saha and Dutta[75] | n-eicosane and paraffin-based heat sinks | The number of fins in the heat sink along with the volumetric % of TCE was varied and found that the 8% volumetric fraction was better. |
| 4 | Kandasamy *et al.*[54] | Single PMHS QFP chip<br>Paraffin wax (Tm: 55°C) | Both experimental and numerical studies. PCM enhances the cooling performance of the QFP chips. |
| 5 | Abokersh *et al.*[12] | Review of PCM for solar energy system | PCM with a melting temperature of 50<br>- 60°C is appropriate for the solar energy system. |
| 6 | Faraji and El Qarnia[55] | Three PMHS in vertical enclosure n-eicosane | Melting of PCM is due to heat dissipation from the heat sources. Bottom heat sources have the lowest<br>temperature. |
| 7 | Zeng *et al.*[68] | 1-Tetradecanol PCM<br>Silver Nano-wire | Experiment study to enhance the thermal conductivity of composite PCM. |
| 8 | Cui *et al.*[15] | Carbon Nano-fiber, carbon Nanotube filled with Soy wax and Paraffin wax | Experimental study to enhance the thermal conductivity of the composite PCM.<br>The carbon Nano-fiber with Soy wax was a more effective composite PCM as compared to the Paraffin wax. |
| 9 | Yavari *et al.*[69] | Octadecanol and nanostructured graphene PCM | The % content of the Nano-structured PCM was varied. |
| 10 | Ye *et al.*[56] | Plate fin system<br>Paraffin wax (Tm: 33 °C - 35°C) | Maximum energy storage at ΔT=20°C.<br>They developed a correlation to design an optimal thermal PC system. |

| | | | |
|---|---|---|---|
| 11 | Baby and Balaji[60] | n- eicosane (Tm: 36.5 °C)<br>Paraffin wax (Tm: 53 - 57°C) | Combine ANN-GA was used for the optimal heat sink, volume fraction and thermal conductivity enhancer. |
| 12 | Salunkhe and Shembekar[77] | Thermal performance of the system | Microencapsulation of the PCM. Challenges in the microencapsulation PCM were reported. |
| 13 | Mahmoud *et al.*[57] | Six PCMs<br>Paraffin wax, HS29P - 29 °C, HS34P - 34°C, OM37P - 37°C, OM46P - 46°C, HS58P<br>- 58°C and Rubitherm RT - 42 42°C | Six different types of heat sink with power inputs 2 ≤ Q ≤ 6 W. The temperature of the heat sinks was lowered using the PCM.<br>Used for portable electronic components. Honeycomb inserts with PCM in heat sink mesh gave better results. |
| 14 | El Qarnia *et al.*[59] | Three PMHS<br>n- eicosane (Tm - 36 °C) | 2D numerical study with power input per unit length of 60 W/m. Melting of PCM is due to the heat dissipation from the heat sources. |
| 15 | Elmozughi *et al.*[51] | NaNO3 – Stainless steel<br>EPCM capsules | Effect of the thermal expansion and volume expansion on energy storage. |
| 16 | Ling *et al.*[78] | Battery thermal management system<br>Expanded Graphite Paraffin | Different power input was supplied in a range of 5W ≤ Q ≤ 15W. Density variation to study the effect on temperature and PCM latent heat. |
| 17 | Rathod and Banerjee[96] | Paraffin wax (Tm: 58 - 60°C) | The melting of PCM at the top end is quicker than at its lower end. |
| 18 | Janarthanan and Sagadevan[97] | Review of PCM for different applications. | Reported the use of PCM for different domains and the characteristics of PCM. |
| 19 | Hasan *et al.*[76] | Salt hydrate, Paraffin wax and Milk fat | Conducted experimental and numerical investigation for different heat inputs, 4 W≤Q≤10 W. |
| 20 | Ashraf *et al.*[63], Ali[64] | Different geometries of the heat sink<br>Paraffin wax, RT-54, RT-44, RT-35HC, SP-31 and n- eicosane | The highest enhancement ratio was obtained by SP-31. Paraffin wax is suitable for the highest power input of 8W. |

| | | | |
|---|---|---|---|
| 21 | Gharbi *et al.*[73] | PCM based Copper heat sink | The heat sink fin height was varied to study the effect on PCM melting. Longer fins gave a better cooling performance. |
| 22 | Hasan and Tbena[80] | n-octadecane, RT44<br>A micro pin-fin heat sink | Un-finned heat sink with n-n-octadecane showed maximum temperature drop.<br>The circular pin-fin PCM heat sink gave a better performance. |
| 23 | Kahwaji *et al.*[79] | Three different Paraffin wax and three different Alkanes | For commercial Paraffin waxes, 150≤latent heat≤200 J/g and greater than 200 J/g for pure Alkanes. |
| 24 | Loganathan and Mani[66] | 10 PCMs<br>Eight criteria were considered | The fuzzy logic modelling Optimum PCM obtained was RT-80 (Tm: 80°C). |
| 25 | Rehman and Ali[98] | Heat sink with Paraffin wax and Copper foam | Experimental investigation on the effect of copper foam porosity on the heat sink temperature. Better performance was obtained for porosity of 0.95, lower power. |
| 26 | Usman *et al.*[67] | Heat sink with Paraffin wax, RT-44, RT-35HC | An experimental study to determine the better pin-fin arrangement. RT-44 has shown the maximum enhancement ratio. |
| 27 | Buonomo *et al.*[72] | Single PMHS<br>n-Octadecane<br>Al2O3 Nano-particle | The maximum concentration of the Nano-particles enhances the cooling performance of PCM based heat sink. |
| 28 | Gasia *et al.*[47] | n-octadecane (Tm: 27.7°C) | Metal foam and PCM have increased thermal energy storage by 14%. |
| 29 | Hamza *et al.*[99] | Single PMHS<br>n-eicosane with CO2 particle | Melting of the PCM has enhanced with the Nano-particle concentration. |
| 30 | Kalbasi *et al.*[48] | PCM heat sink<br>RT-27 (Tm - 30°C) | Numerical study to determine the optimum number of fins, height ratio and volume content of PCM. The optimum number of fins was 12, with a thickness of 2.236 mm for 500 W/m2. |

| | | | |
|---|---|---|---|
| 31 | Karami and Kamkari[82] | One fin and three fin enclosure Lauric acid (Tm: 43.5 - 48°C) | Transient numerical simulation. Different inclination 0° to 180° melting time reduced with the inclination angle and was minimum for the vertical orientation. |
| 32 | Khademi *et al.*[71] | Oleic acid (Tm: 13°C) | Numerical simulation was carried out with Oleic acid and water. The mixture of PCM with water has melted faster and stored maximum energy. |
| 33 | Rabie *et al.*[70] | RT35HC (Tm: 41 - 44°C) | Experimental and numerical study for different inclinations - 45° to 45°. The maximum cooling performance was observed at 45°. |
| 34 | Song *et al.*[83] | Paraffin wax Cold plate | 106 cylindrical batteries. The cold plate was used for liquid cooling. Phase change material helped in reducing the surface temperature of the batteries. |
| 35 | Zarma *et al.*[43] | Pure Salt Hydrate (Tm: 29.8°C) Nano-particles (Al2O3, CuO and SiO2) | The maximum concentration of Al2O3 Nano-particles has enhanced the cooling performance of PCM. The temperature of the solar cells was reduced. |

on phase change material-based cooling for discrete IC chips.

## 6.0 Emerging Technologies

Solid-state elastocaloric circuits offer a groundbreaking approach to cooling technology. By utilizing elastocaloric materials that respond to mechanical stress, these circuits can efficiently regulate temperature without relying on traditional refrigerants. This innovation not only promises enhanced sustainability by reducing harmful emissions but also ensures reliability and durability in cooling applications. Solid-state elastocaloric circuits represent a promising step towards a greener and more efficient future in cooling technology. Cirillo *et al.*[87] designed an elastocaloric device specifically aimed at the cooling of the electronic circuits and the results reveal that the device based on wires bending gives the best performances (+50 % as COP with bending rather than loading). Masselli *et al.*[88] created a 2D model optimized for an elastocaloric heat exchanger with bending wires and air coolant. It investigated wire configuration and operating conditions for best performance (0.5mm spacing, 20cm length).

## 7.0 Overall Findings and Research Gap from the Literature

Investigations into cooling discrete heat sources across diverse modes of heat transfer, including natural, forced, and mixed convection, have been widespread. Researchers commonly utilize uniform heat sources of similar geometry, predominantly employing flush or protrude-mounted configurations in both 1D and 2D setups. However, there's a growing interest in extending

this research to incorporate 3D protrude-mounted heat sources. Various numerical analysis methodologies, such as Finite Element Analysis (FEA) and Computational Fluid Dynamics (CFD) using software like Fluent, Gambit, Flotherm, and MATLAB, have been employed. Optimization techniques like the Design of Experiments (DOE), the Taguchi Method, Sequential Quadratic Programming, and genetic algorithms have also been utilized. Notably, researchers have explored placing heat sources within Phase Change Material (PCM) enclosures, focusing on PCM-based heat sinks and fluid-based cooling through micro-channels and mini-channels. However, studies addressing cooling under mixed convection and non-uniform spacing of heat sources are limited, indicating areas for further research and exploration.

# 8.0 Future Directions, Challenges

## 8.1 Innovative Cooling Technologies

Continued research into novel cooling techniques, such as advanced liquid cooling systems and thermoelectric cooling devices, holds promise for improving thermal management efficiency and reliability.

## 8.2 Materials Advancements

Further exploration of advanced materials, including nanomaterials and composites, could lead to the development of heat sinks and thermal interface materials with superior thermal conductivity and mechanical properties.

## 8.3 Integration and Miniaturization

Future research should focus on integrating cooling systems seamlessly into electronic device designs, particularly in the context of miniaturized devices like IoT sensors and wearables. This requires innovative approaches to thermal management that account for space constraints and power limitations.

## 8.4 Environmental Sustainability

Efforts to enhance the environmental sustainability of electronic cooling systems should be prioritized, including the development of eco-friendly cooling fluids and waste heat recovery technologies.

# 9.0 Conclusion

In conclusion, electronic cooling technologies play a crucial role in maintaining the performance, reliability, and sustainability of future electronic systems. By tackling key challenges and adopting innovative strategies, researchers and engineers can advance the development of more efficient and eco-friendly cooling solutions. For example:

- Thermal Interface Materials (TIM) on ICs can prolong their operational lifespan.
- Substrate boards combined with PCM can adapt to various inclinations.
- Liquid Cold Plates are effective for managing thermal conditions in battery thermal management systems.
- Micro-channel-based liquid cooling systems are practical for use at the base of thermally conductive materials in SMPS boards.
- These findings provide valuable insights for thermal design engineers to optimize IC chip placement on substrate boards, enhancing reliability and extending operational life.

Electronic cooling is vital for ensuring the performance and durability of modern devices. This paper reviews both traditional and advanced cooling methods, highlighting challenges like heat dissipation and recent innovations that enhance energy efficiency and sustainability. The insights provided are crucial for optimizing IC chip placement and addressing the evolving demands of high-performance systems.

# 10.0 References

1. GaneshKumar P, Sivalingam V, Vigneswaran VS, Ramalingam V, Cheol KS, Vanaraj R. Spray cooling for hydrogen vehicle, electronic devices, solar and building (low temperature) applications: A state-of-art review. Renew Sustain Energy Rev. 2024; 189:113931. https://doi.org/10.1016/j.rser.2023.113931
2. Kurhade A, Talele V, Rao TV, Chandak A, Mathew VK. Computational study of PCM cooling for the electronic circuit of smart-phone. Mater Today Proc. 2021; 47:3171-6. https://doi.org/10.1016/j.matpr.2021.06.284

3. Kurhade AS, Murali G. Thermal control of IC chips using phase change material: A CFD investigation. Int J Mod Phys C. 2022; 33(12): 2250159. https://doi.org/10.1142/S0129183122501595
4. Kurhade AS, Murali G, Rao TV. CFD approach for thermal management to enhance the reliability of IC Chips. Int J Eng Trends Technol. 2022; 71(3):65-72. https://doi.org/10.14445/22315381/IJETT-V71I3P208
5. Patil Sp, Kore SS, Chinchanikar SS, Waware SY. Characterization and machinability studies of aluminium-based hybrid metal matrix composites – A critical review. J Adv Res Fluid Mech Therm Sci. 2023; 101(2):137-63. https://doi.org/10.37934/arfmts.101.2.137163
6. Waware SY, Kore SS, Patil SP. Heat transfer enhancement in tubular heat exchanger with jet impingement: A review. J Adv Res Fluid Mech Therm Sci. 2023; 101(2):8-25. https://doi.org/10.37934/arfmts.101.2.825
7. Khot RS, Kadam PR. Structural behavior of fillet weld joint for bimetallic curved plate using Finite Element Analysis (FEA). 6th International Conference on Advanced Research in Arts, Science, Engineering and Technology (ICARASET); 2021.
8. Khot RS, Rao TV. Investigation of mechanical behaviour of laser welded butt joint of Transformed Induced Plasticity (TRIP) steel with effect laser incident angle. Int J Eng Res Technol. 2020; 13(11):3398. https://doi.org/10.37624/IJERT/13.11.2020.3398-3403
9. Khot RS, Rao TV, Natu H, Girish HN, Ishigaki T, Madhusudan P. An investigation on laser welding parameters on the strength of TRIP steel. Strojniški Vestnik – J Mech Eng. 2021; 67(1-2):45-52. https://doi.org/10.5545/sv-jme.2020.6912
10. Khot RS, Rao TV. Effect of quenching media on laser butt welded joint on Transformed -Induced Plasticity (TRIP) steel. Int J Emerg Trends Eng Res. 2020; 8(10):7686-91. https://doi.org/10.30534/ijeter/2020/1588102020
11. Khot RS, Rao TV, Keskar A, Girish HN, Madhusudan P. Investigation on the effect of power and velocity of laser beam welding on the butt weld joint on TRIP steel. J Laser Appl. 2020; 32(1):012016. https://doi.org/10.2351/1.5133158
12. Abokersh MH, Osman M, El-Baz O, El-Morsi M, Sharaf O. Review of the Phase Change Material (PCM) usage for Solar Domestic Water Heating Systems (SDWHS). Int J Energy Res. 2017; 42(2):329-57. https://doi.org/10.1002/er.3765
13. Fujii M, Gima S, Tomimura T, Zhang X. Natural convection to air from an array of vertical parallel plates with discrete and protruding heat sources. Int J Heat Fluid Flow. 1996; 17(5):483-90. https://doi.org/10.1016/0142-727X(96)00051-3
14. Chen S, Liu Y. An optimum spacing problem for three-by-three heated elements mounted on a substrate. J Heat Mass Transf. 2002; 39(1):3-9. https://doi.org/10.1007/s00231-001-0286-3
15. Cui Y, Liu C, Hu S, Yu X. The experimental exploration of carbon nanofiber and carbon nanotube additives on thermal behavior of phase change materials. Sol Energy Mater Sol Cells. 2011; 95(4):1208-12. https://doi.org/10.1016/j.solmat.2011.01.021
16. Bessaïh R, Kadja M. Turbulent natural convection cooling of electronic components mounted on a vertical channel. Appl Therm Eng. 2000; 20(2):141-54. https://doi.org/10.1016/S1359-4311(99)00010-1
17. Aydin O, Yang W. Natural convection in enclosures with localized heating from below and symmetrical cooling from sides. Int J Numer Methods Heat Fluid Flow. 2000; 10(5):518-29. https://doi.org/10.1108/09615530010338196
18. Tou S, Zhang XF. Three-dimensional numerical simulation of natural convection in an inclined liquid-filled enclosure with an array of discrete heaters. Int J Heat Mass Transf. 2003; 46(1):127-38. https://doi.org/10.1016/S0017-9310(02)00253-3
19. Chuang SH, Chiang JS, Kuo YM. Numerical simulation of heat transfer in a three-dimensional enclosure with three chips in various position arrangements. Heat Transf Eng. 2003; 24(2):42-59. https://doi.org/10.1080/01457630304076
20. Bhowmik H, Tso CP, Tou KW, Tan FL. Convection heat transfer from discrete heat sources in a liquid cooled rectangular channel. Appl Therm Eng. 2005; 25(16):2532-42. https://doi.org/10.1016/j.applthermaleng.2004.11.022
21. Bazylak A, Djilali N, Sinton D. Natural convection in an enclosure with distributed heat sources. Numer

Heat Transf A. 2006; 49(7):655-67. https://doi.org/10.1080/10407780500343798
22. Florio LA, Harnoy A. Use of a vibrating plate to enhance natural convection cooling of a discrete heat source in a vertical channel. Appl Therm Eng. 2007; 27(13):2276-93. https://doi.org/10.1016/j.applthermaleng.2007.01.023
23. Desrayaud G, Fichera A, Lauriat G. Natural convection air-cooling of a substrate-mounted protruding heat source in a stack of parallel boards. Int J Heat Fluid Flow. 2007; 28(3):469-82. https://doi.org/10.1016/j.ijheatfluidflow.2006.07.003
24. Bakkas M, Amahmid A, Hasnaoui M. Numerical study of natural convection heat transfer in a horizontal channel provided with rectangular blocks releasing uniform heat flux and mounted on its lower wall. Energy Convers Manag. 2008; 49(10):2757-66. https://doi.org/10.1016/j.enconman.2008.03.017
25. Koca A, Oztop HF, Varol Y. Natural convection analysis for both protruding and flush-mounted heaters located in triangular enclosure. Proc Inst Mech Eng C J Mech Eng Sci. 2008; 222(7):1203-14. https://doi.org/10.1243/09544062JMES886
26. Sudhakar TVV, Shori A, Balaji C, Venkateshan SP. Optimal heat distribution among discrete protruding heat sources in a vertical duct: A combined numerical and experimental study. J Heat Transfer. 2009; 132(1). https://doi.org/10.1115/1.3194762
27. Ahmed SE, Mansour MA, Hussein AK, Sivasankaran S. Mixed convection from a discrete heat source in enclosures with two adjacent moving walls and filled with micropolar nanofluids. Eng Sci Technol Int J. 2016; 19(1):364-76. https://doi.org/10.1016/j.jestch.2015.08.005
28. Nardini G, Paroncini M. Heat transfer experiment on natural convection in a square cavity with discrete sources. Heat Mass Transf. 2012; 48(11):1855-65. https://doi.org/10.1007/s00231-012-1026-6
29. Habib MA, Said SAM, Ayinde T. Characteristics of natural convection heat transfer in an array of discrete heat sources. Exp Heat Transfer. 2013; 27(1):91-111. https://doi.org/10.1080/08916152.2012.731473
30. Coşkun T, Çetkin E. Cold plate enabling air and liquid cooling simultaneously: Experimental study for battery pack thermal management and electronic cooling. Int J Heat Mass Transf. 2023; 217:124702-2. https://doi.org/10.1016/j.ijheatmasstransfer.2023.124702
31. Choi CY, Ortega A. Mixed convection in an inclined channel with a discrete heat source. Int J Heat Mass Transf. 1993; 36(12):3119-34. https://doi.org/10.1016/0017-9310(93)90040-D
32. Du SQ, Bilgen E, Vasseur P. Mixed convection heat transfer in open ended channels with protruding heaters. Heat Mass Transf. 1998; 34(4):263-70. https://doi.org/10.1007/s002310050258
33. Ozsunar A, Arcaklıoglu E, Dur FN. The prediction of maximum temperature for single chips' cooling using artificial neural networks. Heat Mass Transf. 2008; 45(4):443-50. https://doi.org/10.1007/s00231-008-0445-x
34. Özsunar A, Başkaya S, Sivrioğlu M. Numerical analysis of Grashof number, Reynolds number and inclination effects on mixed convection heat transfer in rectangular channels. Int Commun Heat Mass Transf. 2001; 28(7):985-94. https://doi.org/10.1016/S0735-1933(01)00302-5
35. Liu Y, Phan-Thien N, Kemp R, Luo XL. Three-dimensional coupled conduction-convection problem for three chips mounted on a substrate in an enclosure. Numeri Heat Transf A Appl. 1997; 32(2):149-67. https://doi.org/10.1080/10407789708913885
36. Zhou J, Chen Z, Liu D, Li J. Experimental study on melting in a rectangular enclosure heated below with discrete heat sources. J Therm Sci. 2001; 10(3):254-9. https://doi.org/10.1007/s11630-001-0028-3
37. Bhowmik H, Tou KW. Experimental study of transient natural convection heat transfer from simulated electronic chips. Exp Therm Fluid Sci. 2005; 29(4):485-92. https://doi.org/10.1016/j.expthermflusci.2004.06.003
38. Guimarães PM, Menon GJ. Combined free and forced convection in an inclined channel with discrete heat sources. Int Commun Heat Mass Transf. 2008; 35(10):1267-74. https://doi.org/10.1016/j.icheatmasstransfer.2008.08.006
39. Aminossadati SM, Ghasemi B. A numerical study of mixed convection in a horizontal channel with a discrete heat source in an open cavity. Eur J Mech B Fluids. 2009; 28(4):590-8. https://doi.org/10.1016/j.euromechflu.2009.01.001

40. Kargar A, Ghasemi B, Aminossadati SM. An artificial neural network approach to cooling analysis of electronic components in enclosures filled with nanofluids. J Electron Packag. 2011; 133(1). https://doi.org/10.1115/1.4003215
41. Amirouche Y, Bessaïh R. Three-dimensional numerical simulation of air cooling of electronic components in a vertical channel. Fluid Dyn Mater Process. 2012; 8(3):295-310.
42. Ahmed SE, Mansour MA, Hussein AK, Sivasankaran S. Mixed convection from a discrete heat source in enclosures with two adjacent moving walls and filled with micropolar nanofluids. Eng Sci Technol Int J. 2016; 19(1):364-76. https://doi.org/10.1016/j.jestch.2015.08.005
43. Zarma I, Ahmed M, Ookawara S. Enhancing the performance of concentrator photovoltaic systems using Nanoparticle-phase change material heat sinks. Energy Convers Manag. 2019; 179:229-42. https://doi.org/10.1016/j.enconman.2018.10.055
44. Waware SY, Kore S, Kurhade AS, Patil P. Innovative heat transfer enhancement in tubular heat exchanger: An experimental investigation with Minijet impingement. J Adv Res Fluid Mech Therm Sci. 2024; 116(2):51-8. https://doi.org/10.37934/arfmts.116.2.5158
45. Waware SY, Chougule SM, Yadav RS, Biradar R, Patil P, Munde KH, *et al*. A comprehensive evaluation of recent studies investigating nanofluids utilization in heat exchangers. J Adv Res Fluid Mech Therm Sc. 2024; 119(2):160-72. https://doi.org/10.37934/arfmts.119.2.160172
46. Kumar VG, Phaneendra K. Optimization of temperature of a 3D duct with the position of heat sources under mixed convection. Lect Notes Mech Eng. 2018; 275-84. https://doi.org/10.1007/978-981-13-1903-7_32
47. Gasia J, Maldonado JM, Galati F, De Simone M, Cabeza LF. Experimental evaluation of the use of fins and metal wool as heat transfer enhancement techniques in a latent heat thermal energy storage system. Energy Convers Manag. 2019; 184:530-8. https://doi.org/10.1016/j.enconman.2019.01.085
48. Kalbasi R, Afrand M, Alsarraf J, Tran MD. Studies on optimum fins number in PCM-based heat sinks. Energy. 2019; 171:1088-99. https://doi.org/10.1016/j.energy.2019.01.070
49. García F, Treviño C, Lizardi J, Martínez-Suástegui L. Numerical study of buoyancy and inclination effects on transient mixed convection in a channel with two facing cavities with discrete heating. Int J Mech Sci. 2019; 155:295-314. https://doi.org/10.1016/j.ijmecsci.2019.03.001
50. Xie J, Lee HM, Xiang J. Numerical study of thermally optimized metal structures in a Phase Change Material (PCM) enclosure. Appl Therm Eng. 2019; 148:825-37. https://doi.org/10.1016/j.applthermaleng.2018.11.111
51. Elmozughi AF, Solomon L, Oztekin A, Neti S. Encapsulated phase change material for high temperature thermal energy storage – Heat transfer analysis. Int J Heat Mass Transf. 2014; 78:1135-44. https://doi.org/10.1016/j.ijheatmasstransfer.2014.07.087
52. Solomon A. A note on the Stefan number in slab melting and solidification. Lett Heat Mass Transf. 1981; 8(3):229-35. https://doi.org/10.1016/0094-4548(81)90017-5
53. Demirbas MF. Thermal energy storage and phase change materials: An overview. Energy Sources B: Econ Plan Policy. 2006; 1(1):85-95. https://doi.org/10.1080/009083190881481
54. Kandasamy R, Wang XQ, Mujumdar AS. Transient cooling of electronics using Phase Change Material (PCM)-based heat sinks. Appl Therm Eng. 2008; 28(8-9):1047-57. https://doi.org/10.1016/j.applthermaleng.2007.06.010
55. Faraji M, El Qarnia H. Numerical study of melting in an enclosure with discrete protruding heat sources. Appl Math Model. 2010; 34(5):1258-75. https://doi.org/10.1016/j.apm.2009.08.012
56. Ye WB, Zhu DS, Wang N. Numerical simulation on phase-change thermal storage/release in a plate-fin unit. Appl Therm Eng. 2011; 31(17-18):3871-84. https://doi.org/10.1016/j.applthermaleng.2011.07.035
57. Mahmoud S, Tang A, Toh C, AL-Dadah R, Soo SL. Experimental investigation of inserts configurations and PCM type on the thermal performance of PCM based heat sinks. Appl Energy. 2013; 112:1349-56. https://doi.org/10.1016/j.apenergy.2013.04.059
58. Kurhade AS, Rao TV, Mathew VK, Patil NG. Effect of thermal conductivity of substrate board for temperature control of electronic components: A numerical study. Int J Mod Phys

C. 2021; 32(10):2150132. https://doi.org/10.1142/S0129183121501321
59. El Qarnia H, Draoui A, Lakhal EK. Computation of melting with natural convection inside a rectangular enclosure heated by discrete protruding heat sources. Appl Math Model. 2013; 37(6):3968-81. https://doi.org/10.1016/j.apm.2012.08.021
60. Kurhade AS, Biradar R, Yadav RS, Patil P, Kardekar NB, Waware SY, *et al*. Predictive placement of IC Chips using ANN-GA approach for efficient thermal cooling. J Adv Res. Fluid Mech Therm Sc. 2024; 118(2):137-4.
61. Upadhe SN, Mhamane SC, Kurhade AS, Bapat PV, Dhavale DB, Kore LJ. Water saving and hygienic faucet for public places in developing countries. Springer eBooks; 2019. p. 617-24. https://doi.org/10.1007/978-3-030-16848-3_56
62. Ali HM, Ashraf MJ, Giovannelli A, Irfan M, Irshad TB, Hamid HM, *et al*. Thermal management of electronics: An experimental analysis of triangular, rectangular and circular pin-fin heat sinks for various PCMs. Int J Heat Mass Transf. 2018; 123:272-84. https://doi.org/10.1016/j.ijheatmasstransfer.2018.02.044
63. Ashraf MJ, Ali HM, Usman H, Arshad A. Experimental passive electronics cooling: Parametric investigation of pin-fin geometries and efficient phase change materials. Int J Heat Mass Transf. 2017; 115:251-63. https://doi.org/10.1016/j.ijheatmasstransfer.2017.07.114
64. Rehman T -, Ali HM. Experimental investigation on paraffin wax integrated with copper foam based heat sinks for electronic components thermal cooling. Int Commun Heat Mass Transf. 2018; 98:155-62. https://doi.org/10.1016/j.icheatmasstransfer.2018.08.003
65. Arshad A, Ali HM, Khushnood S, Jabbal M. Experimental investigation of PCM based round pin-fin heat sinks for thermal management of electronics: Effect of pin-fin diameter. Int J Heat Mass Transf. 2018; 117:861-72. https://doi.org/10.1016/j.ijheatmasstransfer.2017.10.008
66. Loganathan A, Mani I. A fuzzy based hybrid multi criteria decision making methodology for phase change material selection in electronics cooling system. Ain Shams Eng J. 2018; 9(4):2943-50. https://doi.org/10.1016/j.asej.2017.11.005
67. Usman H, Ali HM, Arshad A, Ashraf MJ, Khushnood S, Janjua MM, *et al*. An experimental study of PCM based finned and un-finned heat sinks for passive cooling of electronics. Heat Mass Transf. 2018; 54(12):3587-98. https://doi.org/10.1007/s00231-018-2389-0
68. Zeng JL, Cao Z, Yang DW, Sun LX, Zhang L. Thermal conductivity enhancement of Ag nanowires on an organic phase change material. J Therm Anal Calorim. 2009; 101(1):385-9. https://doi.org/10.1007/s10973-009-0472-y
69. Yavari F, Fard HR, Pashayi K, Rafiee MA, Zamiri A, Yu Z, *et al*. Enhanced thermal conductivity in a nanostructured phase change composite due to low concentration graphene additives. J Phys Chem C. 2011; 115(17):8753-8. https://doi.org/10.1021/jp200838s
70. Rabie R, Emam M, Ookawara S, Ahmed M. Thermal management of concentrator photovoltaic systems using new configurations of phase change material heat sinks. Sol Energy. 2019; 183:632-52. https://doi.org/10.1016/j.solener.2019.03.061
71. Khademi A, Darbandi M, Shafii MB, Schneider G. Numerical simulation of phase change materials to predict the energy storage process accurately. AIAA Propulsion and Energy 2019 Forum; 2019. p. 4225. https://doi.org/10.2514/6.2019-4225
72. Bondareva NS, Buonomo B, Manca O, Sheremet MA. Heat transfer performance of the finned nano-enhanced phase change material system under the inclination influence. Int J Heat Mass Transf. 2019; 135:1063-72. https://doi.org/10.1016/j.ijheatmasstransfer.2019.02.045
73. Gharbi S, Harmand S, Jabrallah SB. Parametric study on thermal performance of PCM heat sink used for electronic cooling. Green Energy Technol. 2018; 243-56. https://doi.org/10.1007/978-3-319-62572-0_17
74. Saha S, Nayak KC, Srinivasan K, Dutta P. Cooling of electronics using phase change materials and thermal conductivity enhancers. 18th National and 7th ISHMT-ASME Heat Mass Transfer Conference; 2006. p. 4-6.
75. Saha SK, Dutta P, Paruya S, Kar S, Roy S. Cooling of Electronics with Phase Change Materials. AIP Conference Proceedings. 2010; 1298(1):31-6. https://doi.org/10.1063/1.3516323

76. Hasan A, Hejase H, Abdelbaqi S, Assi A, Hamdan MO. Comparative effectiveness of different phase change materials to improve cooling performance of heat sinks for electronic devices. Appl Sci. 2016; 6(9):226. https://doi.org/10.3390/app6090226
77. Salunkhe PB, Shembekar PS. A review on effect of phase change material encapsulation on the thermal performance of a system. Renew Sustain Energy Rev. 2012; 16(8):5603-16. https://doi.org/10.1016/j.rser.2012.05.037
78. Ling Z, Chen J, Fang X, Zhang Z, Xu T, Gao X, Wang S. Experimental and numerical investigation of the application of phase change materials in a simulative power batteries thermal management system. Appl Energy. 2014; 121:104-13. https://doi.org/10.1016/j.apenergy.2014.01.075
79. Kahwaji S, Johnson MB, Kheirabadi AC, Groulx D, White MA. A comprehensive study of properties of paraffin phase change materials for solar thermal energy storage and thermal management applications. Energy. 2018; 162:1169-82. https://doi.org/10.1016/j.energy.2018.08.068
80. Hasan MI, Tbena HL. Enhancing the cooling performance of micro pin fin heat sink by using the phase change materials with different configurations. 2018 International Conference on Advance of Sustainable Engineering and its Application (ICASEA); 2018. p. 205-9. https://doi.org/10.1109/ICASEA.2018.8370982
81. Hasan MI, Tbena HL. Using of phase change materials to enhance the thermal performance of micro channel heat sink. Eng Sci Technol Int J. 2018; 21(3):517-26. https://doi.org/10.1016/j.jestch.2018.03.017
82. Karami R, Kamkari B. Investigation of the effect of inclination angle on the melting enhancement of phase change material in finned latent heat thermal storage units. Appl Therm Eng. 2019; 146:45-60. https://doi.org/10.1016/j.applthermaleng.2018.09.105
83. Song L, Zhang H, Yang C. Thermal analysis of conjugated cooling configurations using phase change material and liquid cooling techniques for a battery module. Int J Heat Mass Transf. 2019; 133:827-41. https://doi.org/10.1016/j.ijheatmasstransfer.2018.12.157
84. Thesiya D, Patel H, Patange GS. A comprehensive review electronic cooling: A nanomaterial perspective. Int J Thermfl. 2023; 19:100382-2. https://doi.org/10.1016/j.ijft.2023.100382
85. Singh A, Rangarajan S, Sammakia B. Utilizing Ragone framework for optimized phase change material-based heat sink design in electronic cooling applications. Int J Heat Mass Transf. 2024; 227:125518-8. https://doi.org/10.1016/j.ijheatmasstransfer.2024.125518
86. Rosli MAM, Saleem SNDN, Sanusi N, Salimen N, Herawan SG, Abdullah Q. Performance optimization of a simulation study on phase change material for photovoltaic thermal. CFD Lett. 2022; 14(9):32-51. https://doi.org/10.37934/cfdl.14.9.3251
87. Cirillo L, Greco A, Masselli C. Development of an electronic circuit cooling system using elastocaloric effect: A FEM comparison among different configurations. Appl Therm Eng. 2023; 219:119463. https://doi.org/10.1016/j.applthermaleng.2022.119463
88. Masselli C, Cirillo L, Greco A. Cooling of electronic circuits through elastocaloric solid-state technology: A numerical analysis for the development of the CHECK TEMPERATURE prototype. Appl Therm Eng. 2023; 230, Part B:120729. https://doi.org/10.1016/j.applthermaleng.2023.120729
89. Narasimham GS. Natural convection from discrete heat sources in enclosures: An overview. Vivechan Int J Res. 2010; 1:63-78.
90. Mahdi MS. Natural convection in a vertical rectangular enclosure. Kirkuk J Sci. 2013; 8:1-16. https://doi.org/10.32894/kujss.2013.87984
91. Korichi A, Laouche N. Pulsed flow in a vertical channel with discrete heat sources. 2nd National Conference on Computional Fluid Dynamics and Technology; 2018. https://doi.org/10.2139/ssrn.3372913
92. Queipo NV, Gil GF. Multiobjective optimal placement of convectively and conductively cooled electronic components on printed wiring boards. J Electron Packag. 1999; 122(2):152-9. https://doi.org/10.1115/1.483148
93. da Silva AK, Lorente S, Bejan A. Optimal distribution of discrete heat sources on a plate with laminar forced convection. Int J Heat Mass Transf. 2004; 47(10-11):2139-48. https://doi.org/10.1016/j.ijheatmasstransfer.2003.12.009
94. Premachandran B, Balaji C. Mixed convection heat transfer from a horizontal channel with protruding

heat sources. Heat Mass Transf. 2004; 41(6):510-8. https://doi.org/10.1007/s00231-004-0570-0

95. Chaurasia NK, Gedupudi S, Venkateshan SP. Studies on three-dimensional mixed convection with surface radiation in a rectangular channel with discrete heat sources. Heat Transf Eng. 2017; 40(1-2):66-80. https://doi.org/10.1080/01457632.2017.1404826
96. Rathod MK, Banerjee J. Experimental investigations on latent heat storage unit using paraffin wax as phase change material. Exp Heat Transfer. 2013; 27(1):40-55. https://doi.org/10.1080/08916152.2012.719065
97. Janarthanan B, Sagadevan S. Thermal energy storage using phase change materials and their applications: A review. Int J Chemtech Res. 2015; 8:250-6.
98. Tauseef-ur- Rehman and Ali HM. Experimental investigation on paraffin wax integrated with copper foam based heat sinks for electronic components thermal cooling. Int Commun Heat Mass Transf. 2018; 98:155-62. https://doi.org/10.1016/j.icheatmasstransfer.2018.08.003
99. Hamza F, Mustapha F, El Alami Mustapha. Effect of nano-particles insertion on heat storage efficiency in a phase change material. 2019 International Conference on Wireless Technologies, Embedded and Intelligent Systems (WITS); 2019. p. 1-5. https://doi.org/10.1109/WITS.2019.8723693