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Review Article

A Review of Microchannel Heat Sinks

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ABSTRACT

The progressive miniaturization of electronic components alongside escalating power densities has generated unprecedented thermal management challenges, with heat flux values attaining 10^4 W/cm^2 in specialized applications. Microchannel heat sinks (MCHSs) have established themselves as a highly effective cooling solution owing to their exceptional heat dissipation capacity and favorable surface-area-to-volume characteristics. This review synthesizes findings from previous investigations, encompassing heat transfer enhancement approaches, including rib structures, cavity configurations, pin-fin arrays, and biomimetic designs, advanced working fluids, flow instability phenomena, machine learning implementations, and multi-objective optimization strategies.

1. Introduction

The contemporary trend toward device miniaturization across numerous technological sectors has generated urgent requirements for effective heat extraction from highly compact systems, including advanced computing processors, laser diodes, and nuclear reactor facilities. Thermal flux levels have been documented reaching 10^4 W/cm^2 within nuclear reactor environments. Microscale flow passages offer exceptional thermal exchange capabilities due to their substantial surface area relative to coolant volume, enabling outstanding heat dissipation performance [1].

The appropriate categorization of microscale channels remains an unresolved subject within technical literature. Certain investigators propose classification according to hydraulic diameter dimensions, while alternative perspectives suggest flow stability characteristics should govern categorization. Kandlikar and Grande recommended diameter boundaries of 10-200 μm for microchannel designation, whereas Mehendale and colleagues proposed limits of 1-100 μm. Cornwell and Kew [2] introduced a confinement parameter to differentiate between macro-scale and micro-scale boiling phenomena. According to their criterion, channels exhibiting confinement values of 0.5 or greater qualify as microchannels, since surface tension forces dominate over gravitational effects beyond this threshold.

The pioneering work of Tuckerman and Pease [3] demonstrated a silicon-based microchannel cooling device achieving 790 W/cm^2 heat dissipation capability using water as the circulating medium. Their findings indicated enhanced operational performance of VLSI circuits when employing such microchannel configurations. Keyes performed a theoretical examination of finned microchannel arrangements using conventional heat exchanger analytical methods, concluding that dimensional optimization of both fin elements and flow passages could maximize cooling effectiveness across diverse operational conditions. Phillips [4] conducted thermal performance evaluations on

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silicon and indium phosphate microchannel cooling devices, observing that microchannel configurations demonstrated approximately twice the thermal effectiveness compared to conventional channel designs.

Commercial microprocessors introduced during 1970 occupied approximately 100 square millimeters while containing roughly 2000 transistors [5]. Throughout the 1990s, device dimensions continued decreasing while transistor quantities steadily increased, with individual chips containing hundreds of thousands to millions of transistors. Average chip dimensions have been reduced substantially to several or tens of square millimeters. Further advancements in transistor scaling occurred during the 2000s, with transistor counts reaching millions to tens of millions per chip. By the 2010s, microchips surpassed 100 million transistors due to sophisticated manufacturing processes and transistor architectures, eventually reaching billions of transistors on single chips. Contemporary microchips frequently possess dimensions within the single-digit square millimeter range [5].

During 2018, Intel Corporation introduced a 10 nm processor containing over 100 million transistors within only 100 square millimeters of surface area [5]. This dimensional reduction of microprocessors, accompanied by simultaneous computational power enhancement, represents substantial technological progress. Nevertheless, this miniaturization trend, together with increased computing capabilities, has produced a dramatic elevation of thermal flux generated by these devices. Insufficient heat removal creates concentrated thermal zones that compromise device integrity and reduce operational lifetime. Consequently, thermal regulation constitutes a critical consideration for engineers seeking to maintain reliable device operation over extended periods.

The microchannel heat sink concept was initially proposed by Tuckerman and Pease at Stanford University in 1981 [3]. Subsequently, numerous researchers have conducted extensive investigations into MCHS technology. The MCHS incorporates microscopic protrusions enabling coolant circulation through the device for thermal management of electronic components. These devices achieve exceptional heat transfer rates through reduced flow passage dimensions combined with enhanced surface-area-to-volume characteristics.

Several design parameters require consideration during MCHS development to minimize pressure losses and thermal resistance, including device material, fin quantity, geometric configuration, and spatial arrangement [6]. Material selection primarily depends on thermal conductivity properties. MCHS fabrication utilizes thermally conductive materials such as copper and aluminum. Although copper commands a higher cost than aluminum, its thermal conductivity approximately doubles that of aluminum, justifying its use in demanding applications. Aluminum offers lightweight characteristics and excellent formability while imposing reduced mechanical stress on fragile components, enabling fabrication of complex cross-sectional geometries. Zinc also serves as an acceptable heat sink material, though its thermal conductivity falls below both copper and aluminum values [6].

Heat transfer enhancement strategies for MCHSs divide into active and passive classifications [5]. Active approaches utilize external energy sources to improve thermal performance in microchannel heat sinks. The primary motivation for employing either active or passive techniques involves flow disruption and secondary flow generation. Due to dimensional constraints, active techniques have seen limited application in microchannels compared to passive approaches. Researchers have explored various methods, including electrostatic fields, flow pulsation, and mechanical vibration.

Passive approaches depend on natural heat transfer mechanisms, including convection, conduction, and radiation, for thermal removal without requiring mechanical components such as fans or pumps [5]. These methods enhance heat transfer utilizing inherent properties of the heat sink and its surrounding environment. Within MCHS applications, passive cooling techniques serve thermal management needs across electronics, automotive, aerospace, and other sectors. By reducing or eliminating dependence on active cooling components, passive methods offer silent operation, reduced energy consumption, and enhanced system dependability.

This review paper provides a comprehensive examination of microchannel heat sink technology. The following sections on advances in the field are based on original research papers covering passive enhancement techniques, working fluid innovations, hotspot thermal management, flow instability, machine learning applications, and multi-objective optimization methodologies. Research gaps and future challenges are also identified.

2. Advances in the Field

2.1 Material Selection for Microchannel Heat Sinks

The microchannel material directly affects manufacturing processes and heat dissipation performance. Material selection primarily depends on thermal conductivity characteristics.

For external microchannel applications, materials mainly include silicon, stainless steel, copper, aluminum, and ceramics. Silicon predominates due to its superior properties, enabling lithographic patterning and deep etching for high-aspect-ratio features. Copper provides advantageous combinations of moderate hardness, excellent thermal conductivity, and wear resistance.

For embedded microchannel applications, the material often matches the electronic chip substrate, including silicon, silicon carbide, diamond, and composite structures. Kumar et al. [7] performed conjugate heat transfer simulations comparing copper, aluminum, and silicon substrate materials. Results indicated that silicon microchannels produced the maximum coolant temperature rise. The parametric investigation revealed that increasing the mass flow rate substantially affects the average temperature and the thermal differential.

2.2 Rib and Groove Structures

Incorporating ribs on microchannel walls is a widely adopted flow-disruption technique. Wang et al. [8] documented Nusselt number enhancements of 1.1 to 1.55 times relative to smooth channel configurations when microscale ribs and grooves were added. Friction factors for rib-grooved channels exceeded smooth channel values by factors up to 4.09.

Zhang et al. [9] numerically investigated six surface enhancement geometries, including rectangular, triangular, and hexagonal rib and cone configurations (Fig. 1). Results demonstrated that 45-degree tapering reduced frictional losses with maximum pressure drop decreases of 85%, although thermal performance compromise was observed with maximum Nusselt number reductions of 25%. Triangular ribs demonstrated greater thermal energy transfer capability than rectangular and hexagonal configurations.

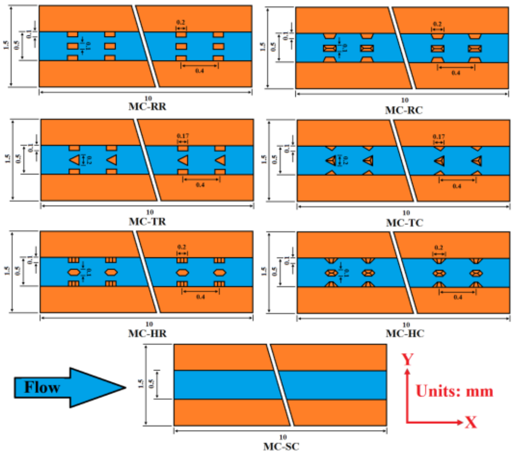

Fig. 1. Different rib configurations in a MCHS [9].

Wen et al. [10] examined thermal and flow characteristics combining secondary channels with various rib geometries, including diamond, rectangular, rear-triangular, front-triangular, and elliptical configurations. Front-triangular ribs combined with secondary channels produced superior overall performance, achieving up to 34% improvement at Re = 200.

2.3 Cavity and Dimple Configurations

Implementing cavities and dimples on microchannel surfaces provides an alternative heat transfer enhancement approach. Xu et al. [11] demonstrated average Nusselt number increases from 8.21 to 9.44 (15% enhancement), accompanied by 2% pressure drop reduction using dimple configurations.

Moon et al. [12] experimentally studied turbulent flow over dimpled surfaces, finding that dimpled walls exhibited Nusselt numbers 2.1 times greater than conventional channels, while friction factors were only 1.6 to 2.0 times higher in thermally developed regions.

2.4 Pin-Fin Arrays

Incorporating micro-scale pin-fins provides additional flow disruption within microchannel heat sinks. Dogan et al. [13] found that maximum heat transmission occurred at 8-9 mm spacing, with optimal spacing dependent on Rayleigh number.

Wazir et al. [14] determined that mixed-configuration pin-fin arrangements achieved maximum thermal enhancement factors of 1.4 with Nusselt number increases 2.3 times greater than smooth microchannel values.

Feng et al. [15] developed a hybrid neural network architecture to optimize hybrid pin-fin microchannel heat sink designs, achieving prediction accuracy exceeding 94.33%. NSGA-II-based optimization yielded performance improvements of 5.58%, 10.76%, and 45.73% for high-power heat source temperature, low-power heat source temperature, and pressure drop, respectively.

2.5 Channel Curvature Modifications

Channel curvature modification represents another method for enhancing thermal performance. Deng et al. [16] found that reentrant microchannel heat sinks achieved Nusselt number increases up to 39% with thermal resistance decreases up to 22% within a Reynolds number range of 150 to 1100.

Ghaedamini et al. [17] examined converging-diverging microchannels (Fig. 2), finding performance factor improvements of 0.8, 1.0, and 1.2 at Reynolds numbers of 200, 400, and 600, respectively, compared to conventional microchannels.

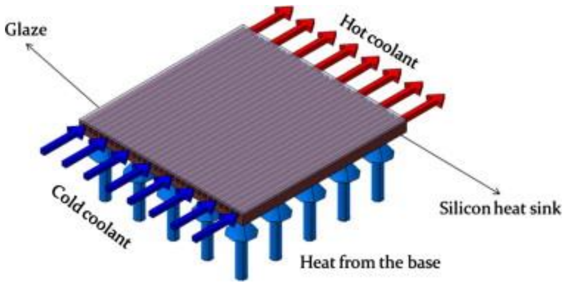

Fig. 2. Schematic of converging-diverging microchannels [17].

Huo et al. [18] investigated asymmetric sinusoidal wavy microchannels with elliptical microcolumns. Results showed that adding elliptical microcolumns and increasing the inlet flow rate significantly enhanced heat transfer. Compared to the baseline linear structure, the Nusselt number increased by a factor of 2.2, with 33.7% improvement in the performance evaluation criterion.

2.6 Bionic and Biomimetic Structures

Drawing inspiration from shark skin placoid scale morphology, Wang et al. [19] developed a bionic microchannel heat sink incorporating biomimetic structures on internal channel surfaces. Numerical simulations revealed that placoid structure arrangement, quantity, and inclination angle significantly influence thermal transfer by modifying flow patterns, increasing effective heat exchange area, and restructuring thermal boundary layers. An 8-degree inclination angle provided optimal flow acceleration with acceptable pressure drop.

Periasamy and Narendran [20] explored topology-optimized heat sinks employing alveoli-inspired structural designs that mimic natural heat and mass exchange mechanisms. Alveoli structure density was selectively increased in hotspot locations. The D4 configuration demonstrated 68.4% heat transfer enhancement with 14.32% pressure drop increase, yielding 61% performance evaluation criterion improvement.

2.7 Nanofluid Coolants

Conventional fluids, including water, exhibit limited thermal conductivity, restricting heat transfer efficiency. Suspending nano-scale solid particles within base fluids creates nanofluids with enhanced thermal conductivity.

Rostami et al. [21] performed a numerical simulation of pin-fin-enhanced heat sinks using nanofluid circulation through helical microchannels with phase change material occupying interstitial spaces (Fig. 3). Reynolds number elevation substantially reduced outlet nanofluid temperature, while increasing nanoparticle volume fraction produced modest temperature decreases.

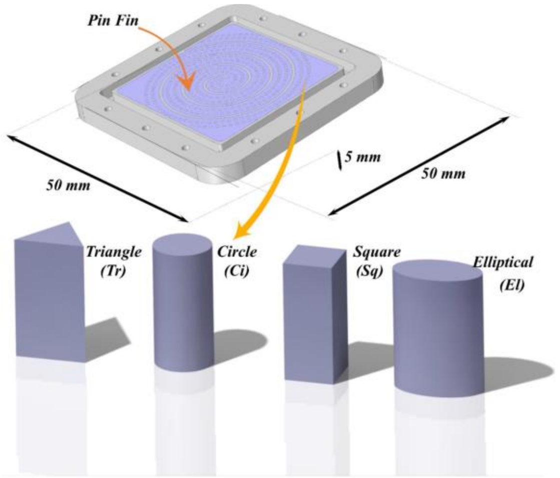

Fig. 3. Schematic of an MCHS proposed by Rostami et al. [21].

Aziz and Alazzam [22] integrated computational fluid dynamics with a two-stage hybrid machine learning framework to model graphene nanofluid flow within sinusoidal microchannels. Amplitude variation enhanced heat transfer up to 5.9%, although high frequency-amplitude combinations reduced the average Nusselt number by 2.7%. Nanoparticle effects were most pronounced at low Reynolds numbers.

2.8 Phase-Change Materials and Flow Boiling

Flow boiling achieves substantially elevated heat transfer coefficients and improved cooling capacity at specified flow rates. Due to microchannel dimensional constraints, bubbles become confined within restricted spaces, making surface tension effects more influential than in conventional-scale channels.

Solid-liquid phase change applications utilize microencapsulated phase change material slurries possessing substantial latent heat, offering benefits for thermal energy storage and temperature regulation. Slurry convective heat transfer coefficients exceed water values by substantial margins.

Rostami et al. [21] investigated phase change material melting and solidification within heat sink thermal management systems. At Reynolds numbers of 100, 200, and 300, phase change material melting initiated at approximately 150, 200, and 250 seconds, respectively, while at Reynolds numbers of 400 and 500, melting remained minimal (Fig. 4).

2.9 Hotspot Thermal Management

In hotspot regions where thermal flux may exceed surrounding areas by orders of magnitude, managing elevated temperatures becomes critically important. Cao and Wu [23] introduced manifold microchannel (MMC), radial microchannel (RMC), and manifold annular microchannel (AMC) configurations. The MMC structure achieved 81.4% pressure drop reduction compared to straight parallel microchannel designs. The RMC configuration demonstrated superior temperature uniformity. The AMC design integrated the benefits of both configurations, achieving 87.9% pressure drop reduction.

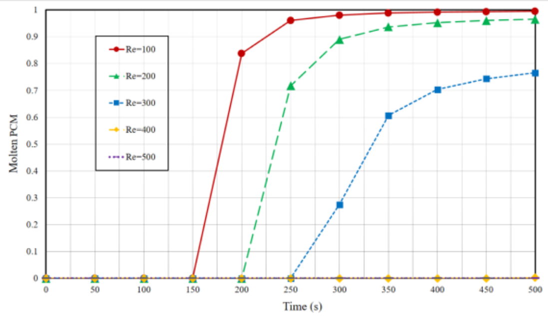

Fig. 4. Variations of Molten PCM with time [21].

Wang et al. [24] presented a microchannel heat sink incorporating integrated temperature sensors capable of monitoring real-time temperature variations. The temperature profile along the microchannel was extracted, and the heat source-formed temperature peak shifted toward the flow direction with increasing flow rate.

Cang et al. [25] proposed embedding microchannels within interposer substrates while integrating through-silicon vias into channel walls. The optimized TSV-integrated microchannel heat sink demonstrated 5.58% maximum temperature reduction for high-power heat sources and 45.73% pressure drop reduction compared to conventional designs.

2.10 Flow Maldistribution and Instability

Periasamy and Narendran [19] investigated flow maldistribution and hotspot formation. Hotspot-embedded baseline topology 2 exhibited 5-6% higher heat transfer coefficient than topology 1 with thermal resistance of 0.8×10^{-2} K/W. The optimized gradient structure with 95.21 mm^3 flow path volume increased heat transfer by 68.4% while increasing pressure drop by 14.32% (Fig. 5).

2.11 Artificial Neural Networks

Artificial neural networks have been proposed for modeling complex nonlinear relationships between input parameters and performance outputs. Ma et al. [26] identified the fin attack angle as the most influential parameter affecting Nusselt number and pressure drop predictions.

Aziz and Alazzam [22] employed Random Forest regression to upscale numerical datasets prior to artificial neural network training, reducing mean squared error by 58.4% and improving regression coefficients by 8.8%. Validation against additional computational fluid dynamics cases yielded average prediction errors below 5%.

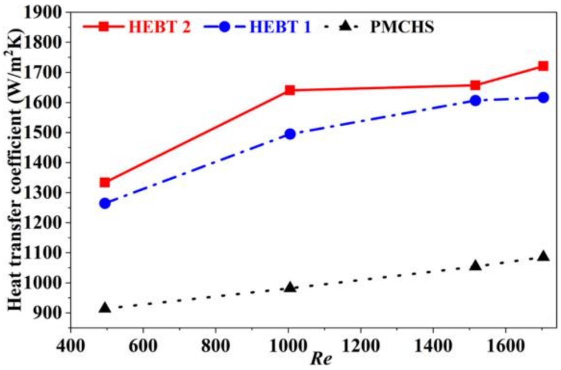

Fig. 5. Heat transfer coefficient versus Re for various MCHSs [19].

2.12 Hybrid Neural Network Architectures

Feng et al. [15] developed a hybrid neural network combining a deep neural network and a convolutional neural network component, achieving prediction accuracy exceeding 94.33%. The hybrid architecture outperformed conventional networks across root mean square error, mean absolute error, and relative error metrics.

Wang et al. [27] developed a hybrid architecture combining fully connected neural network and convolutional neural network components with proximal policy optimization reinforcement learning. Compared to initial structures, the maximum temperature and pressure drop were reduced by 6.8% and 11.5%, respectively.

2.13 Multi-Objective Optimization

Comprehensive evaluation of pressure drop, heat transfer performance, and temperature uniformity requires appropriate performance criteria. Wen et al. [10] defined the performance factor as the ratio of Nusselt number enhancement to the 1.5th power of friction factor increase.

He et al. [28] constructed a composite objective function using a linear weighted summation of dimensionless maximum temperature difference and dimensionless pumping power consumption. The composite function reached a double minimum value of 0.857 at optimal height-width ratios of 5.0 and 14.8, representing 14.26% improvement compared to the initial design.

The LINMAP method identified optimal designs with Nusselt number and friction factor values of 13.60 and 0.119 [29]. TOPSIS methodology yielded optimal configurations with an aspect ratio of 4.53 and a height-width ratio of

11.05, achieving 35% reduction in pumping power [30].

3. Research Gaps and Challenges

Despite significant progress in microchannel heat sink technology, several research gaps and challenges remain:

Flow regime characterization: Unlike conventional-scale channels, microchannel flow regimes remain inadequately characterized. The transition boundaries between different flow patterns vary dramatically even for identical geometries under the same flow conditions, requiring the development of comprehensive flow pattern maps specifically for microchannel configurations.

Generalized heat transfer correlations: Existing heat transfer correlations demonstrate inconsistency and substantial deviation from experimental measurements, attributable to limited experimental ranges, varying operating conditions, and diverse channel geometries across studies. Future research must focus on developing generalized correlations applicable across wide parameter ranges.

Flow instability mitigation: Two-phase flow instabilities, including flow reversal, pressure fluctuations, and wall temperature oscillations, represent primary constraints limiting microchannel application deployment. Although inlet restrictors, re-entrant cavities, and operating condition adjustments have been proposed, robust passive stabilization methods remain underdeveloped.

Hotspot management under non-uniform heating: Most existing studies assume uniform heat distribution, whereas real applications involve localized high-flux regions. Developing gradient density structures and variable fin arrangements that adapt to non-uniform thermal loads requires further investigation.

Manufacturing complexity and cost: Bionic structures, topology-optimized designs, and TSV-integrated configurations present significant fabrication challenges, particularly for semiconductor materials. Advanced manufacturing techniques, including additive manufacturing and precision etching, need further development for cost-effective production.

Nanofluid stability and long-term performance: Nanoparticle agglomeration, sedimentation, and channel clogging remain unresolved issues for nanofluid applications. Long-term stability testing and development of stable nanoparticle suspensions are essential for practical implementation.

Machine learning model generalization: Current machine learning models are trained on specific datasets with limited parameter ranges. Developing generalized models capable of accurate prediction across diverse geometries, operating conditions, and fluid types remains challenging.

Multi-objective optimization trade-offs: The inherent trade-off between heat transfer enhancement and pressure drop increase requires balanced optimization. Future research should explore novel geometries that decouple this relationship, achieving high heat transfer with minimal hydraulic penalty.

4. Conclusions

Flow disruption techniques, including rib structures, groove features, cavity configurations, dimple patterns, and pin-fin arrays, contribute significantly to thermal performance enhancement. Tapered rib designs at 45-degree angles reduce pressure drop by 85% while incurring 25% Nusselt number reduction [9]. Channel curvature modification improves heat transfer by generating Dean vortices that enhance fluid mixing. Sinusoidal channel geometries achieve Nusselt number increases up to 2.2 times with 33.7% performance evaluation criterion improvement [18].

Biomimetic structures inspired by shark skin placoid scale morphology substantially improve thermal performance through flow pattern modification and heat transfer area enhancement [19]. Nanofluids demonstrate enhanced thermal conductivity compared to base fluids, with nanoparticle effects most pronounced at low Reynolds numbers [21,22]. Hybrid neural network architectures achieve prediction accuracy exceeding 94% with determination coefficients above 0.99, offering efficient approaches for performance prediction and design optimization [15,22,27].

Manifold microchannel and related configurations achieve significant pressure drop reductions of 81.4% to 87.9% relative to straight parallel microchannel designs for hotspot thermal management [23].

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