Journal of Mines, Metals and Fuels, *72(8):843-861; 2024. DOI: 10.18311/jmmf/2024/45374*

Print ISSN : 0022-2755

Journal of Mines, Metals and Fuels

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

State-of-the-Art Cooling Solutions for Electronic Devices Operating in Harsh Conditions

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Abstract

The ongoing push for miniaturization and increased computational power in electronic devices has intensified thermal management challenges, especially in harsh environments with extreme heat, moisture, vapour, dust, and vibration. This paper provides a comprehensive analysis of both direct and indirect cooling methods, focusing on heat transfer efficiency, optimization techniques, and practical applications. It emphasizes the critical importance of thermal management for maintaining the performance, reliability, and durability of electronic systems under tough conditions. The review explores advanced materials and cooling technologies, including the role of Thermal Interface Materials (TIMs) in prolonging the lifespan of Integrated Circuits (ICs) and the use of Phase Change Materials (PCMs) in substrate boards for versatile thermal management. It also discusses the effectiveness of Liquid Cold Plates for battery module thermal management and the potential of micro-channel liquid cooling systems in Switching Mode Power Supplies (SMPS) boards. By offering detailed insights into thermal design principles, the paper guides engineers in optimizing IC chip placement and improving system reliability. Additionally, it examines the evolution of traditional cooling methods, the rise of innovative techniques like thermoelectric cooling, and the impact of advancements in materials, design, and manufacturing on energy efficiency and environmental sustainability. The review highlights promising research areas and emerging technologies, contributing to the development of more efficient, reliable, and eco-friendly cooling solutions for extreme environments.

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

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1.0 Introduction

In recent years, the exploration of effective thermal management for electronic components has emerged as a critical area of research, capturing the attention of numerous scholars. Meeting the escalating demands of heat dissipation from electronic components poses a significant challenge, resulting in elevated temperatures and the looming threat of overheating. Ensuring efficient thermal management methods becomes imperative for bolstering the resilience and longevity of electronic devices. Today, integrated circuits are utilized in nearly all electronic devices, deeply embedding various electronic products into modern life, as illustrated in Figure 1 Integrated Circuit (IC) chips predominantly crafted from silicon and housed on Printed Circuit Boards (PCBs), exhibit high sensitivity to temperature fluctuations. The Arrhenius law dictates that with every 20°C rise in chip temperature, the failure rate doubles, underscoring the urgent need for meticulously designed thermal strategies to prolong IC chip lifespan. Strategic chip placement on the PCB further optimizes cooling efficiency, thereby enhancing overall chip durability.

As the electronics industry undergoes rapid expansion and spatial optimization remains paramount, electronic component and IC chip dimensions continue to shrink. This downsizing, facilitated by modern technology, exacerbates heat generation within confined spaces, jeopardizing device performance and reliability. The ensuing surge in component density diminishes the area available for heat dissipation, exacerbating thermal management challenges due to restricted airflow and surface area for heat transfer.

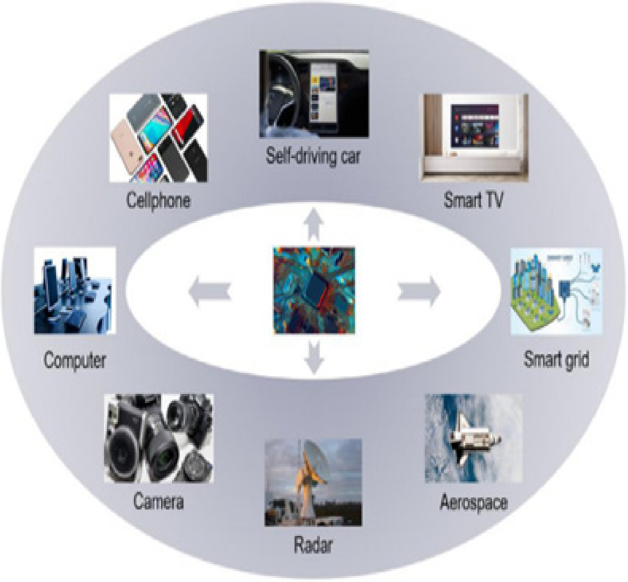

Figure 1. Application areas of integrated circuits[1].

The crux of the challenge lies in extending the IC chip lifespan through a spectrum of cooling methods while ensuring temperatures remain below critical thresholds. This necessitates a delicate balance between escalating heat production and the deployment of effective cooling strategies to fortify chip efficiency and reliability.

This review comprehensively addresses the formidable obstacles associated with electronic cooling, including heat dissipation, thermal management intricacies, and reliability apprehensions. It scrutinizes the limitations of conventional cooling techniques and underscores the urgency for innovative solutions to surmount these impediments. Encompassing both conventional and advanced cooling methodologies such as air, liquid, and phase-change cooling, alongside nascent techniques like thermoelectric and immersion cooling, the review illuminates recent strides in materials, designs, and manufacturing processes reshaping electronic cooling landscapes.

Moreover, the review delineates future research avenues and innovation prospects in electronic cooling, contemplating their ramifications on energy efficiency, sustainability, and cost-effectiveness. It also delves into challenges pertaining to integrating cooling systems into device designs and addressing thermal concerns in IoT technologies.

Key challenges in heat dissipation and thermal regulation for modern electronic devices include managing increased heat from higher power densities and limited space for cooling in compact designs. Thermal interface materials degrade over time, causing performance issues, and uneven heat distribution leads to hot spots. Heat management in multi-layered 3D ICs is complex, and balancing performance with energy efficiency is difficult due to material limitations. High temperatures can reduce device reliability, requiring designs that handle varying ambient temperatures. Active cooling solutions introduce noise and power consumption, and advanced cooling technologies need to be both cost-effective and compatible with current manufacturing processes.

In summation, this review aspires to provide insights into the current state of electronic cooling, identify areas ripe for enhancement, and chart a course for future research and development endeavors in this pivotal domain.

2.0 Cooling Methods

Electronic cooling methods encompass a variety of techniques designed to manage, the reliability, and longevity of electronic devices. These methods can be broadly categorized into traditional approaches and more advanced or emerging technologies as shown in Figure 2. Innovative cooling techniques play a critical role in improving the reliability and performance of IC chips. By maintaining stable temperatures, preventing overheating, and effectively managing hotspots, these techniques extend the lifespan and operational stability of chips. They also enable higher processing speeds, greater power efficiency, support for higher power densities, and improved signal integrity, all of which are crucial for the continued advancement of semiconductor technology.

2.1 Air Cooling

Air cooling is one of the most common and cost-effective methods of electronic cooling. It typically involves the use of fans or natural convection to circulate air around electronic components, facilitating heat transfer and dissipation.

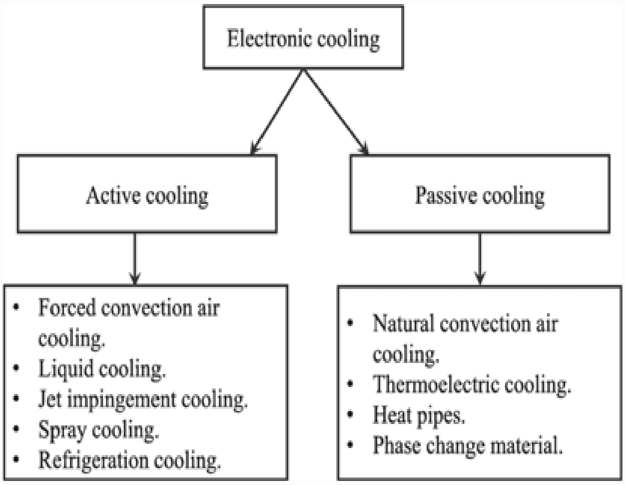

Figure 2. Different cooling ways.

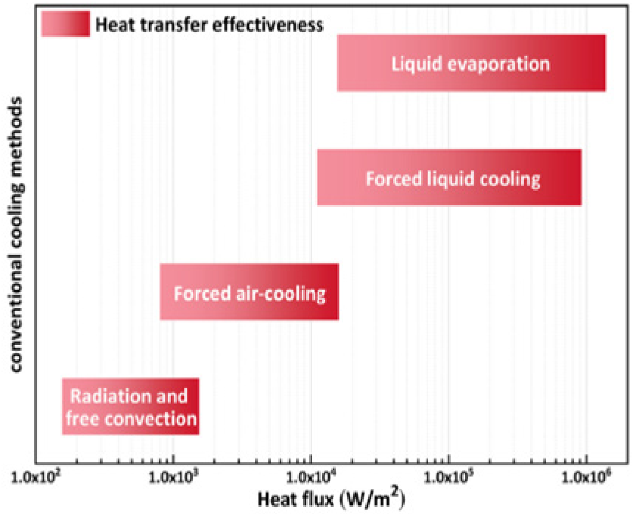

Figure 3. Heat flux density[2].

Figure 3 shows heat dissipation below 1550 W/m^2. Thus, forced air or liquid cooling is more reliable for high-power electronic devices. Traditional air cooling is cost-effective, simpler to maintain, and sufficient for most consumer electronics and general-purpose applications. Liquid cooling, while more complex and expensive, offers superior heat dissipation, making it the preferred choice for high-performance computing, overclocked systems, and scenarios requiring efficient thermal management. More straightforward and cost-effective, air cooling is suitable for moderate heat loads and applications with space constraints. However, it is less efficient for high-power or high-density scenarios and can struggle with heat dissipation in compact designs.

2.2 Liquid Cooling

Liquid cooling involves circulating a liquid coolant, such as water or a specialized cooling fluid, through channels or heat sinks attached to electronic components. Liquid cooling systems can provide more efficient heat transfer than air cooling and are often used in high-performance computing systems. Air cooling is generally sufficient for most consumer electronics and scenarios with moderate heat generation, offering simplicity and lower cost. Liquid cooling, on the other hand, provides superior thermal management and is better suited for high-performance, high-power-density applications where temperature control is critical, but it comes with higher costs and complexity. Provides superior heat dissipation and is effective for managing high thermal loads, making it ideal for high-performance and noise-sensitive applications. It is more complex and costly but offers better cooling efficiency and stability for demanding conditions.

2.3 Phase-Change Cooling

Phase-change cooling utilizes the latent heat of vaporization or condensation to absorb and dissipate heat from electronic components. This method typically involves the use of refrigerants or other volatile substances that undergo phase transitions to remove heat efficiently. Figure 4 shows phase change cooling with Steady-State Behavior of a Three-Dimensional Pool-Boiling System.

2.4 Thermoelectric Cooling

Thermoelectric cooling relies on the Peltier effect, where an electric current passing through a junction of two different materials generates a temperature difference. This temperature gradient can be used to transfer heat away from electronic components, although thermoelectric coolers are typically less efficient than

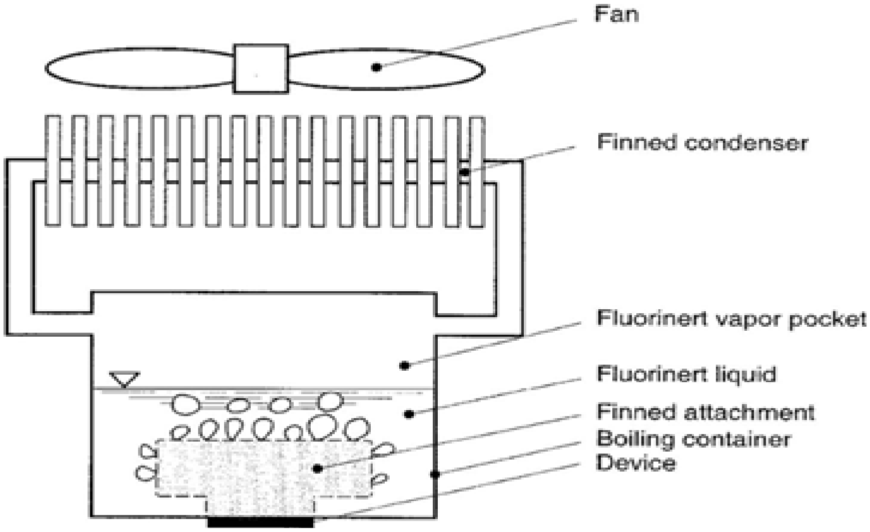

Figure 4. Phase change cooling[3].

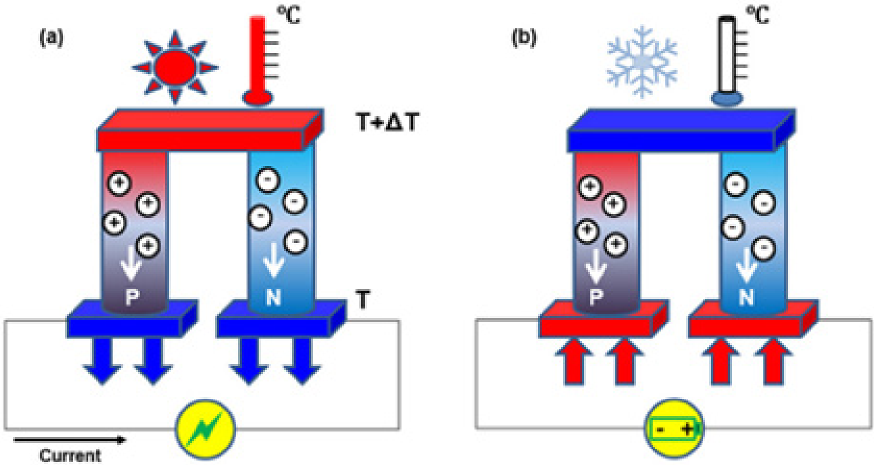

Figure 5. Schematic diagram of the TE module based on **(a)** Seebeck effect, **(b)** Peltier effect[4].

other methods. Thermoelectric cooling technologies offer precise, reliable, and compact cooling solutions but are limited by lower efficiency, cooling capacity, and higher costs. They are best suited for applications where their unique advantages provide significant value over traditional cooling methods explained in Figures 5(a-b). Thermoelectric cooling technologies offer several advantages, including compactness, precise temperature control, reliability, silent operation, and environmental friendliness. However, they are limited by lower efficiency, reduced cooling capacity, the need for additional heat dissipation, higher costs, and potentially high power consumption. These factors make TECs more suitable for niche applications where their unique benefits outweigh the limitations.

2.5 Immersion Cooling

Immersion cooling submerges electronic components or entire systems in a dielectric liquid coolant, such as mineral oil or synthetic fluids. The coolant absorbs heat from the components and carries it away, providing efficient and uniform cooling across all surfaces. Figure 6 illustrates how a PCB is cooled by immersing it in a liquid. Parts (c), (d), and (e) of the figure show pictures of bubbles forming under different levels of heat, captured with a high-speed camera.

2.6 Heat Pipes

Heat pipes are heat transfer devices that utilize the phase transition of a working fluid to transport heat from one location to another. They are often used to transfer heat away from electronic components to heat sinks or other cooling elements.

2.7 Phase Change Material

Phase Change Materials (PCMs) are gaining significant attention in electronic cooling due to their unique properties, such as low thermal conductivity, specific

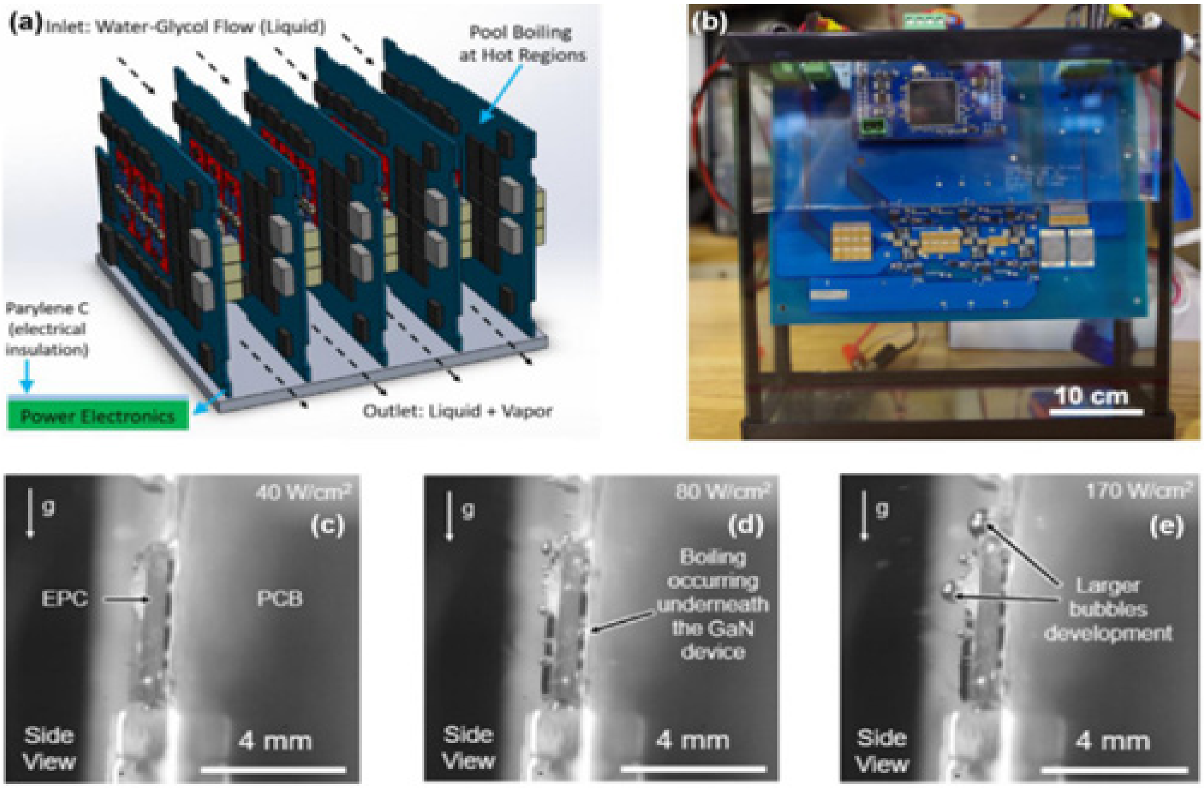

Figure 6. Schematic overview of immersion cooling for a printed circuit board in parts **(a)** and **(b)**. Parts **(c)** through **(e)** display images of bubble formation captured using a high-speed camera under varying heat conditions[3].

melting points, and latent heat of fusion, which enable thermal energy storage. These materials transition between solid and liquid with temperature changes, without vaporizing, making them ideal for electronic cooling, solar energy, and battery thermal management. PCMs are chosen based on their melting points and thermal conductivity to suit specific applications. Kurhade *et al.*[5-7] studied the smartphones and their thermal performance. Anant *et al.*[8] used phase change material to minimise the temperature of chips and found that N-eicosane controls the system's temperature, and its values vary from 53.234 degrees Celsius in the general model to 51.520 degrees Celsius and drop in temperature of 0.5 degrees Celsius when compared to the paraffin wax and 1.35 degrees Celsius compared to the ATP 78. N-eicosane has the potential to reduce junction temperature by increasing PCM's latent storage capacity.

2.8 Heat Sinks

Heat sinks are passive cooling devices designed to absorb and dissipate heat from electronic components by increasing the surface area available for heat transfer. They are typically made of materials with high thermal conductivity, such as aluminium or copper.

2.9 Hybrid Cooling Systems

Hybrid cooling systems combine multiple cooling methods, such as air and liquid cooling, to achieve enhanced thermal management and efficiency. These systems are often tailored to specific applications or environments to optimize performance and reliability.

Innovative cooling techniques greatly improve the reliability and performance of IC chips by keeping optimal temperatures, minimizing thermal stress, and allowing for higher performance. This supports the development of more advanced and energy-efficient chip designs, driving progress in electronic technology.

Waware *et al.*[9-11] provide critical reviews on heat transfer and Heat Transfer Enhancement in Tubular Heat Exchangers with Jet Impingement. Rahul Khot *et al.*[12-17] explain the investigation of Laser Welding Parameters on the Strength of TRIP Steel. Gadekar T.D. *et al.*[18-20] explain an Experimental Study on Gear EP Lubricant Mixed with $Al_2O_3/SiO_2/ZrO_2$ Composite Additives to Design a Predictive System. Patil, P *et al.*[21] used a water-based Al_2O_3 nanofluid was used in this work to grind materials due to its outstanding convective heat transfer and thermal conductivity qualities.

Effective electronic cooling solutions rely on both design and manufacturing techniques. Optimized design ensures proper component placement, efficient thermal paths, appropriate material selection, and integration of cooling systems. Advanced manufacturing provides precision, reliable thermal interfaces, custom component fabrication, and strict quality control. Combined, these techniques enhance thermal management, boosting device performance, reliability, and longevity. Effective electronic cooling is crucial for preserving and improving the performance, reliability, and lifespan of modern electronic devices. It aids in energy efficiency, ensures user safety, and facilitates the creation of compact, high-performance technologies. By tackling thermal management issues, manufacturers can develop more durable and sustainable electronic products that cater to the ever-changing demands of today's technological environment.

Progress in materials science, such as the creation of materials with excellent thermal conductivity such as graphene, nanostructured composites, and engineered phase change materials, is leading to more effective and dependable thermal management solutions. These materials enhance heat dissipation and bolster the overall performance, dependability, and lifespan of electronic devices across various uses.

Each of these cooling methods has its advantages and limitations, and the choice of cooling technique depends on factors such as the heat dissipation requirements, space constraints, cost considerations, and performance goals of the electronic system. Ongoing research and development efforts continue to refine existing cooling technologies and explore innovative approaches to address the evolving challenges of electronic cooling in an increasingly complex and demanding technological landscape.

The main challenges in heat dissipation and thermal regulation in modern electronics include managing increased power density in compact designs, overcoming material limitations, and addressing hotspot formation, all while balancing energy efficiency, reliability, environmental adaptability, cost, and aesthetics. These issues necessitate innovative materials, advanced cooling techniques, and thoughtful design to ensure efficient and reliable device operation. Innovative cooling techniques significantly enhance the reliability and performance of IC chips by providing better temperature control, preventing overheating, and managing hotspots effectively. They enable higher processing speeds, improve power efficiency, support higher power densities, and preserve signal integrity. By addressing thermal challenges, these cooling solutions contribute to the development of more robust, high-performing, and reliable electronic systems.

The thorough analysis of available literature centres on the interrelated topics pertinent to the present investigation.

1. Research exploring the ideal arrangement of individual heat sources
2. Investigations into the impact of surface radiation on electronic component cooling
3. Research examining hybrid cooling methods for electronic systems.
4. A comprehensive examination of liquid cooling for individual heated modules

Table 1 shows Literature relevant to the ideal arrangement of individual heat sources, Investigations

Table 1. Literature relevant to the ideal arrangement of individual heat sources, Investigations into the impact of surface radiation on electronic component cooling, hybrid cooling methods for electronic systems and liquid cooling for individual heated module

Compilation of Literature Relevant to the Ideal Arrangement of Separate Heat Emitters						
S. No.	**Authors and references**	**Method used**	**Mode used NC, FC, MC**	**Working fluid**	**Temperature drop/heat flux removal**	**Electronic component (size)**
1	Queipo *et al.*[22]	Experimental Genetic Algorithms	NC	Air	--	IC chips
2	Liu *et al.*[23]	Experimental GMR	FC	Air	90 °C	Five identical heat sources (20cm X0.635cm)
3	Liu and Phan-Thien[24]	Numerical and Optimization	NC	Air	--	Three identical IC chips
4	Ozsunar *et al.*[25]	Numerical ANN	NC	Air	45°C -50 °C	Single heating element
5	Sudhakar *et al.*[26]	Experimental, Numerical ANN	FC	Air	5–25 W	15 square heat sources (1.5cm X 1.5cm)
6	Kadiyala and Chattopadhyay[27]	Numerical ANN and GA	NC	Air	44°C	--
7	Athavale et al.[28]	Numerical ANN and POD	NC	Water	40 °C	Data centers
8	Mathew and Patil[29]	Numerical Fuzzy logic	NC, FC and MC	Air	0.15W/ cm^2- 0.2 W/ cm^2 53.29 °C	Five non-identical IC chips

Compilation of Literature Relevant to the Influence of Surface Radiation on Electronic Component Cooling						
1	Patra *et al.*[30]	Analytical	NC and Radiation	Air	--	--
2	Vasu *et al.*[31]	Analytical and Numerical	NC and Radiation	Air	--	--
3	Kanna *et al.*[32]	Experimental	FC	Water, Alcohol and Petrol	10 -60W	Square heated element (3.5cm X 3.5cm)
Compilation of Literature Relevant to Hybrid Cooling Systems						
1	Delia *et al.*[33]	Liquid cold plate	FC	Water Experimental	27W, 64 W/ cm^2	IBM system processor 121 chips
2	Knight *et al.*[34]	Heat sink	Condition and convection	Water Experimental	12.2W	20 square heat sources, $0.635cm^2$
3	Lee[35]	Heat sink	FC	Water Experimental	--	--
4	Lee[36]	Heat sink –liquid cold plate	FC	Water Numerical	1200W, 100 °C	Square IGBT (0.95cm X 0.95cm)
5	Hetsroni *et al.*[37]	Micro-channel heat sink	FC	Dielectric liquid Experimental	160-400KW/ cm^2	Square electronic device, $10mm^2$
6	Kang *et al.*[38]	Closed loop liquid cold plate	FC	Water Experimental	500 W/ cm^2	High-power electric devices
7	Nguyen *et al.*[39]	Heat sink	FC	Al_2O_3-Water Experimental	100W	CPU micro-processor (6cm X 6cm 7.5cm)
8	Wei *et al.*[40]	Stacked micro-channel heat sinks	FC	DI water Experimental	18W and 70W	Micro-electronic chip (1cm X 1cm)
9	Williams and Roux[41]	Liquid cold plate	FC	Water Experimental Numerical	20-42W	Power amplifier chip (0.94cm X 0.94cm)
10	Acikalin and Schroeder[42]	Cold plate-based indirect channel heat sink	FC	Water Experimental	300W	Die package electronic, (1.18cm X 1.18cm)

11	Sohel *et al.*[43]	Mini-channel heat sink	FC	Experimental TiO_2-Water and SiC-Water	2 heater each 200W	Electronic chips
12	Ge *et al.*[44]	Heat sink	FC and NC	Numerical GA	--	Electronic devices
13	Arun and Kumar[45]	Cooling of electronic system	All convective mode	--	--	Electronic devices
14	Wang *et al.*[46]	Liquid cold plate	FC	Water	238.80W, Tmax=42°C	Electronic devices
15	Andersson *et al.*[47]	Heat sink	FC and Numerical	Water based Nano-particles	23W	Electronic devices
16	Tan *et al.*[48]	spider netted micro-channel heat sink and straight micro-channel	FC	Water	10 to 100W/cm^2	Electronic device
17	Chen and Ding[49]	Heat sink	FC	Experimental Water - $_{\gamma}$Al2O$_3$		Electronic devices
18	Back *et al.*[50]	Micro-channel heat sinks (MRNH)	FC	Dielectric fluid HFE-7100	2870 W/cm^2 and 112°C	High-power electric devices
19	Erp *et al.*[51]	Micro-channel heat sinks (MRNH)	FC	Water	4.62 to 26.2 W/cm^3, 70°C	Ultra-high power density power
20	Liu *et al.*[52]	Micro-channel heat sinks (MRNH & MRSH)	FC and Numerical	Water	100 W and 62W/cm^2	Six film resistors (1.15cm X 1.4cm)
Compilation of Literature Relevant to liquid cooling for individual heated modules						
1	Honnor and Thomas[53]	Critical review	Free, Forced and Mixed	FC-72 and FC-87	100W/cm^2	Square chips (1.27cm X 1.27cm)
2	Baker[54]	Experimental and Analytical	Free and forced	Freon-113 and silicon dielectric liquid	500-10000 W/m^2	Small micro-electronic chips, (2cm X 2cm) and resistors
3	Tuckerman[55]	Experimental	FC	water and dielectric liquids	20 W/cm^2 and 108°C	densely-packed IC chips
4	Kiper[56]	Experimental	FC	Water	500 W/cm^2 and 80^{o}C	VLSI circuits (8cm X 8cm)

5	Incropera *et al.*[57]	Experimental	FC	Water FC-77	80-100°C	Square IC chips (1.27cm X 1.27cm)
6	Samant and Simon[58]	Experimental	FC	R-113 and FC-72	2.04MW/m^2 and 80°C	Small electronic patch 0.025cm X 0.2cm
7	Agbim[59]	Experimental Numerical	FC	Water	180-230W/cm^2	Power electronic devices (MOSFETs, HEMTs and IGBTs
8	Carmona and Keyhani[60]	Experimental	FC	Ethylene glycol and FC-75	11W	16.5cm X 14.1cm X 0.65cm
9	Joshi *et al.*[61]	Experimental	Free convection	Water	45 W/cm^2	Rectangular chips (23.7mm X 7.6mm X 10.18mm)
10	Jaeger *et al.*[62]	Experimental	FC	Freon-12	200 W/cm^{2}and 50K	
11	Mudawar and Maddox[63]	Experimental	FC	FC-72	106 W/cm^2	Square chips (1.27cm X 1.27cm)
12	Wadsworth and Mudawar[64]	Experimental	FC	FC-72	100W/cm^2	3x3 Square array chips (1.27cm X 1.27cm)
13	Mahaney *et al.*[65]	Experimental	MC	FC-77 and water	50 - 200W/cm^2	3 X 4 arrays of VLSI chips (1.27cm X 1.27cm)
14	Besserman *et al.*[66]	Experimental	FC	Water and dielectric fluorocarbon	248 W/cm^2	Square electrical heater (1.27cm X 1.27cm)
15	Schafer *et al.*[67]	Experimental	FC	FC -72 water and FC-77	40 W/cm^2 -250 W/cm^2	Square IC chips (1.27cm X 1.27cm)
16	Ali and Ramadhyan[68]	Experimental	FC	FC-72 and FC-77	50 W/cm^2	Square IC chips (7.6cm X 7.6cm)

17	Gersey and Muddawar[69]	Experimental	FC	FC-72	0.13 - 120 W/cm^2	Square IC chips (1cm X 1cm)
18	Heindel *et al.*[70]	Experimental	FC	Water and FC-77	2W	Square IC chips (2.54cm X 2.54cm)
19	Maddox and Bar-Cohen[71]	Experimental	FC	Water and FC-77	100W, 80°C	Square IC chips (1cm X 1cm)
20	Lam and Prakash[72]	Numerical and Optimization	FC	Water and Al_2O_3	--	Cooling of Hot spot
21	Heindel *et al.*[73]	Experimental	Conjugate natural convection	Water and FC-77	65 - 80°C, 0.35 - 28.2 W/cm^2	Square IC chips (1.27cm X 1.27cm)
22	Estes and Mudawar[74]	Experimental	FC	Water and FC-72	83W/cm^2	Square IC chips (1.27cm X 1.27cm)
23	Gupta and Jaluria[75]	Experimental	FC	Deionized water	400W	3 X 4 arrays (1.27cm X 1.27cm X 0.55cm)
24	Tou *et al.*[76]	Experimental	FC	FC-72 and Water	100 - 200W/cm^2	Square IC chips (1cm X 1cm)
25	Leena *et al.*[77]	Experimental Numerical	FC	--	--	Square copper block (7.4cm X 7.4cm)
26	Chang[78]	Experimental Numerical	FC	Water	17-20 MW/m^2	
27	Wang *et al.*[79]	Numerical Analytical	FC	Water and FC-72	1.3 - 5.4 W/cm^2	High-performance electronic device (23.3cm × 16cm)
28	Cheng *et al.*[80]	Experimental	FC	FC-72	60°C, 60 - 70 W/cm^2	Rectangular resistors (12.7mm X 8mm)
29	Saini and Web[81]	Experimental And Optimization	FC	Air and water	80°C and 103.4W	8cm X 6cm

30	Mcglen *et al.*[82]	Experimental and Numerical	FC	Water	17-20 MW/m^2	Square IC chips (1cm X 1cm) Electronic devices (resistors, diodes, logical gates)
31	Overholt *et al.*[83]	Experimental	FC	Water	300-1000 W/cm^2	Square Electronic components (1cm × 1cm)
32	Bhowmik and Tou[84]	Experimental	FC	FC-72	1 - 7 W/cm^2	Square chips (1cm × 1cm)
33	Fabbri and Dhir[85]	Experimental	FC	Deionized water and FC-40	310 W/cm^2 and 73.9°C	Six rectangular heaters 7.62cm X 2.65cm
34	Robinson and Schnizler[86]	Experimental	FC	Water	300W	Cylindrical heater Dia 3.15cm and 30cm long
35	Flores *et al.*[87]	Experimental	MC	--	727-2970W/m^2	Square heat source
36	Maddox *et al.*[88]	Experimental	FC	Deionized water	45-60°C	Heater block 10.16cm X 10.16cm X 7.63cm
37	Sung and Muddwar[89]	Experimental	FC	PF-5052 Dielectric	1000 W/cm^2	4 X 4 cartridge heaters
38	Colgan *et al.*[90]	Experimental	FC	--	300-400 W/cm^2 and 63°C	
39	Amon *et al.*[91]	Experimental	FC	HFE 7200	100W/cm^2	Square chip (2.54cm X 2.54cm)
40	Ijam and Saidur[92]	Experimental	FC	TiO_2-water	--	--
41	Calame *et al.*[93]	Experimental	FC	Water	1.5 - 3.9 kW/m^2, 203°C	0.36cm X 47cm
42	Naphon and Wongwises[94]	Numerical	FC	Water with TiO_2, CuO, Al_2O_3	--	CPU of the computer
43	Roberts and Walker[95]	Experimental	FC	Aluminium - Water nanoparticles	--	Coper block

into the impact of surface radiation on electronic component cooling, hybrid cooling methods for electronic systems and liquid cooling for individual heated modules.

3.0 Summary of Findings and Identified Research Gap from the Literature

Researchers have extensively studied the cooling of discrete heat sources using natural, forced, and mixed heat transfer modes, typically employing identical geometries. While flush and protruding heat sources with 1D and 2D geometries are common, there is potential for exploring 3D protruding heat sources. Combined modes of heat transfer for cooling have also been investigated. Numerical analyses such as FEA, CFD-Fluent (FVM), Gambit, Flotherm, and MATLAB, along with optimization techniques like DOE, the Taguchi Method, Sequential Quadratic Programming, and genetic algorithms, have been utilized. Various hybrid cooling methods have been explored. However, research gaps include limited studies on cooling under combined heat transfer modes, non-uniform spacing, and non-identical heat sources, with most studies focusing on 2D geometries and steady-state heat transfer. Additionally, literature on hybrid cooling methods is scarce. In addition Kurhade *et al.*[96-100] focuses on improving the thermal management of electronic components, particularly in Switch-Mode Power Supply (SMPS) boards. The study examines how the thermal conductivity of the substrate board affects component temperatures and explores the effectiveness of using Phase Change Materials (PCMs) for heat dissipation. Both numerical simulations and experimental testing were conducted to analyze the influence of different substrate materials and cooling methods on the overall thermal performance of the electronic components. Kurhade *et al.*[101-104] explores various sustainable energy applications. First, it investigates the performance of solar collectors constructed from recycled aluminum cans for drying purposes. Secondly, a comprehensive study evaluates the use of biodiesel derived from *Calophyllum inophyllum* and dimethyl carbonate blends in diesel engines, focusing on optimizing performance and reducing emissions. Lastly, the project delves into aerodynamic efficiency, analyzing aerofoil design through computational fluid dynamics (CFD) simulations and wind tunnel experiments. Additionally, fuzzy logic techniques are employed to predict heat transfer enhancement in heat exchangers using twisted tape inserts.

4.0 Future Scope

Future research in cooling technologies should prioritize the development of innovative techniques, such as advanced liquid cooling systems and thermoelectric cooling devices, to enhance thermal management efficiency and reliability. Exploration of advanced materials, including nanomaterials and composites, could lead to superior heat sinks and thermal interface materials. Integrating cooling systems seamlessly into the design of miniaturized devices, like IoT sensors and wearables, requires innovative thermal management approaches that address space constraints and power limitations. Additionally, enhancing the environmental sustainability of electronic cooling systems should be a priority, focusing on eco-friendly cooling fluids and waste heat recovery technologies. Thermal design engineers can enhance IC chip placement and cooling by strategically positioning heat-generating components, optimizing layout for airflow, and leveraging advanced cooling technologies like liquid cooling and thermoelectric systems. Employing high-performance TIMs, using PCMs for thermal buffering, and conducting thorough thermal analysis are also crucial for effective cooling. Balancing performance with cost considerations ensures that the cooling solutions are both efficient and economical.

5.0 Conclusion

In conclusion, effective thermal management is paramount for ensuring the performance, reliability, and longevity of electronic devices operating in demanding environments. This paper has provided a comprehensive overview of state-of-the-art cooling techniques, including direct and indirect methods, with a particular focus on their application in mitigating thermal challenges posed by extreme heat, moisture, vapour, dust, and vibration. By understanding heat transfer principles and optimizing IC chip placement, thermal design engineers can significantly improve system reliability. Furthermore, this paper emphasizes the importance of adopting a holistic approach to thermal management, considering factors such as material advancements, design innovations, and manufacturing processes. As electronic devices continue to evolve, the development of novel cooling technologies and strategies will be essential to meeting the increasing demands for performance and efficiency while minimizing environmental impact. Future research should focus on exploring advanced materials, innovative cooling techniques, and integrated thermal management solutions to address the challenges posed by next-generation electronic systems. By combining theoretical advancements with practical applications, the electronics industry can develop more robust and sustainable products capable of operating reliably in the most demanding conditions.

Key areas for future research include:

1. Development of high-performance TIMs and PCMs with enhanced thermal conductivity and phase change properties.
2. Exploration of novel cooling techniques, such as two-phase cooling, jet impingement cooling, and thermal metamaterials.
3. Integration of thermal management systems with power electronics and energy storage components.
4. Development of advanced simulation tools for accurate thermal modelling and optimization.

By investing in research and development in these areas, the electronics industry can create a foundation for a future where thermal management is no longer a limiting factor in device performance and lifespan. Designing electronic devices involves a careful balance of thermal management, performance optimization, and practical constraints. By prioritizing effective cooling, optimizing component placement, and addressing reliability, efficiency, and environmental factors, engineers can create robust and high-performing electronic devices. Staying informed on new technologies and fostering collaboration are also essential for successful design outcomes.

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