

A REVIEW ON SUSTAINABILITY, RELIABILITY, AND SAFETY OF MICROCHANNEL HEAT SINKS IN ELECTRONIC COOLING APPLICATIONS

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Abstract

Day by day, the rapid growth in the miniaturization of electronic devices ranging from mini, micro, to nano scales for various applications has drastically increased. However, the fabrication of such devices and the dissipation of heat from their bodies to the surrounding environment remain challenging. Due to these thermal management issues, electronic devices, MEMS, and other microfluidic and biomedical systems face significant sustainability, reliability, and safety concerns. In the present paper, we address various methods to overcome these problems in existing devices by using microchannels (MICs). MICs are used to remove heat from electronic components, thereby improving device safety and enabling them to operate within permissible temperature limits. A comprehensive literature review is presented, covering the classification of MICs, their fabrication methods, and their applications in enhancing the reliability and safety of various devices. Sustainable design aspects are also considered to improve energy efficiency, optimize material usage, reduce the environmental impact of coolants, and enhance product life cycle performance. Furthermore, the paper outlines potential future research directions and fields of innovation for further advancements in this domain.

Keywords: Microchannel, reliability, safety, cooling of electronic devices, MEMS

I. Introduction

In the past two decades, the drastic growth of miniaturization of electronic devices such as MEMS, microfluidic devices, biomedical devices, and high-density electronics has revolutionized engineering, research, and technology in several areas. As devices decrease in compactness in size to microscopic and nanoscopic dimensions, they more and more produce substantial high heat fluxes as a result of high power densities, imposing drastic requirements on thermal management. Inadequate

heat dissipation from the devices or system makes the devices much less reliable and sustainable as well as increases the safety risks for both users and devices when utilized in some applications [1-2]. However, conventional cooling methods like mini-channel heat sinks [3-6], natural circulation loops [7-9], passive airflow, and finned configurations are not sufficient for these small, high-power systems and MEMS and electronics devices.

To resolve these issues, microchannel heat sinks (MCHSs) have proven to be a very effective option, with high heat transfer because of their large surface-area-to-volume ratios, compactness, low coolant usage, and high coefficients of heat transfer. Furthermore, MCHSs provide efficient thermal management and enable devices to function safely within acceptable temperature ranges [10]. Also, several fabrication and design techniques have been investigated to enhance MCHS performance. Passive augmentations such as adding ribs, cutting grooves, pin fins, and different cross-sectional geometries increase turbulence, disturb thermal boundary layers, and enhance heat dissipation from the device to the environment. Furthermore, various different applications of nanofluids and phase-change fluids and materials are used to enhance thermal capability, with enhanced thermal conductivity above that of standard fluids.

However, apart from the passive method, some active methods are also available, which improve the heat transfer rate. These active methods are flowing pulsation, electrostatic modulation, magnetic fields, and acoustic or vibrational stimulation that have come into play for improving the heat transfer by externally caused effects. Simultaneously, some important numerical and experimental methods are more frequently being used to optimize microchannel geometry [11-12]. Topology optimization and surrogate modelling are some methods that expedite design cycles while providing drastic enhancements in thermal resistance and pumping power efficiency.

Design and fabrication of the MICHs are progressively advancing with innovations to improve the heat dissipation rate for increasing sustainability, reliability, and safety of the devices. Some of the design is inspired by bionic topologies, non-traditional cross-sections (trapezoidal or triangular), and interrupted flow structures like cavities and ribs that optimize heat removal by maximizing surface area and inducing mixing and uniform cooling. Additionally, through-chip MICH embedded in 3D stacked circuits are a leading area of thermal management with direct, internal cooling and huge potential for performance. Sustainability aspects form an intrinsic part of cooling system development. MCHS is used for improving energy-efficient, compact designs with minimal material requirements and environmental footprint. Their durability and flexibility with sustainable industrial principles minimize waste and maximize lifecycle performance. Future research places as much emphasis on sustainable operation, considering eco-friendly coolants, materials, processes, and system lifecycle effects as thermal performance [13-15].

Based on the several advantages of the MICHs for heat transfer from the device to the environment, there are still various problems and disadvantages of the MICHs that require improvement for the sustainability, reliability, and safety of the electronic devices. Also, there are many problems that occur in producing and fabricating MICHs. Producing intricate MICHs in volume and packaging them economically into production lines is still not trivial. Creating coolants that are both high-performance and environmentally friendly is a two-way obligation. Maintaining design consistency so MICHs provide uniform cooling among devices is critical to prevent hotspots, which can significantly compromise reliability.

In this context, the paper presents a critical literature review of MICHs for thermal management in miniaturized electronics devices. The review covers categorization of microchannel geometries, fabrication processes, and implementation in device safety improvement and reliability enhancement in a systematic manner. The review also incorporates environmentally conscious design factors such as energy efficiency, material optimization, coolant environmental responsibility, and lifecycle performance. Further, the promising directions for future research focused on developing MICH-based cooling technologies are proposed for improving the safety and reliability of the electronic devices.

II. Literature Review

MICH's sustainability and reliability are important factors in their use across a wide range of industries, from petrochemicals and electronics to thermal management. MICHs provide improved heat transfer and energy efficiency but also face special reliability and safety challenges at their small scale and operating conditions. The literature review, a comprehensive study of literature, has led to a detailed investigation into the aspects of reliability, sustainability, and safety of MICHs in terms of classification of the channel, fabrication, materials used for fabrication, thermal management, and cooling of electronic devices. The literature review primarily covers the period from 2000 to 2023, providing a contemporary perspective on the field, followed by an investigation of the different fabrication methods and heat transfer methods to enhance the reliability, sustainability, and safety of MICHs.

I. Fundamental Principle of the Microchannel

MCHs are working based on the principle of convective heat transfer, wherein a working fluid absorbed heat from the surface of an electronic component as it travels through narrow channels within the heat sink. Because of the high surface area-to-volume ratio and minimal diffusion paths within microchannels, MCHs provide significant heat transfer than traditional cooling techniques. When a fluid (liquid or nanofluid) is going through microchannels, heat from the electronic device is dissipated to the fluid through conduction through the heat sink material and convection along the channel walls. The heated fluid is transported away from the device at a safe operating temperature. These are mainly two types of force convection and free convection. But mostly force convection methods were used to remove the heat from the electronic devices for enhance their reliability, sustainability, and safety. Figure 1 depicts the schematic diagram of the working of the MCHs [16].

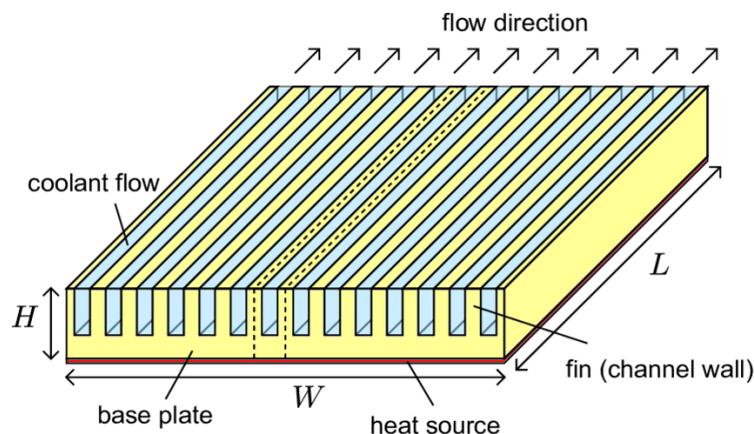


Figure 1: Schematic diagram of the microchannel

II. Classification of Microchannel and Materials and Coolant used in this for Improving the Safety of the Devices

MCHs are developed in various designs, such as single and manifold channels, serpentine channels, pin fins, interrupted channels, etc., that are made of different materials for improving the heat transfer from the electronic devices by employing several coolants for the safety of the device. Figure 2 shows the classification of the MICH based on the optimizing heat transfer criteria and THP, which provide the significant safety of the electronic devices as well as improve the life span of them. Based on the

previously reported research, MICHs are classified in three categories, such as cross-sectional geometry optimization, complex geometry optimization, and wall geometry optimization. Similarly, various materials are used to fabricate the MICHs to prevent damage to the channels and improve the thermal performance, structural integrity, and corrosion resistance, as well as to choose the materials based on their high thermal conductivity and light weight.

Mainly, copper, aluminum, silicon ceramics, and polymers (with fillers) are used, which improve the THP of the channel and provide higher safety to the electronic devices. Similarly, selection of the working fluid is a critical parameter of MICHs for improving the cooling effect and preventing the devices from burning and damage. The THP and pressure drop in the channel are affected by the thermal properties, electrical conductivity, and chemical stability of the coolant, which directly affect system efficiency and safety. Several coolants are used in MICHs to improve the sustainability, reliability, and safety of the electronic devices. Mainly deionized water, nanofluids, dielectric fluids (i.e., Fluorinert, Novec), refrigerants, mixtures of two different fluids, etc., due to high specific heat, higher thermal conductivity, and electrical non-conductivity, as well as the capability of improving the THP and reducing the friction loss in the channels [17-19].

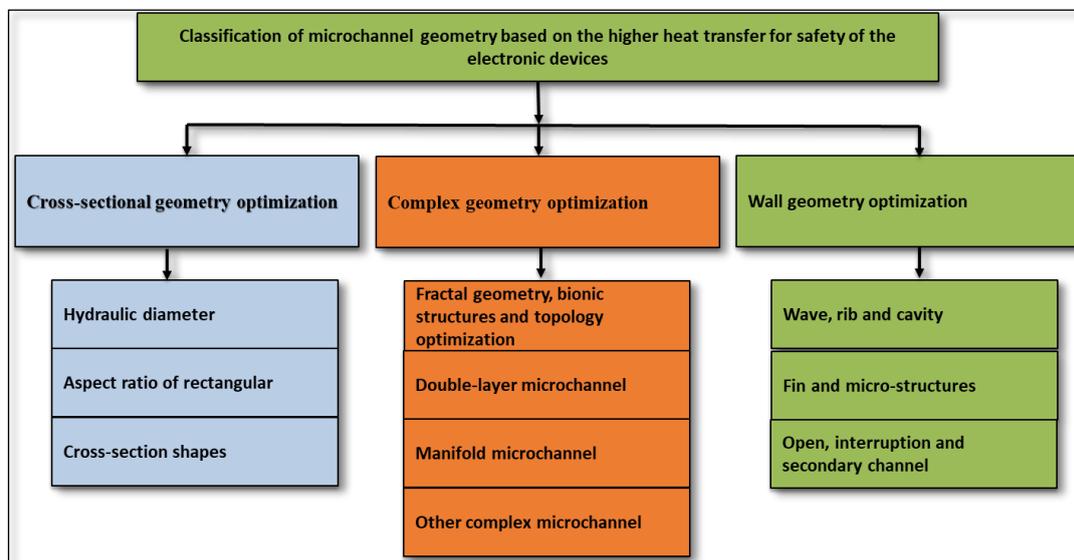


Figure 2: Classification of the microchannel based on the higher heat transfer for improving safety of the electronics devices.

III. Sustainability Aspects, Thermal Safety and Overheating Risks, Mechanical and Thermal Reliability of the Devices

As electronic devices rapidly miniaturize and become more power dense and thermally demanding, the sustainability, reliability, and safety of thermal management solutions become very important. MICHs are used in various electronic devices due to their compact size and higher THP. Therefore, it must be evaluated not only for THP and efficiency but also for its long-term environmental and resource impacts and small-scale, complex flow dynamics and integration with sensitive electronics, as well as ensuring safety in operation for protecting both devices and users from hazards.

Wang et al. [20] optimized the thermal hydraulic performance (THP) of an MCHS using numerical and artificial neural networks (ANNs) methods. With drastic demand for high-performance electronic devices, rapid cooling of these devices is essential to work under the limiting temperature of the device which provides safety as well as ensures reliability of the devices. They were used a numerical model with hexagonal fins which was developed in COMSOL, while other ANN models were trained to accurately predict Nusselt number and pressure drop with high accuracy ($R^2 = 0.999$). The outcomes revealed that the distance of fins from sidewalls has depicted a significant effect and increased the Nu by 66.3% and ΔP by 37.6%. Three optimal configuration

parameters were identified, such as $Nu = 27.596$, $\Delta P = 282.3$ Pa, and an overall efficiency of 1.491, and compared to the benchmarks result, the optimized design enhanced total performance by 49.1% and concluded that ANN-based optimization is an effective tool for designing high-performance MCHSs, which are capable of optimizing the safe and reliable parameters of MCHS for dissipating heat from electronic devices to the surroundings.

Elbadawy et al. [21] numerically investigated the THP of offset strip finned MCHSs with various MICH cross-sectional shapes, such as rectangular, trapezoidal, triangular, and circular, for providing the safety of the electronic devices. They optimized the Nu, pressure drop, and overall efficiency to identify optimal geometry shapes and sizes for providing efficient cooling of electronic devices to increase the life span of the devices. Its results showed that MICH shape significantly affects the safety and reliability of the devices. It was observed that trapezoidal and triangular shapes provided higher heat transfer as compared to rectangular and circular. However, trapezoidal and triangular shapes gave higher pressure drops. The correlation between Nu and pressure drop was developed using a performance evaluation criterion (PEC), which showed that trapezoidal channel is the effective configuration that provides higher heat dissipation rate as compared to the others as well as provides the safety of the electronic devices at less friction loss.

Shakir et al. [22] numerically and experimentally investigated single-phase and two-phase boiling heat transfer in aluminum MICH using R113 as the working fluid. A square cross section of the test setup was developed of 0.5 mm and 0.5 mm, and constant heat flux is applied to the bottom of the channel, which varied from 40 to 600 W at three different mass flow rates, such as 0.0125 kg/s, 0.015 kg/s, and 0.0175 kg/s. In this, they analyzed heat transfer coefficients (HTC), exit quality, and pressure drops for both subcooled and saturated boiling regimes to provide the safety and reliability of the electronic devices. Its outcome showed that single-phase flow at laminar and fully developed characteristics with HTCs increase with increasing the mass flux, whereas fluid temperature is decreased with increasing the mass flux. However, in two-phase flow, HTC was significantly affected by heat flux, mass flow rate, and vapor quality. Onset of boiling was seen around 47°C, and pressure drop behavior showed two different regimes for single- and two-phase flow, which was also shown both numerically and experimentally, and developed empirical correlations for safety of the electronic devices. Furthermore, the effect of MICH geometry and operating conditions on boiling heat transfer and instabilities was investigated to accurately provide the robust condition for providing the safety and reliability of the electronic devices.

Chen et al. [23] conducted numerical simulation combined with response surface methodology (RSM) to investigate the thermal-hydraulic optimization of trapezoidal MCHSs by incorporating different rib geometries to protect the failure of electronic devices. In this study, they used four different rib shapes, such as triangular, rectangular, semicircular, and trapezoidal, with varying rib height and pitch to predict the effects on Nusselt number (Nu), friction factor (FF), and performance evaluation criterion (PEC) to enhance the safety of the electronic devices. Its results demonstrated that rib structures significantly improve HTC and Nu due to flow disturbance and secondary vortices. However, pressure drop is increased, which reduces the reliability of the device wall. Furthermore, trapezoidal ribs provided significant HTC and minimum pressure drop, which provided the highest safety and reliability of the electronic devices during cooling among all other shapes of the test ribs. Furthermore, RSM-based optimization identified the optimal rib geometry and their arrangement for higher safety of the devices by improving the heat dissipation rates.

Zhang et al. [24] numerically examined the effect of different MICH cross-sectional geometries, such as rectangular, trapezoidal, triangular, and circular, on the heat transfer rate and THP performance of MCHSs. Also, they were evaluated for Nu, FF, and performance evaluation criteria to ensure the safety of the electronic devices. Its results revealed that trapezoidal and triangular channels had significantly improved heat transfer compared to rectangular and circular-shaped channels. However, the pressure drop was observed to be maximal. The trapezoidal-shaped MICH gave a higher heat transfer rate at minimum pressure drop, which is similar to Chen et al. [23]. This finding suggested that optimizing the MICH cross-sectional shape is a crucial parameter for

improving and enhancing the safety of the electronic devices as well as for use in various advanced thermal management applications, particularly for microelectronic device cooling.

Wunderle et al. [25] extensively reviewed and summarized advancements in MCHS designs with various channel cross-sectional geometries to improve heat transfer rate in the microelectronic devices. They suggested that rectangular MICH is widely used for cooling the electronic devices, which experience higher pressure drop and relatively lower heat transfer performance compared to non-rectangular geometries such as trapezoidal, triangular, and circular shapes. Researchers demonstrated that non-rectangular channels enhance heat transfer through the promotion of secondary flows and larger surface areas, often at the cost of higher pressure drops. They concluded that trapezoidal and triangular geometries provide higher heat transfer rates as well as experience higher pressure drops.

Sidik et al. [26] examined the effect of several different cross section geometries such as rectangular, triangular, semicircular, and trapezoidal shapes, on the THP of MCHSs using 3D-CFD tool ANSYS and reported that Nu, f , and THP varied at varying Reynolds numbers. Also, they suggested that the heat transfer rate increases with increased Reynolds numbers at low friction loss and pressure drop as well as rectangular cross-section MICH had the least heat transfer and the higher-pressure drop, which makes electronic devices less safe and reliable.

Mudawar [27] conducted numerical investigations in 2002 to determine the THP of MCHSs, including different designs of the MICH, such as zigzag, sinusoidal, and wavy designs, as well as combining the effect of the structure or improving the cooling efficiency to provide safety of the electronic devices. Simulations were conducted to evaluate Nu and pressure drop (ΔP) at various Reynolds numbers. Its outcome showed that using a zig-zag channel significantly improves heat transfer due to fluid mixing and changing the flow boundary layers, as well as increasing the pressure drop. Among all designs, zigzag and sinusoidal structures showed higher heat dissipation rates, which provide better safety for electronic devices as well as improve their lifespan.

Spizzichino et al. [28] presented a numerical analysis of the THP of wavy MCHSs with different wave structures, such as sinusoidal, triangular, and trapezoidal profiles, and they suggested that wavy MICH showed maximum heat transfer as compared to other designs with a higher-pressure drop.

Furthermore, Ko et al. [29] developed a low-temperature MEMS fabrication method for MICH and integrated it with temperature sensors and micro-heaters to measure local heat transfer during the working of the electronic devices. In this study, they used low-thermal-conductivity materials such as epoxy, Pyrex, PMMA, SU-8, and a two-stage process. Air is used as a working fluid in the channel for cooling the HTC revealed that HTC is significantly affected by using the MICH for heat transfer from the electronic device, which can improve the safety and life of the devices. Also, they suggested the impact of size effects and wall properties and demonstrated the feasibility of micro-channel cooling for high-power devices such as future CPU chips.

Tiseljet al. [30] experimentally investigated heat transfer in silicon-based MICHs. In this study, they used MEMS sensors to accurately predict the wall temperature of the electronic devices as well as HTC. Also, a fabrication method that allows for the accurate positioning of heaters and thermocouples within high-aspect-ratio MICHs, thereby reducing conduction losses and enhancing measurement precision. Experimental findings for single-phase liquid flow demonstrate that traditional macroscale heat transfer correlations tend to overestimate microchannel performance, highlighting notable scale effects. Its outcomes identify variations in local Nusselt number trends, indicating diminished heat transfer rates and uneven distributions along the channel. The findings suggested that MICHs have a compact design and high-performance cooling systems for microelectronics and demonstrate that microscale heat transfer necessitates advanced theoretical models that extend beyond classical assumptions.

Ding et al. [31] studied both experimentally and numerically to analyze heat transfer through MCHS at different aspect ratios using water as a working fluid. Its results revealed that intermediate channel widths improve the flow inside the channel due to less frictional pressure drop, variation of

wall temperature along the length, and THP. Based on this, a correlation of heat transfer and width of the channel was developed to maintain the working temperature under limiting temperature.

Lorenzo Consolini and Thome [32] reported heat transfer through MICH from electronic devices in single- and two-phase flow using three different working fluids (R-134a, R-236fa, and R-245fa) and two different hydraulic diameters (510 and 790 μm) of the channels. Also, a parametric study was performed to determine the two-phase flow instability, which develops a thermal fatigue load that is harmful for devices as well as MICH. Its results revealed that the HTC of R-134a and R-236fa are significantly dependent on the heat flux and mass flow rate at low and high dryness fractions. However, R245fa showed the opposite of the other fluid, which developed instability in the channel and degraded the lifespan of the channel.

Jahar Sarkar [33] suggested heat transfer through MICH significantly improved using supercritical carbon dioxide as a working fluid in electronic devices. Also, parametric studies were performed for two different fluids, supercritical carbon dioxide and water, to examine which fluid gives higher heat transfer at lower resistance. Its results showed that heat transfer was improved by 30% as compared to water at low thermal resistance, which provides higher safety to the electronic devices.

Xiang et al. [34] numerically investigated the MCHS using a thermal resistance model to accurately predict the heat transfer rate from the electronic devices. In this study, they fabricated the MCHS and tested for heat transfer. Its result showed that developed MCHS hives have higher heat transfer as compared to conventional metal made of MCHS, which is recorded for heat transfer from LED applications.

Bello-Ochende et al. [35] numerically investigated the heat transfer through MICH using the 3D model finite volume method to reduce the wall temperature of the MICH from the working fluids. The results indicated that the maximum temperature of the MICH is significantly reduced by increasing the working fluid flow rate in the channel as well as increasing the aspect ratio of the channel.

Li et al. [36] suggest a correlation to distinguish between mini and MICH for heat transfer from electronic devices. In this study, they used single and manifold types of MICH as well as single and two-phase flow. Also, in this study, seven pre-developed correlations were used to predict and verify heat transfer of the 4228 databases. Based on this correlation, they proposed a new correlation, $Bo \cdot Re^{0.5} = 200$, to accurately predict the heat transfer rate through MICH.

Spizzichino et al. [37] investigated heat transfer and flow characteristics of parallel MICH (i.e., 10 channels) using both experiments and numerical simulation methods, and deionized water was used as the working fluid. Results show that uniform-width channels cause higher pressure drops and mass flow in intermediate channels, leading to uneven base temperatures, while refining intermediate channel widths produces more uniform flow and wall temperature distributions. A new Performance Evaluation Criterion for Non-uniform Channels (PECNC) was proposed to assess designs, with structure VI emerging as the optimal configuration. Additionally, a mathematical expression was developed to guide the design of width distributions that promote uniform temperature fields.

Qu and Mudawar [38] investigated the heat transportation phenomenon of two phase in MICH to improve the safety and reliability of the electronic cooling devices. In this study they suggested the basic reliable operation of a two-phase MICH transport phenomenon integrated with convective boiling in single and parallel channels. They used high-speed photographic methods to accurately predict hydrodynamic instability, two-phase flow patterns, pressure drop, and convective boiling heat transfer. The study's findings indicate that MICH primarily experiences two types of instability: a drastic pressure drop and a mild parallel channel.

Sehgal et al. [39] conducted several experiments to examine the effect of the inlet and outlet plenums in different arrangements of various MICH shapes such as U, P, and S types on improving the cooling of electronic devices as well as enhancing their thermal-hydraulic performance (THP). A heat input ranging from 125 W to 375 W was applied to the wall of the MICH, with Reynolds numbers (Re) varying from 224 to 1121 to assess THP. Higher heat dissipation was observed in the U-

shaped MICH, while a greater pressure drop occurred in the S-type MICH among other channels, which improve the reliability and safety for electronic devices.

Xia et al. [40] numerically investigated the effect of the position of the MICH on the 3D-IC in heat transfer for improving the performance and safety of the devices as well as thermal management of the electronic devices. In this study, two types of cavities are considered, namely triangular reentrant cavities (TRC) and fan-shaped reentrant cavities (FRC) having a pitch and height of 1/0.2 mm and 0.2 mm, respectively. The effect of both cavities of MICH was compared with rectangular MICH. Its results revealed that the distribution of the heat rate and pressure drop was uniform along the length of each layer, as well as the pitch of 0.1 mm of MICH. Higher heat transfer and THP were observed at a higher pressure drop and pumping power, which significantly affected the safety of the devices as well as reduced their life span.

Markal et al. [41] developed MICH, which consists of MICH with pin-type fins, which gives higher heat dissipation by optimizing the design and geometry sizes of the channel and fins to minimize the thermal resistance and pressure drops to increase the safety of the electronic devices. Similarly, Li et al. [36] developed lattice-interconnected channels and nanofluid in the MICH to improve the cooling rate of the devices and reported that heat transfer is increased with using the nanoparticle in the coolant, and the pressure drop is reduced in the channel.

Also, Huang et al. [42] implanted phase-change materials (PCMs) with graphite foam to absorb cyclic generated heat from electronic devices, which reduced the limiting temperature of the chips and electronic devices and provided better safety and reliability of the devices. Xiang et al. [34] also developed a vacuum-assisted two-phase honeycomb heat sink to reduce the electronic device temperature approximately 15°C at 90 W and validated performance through both experiments and numerical analysis.

Rai et al. [43] conducted several single- and two-phase numerical and experimental studies in single- and two-phase flow through MICH for improving the safety and reliability of the electronic devices. They used deionized water as a working fluid and three different MICH geometries. They developed a correlation between mass flow rate and generated heat power from the electronic devices to reduce the working temperature of the device to under 40°C, which improves the safety and reliability of the electronic devices. Also, in numerical studies, they optimized the geometry for higher heat transfer in rectangular, square, and trapezoidal shapes and reported that trapezoidal geometry provides high heat transfer. To enhance the safety and reliability of the electronic devices, hybrid methods are employed alongside geometry optimization, which is necessary to prevent drastic pressure changes inside the MICH.

Several recent experimental and numerical research works were reported to improve the safety and reliability of the electronic devices by improving the heat transfer rate from these devices due to their compact size. Table 1 shows a comparative summary of recently reported research to improve the safety of electronic devices using different designs, shapes, and working fluids. It can be seen from table 1 that MCHS is mainly used for electronics devices cooling and is significantly suggested by the numerous researchers to use hybrid designs and integrated optimization to increase heat dissipation at low volume to area ratio.

Table 1: Summary of different methods and working fluid used to improve the safety of the electronic devices.

Author	Design / Method	Working fluids	Main Findings
Markal et al. [41]	MICH with pin-fin heat sink	Deionized water	<ul style="list-style-type: none"> Higher heat transfer but increased pressure drop Optimal fin height and channel width significantly improved the THP. Thermal resistance reduced by approximately 15–20%

			and pressure drops increased by 30–40% as compared to plain MICH.
Li et al. [36]	MICH with nanofluid	Water + Al ₂ O ₃ nanofluid	<ul style="list-style-type: none"> • Best lattice geometry improved THP • Peak temperature drops up to 12 °C and pressure drop approximately 20% compared to straight MICH.
Huang et al. [42]	Phase-change material (PCM) with graphite foam embedded in walls	Water (base) + PCM for transient loads	<ul style="list-style-type: none"> • PCM and high-conductivity foam maximized THP • Peak temperature of the reduced approximately 15°C vs. solid plate at 90 W • Reduced peak chip temperature under cyclic heat input from the devices. • PCM absorbed heat generates from the devices.
Xiang et al. [34]	Vacuum-assisted two-phase honeycomb MICH	Water + R134a (two-phase mix)	<ul style="list-style-type: none"> • Optimal regular hexagon, 2 mm pitch, 0.5 mm depth, 8 mm radius • Max chip temp reduced from 85 °C to 70 °C at 90 W with ± 1°C
Rai et al. [43]	Single MICH (Single and Two Phase)	Deionized water (single and two phase)	<ul style="list-style-type: none"> • Working temperature of the device to maintained under 40°C • Experimental and numerical validation showed ±6.04 errors.
Husain et al. [44]	Different designs of MICHs (Square, rectangular and trapezoidal and different boundary conditionss)	Deionized water (H methods)	<ul style="list-style-type: none"> • Optimizing the design of the MICH and applying 2H and 4H boundary conditions to enhance the heat transfer rate and improve the safety of the electronic devices.

IV. Research Gaps

After extensively reviewing the previously reported works of several researchers, some concise observations regarding the use of different single- and two-phase cooling methodologies as well as various designs used to improve the safety and reliability of the electronic devices are as follows:

- Traditional cooling methods such as air-cooled heat sinks and fans are not sufficient to provide enough safety to the high-performance electronic devices such as chips, integrated chips, high-frequency processors, laser diodes, and power electronics due to compact sizes. Therefore, robust design with higher THP of MICHs is required, which can remove higher heat flux from the devices to improve the safety and reliability of the electronic devices [45].

- One of the major challenges is the fabrication of the MICHs, which requires precision machining, etching, micro-milling, etc., that are costly and time-consuming, as well as high-precision sealing and assembly processes to completely seal channels, which can protect the electronic devices from short circuits during operation.
- Very limited studies on the manifold and serpentine types of MICHs are available in literature, which can be needed to extensively study for improving the THP as well as the safety of the electronic devices.
- Very limited working fluids are used in the MICHs for improving the THP and efficiency of the channel. Supercritical fluids can be used to improve the THP and safety of the electronic devices.

V. Conclusion and Future Scope

In this present work, an extensive literature review is conducted on the available literature related to the sustainability, reliability, and safety of MICHs in the application of electronics devices which are used in various industries such as electronics, aerospace, automotive, biomedical and microfluid devices, etc. Several important findings are observed from this extensive literature review, which are given below.

- Day by day, electronic devices are drastically increasing with miniaturization, minimizing their sizes and increasing their power densities. Therefore, effective thermal management is required as well as a required determinant of system longevity, energy efficiency, and operational safety. MICH and MCHSs can remove the significant amount of heat from the electronic devices, which improves the sustainability of the electronic devices. Also, MICH reduces energy consumption and improves device lifespans and does not affect the environment. However, careful selection of materials and coolants is necessary to ensure recyclability and minimize environmental risks.
- MICH is a better solution for improving the safety of the electronic devices as compared to the traditional cooling methods.
- The cyclic heat load can be removed by using the PCM in the MICHs which increases the safety of the electronic devices by absorbing 10 to 15 °C temperatures.
- The trapezoidal design of MICHs provides higher heat transfer than other designs such as rectangular, square, and circular types of MICHs.
- Two phase and boiling methods provide higher heat transfer as compared to single phase cooling methods and improve the safety and reliability of the electronic devices.

By using the MICHs, various problems have been resolved to improve safety and increase The lifespan of electronic devices. However, there are still several issues that have remained open to resolve for improving the safety of the MICHs during use in the electronic cooling devices. 3D modeling using different designs and shapes of the MICHs can improve the safety of the devices. 3D printers can be used to fabricate the MICHs. Also, for real-time monitoring of temperature, flow rate, pressure, and THP of the MICHs, a combined system (including sensors, IoT devices, and machine learning) can be used. Furthermore, robust pressure control, leak-proof design, and accurate heat input prediction are required to improve the sustainability, reliability, and safety of electronic devices.

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