# A Case study on the Modern state of art in Electrical and Electronic Devices Cooling

Rekha P [1], Vishalakshi V [2], Chamaraju Y S [3]

[1] *Lecturer, Department of Electrical and Electronics Engineering, Government Polytechnic Arakere, Karnataka, India.*
[2] *Lecturer, Department of Electrical and Electronics Engineering, Government Polytechnic Channapatna, Karnataka, India.*
[3] *Lecturer, Department of Electronics and Communication Engineering, Government CPC polytechnic Mysore, Karnataka, India.*

## ABSTRACT

Cooling or thermal management concerns are confronting serious challenges as electrical and electronic devices continue to miniaturize and heat flow increases rapidly. Significant work has been put into developing high-efficiency cooling and adaptable thermal management technologies, as well as accompanying design tools. This article highlights the most recent advances and state-of-the-art in electrical and electronic cooling, which may inspire future study. The generally utilized techniques of electrical and electronic cooling, classed as direct and indirect cooling, are examined and explored in depth. Direct cooling includes air cooling, spray and jet impingement cooling, immersion cooling, and droplet electrowetting. The most common and hot subjects in indirect cooling are the use of microchannel, heat pipe, vapour chamber, thermoelectric, and PCM. The efficiency of thermal management strategies for various levels of electrical and electronic cooling requirements, as well as approaches to increase heat transfer capabilities, are discussed in detail. Meanwhile, the advantages and disadvantages of various thermal management technologies are explored in terms of their intrinsic heat transfer performance/characteristics, optimization approaches, and applicable applications. In addition, the present issues of electrical and electronic cooling and thermal management technologies are discussed, as well as potential future developments.

**Keywords:** Electrical and electronic, Thermal management, Heat flow, Cooling, Modern state.

## 1. INTRODUCTION

Since Werner Jacobi established the early notion of the integrated circuit in 1949 [1], the integrated circuit has evolved fast over the last 50 years. An integrated circuit is typically a tiny chip consisting of the semiconductor material silicon, created using a several-nanometer process, and capable of accommodating millions to billions of microstructures such as transistors, resistors, and capacitors. Nowadays, integrated circuits are utilized in practically all electronic devices, and modern life is inextricably linked to diverse electronic items, as seen in Figure 1. These applications have dramatically increased the efficiency and quality of modern people's labor, manufacturing, and lives. The renowned "Moore's Law" was proposed in the 1960s, in response to the rapid expansion of the integrated circuit industry [2]. Although "Moore's Law" is primarily an empirical connection in production rather than natural law, its correctness has been demonstrated for decades, and the rule has been widely utilized to influence semiconductor industry research and development objectives. Based on "Moore's law," the number of transistors that can be accommodated on the integrated circuit will continue to increase, as illustrated in Fig. 2 (a). Simultaneously, with increased market demand, modern electronic products are becoming smaller, thinner, and lighter. However, more transistors and a smaller device size result in increased power and heat flux density. The heat flux density of sophisticated server equipment chips can approach 1 MW/m$^2$, while phased array radar and other equipment may reach 5-10 MW/m$^2$ [3]. As a result, these conditions provide significant difficulties to thermal management solutions in order to keep operations within acceptable limits. According to a research done by the US Air Force Avionics Integrity Program [4], temperature issues are responsible for roughly 55% of electronic equipment failures, as illustrated in Fig. 2 (b). Furthermore, Black's equation [5] shows that increasing temperature will hasten the breakdown process of electrical equipment. As a result, dealing with temperature difficulties in electrical equipment has grown in importance in recent years.

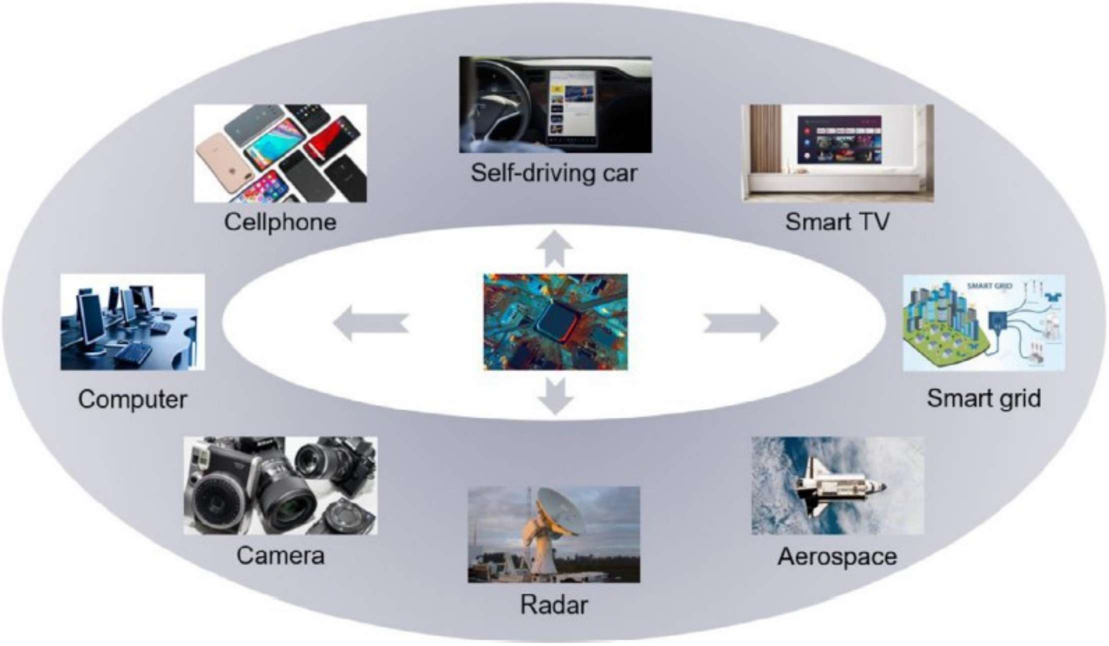

**Fig. 1 : Typical uses for integrated circuits.**

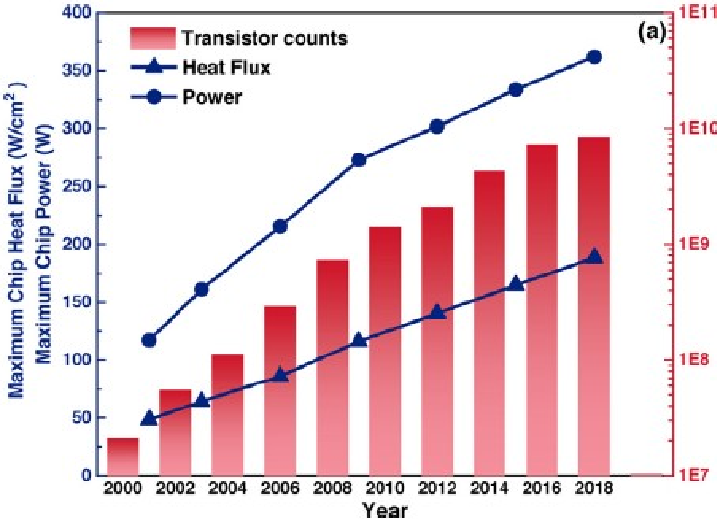

**Fig. 2 : (a) The development trend of chip maximum power consumption, heat flux density, and approximate transistor counts in the past 18 years**

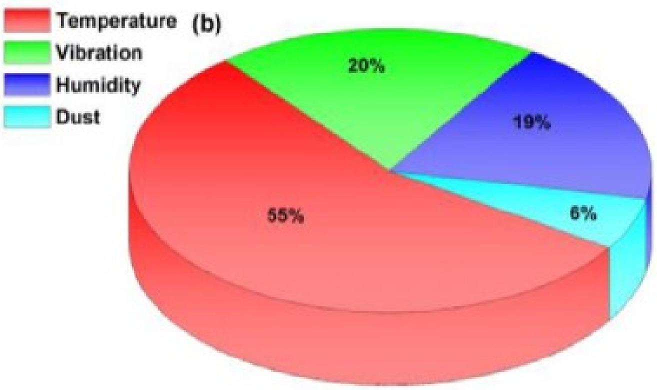

**Fig. 2 : (b) Distribution of failure causes of electrical and electronic equipment.**

As previously said, heat generation is growing as the integrated circuit manufacturing process continues to improve. As a result, the integrated circuit industry requires effective thermal management solutions, which are projected to continue enhancing the performance and durability of electronic devices. Even while traditional air cooling may handle heat dissipation difficulties by optimizing heat sink design for some conventional electronic equipment [7], additional cooling techniques for sophisticated high-performance electronic devices are necessary. As a result, as seen in Fig. 3, a variety of electronic cooling approaches have been presented and thoroughly investigated.Typically, these thermal management techniques are separated into active and passive cooling strategies [8]. The primary distinction between them is that passive cooling systems rely on natural convection, whereas active cooling systems require additional energy, often electric energy, to improve the heat dissipation capabilities of the heat sink. Naturally, active cooling systems have superior heat transfer capabilities, thus most cooling methods are evolving around active cooling and are extensively employed in the thermal management of high-power electronic equipment. As a result, active cooling systems are thoroughly discussed in this review article due to their superior heat transfer performance and wide variety of applications. Furthermore, as seen in Fig. 3, thermal management methods are classified as coolings with direct or indirect contact with the cooling fluid, depending on whether the cooling medium makes contact with the objectives.

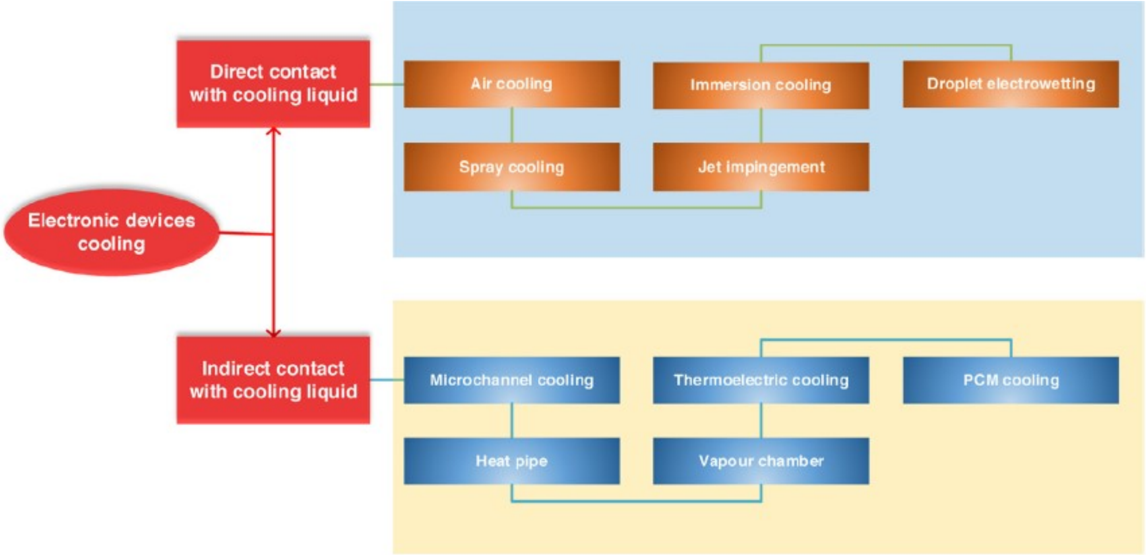

**Fig. 3 : Classification of commonly used thermal management methods.**

Liquid cooling has received increased attention for direct contact cooling since it dissipates heat more effectively than conventional air cooling. Spray cooling is one of the most frequently researched of these [9, 10]. Spray cooling uses high-pressure pumps and nozzles to atomize droplets, which then cover an electronic device's whole heating surface (insulating surface). Spray cooling provides the advantages of high heat transmission, great temperature homogeneity, and a large cooling surface. Jet impingement cooling is comparable to spray cooling, but does not need droplet atomization. The work on jet impingement heat transfer improvement focuses on optimisation of jet parameters, liquid characteristics, and heating surface structures [11]. Furthermore, the immersion cooling technology provides great cooling performance and may be applied to data centers [12] and servers [13]. Similarly, researchers use droplet electrowetting to regulate hot spots in electronic equipment. Because surface wettability may be adjusted to regulate droplet motion, the design of surface structures or mophologies may have a considerable impact on heat management methods. Indirect cooling technologies, which relate to the coolant dispersing heat through heat sinks, have also been thoroughly investigated and widely utilized. The pipeline heat exchanger is the most typical component found in external heat sinks. Unlike direct contact cooling, indirect contact cooling must account the contact thermal resistance of external heat sinks. Thus, thermal interface materials (TIMs) are proposed and play an important role in the thermal control of electronic devices [14]. The microchannel heat sink is popular among indirect cooling technologies because to its excellent heat transfer capabilities and small size. As a result, microchannel cooling is frequently employed for thermal control in compact and high-power electronic equipment. The primary goal of microchannel heat sink optimization is to strike a balance between reduced flow resistance and increased heat transfer. Much study has been conducted to investigate the influence of microchannel construction parameters [15], liquid properties [16, 17], and the phase change process [18, 19] on flow and heat transfer performance. Furthermore, heat pipes and vapour chambers as con-duct heat devices are widely utilized in the thermal management of electronics. Heat pipes and vapour chambers often use similar operating principles, such as wick structures and a two-phase flow and heat transmission method. Both would pass through the liquid, which evaporates in the hot end and condenses in the cold end, before returning to the hot end via the wick structure and capillary force. The heat transfer characteristics in the heat pipe and vapour chamber are usually one-dimensional heat transport and two-dimensional heat spreading [20]. Miniaturization and high efficiency of heat pipes and vapour chambers are now being researched to make them appropriate for smaller-sized electronic devices such as laptops and smartphones. Many research have focused on this problem, which will be examined in depth in this review article. In addition, the thermoelectric (TE) cooler is one of the viable options for thermal control of electronic equipment. It has the advantages of being noise-free, polluting-free, and having a long operating life, thus many research focus on optimizing TE material to increase cooler working performance [21]. Furthermore, the phase change material (PCM) cooling approach is a viable thermal management solution. It is based on the idea of latent heat storage, which keeps the temperature constant while providing a high energy storage density [22]. For electronic devices with pulsed heat flux density, the PCM-based heat sink may efficiently absorb heat during pulse operation and restore it to the device during low-temperature operation, allowing the operating temperature of electronic devices to remain reasonably steady. So far, various research have been undertaken to optimize the structures of PCM-based heat sinks [23], enhance PCM properties [24], and examine integration with other types of thermal management devices [25].

Overall, the background of electronic device cooling is addressed and summarized. The current paper provides a complete evaluation of cutting-edge thermal management strategies for electronic devices, with a focus on active cooling.

## 2. DIRECT CONTACT WITH COOLING FLUID

The simplest and most cost-effective technique to do electronic thermal management is to employ natural or free convection cooling. Meng et al.'s [26] investigation of the impact of mounting angle on natural convection heat transfer was based on this. According to the findings, the straight-fin heat sink performs best at 90° mounting angles and poorest at 15° installation angles. However, as Figure 4 illustrates, radiation and free convection are only advised for heat dissipation that is less than 1550 W/m 2 of heat flux density [27]. Therefore, liquid or forced air cooling is more dependable for high-power electrical equipment. There are two categories for externally induced cooling based on thermal management techniques. First, the electronic device's surface is immediately impacted by the cooling fluid (air or liquid). In order to increase the heat exchange area and improve the heat transfer process even further, the heat is subsequently dispersed via an intermediary heat sink. These days, there isn't much research done on natural cooling for electronics [28]. One possible explanation might be that natural cooling is an established technology used in low-power gadgets like TVs and VCRs [29]. For data centers and other thermally managed locations, forced liquid cooling—with or without phase change—is essential. Therefore, this article will provide a thorough overview and discussion of the thermal management techniques that use liquid as the cooling medium.

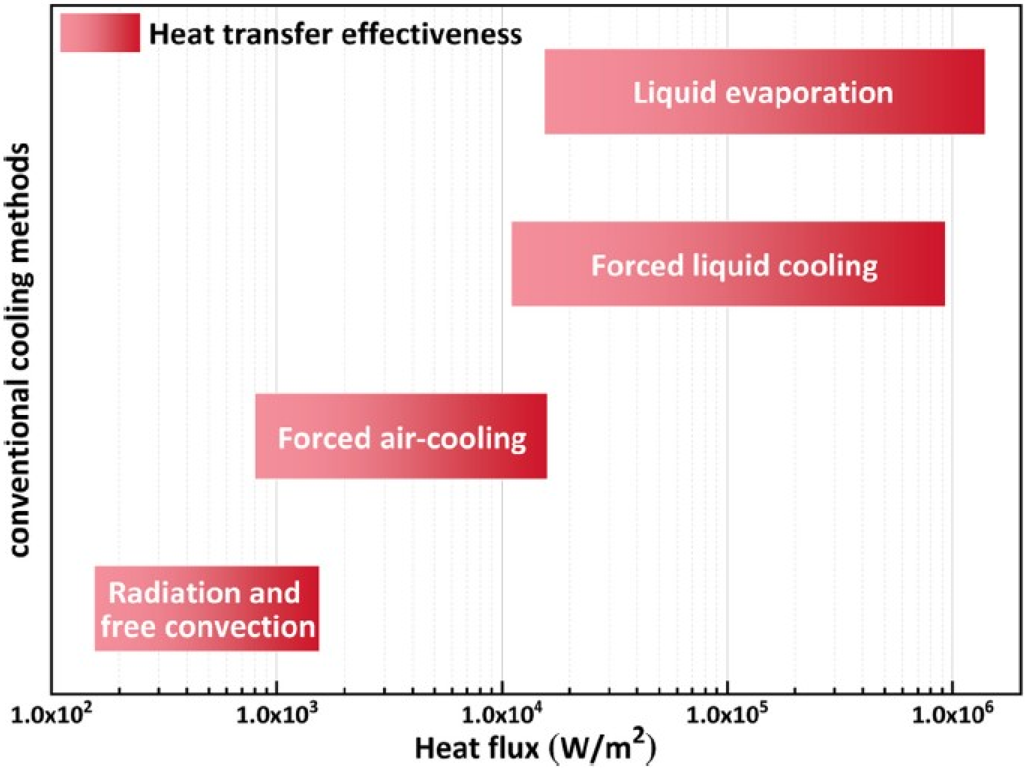

**Fig. 4 : The range of heat flux density applies to conventional cooling methods.**

Spray cooling's large cooling surface and strong heat flux dissipation capacity make it one of the best thermal management techniques for high-power electronic devices [9]. It employs a nozzle to apply high pressure, causing the cooling fluid to split up into many small droplets. The droplets then make direct contact with the heated surface, which improves heat transmission. The practical spray-cooling process may be broken down into three steps at varying wall temperatures, as seen in Fig. 5. The first stage is known as the single-phase regime, during which the cooling fluid's phase does not really change and the wall temperature stays in a lower range while increasing almost linearly. After then, the spray cooling would transition to a two-phase regime with a rise in surface temperature, and the curve's slope would greatly increase. The energy barrier that improves heat absorption must be broken through the bubble nucleation process, which requires a lot of energy. Moreover, the collision of droplets agitates the liquid layer, which enhances heat transmission efficiency. Eventually, the heat flow will cease to rise when the surface temperature reaches a particular critical threshold. There are several variables and conditions that might impact spray cooling. These may be divided into three categories based on the spray cooling system's spatial configuration: heating surface attributes, cooling fluid characteristics, and nozzle parameters. These variables are connected to one another regarding the impact of the spray cooling mechanism.

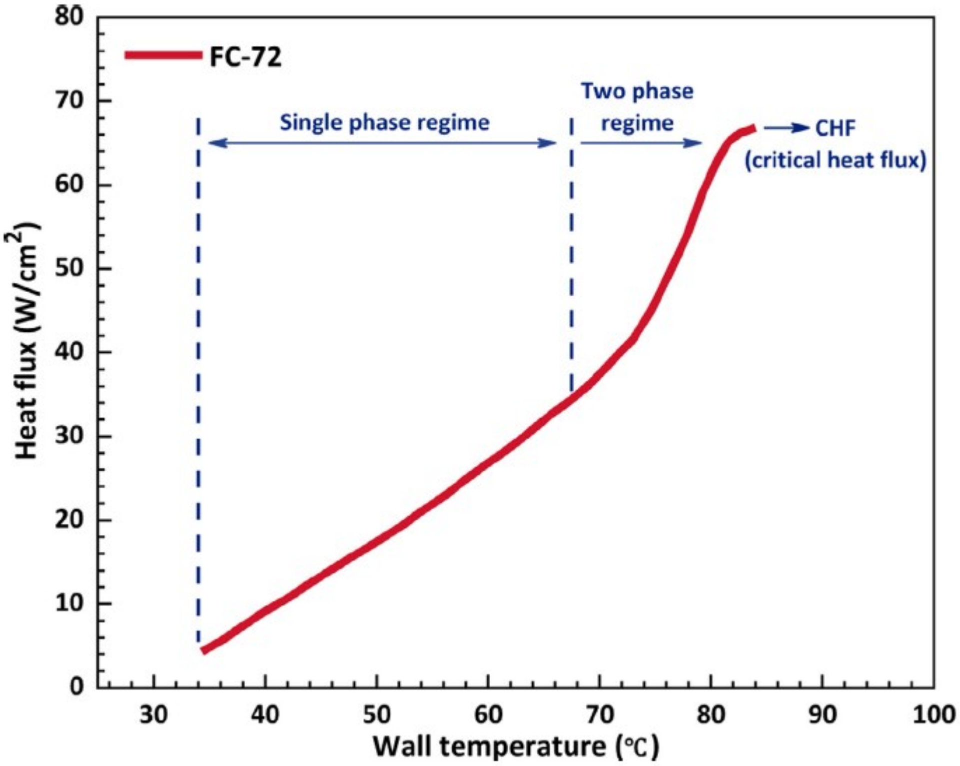

**Fig. 5 : Typical cooling curve.**

## 3. RESULTS AND REMARKS

In summary, because of its simple system design, decreased thermal resistance, and efficient heat transfer performance, jet impingement cooling may potentially become a popular choice for high-power electronics thermal management. Jet impingement cooling does, however, have some problems that must be resolved. One apparent drawback of single-phase jet impingement cooling is the sharp decline in the heat transfer coefficient that occurs while moving out from the stagnation zone, which causes a notable surface temperature variation. Under some particular circumstances, the cooling performance might also be impacted by the flow blockage between closely spaced numerous jets. The article highlights the ongoing challenges faced by cooling and thermal management systems as electrical and electronic devices become increasingly miniaturized and heat generation rises rapidly. It discusses recent advancements and state-of-the-art technologies in electrical and electronic cooling, providing insights that could inspire future research in the field. Two main categories of electronic cooling techniques are explored: direct and indirect cooling. Direct cooling methods include air cooling, spray and jet impingement cooling, immersion cooling, and droplet electrowetting. Indirect cooling techniques, on the other hand, encompass microchannel cooling, heat pipes, vapor chambers, thermoelectric cooling, and phase change materials (PCM). The efficiency of these thermal management strategies is evaluated across various levels of electrical and electronic cooling requirements, along with discussions on approaches to enhance heat transfer capabilities. The article delves into the advantages and disadvantages of each thermal management technology, considering factors such as intrinsic heat transfer performance, optimization methods, and applicable applications. Furthermore, the article addresses current issues in electrical and electronic cooling and thermal management technologies, while also exploring potential future developments. This comprehensive overview provides valuable insights into the evolving landscape of electrical and electronic cooling, offering a road map for researchers and engineers working in this domain.

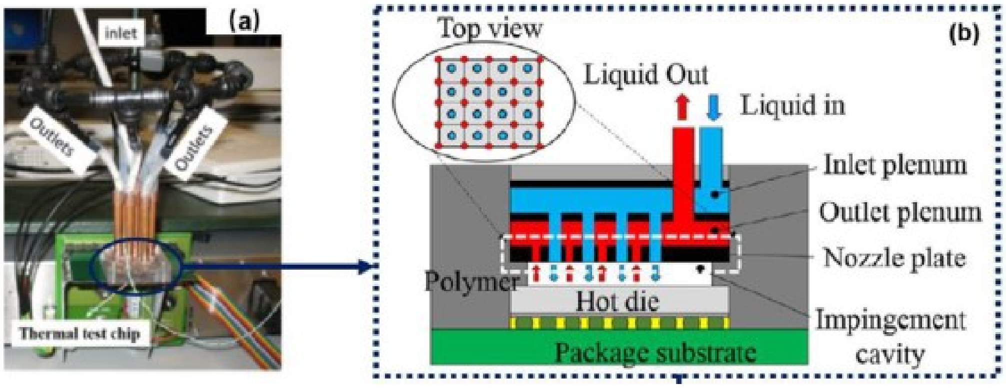

**Fig. 6 : (a) Experimental devices (b) cross-section of the chip-level jet impingement cooler.**

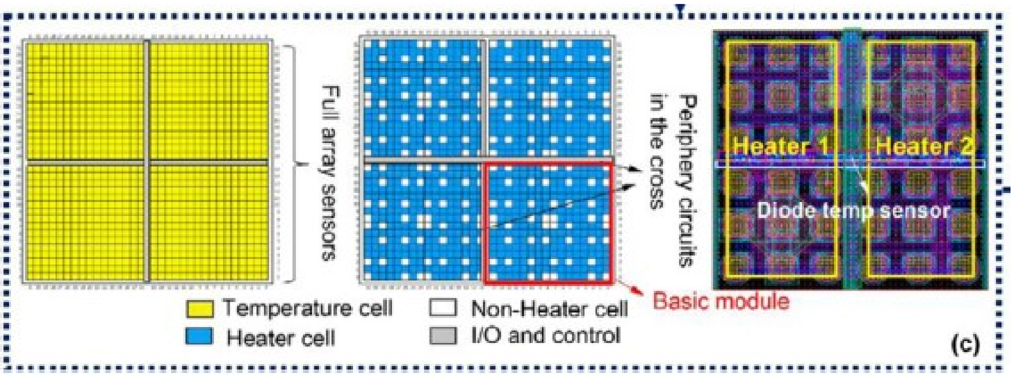

**Fig. 6 : (c) Schematic diagram of the thermal test chip with temperature sensors and heater cells.**

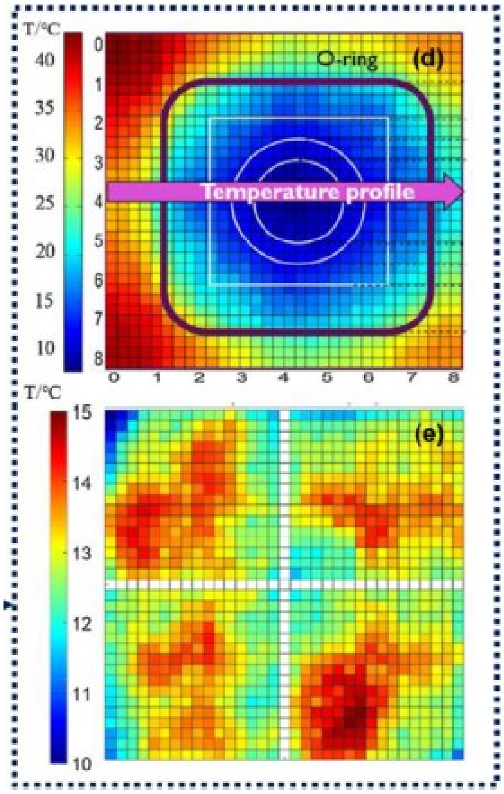

**Fig. 6 : (d) and (e) temperature distribution map of the single-jet and multi-jet (4 ×4) impingement cooling based on the experimental measure results**

**Table 1 :The commonly used coolants in immersion cooling.**

| Fluids | Thermal conductivity (Unit: W/m•K) | Cooling mechanism | Boiling point (°C) |
|---|---|---|---|
| Ethanol | 0.167 | Two phases | 78 |
| Water-ethylene glycol (1:1) | 0.37 | Single/Two phase | 107.3 |
| Minera oil | 0.13 | Single-phase | – |
| Novec 649 | 0.059 | Two phases | 49 |
| Novec 7000 | 0.075 | Two phases | 34 |
| FC-3283 | 0.066 | Single-phase | 128 |
| FC-43 | 0.065 | Single-phase | 178 |
| FC-72 | 0.057 | Two phases | 56 |

Table 1 lists the coolants that are often used. A hybrid cooling technique that combines immersion and spray cooling was presented by Wang. They discovered that, under some circumstances, the hybrid cooling technique outperformed typical spray cooling in terms of heat flux, with improvements of up to 65.6%. In a similar vein, Patil have noted that, as compared to natural convection, immersion cooling of a flowing dielectric fluid might enhance cooling efficacy by almost 46%. As previously indicated, because water has weak insulating qualities, dielectric fluid is used as cooling fluid in many experiments but not water.

## 4. CONCLUSIONS

This study provides a comprehensive overview of the most recent advancements in widely used technologies and approaches for electrical and electronic device thermal control. This provides a thorough review of the various thermal management technologies and may serve as inspiration for new approaches. It covers the major techniques of direct cooling and indirect cooling. In particular, their application, optimization, and heat transfer performance are discussed. It is concluded that liquid cooling is more flexible in meeting the needs of effective thermal management when it comes to the rise in heat flux of electronic devices as compared to air cooling. Because the cooling fluid may interact directly with the heated surface of the electronic equipment, direct contact cooling methods including spray and immersion coolings have a low thermal resistance. Its lightweight and small design also allows it to be used in other industries and with a variety of electrical equipment. The enhancement of structural designs will continue to be crucial for electronic device heat management. The thermal management system's basic components, including the spray cooling nozzle, may be enhanced to effectively increase the system's cooling capacity. Additionally, as electronic devices become more portable, flexible, and smaller, heat management systems face greater hurdles. Consequently, in order to keep up with the advancement of electronic gadgets, it is imperative that new thermal management structures be researched and designed. Thermal management depends critically on the thermal conductivity of the materials used for the heat sink, heat spreaders, and TIM. To increase heat conductivity, appropriate substitute materials or processing techniques must be found. To identify the materials with greater ZT for TE cooling, more advancements are required. Furthermore, careful consideration must be given to the effects of corrosion and heat stress on the materials used in devices. Electronic cooling has made advantage of the greater thermal conductivity nanofluid. Even so, it still has issues, such the tendency for deposits to build and clogs in nozzles and channels after extended use; occasionally, this can even cause damage to electrical components and thermal management systems.

## REFERENCES

1. M. Guarnieri , The unreasonable accuracy of Moore’s Law [historical], IEEE Ind. Electron. Mag. 10 (1) (2016) 40–43.
2. G.E. Moore , Cramming More Components Onto Integrated Circuits, McGraw-Hill, New York, 1965 .
3. S.G. Kandlikar , A.V. Bapat , Evaluation of jet impingement, spray and microchannel chip cooling options for high heat flux removal, Heat Transf. Eng. 28 (11) (2007) 911–923 .
4. H.-M. Tong , Y.-S. Lai , C. Wong , Advanced Flip Chip Packaging, Springer, 2013 .
5. J.R. Black , Electromigration —a brief survey and some recent results, IEEE Trans. Electron. Devices 16 (4) (1969) 338–347.
6. S.S. Murshed , C.N. De Castro , A critical review of traditional and emerging tech- niques and fluids for electronics cooling, Renew. Sustain. Energy Rev. 78 (2017) 821–833.
7. C.-C. Wang , A quick overview of compact air-cooled heat sinks applicable for elec- tronic cooling —recent progress, Inventions 2 (1) (2017) 5.
8. S.M.S. Murshed , Electronics Cooling, IntechOpen, 2016.
9. G. Liang , I. Mudawar , Review of spray cooling–Part 1: single-phase and nucle- ate boiling regimes, and critical heat flux, Int. J. Heat Mass Transf. 115 (2017) 1174–1205.
10. G. Liang , I. Mudawar , Review of spray cooling–Part 2: high temperature boil- ing regimes and quenching applications, Int. J. Heat Mass Transf. 115 (2017) 1206–1222.
11. A. Arshad , M. Jabbal , Y. Yan , Synthetic jet actuators for heat transfer enhancemen- t–a critical review, Int. J. Heat Mass Transf. 146 (2012) 118815.
12. I. Kuncoro , N. Pambudi , M. Biddinika , I. Widiastuti , M. Hijriawan , K. Wibowo , Immersion cooling as the next technology for data center cooling: a review, Journal of Physics: Conference Series, IOP Publishing 1402 (4) (2017) 044057.
13. J. Wei , Liquid Cooling, opportunity & challenges toward effective and efficient scalabilities, in: 2019 IEEE CPMT Symposium Japan (ICSJ), IEEE, 2018, pp. 83–84.
14. A. Abdollahi , R.N. Sharma , A. Vatani , Fluid flow and heat transfer of liquid-liquid two phase flow in microchannels: a review, Int. Commun. Heat Mass Transf. 84 (2017) 66–74.
15. A.J. Chamkha , M. Molana , A. Rahnama , F. Ghadami , On the nanofluids applica- tions in microchannels: a comprehensive review, Powder Technol 332 (2018) 287–322.

16. S. Twaha , J. Zhu , Y. Yan , B. Li , A comprehensive review of thermoelectric tech- nology: materials, applications, modelling and performance improvement, Renew. Sustain. Energy Rev. 65 (2016) 698–726.
17. X. Meng , J. Zhu , X. Wei , Y. Yan , Natural convection heat transfer of a straight-fin heat sink, Int. J. Heat Mass Transf. 123 (2018) 561–568.
18. A.W. Scott , Cooling of Electronic Equipment, Wiley, 1974.
19. M. El Alami , M. Najam , E. Semma , A. Oubarra , F. Penot , Electronic components cooling by natural convection in horizontal channel with slots, Energy Convers. Manage. 46 (17) (2005) 2762–2772.
20. X. Liu , R. Xue , Y. Ruan , L. Chen , X. Zhang , Y. Hou , Effects of injection pressure difference on droplet size distribution and spray cone angle in spray cooling of liquid nitrogen, Cryogenics 83 (2017) 57–63.
21. X. Liu , J. Liu , R. Xue , L. Chen , Y. Hou , Heat transfer optimization of R134a phase change spray cooling in a closed loop system, Exp. Therm. Fluid Sci. 92 (2018) 248–258.
22. Y.A. Cengel , Heat Transfer: a Practical Approach with EES CD, McGraw-Hill Higher Education, 2002.
23. J. Kim , Spray cooling heat transfer: the state of the art, Int. J. Heat Fluid Flow 28 (4) (2007) 753–767.
24. W.-L. Cheng , Q.-N. Liu , R. Zhao , H.-l. Fan , Experimental investigation of parameters effect on heat transfer of spray cooling, Heat Mass Transf. 46 (8) (2010) 911–921.
25. X. Gao , R. Li , Effects of nozzle positioning on single-phase spray cooling, Int. J. Heat Mass Transf. 115 (2017) 1247–1257.
26. N. Zhou , F. Chen , Y. Cao , M. Chen , Y. Wang , Experimental investigation on the performance of a water spray cooling system, Appl. Therm. Eng. 112 (2017) 1117–1128.
27. J. Xie , H.M. Lee , J. Xiang , Multi-nozzle closed loop spray cooling systems in elec- tronics cooling, IOP Conference Series: Earth and Environmental Science, IOP Pub- lishing, 2018.
28. H. Liu , C. Cai , H. Yin , J. Luo , M. Jia , J. Gao , Experimental investigation on heat transfer of spray cooling with the mixture of ethanol and water, Int. J. Therm. Sci. 133 (2018) 62–68.
29. A. Pati , A. Kumar , S.S. Mohapatra , Upward and downward facing high mass flux spray cooling with additives: a novel technique to enhance the heat removal rate at high initial surface temperature, Heat Mass Transf. 54 (6) (2018) 1669–1680.
30. W.-W. Zhang , Y.-Y. Li , W.-J. Long , W..L. Cheng , Enhancement mechanism of high alcohol surfactant on spray cooling: experimental study, Int. J. Heat Mass Transf. 126 (2018) 363–376.
31. N.M. Abdulrazzaq , N.C. Anumbe , J.A. Khan , Experimental investigation of the per- formance of refrigerant R134A working in a spray cooling, in: 3rd Thermal and Fluids Engineering Conference (TFEC), 2018, 4–7 March , Fort Lauderdale, FL, USA, ASTFE Digital Library, Begel House Inc., 2018, pp. 1355–1368.
32. L. Zhong , Z. Guo , Effect of surface topography and wettability on the Leidenfrost effect, Nanoscale 9 (19) (2017) 6219–6236.