Sustainability, reliability, and safety assessment of microchannel heat sinks in electronic cooling applications: a detailed study with a focus on smart fabrics and wearable electronics

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ABSTRACT – REZUMAT

Sustainability, reliability, and safety assessment of microchannel heat sinks in electronic cooling applications: a detailed study with a focus on smart fabrics and wearable electronics

The ongoing miniaturisation of electronics poses significant thermal management challenges due to rising power densities within constrained volumes. This study addresses the critical need for efficient heat dissipation to ensure the sustainability, reliability, and safety of these systems. We present a detailed assessment of microchannel (MICH) heat sinks, a high-performance cooling technology particularly relevant for advanced electronic applications. The core of this work is a comprehensive review and analysis of MICH classifications, fabrication methods, and performance metrics. A primary focus is placed on a sustainability assessment, including the optimisation of material usage, enhancement of energy efficiency, and reduction of the environmental impact of coolants, all of which contribute to a longer product lifecycle. The paper also explores how MICH technology improves system reliability by maintaining components within safe operating temperature ranges, thereby preventing performance degradation and premature failure. We pay special attention to the emerging application of integrating MICH technology into smart fabrics and wearable electronics, a domain where thermal management is a critical and complex challenge. By examining this specific use case, we demonstrate the versatility and potential of MICH heat sinks. The paper concludes by outlining future research directions and innovations necessary for the widespread commercial viability and adoption of MICH-based cooling solutions in both traditional and next-generation electronic devices.

Keywords: *smart fabrics, wearable electronics, microchannel, reliability, safety, electronic devices cooling, MEMS*

Evaluarea sustenabilității, fiabilității și siguranței radiatoarelor cu microcanale în aplicațiile de răcire electronică: un studiu detaliat cu accent pe materiale textile inteligente și electronice purtabile

Miniaturizarea continuă a componentelor electronice ridică provocări semnificative în ceea ce privește gestionarea termică, din cauza densităților de putere în creștere în volume limitate. Acest studiu abordează nevoia critică de disipare eficientă a căldurii pentru a asigura sustenabilitatea, fiabilitatea și siguranța acestor sisteme. Prezentăm o evaluare detaliată a radiatoarelor cu microcanale (MICH), o tehnologie de răcire de înaltă performanță, deosebit de relevantă pentru aplicațiile electronice avansate. Elementul central al acestei lucrări îl constituie o trecere în revistă și o analiză cuprinzătoare a clasificărilor MICH, a metodelor de fabricație și a indicatorilor de performanță. Un accent principal este pus pe evaluarea sustenabilității, incluzând optimizarea utilizării materialelor, îmbunătățirea eficienței energetice și reducerea impactului asupra mediului al agenților de răcire, toate acestea contribuind la un ciclu de viață mai lung al produsului. Studiul explorează, de asemenea, modul în care tehnologia MICH îmbunătățește fiabilitatea sistemului prin menținerea componentelor în intervale de temperatură de funcționare sigure, prevenind astfel degradarea performanței și defectarea prematură. Acordăm o atenție specială aplicației emergente a integrării tehnologiei MICH în materialele textile inteligente și în dispozitivele electronice purtabile, un domeniu în care gestionarea termică reprezintă o provocare critică și complexă. Prin examinarea acestui caz de utilizare specific, demonstrăm versatilitatea și potențialul radiatoarelor MICH. Studiul se încheie cu o prezentare a direcțiilor viitoare de cercetare și a inovațiilor necesare pentru asigurarea viabilității comerciale pe scară largă și a adoptării soluțiilor de răcire bazate pe tehnologia MICH, atât în dispozitivele electronice tradiționale, cât și în cele de nouă generație.

Cuvinte-cheie: *materiale textile inteligente, dispozitive electronice purtabile, microcanale, fiabilitate, siguranță, răcirea dispozitivelor electronice, MEMS*

INTRODUCTION

In the past two decades, the drastic growth of miniaturisation of electronic devices such as MEMS, microfluidic devices, biomedical devices, and high-density electronics has revolutionised engineering, research, and technology in several areas. As devices decrease in compactness in size to microscopic and nanoscopic dimensions, they more and more produce increasingly 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 utilised in some applications [1, 2]. However, conventional cooling methods like mini-channel heat sinks [3–6], natural circulation loops [7–9], passive airflow, and fine 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 applications of nanofluids, 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 optimise microchannel geometry [11, 12]. Topology optimisation 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 optimise heat removal by maximising surface area and inducing mixing and uniform cooling. Additionally, through-chip MICH embedded in 3D stacked circuits is a leading area of thermal management with direct, internal cooling and huge performance potential.

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 minimise waste and maximise 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 comprehensive literature review of MICHs that is based on the safety, reliability and thermal management in miniaturised electronics devices such as electronic devices, MEMS, microfluid devices, sensors, etc., which are used in several wearable electronic devices as well as in fabric to remove the heat. The review covers categorisation of microchannel geometries, optimisation of heat transfer in single and two phases, heat transfer mechanism through microchannel, 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 optimisation, coolant environmental responsibility, and lifecycle performance. Further, promising directions for future research focused on developing MICH-based cooling technologies are proposed for improving the safety and reliability of electronic devices.

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 2025, 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.

Methodology for reviewing literature

This study follows a structured literature review methodology to evaluate the sustainability, reliability, and safety performance of MICH for electronic cooling that is used in smart fabrics and wearable electronic systems, such as biosensors, microfluidics, etc. The review centres on comprehending MICH classifications, fabrication methodologies, material and coolant selection, environmental ramifications, thermal performance metrics, and the viability of integration into flexible substrates. Previously published articles were searched across Scopus, Web of Science, IEEE Xplore, ScienceDirect, Google scholar, Elsevier, and Springer, etc. Various important keywords were used, such as Micro-channel, signal and two-phase, sensor, biosensor, microchannel heat sink, microfluidic cooling, sustainable cooling, energy-efficient electronics, wearable thermal management, smart fabrics cooling, and reliability in electronic cooling. We used Boolean operators (AND/OR) and only looked at literature from 2000 to 2025, with a focus on more recent work to find the most up-to-date progress.

Criteria for inclusion and exclusion of the article in this study

In this study, several papers were included based on the peer-reviewed papers about MICH design, thermal modelling, choosing materials, cooling fluids, evaluating sustainability, and wearable integration. Studies that are analytical, experimental, numerical, and review. Works that report thermal performance metrics like the heat transfer coefficient, pressure drop, pumping power, Nusselt number, and temperature drop. Also, some articles are excluded from the present study based on the studies on cooling that don't use microchannels unless they are comparative. Articles that don't include a performance evaluation or don't give enough details about the methodology. Patents, preprints without technical data, and publications that aren't in English. Also, we have used some traditional processes to include and exclude in this study based on the screening, classifying, and putting together. We looked at the titles and abstracts to see if they were relevant, and then we looked at the whole text.

Based on the selected articles, we put the chosen articles into three groups based on their themes such as geometries (rectangular, trapezoidal, fractal, wavy, porous), MEMS/AM fabrication, and nano-enhanced coolants, aspects of sustainability, reliability, and safety include material efficiency, the effect of the coolant on the environment, lifecycle assessment, and preventing overheating failures and use in smart fabrics and wearable electronics which limits on flexibility, biocompatibility, mechanical durability, comfort, and thermal load distribution.

Fundamental principle of the microchannel and mechanism of heat dissipation through the microchannel

MCHs work based on the principle of convective heat transfer, wherein a working fluid absorbs heat from the surface of an electronic component as it travels through narrow channels within the MCH (figure 1). Because of the high surface area-to-volume ratio and minimal diffusion paths within microchannels, MCHs provide significantly more 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 forced convection methods were used to remove the heat from the electronic devices to enhance their reliability, sustainability, and safety. Figure 1 depicts the schematic diagram of the working of the MCHs [16].

From figure 2, it can be seen that the heat transfer mechanism through the MCH works by moving fluid from the reservoir through a saline tube that is controlled by a fluid regulator before entering the MCH test section. The power supply unit powers and controls the heated surface, which is where the fluid flows through the MCH and absorbs heat. To keep an eye on heat distribution and thermal performance, several thermocouples (B1–B6, A1, A2) are placed along the channel to measure temperature changes at different points. A digital temperature indicator shows the temperature readings, which help to determine the temperature of the wall and fluid of the channel and transfers of heat through convection. The fluid goes through the microchannel, where it

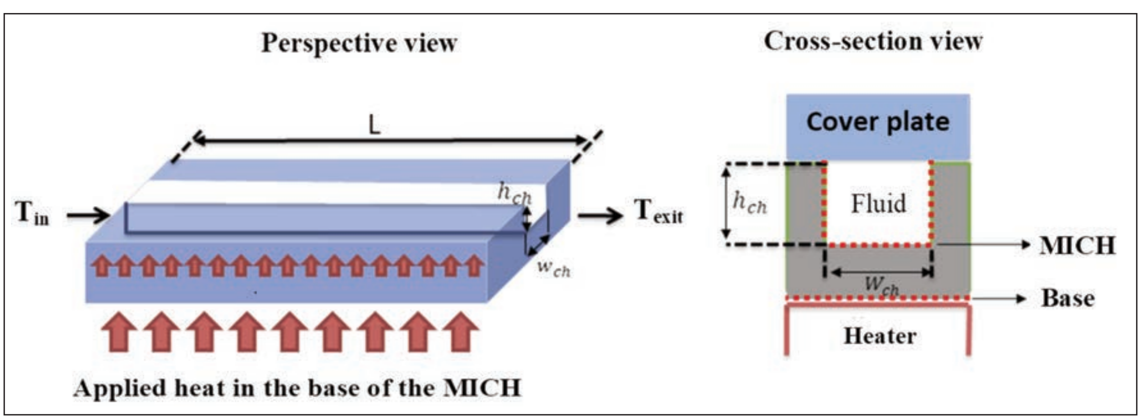


Fig. 1. Schematic diagram of the microchannel

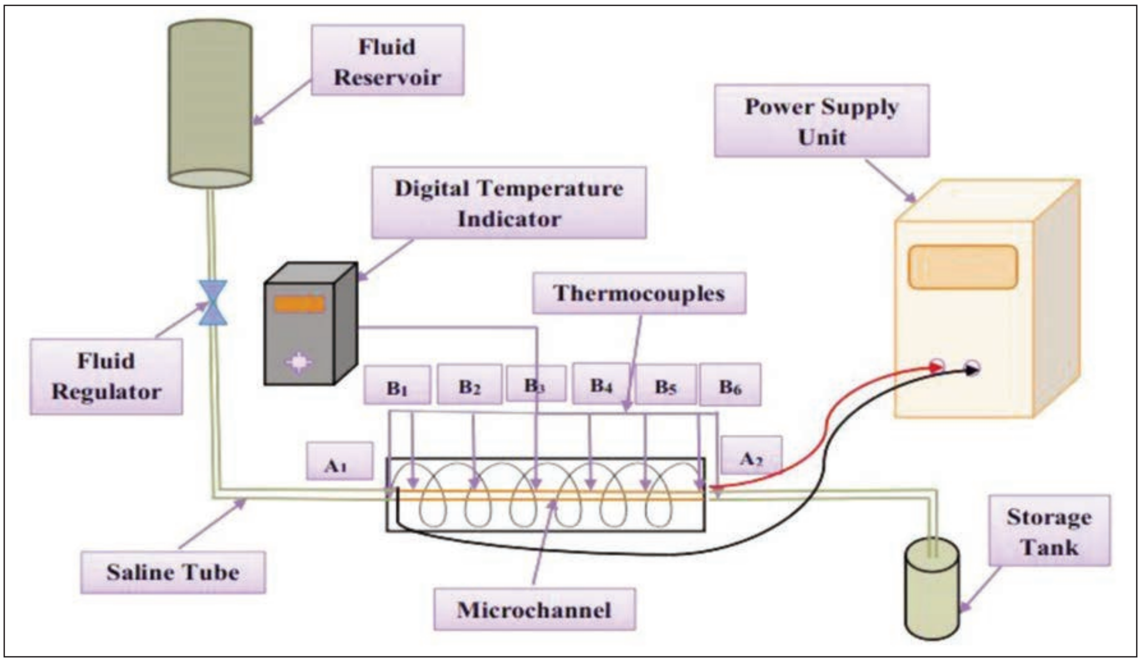


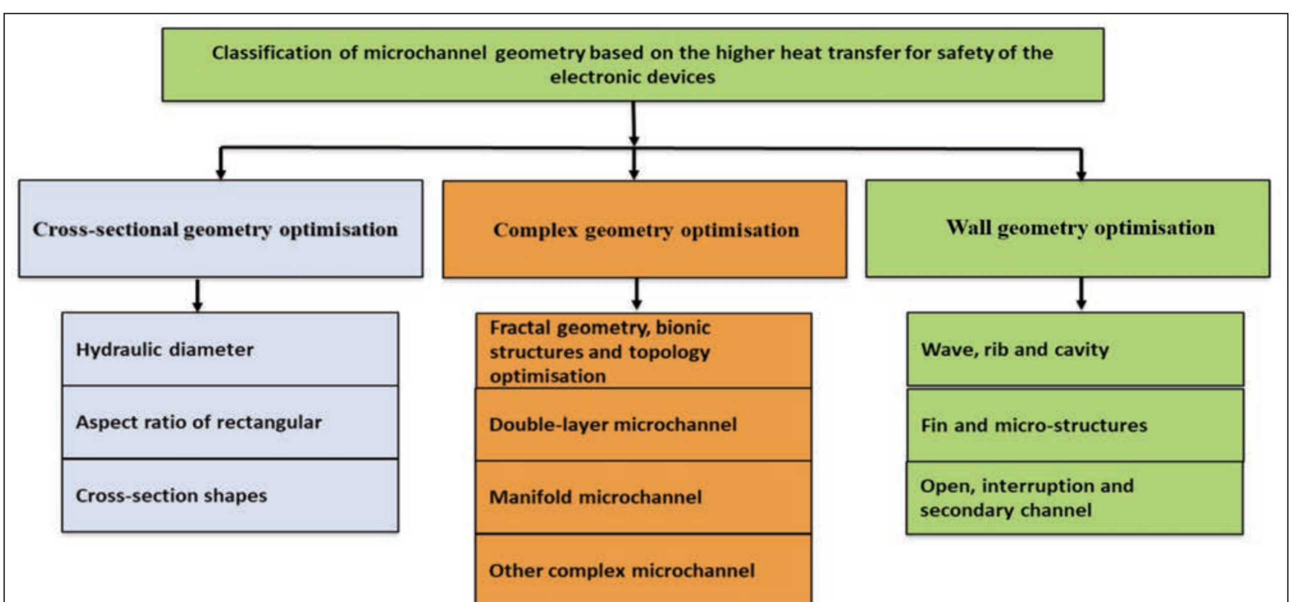
Fig. 2. Schematic diagram of the heat transfer through a microchannel

picks up heat, then leaves and is stored in the storage tank. This completes the flow loop and depicts the heat transfer mechanism in the experimental setup.

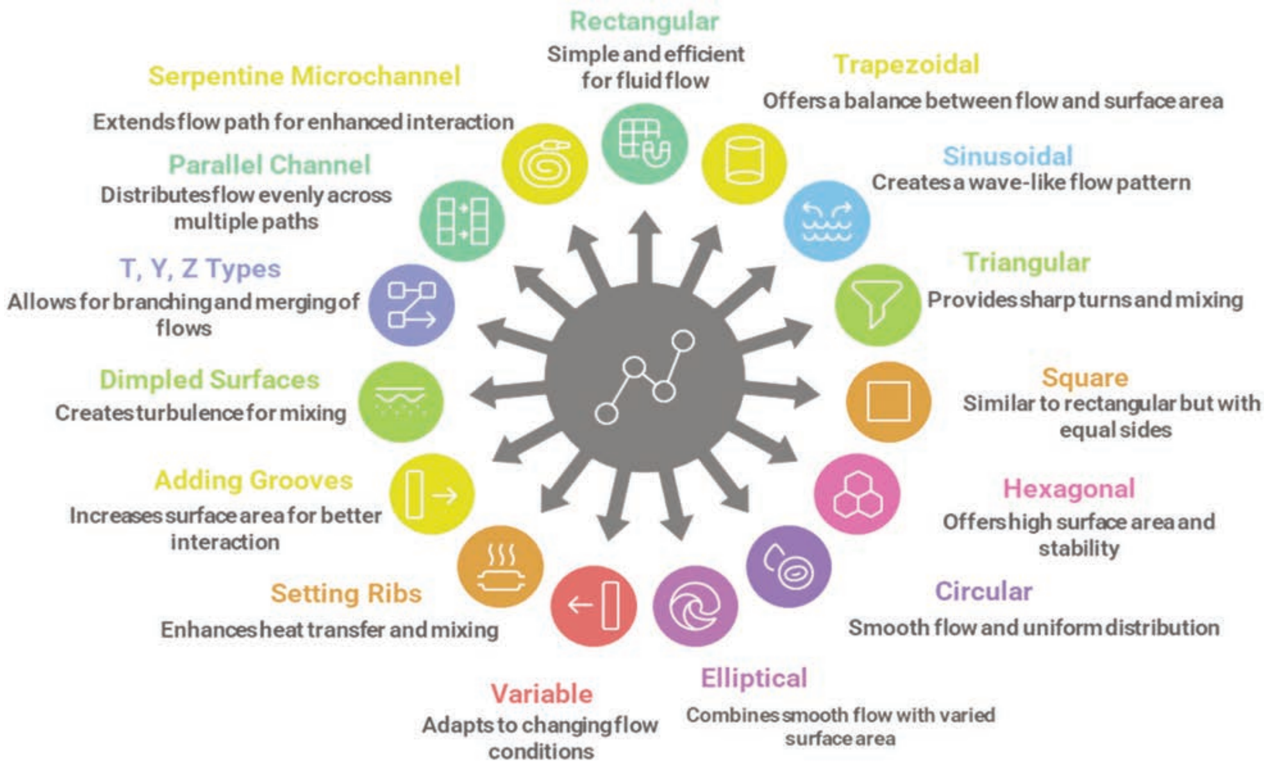
Classification of microchannel and materials and coolant used in this for improving the safety of the devices

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 3, *a* shows the classification of the MICH based on the optimising heat transfer criteria and THP, which provides significant safety of the electronic devices as well as improves the life span.

Based on the previously reported research, MICHs are classified into three categories: cross-sectional geometry optimisation, complex geometry optimisation, and wall geometry optimisation. 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, aluminium, 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



a



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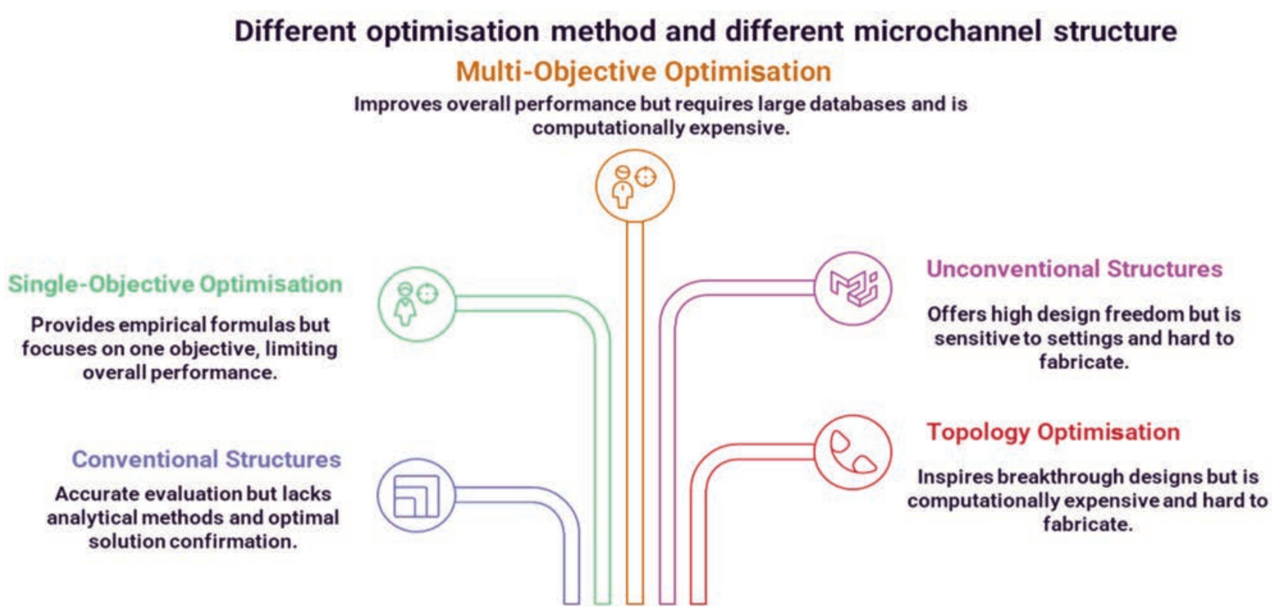

c

Fig. 3. Representation of: *a* – classification of the microchannel based on the higher heat transfer for improving the safety of the electronics devices; *b* – classification of the microchannel based on different microchannel structures; *c* – advantages and disadvantages of different optimisation methods and structure of MCHs

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 deionised 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]. Also, various shapes, geometries, and their modification of MCH were developed with time to improve the heat transfer rate and reduce the pressure drop in the application of wearable electronic devices, which is given in figure 3, *b*. Further, it is very useful to optimise possible thermal improvement methods for MCHSs by changing configuration and shapes, sizes and their surface microstructures. Their advantages and disadvantages, and the method of MCHs depicted in figure 3, *c*.

SUSTAINABILITY ASPECTS, THERMAL SAFETY AND OVERHEATING RISKS, MECHANICAL AND THERMAL RELIABILITY OF THE DEVICES

As electronic devices rapidly miniaturise 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] optimised the thermal hydraulic performance (THP) of an MCHS using numerical and artificial neural networks (ANNs) methods. With the 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 the reliability of the devices. They 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, ΔP = 282.3 Pa, and an overall efficiency of 1.491, and compared to the benchmark result, the optimised design enhanced total performance by 49.1% and concluded that ANN-based optimisation is an effective tool for designing high-performance MCHSs, which are capable of optimising 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, to provide the safety of the electronic devices. They optimised 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 the 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 shapes. 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 the trapezoidal channel is the effective configuration that provides a 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 aluminium MICH using R113 as the working fluid. A square cross-section of the test setup was developed with dimensions of 0.5 mm and 0.5 mm, and a constant heat flux was 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 analysed 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 decreases with increasing the mass flux. However, in two-phase flow, HTC was significantly affected by heat flux, mass flow rate, and vapour quality. Onset of boiling was seen around 47°C, and pressure drop behaviour showed two different regimes for single- and two-phase flow, which was also shown both numerically and experimentally, and developed empirical correlations for the 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 a 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 optimisation 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 optimisation identified the optimal rib geometry and its 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 optimising 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. Further, Wunderle et al. [25] extensively reviewed and summarised advancements in MCHS designs with various channel cross-sectional geometries to improve the 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. Also, 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 the 3D-CFD tool ANSYS and reported that Nu, ff, 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 highest-pressure drop, which makes electronic devices less safe and reliable.

Mudawar in 2002 [27] conducted numerical investigations 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. Similarly, 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 operation 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 analyse 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 the width of the channel was developed to maintain the working temperature under the 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 that 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 the heat transfer of the 4228 databases. Based on this correlation, they proposed a new correlation, Bo*Re0.5 = 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 deionised 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 improves 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 that of 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.

Several recent experimental and numerical research works were reported to improve the safety and reliability of 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 optimisation to increase heat dissipation at a low volume-to-area ratio. Markal et al. [41] developed MICH, which consists of MICH with pin-type fins, which gives higher heat dissipation by optimising the design and geometry sizes of the channel and fins to minimise 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 by 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 cyclically 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 by approximately 15°C at 90 W and validated performance through both experiments and numerical analysis. Further, Rai et al. [43] conducted several single- and two-phase numerical and experimental studies in single- and two-phase flow through MICH

Table 1

SUMMARY OF DIFFERENT METHODS AND WORKING FLUIDS 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	• 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_2O_3 nanofluid	• Best lattice geometry improved THP. • Peak temperature drops up to 12°C and pressure drops approximately 20% compared to straight MICH.
Huang et al. [42]	Phase-change material (PCM) with graphite foam embedded in the walls	Water (base) + PCM for transient loads	• PCM and high-conductivity foam maximised 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 generated from the devices.
Xiang et al. [34]	Vacuum-assisted two-phase honeycomb MICH	Water + R134a (two-phase mix)	• 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)	Deionised water (single and two-phase)	• Working temperature of the device is to be 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 conditions)	Deionised water (H methods)	• Optimising 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.

for improving the safety and reliability of the electronic devices. They used deionised 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 optimised 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 optimisation, which is necessary to prevent drastic pressure changes inside the MICH.

Heat transfer in single and two-phase microchannels

Several researchers have carried out various experimental and numerical studies to predict the heat transfer and Nusselt (Nu) number at different mass flow rates, inlet velocity and Reynolds (Re) number. Wu et al. [45] developed MCHs with widths of 130–200 µm and depths of 30–60 µm using a photolithographic technique and predicted the Nu at different Re numbers. Similarly, Hao et al. [46], Gnielinski et al. [47] and Admas et al. [48] developed MCHs to predict the heat transfer rate through MCHs. However, they modified the hydraulic diameter. It can be seen from figure 4 that Wu et al. [45], Hao et al. [46], and Gnielinski et al. [47] predicted Nu correlation showed a similar profile. However, the quantitative values depicted higher different to each other. Also, Admas et al. [48] used Gnielinski's correlation [47] with certain modifications of Re and Dh to

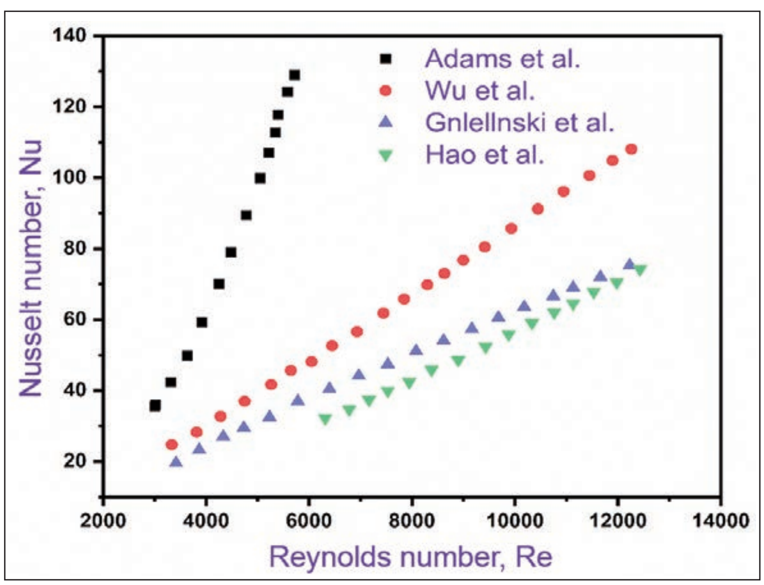

Fig. 4. Variation of Nusselt numbers at different Reynolds numbers

predict the Nu and HTC in MICH and found that at Re numbers 3000 to 6000, Nu and HTC were observed to be higher as compared to other proposed correlations.

Advanced textile microfluidic systems for sweat analysis, cooling, and wearable healthcare monitoring

Textile-based microfluidic biosensors, microchannel- and nanochannel-based devices, and sensors exemplify a novel integration of multiple interdisciplinary domains, encompassing bioelectronics, materials science, and microfluidics. Their potential in biomedicine is considerable, as they utilise textiles to meet the stringent requirements of biocompatibility with the human body and adapt to its uneven surfaces. In microfluidics, a fabric treated with hydrophobic substances functions as a conduit for the accurate transmission of liquids to the sensing element, specifically a biosensor [49–55]. Khosravi et al. [56] developed wearable sweat biosensors for detecting health parameters, which are fabricated in a textile that is easily mounted over a human in a very easy manner. It can be mounted on the daily use cloth and operated for a long time. However, after operating for a long time, the sensor gets heated, and its life span decreases. Therefore, MCHs are used to remove heat from the sensor to the environment to maintain the working temperature under working limits. Yin et al. [57] introduce wearable sweat biosensors that utilise MCHs and nanochannels to detect human health. These types of channels are capable of easily absorbing the heat and sweat from the human body to detect the body temperature, and with the help of sweat sensors, they are able to detect human health to provide safety. Zhang et al. [58] presented a fabric-based microfluidic device that is integrated with cloth to monitor the health of humans for providing safety. They have performed experimental and numerical tests using MCH to properly absorb and deliver the sweat in the sensors, which showed that it is more efficient. Kim et al. [59] presented a flexible textile-based hybrid microbial–enzymatic biofuel cell using a Y-shaped screen-printed MCH and optimised electrode/catalyst configurations to enhance performance. Achieving high power and current densities, the device demonstrates a safe, wearable microscale power platform superior to previous textile or paper microfuel cells. Similarly, Chen et al. [60] suggested a laser-engraved textile microfluidic design using fractal, tree-like bifurcating channels to enable rapid, leakage-free sweat collection with high wicking efficiency. The optimised geometry provides fast induction (<1 min) and high sweat flux, ensuring complete droplet capture for reliable sampling. Integrated with printed sensors and microchips, the system enables real-time wireless monitoring of sweat rate and electrolyte levels, demonstrating strong practicality in field tests. Also, Lingling et al. [61] demonstrated a simple, sustainable method for fabricating moist-electric generators (MEGs) using biomass Juncus effusus fibres, whose natural 3D microchannel networks and LiCl loading enhance moisture capture and continuous energy generation. The resulting JE-based MEG delivers stable long-term output (306.2 mV, 1.11 mA, 13.60 mWcm^{-2}) with strong durability under bending and abrasion.

Demonstrations powering LEDs and a watch highlight its potential as a wearable, textile-integrated power source for portable electronics. Laha et al. [62] experimentally investigated viscoelastic polymer solutions interacting with deformable microchannels, revealing a strong dependence of flow-induced deformation on polymer concentration and molecular weight. Higher concentrations and elastic effects intensify wall deformation, alter local pressure-drop behaviour, and produce nonlinear fluid–structure interactions. Theoretical modelling further confirms the coupled rheology–deformation mechanisms, offering insights for designing adaptive microfluidic devices handling complex fluids. Furthermore, Askar et al. [63] suggested a skin-strain-actuated microfluidic pump (SAMP) that records human activity using asymmetric aspect-ratio microchannels, enabling passive, image-based data capture. The device changes the hydraulic resistance in a way that turns cyclic skin strain into one-way liquid flow. This has been shown to work in both analytical modelling and benchtop tests. Fabricated using PDMS soft lithography, the SAMP reliably tracks repetitive wrist motions and distinguishes between different shoulder movements. The equivalent electrical circuit model accurately predicts pumping efficiency, confirming strain-dependent asymmetric channel behaviour as the core mechanism. Overall, the SAMP functions as a fluidic memory device for summarising human activity, offering a simple, low-power alternative to conventional electronic wearables.

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 their compact sizes. Therefore, a 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 [64].
- 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 the 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.
- There is significant potential for the integration of MCHs and nanochannels in the textile industry, particularly for thermal management in wearable electronics and microfluidic devices embedded within fabrics and clothing, which are very limited.

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 miniaturisation, minimising their sizes and increasing their power densities. Therefore, effective thermal management is required as well as a determinant of system longevity, energy efficiency, and operational safety. MICH and MCHSs can remove a 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 minimise environmental risks.
- MICH is a better solution for improving the safety of electronic devices as compared to 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 temperatures of 10°C to 15°C.
- The trapezoidal design of MICHs provides higher heat transfer than other designs, such as rectangular, square, and circular types of MICHs.
- MCHs are increasingly utilised in textile-based systems to integrate wearable biosensors and microfluidic devices for real-time human health monitoring.
- 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 be resolved for improving the safety of the MICHs during use in the electronic cooling devices. 3D modelling using different designs and shapes of the MICHs cab 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.

REFERENCES

[1] Yu, Z., Q., Li, M.T., Cao, B.-Y., *A comprehensive review of microchannel heat sinks for electronics cooling*, In: International Journal of Extreme Manufacturing, 2024, 6, 022005

[2] Rai, S.K., Sharma, R., Saifi, M., Tyagi, R., Singh, D., Gupta, H., *Review of recent applications of micro channel in MEMS devices*, In: International Journal of Applied Engineering Research, 2018, 13, 9, 64–69

[3] Tuckerman, D.B., Pease, R.F.W., *High-performance heat sinking for VLSI*, In: IEEE Electron Device Letters, 2005, 2, 5, 126–129

[4] Lu, K., Wang, C., Wang, C., Fan, X., Qi, F., He, H., *Topological structures for microchannel heat sink applications – a review*, In: Manufacturing Review, 2023, 10, 2

[5] Japar, W.M.A.A., Sidik, N.A.C., Saidur, R., Asako, Y., Nurul Akmal Yusof, S., *A review of passive methods in microchannel heat sink application through advanced geometric structure and nanofluids: Current advancements and challenges*, In: Nanotechnology Reviews, 2020, 9, 1, 1192–1216

[6] Ayatollahi, S.M., Ahmadpour, A., Hajmohammadi, M.R., *Performance evaluation and optimization of flattened microchannel heat sinks for the electronic cooling application*, In: Journal of Thermal Analysis and Calorimetry, 2022, 147, 4, 3267–3281

[7] Rai, S.K., Kumar, P., Tiwari, M., Panwar, V., Kumar, D., Sharma, V.K., *A comprehensive overview of advancements, applications, and impact of supercritical fluid natural circulation loops*, In: Annals of Nuclear Energy, 2025, 211, 110971

[8] Suman, S., Upadhyaya, R., Raghuvanshi, N.S., Gupta, M.K., Shah, S., Alam, S., *A state of art review of instability in parallel channels of supercritical fluid in nuclear applications*, In: Materials Today: Proceedings, 2022, 62, 226–232

[9] Rai, S.K., Kumar, P., Panwar, V., *Computational analysis of static flow instabilities in supercritical natural circulation loop*, In: Proceedings of International Conference on Thermofluids: KIIT Thermo 2020, Singapore: Springer Singapore, 2020, 387–395

[10] Mala, G.M., Li, D., Dale, J.D., *Heat transfer and fluid flow in microchannels*, In: International Journal of Heat and Mass Transfer, 1997, 40, 13, 3079–3088

[11] Kandlikar, S., *Heat transfer and fluid flow in minichannels and microchannels*, Elsevier, 2006

[12] Cova, P., Santoro, D., Spaggiari, D., Portesine, F., Vaccaro, F., Delmonte, N., *CFD modeling of additive manufacturing liquid cold plates for more reliable power press-pack assemblies*, In: Microelectronics Reliability, 2020, 114, 113734
[13] Sidik, N.A.C., Muhamad, M.N.A.W., Japar, W.M.A.A., Rasid, Z.A., *An overview of passive techniques for heat transfer augmentation in microchannel heat sink*, In: International Communications in Heat and Mass Transfer, 2017, 88, 74–83
[14] Gupta, H.K., Rai, S.K., &Sheorey, T., *Boiling flow heat transfer in microchannel: Experimental and numerical investigation*, In: Proceedings of the 23rd National Heat and Mass Transfer Conference and 1st International ISHMT-ASTFE Heat and Mass Transfer Conference IHMTC-2015, 2015, 1–8
[15] Singh, D., Rai, S., Shukla, S., *Numerical analysis of two phase flow boiling heat transfer through microchannel*, In: IJERT, 2017, 6, 1–6
[16] Ohadi, M., Choo, K., Dessiatoun, S., Cetegen, E., *Fundamentals of microchannels. In Next Generation Microchannel Heat Exchangers,* New York, NY: Springer New York, 2012, 1–32
[17] Tullius, J.F., Vajtai, R., Bayazitoglu, Y., *A review of cooling in microchannels*, In: Heat Transfer Engineering, 2011, 32, 7–8, 527–541
[18] Yu, Z.Q., Li, M.T., Cao, B.Y., *A comprehensive review on microchannel heat sinks for electronics cooling*, In: International Journal of Extreme Manufacturing, 2024, 6, 2, 022005
[19] Dixit, A., Maithani, R., Sharma, S., *Enhancing electronic system cooling: exploring minichannel heat sink solutions*, In: Journal of Thermal Analysis and Calorimetry, 2025, 1–51
[20] Wang, X., Su, Z., Mansir, I.B., Singh, P.K., Othman, N.A., Zhang, L., Deifalla, A., *Thermal and hydrodynamic management of a finned-microchannel heat sink applying artificial neural network*, In: Case Studies in Thermal Engineering, 2023, 45, 102996
[21] Elbadawy, I., Alhajri, A., Doust, M., Almulla, Y., Fayed, M., Dinc, A., Al-Kouz, W., *Reliability of different nanofluids and different micro-channel configurations on the heat transfer augmentation*, In: Processes, 2023, 11, 3, 652
[22] Shakir, R., *Boiling heat transfer in a micro-channel complex geometry*, In: IOP Conference Series: Materials Science and Engineering, IOP Publishing, 2020, 928, 2, 022129
[23] Chen, L., Zhang, X.R., Okajima, J., Komiya, A., Maruyama, S., *Numerical simulation of stability behaviors and heat transfer characteristics for near-critical fluid microchannel flows*, In: Energy Conversion and Management, 2016, 110, 407–418
[24] Zhang, X., Jaluria, Y., *Reliability-based optimization and design limits of microchannel cooling systems*, In: International Journal of Heat and Mass Transfer, 2020, 149, 119202
[25] Wunderle, B., Schacht, R., Wittler, O., Michel, B., Reichl, H., *Performance and thermo-mechanical reliability of micro-channel coolers-a parametric study*, In: The Ninth Intersociety Conference on Thermal and Thermomechanical Phenomena in Electronic Systems (IEEE Cat. No. 04CH37543), IEEE, 2004, 2, 11–16
[26] Sidik, N.A.C., Muhamad, M.N.A.W., Japar, W.M.A.A., Rasid, Z.A., *An overview of passive techniques for heat transfer augmentation in microchannel heat sink*, In: International Communications in Heat and Mass Transfer, 2017, 88, 74–83
[27] Mudawar, I., *Assessment of high-heat-flux thermal management schemes*, In: IEEE Transactions on Components and Packaging Technologies, 2002, 24, 2, 122–141
[28] Spizzichino, M., Sinibaldi, G., Romano, G.P., *Experimental investigation on fluid mechanics of micro-channel heat transfer devices*, In: Experimental Thermal and Fluid Science, 2020, 118, 110141
[29] Ko, H.S., Liu, C.W., Gau, C., Yang, C.S., *Fabrication and design of a heat transfer micro-channel system by a low temperature MEMS technique,* In: Journal of Micromechanics and Microengineering, 2007, 17, 5, 983
[30] Tiselj, I., Hetsroni, G., Mavko, B., Mosyak, A., Pogrebnyak, E., Segal, Z., *Effect of axial conduction on the heat transfer in micro-channels,* In: International Journal of Heat and Mass Transfer, 2004, 47, 12-13, 2551–2565
[31] Ding, Y.Y., Liu, M.G., Jin, Q., *Experimental and numerical investigation of the influence of varying micro-channel width on flow and heat transfer uniformity*, In: International Journal of Thermal Sciences, 2025, 208, 109394
[32] Consolini, L., Thome, J.R., *Micro-channel flow boiling heat transfer of R-134a, R-236fa, and R-245fa*, In: Microfluid Nanofluid, 2009, 6, 731–746
[33] Sarkar, J., *Improving thermal performance of micro-channel electronic heat sink using supercritical CO2 as coolant*, In: Thermal Science, 2019, 23, 1, 243–253
[34] Xiang, J., Deng, L., Zhou, C., Zhao, H., Huang, J., Tao, S., *Heat transfer performance and structural optimization of a novel micro-channel heat sink*, In: Chinese Journal of Mechanical Engineering, 2022, 35, 1, 38
[35] Bello-Ochende, T., Liebenberg, L., Meyer, J.P., *Constructal cooling channels for micro-channel heat sinks*, In: International Journal of Heat and Mass Transfer, 2007, 50, 21–22, 4141–4150
[36] Li, W., Wu, Z., *A general criterion for evaporative heat transfer in micro/mini-channels*, In: International Journal of Heat and Mass Transfer, 2010, 53, 9–10, 1967–1976
[37] Spizzichino, M., Sinibaldi, G., Romano, G.P., *Experimental investigation on fluid mechanics of micro-channel heat transfer devices*, In: Experimental Thermal and Fluid Science, 2020, 118, 110141
[38] Qu, W., Mudawar, I., *Transport phenomena in two-phase micro-channel heat sinks*, In: Journal of Electronic Packaging, 2004, 126, 2, 213–224
[39] Sehgal, S.S., Murugesan, K., Mohapatra, S.K., *Experimental investigation of the effect of flow arrangements on the performance of a micro-channel heat sink*, In: Experimental Heat Transfer, 2011, 24, 3, 215–233
[40] Xia, G.D., Ma, D.D., Wang, W., Zhai, Y.L., *Effects of different structures and allocations on fluid flow and heat transfer performance in 3D-IC integrated micro-channel interlayer cooling*, In: International Journal of Heat and Mass Transfer, 2015, 91, 1167–1175
[41] Markal, B., Evcimen, A., *Investigation of flow boiling phenomenon in micro-pin-fin heat sinks adapted to actively direction-changing moving systems*, In: International Communications in Heat and Mass Transfer, 2024, 159, 108310
[42] Huang, S., Long, C., Hu, Z., Xu, Y., Zhang, B., Zhi, C., *Thermal Performance of Heat Sink Filled with Double-Porosity Porous Aluminum Skeleton/Paraffin Phase Change Material*, In: Micromachines, 2024, 15, 6, 806
[43] Rai, S.K., Goyat, V., Gupta, M.K., Ghangas, G., Bhatt, D., Uniyal, A., Shrivas, N.V., *Numerical and experimental heat transfer analysis of two-phase flow through microchannel for development of heat dissipation correlation*, In: Journal of Non-Equilibrium Thermodynamics, 2025

[44] Hussain, M.E., Rai, S.K., Suman, S., Gupta, P., Gupta, M.K., *Computational Analysis of Transfer of Heat in Micro Size Channels Using Different Boundary Condition in Laminar Flow*, In: Biennial International Conference on Future Learning Aspects of Mechanical Engineering, Singapore: Springer Nature Singapore, 2022, 445–455
[45] Peiyi, W., Little, W.A., *Measurement of friction factors for the flow of gases in very fine channels used for microminiature Joule-Thomson refrigerators,* In: Cryogenics, 1983, 23, 5, 273–277
[46] Hao, P.F., He, F., Zhu, K.Q., *Flow characteristics in a trapezoidal silicon microchannel*, In: Journal of Micromechanics and Microengineering, 2005, 15, 6, 1362
[47] Gnielinski, V., *New equations for heat and mass transfer in turbulent pipe and channel flow*, In: International Chemical Engineering, 1976, 16, 2, 359–367
[48] Adams, T.M., Abdel-Khalik, S.I., Jeter, S.M., Qureshi, Z.H., *An experimental investigation of single-phase forced convection in microchannels*, In: International Journal of Heat and Mass Transfer, 1998, 41, 6–7, 851–-857
[49] Sun, X., Zhao, C., Li, H., Yu, H., Zhang, J., Qiu, H., Liang, J., Wu, J., Su, M., Shi, Y., Pan, L., *Wearable near-field communication sensors for healthcare: Materials, fabrication and application*, In: Micromachines, 2022, 13, 5, 784, https://doi.org/10.3390/mi13050784
[50] Milić, L., Zambry, N.S., Ibrahim, F.B., Petrović, B., Kojić, S., Thiha, A., Stojanović, G.M., *Advances in textile-based microfluidics for biomolecule sensing*, In: Biomicrofluidics, 2024, 18, 5
[51] Hanze, M., Piper, A., Hamedi, M.M., *Stitched textile-based microfluidics for wearable devices,* In: Lab on a Chip, 2025, 25, 1, 28–40
[52] Watel, Q., Cayla, A., Aubert, V., Salaün, F., Viovy, J.L., Boussu, F., *Fully woven textile-based closed microfluidic system design*, In: The Journal of The Textile Institute, 2025, 116, 7, 1358–1367
[53] Yu, W., Li, Q., Zhao, Z., Gong, J., Li, Z., Zhang, J., *A yarn/fabric-based microfluidic patch for sweat sensing and monitoring*, In: The Journal of The Textile Institute, 2024, 115, 11, 2331–2342
[54] Akter, A., Apu, M.M.H., Veeranki, Y.R., Baroud, T.N., Posada-Quintero, H.F., *Recent studies on smart textile-based wearable sweat sensors for medical monitoring: a systematic review*, In: Journal of Sensor and Actuator Networks, 2024, 13, 4, 40
[55] Galliani, M., Ismailova, E., Azizian, P., Makhinia, A., Cabot, J.M., *Vertical textile microfluidics: advancing on-garment sweat sampling for real-time biosensing*. In: Flexible Electronics, 2025, 9, 1, 38
[56] Khosravi, S., Soltanian, S., Servati, A., Khademhosseini, A., Zhu, Y., Servati, P., *Screen-printed textile-based electrochemical biosensor for noninvasive monitoring of glucose in sweat*, In: Biosensors, 2023, 13, 7, 684, https://doi.org/10.3390/bios13070684
[57] Yin, J., Li, J., Reddy, V.S., Ji, D., Ramakrishna, S., Xu, L., *Flexible textile-based sweat sensors for wearable applications*, In: Biosensors, 2023, 13, 1, 127, https://doi.org/10.3390/bios13010127
[58] Zhang, T., Ratajczak, A., Chen, H., Terrell, J.A., Chen, C., *A step forward for smart clothes: Fabric-based microfluidic sensors for wearable health monitoring*, In: ACS Sensors, 2022, https://doi.org/10.1021/acssensors.2c01827
[59] Kim, J., Kong, H.G., Ahn, Y., *Textile-Based Membraneless Microfluidic Double-Inlet Hybrid Microbial–Enzymatic Biofuel Cell*, In: ACS Applied Materials & Interfaces, 2024, 16, 33, 43661-43669
[60] Chen, Y.C., Shan, S.S., Liao, Y.T., Liao, Y.C., *Bio-inspired fractal textile device for rapid sweat collection and monitoring*, In: Lab on a Chip, 2021, 21, 13, 2524–2533
[61] Su, L., Zhang, C., Tang, W., Fu, Z., Gong, J., Qin, J., Xu, W., *Moist-electric generators using biomass Juncus effusus fibers with 3D microchannels for wearable applications*, In: Chemical Engineering Journal, 2024, 499, 156106
[62] Laha, S., Mukherjee, S., Chakraborty, S., *Dynamical Response of Deformable Microchannels under Pressure-Driven Flow of Aqueous Polymer Solutions*, arXiv preprint, 2025, arXiv:2509.21343
[63] Askar, C.B., Cmager, N., Altay, R., Araci, I.E., *Human Activity Recording Based on Skin-Strain-Actuated Microfluidic Pumping in Asymmetrically Designed Micro-Channels*, In: Sensors, 2024, 24, 13, 4207
[64] Kumar, P., Kumar, D., Chalisgaonkar, R., Sharma, V.K., Rai, S.K., *A Critical Review of Ram Methodology: Analysis and Performance Evaluation in Industrial Complexities*, In: Reliability: Theory & Applications, 2024, 19, 4, 80, 83–89

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