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A Review on Microchannel Heat Sink Focusing on Architecture Design for Improvement of Thermal Resistance and Pumping Power

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Abstract. Microchannel heat sinks (MCHS) are pivotal for thermal management in high-heat-flux electronics. However, conventional straight parallel microchannels suffer from inherent limitations including thermal boundary layer development, flow maldistribution, and substantial pressure drop. This review systematically explores and categorizes advanced design strategies to overcome these challenges. Five key modification approaches are critically examined: non-uniform cross-sectional designs, wavy or sinusoidal channels, double-layered/multi-layered counter-flow configurations, integration of porous structures, and bio-inspired architectures. Each design is evaluated based on its impact on the core performance metrics: thermal resistance, pressure drop, and temperature uniformity. The analysis reveals that while most innovations effectively enhance heat transfer efficiency, they often involve a trade-off with increased hydraulic resistance. Furthermore, hybrid designs that synergistically combine multiple strategies, such as wavy channels with porous ribs, emerge as a promising direction for achieving comprehensive performance optimization. This review provides a structured framework for understanding the evolution of MCHS designs and highlights future trends for developing next-generation high-efficiency cooling devices.

Keywords: Microchannel heat sink, Heat transfer enhancement, Topology, Structure design

1. Introduction

The relentless pursuit of higher processing power and greater component integration in electronics has led to unprecedented increases in heat flux, making thermal management a critical bottleneck for performance and reliability [1]. Microchannel heat sinks (MCHS), first pioneered by Tuckerman and Pease [2], have long been regarded as a forefront solution for high-efficiency cooling due to their exceptionally high surface-area-to-volume ratio. The straightforward parallel microchannel design has been extensively studied and utilized for its simplicity in modeling and fabrication.

Nevertheless, the conventional straight microchannel architecture is plagued by several fundamental drawbacks. The predominantly laminar flow leads to the development of a thermal boundary layer, which acts as an insulating barrier and diminishes heat transfer efficiency [3-5]. Manufacturing inconsistencies can cause flow maldistribution among channels, creating detrimental

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hot spots. Furthermore, the continuous pressure drop along the channel length necessitates powerful, energy-consuming pumps, especially in systems with long or narrow channels [6].

In response to these challenges, significant research efforts have been directed toward innovating and optimizing MCHS designs beyond the conventional paradigm [1-7]. This review aims to synthesize and categorize these advancements into coherent themes. It will focus on five prominent design modification categories: alterations to the channel's cross-section, the implementation of wavy pathways, the stacking of layers in counterflow arrangements, the incorporation of porous media, and the adoption of bio-inspired geometries. The primary objective is to provide a comprehensive overview of how these novel designs address the tripartite challenge of minimizing thermal resistance, reducing pressure drop, and improving temperature uniformity, thereby outlining the current state and future trajectory of MCHS technology development.

2. Structure and principle of microchannel heat sinks

2.1. Description the structure of MCHS

The structure of a conventional rectangular microchannel heat sink is illustrated in Fig. 1a. It consists of many channels sandwiched by solid ribs. All the channels are usually offshoots of a main channel that is connected to a pump and recombined at the end of the heat sink as demonstrated in Fig. 1b. In a traditional heat sink, each individual channel should be rectangular and structurally identical to every other channel. The fluid used in the system can also vary, but most commonly, water is used although there are occasionally studies that use air as the heat transfer fluid.

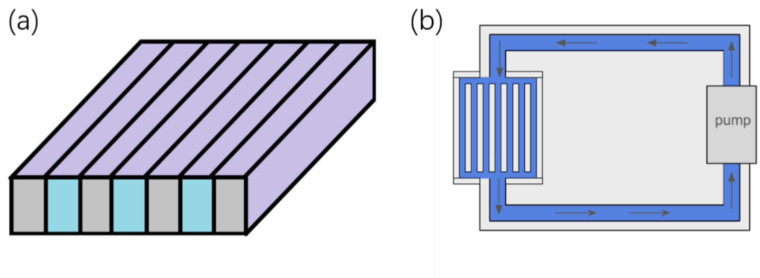

Figure 1. Schematic diagram of microchannel heat sink. (a) Conventional rectangular microchannel; (b) Simplified layout of standard microchannel heat sink and pump

2.2. Governing equations for the MCHS

The principles of an MCHS are governed by the following flow and heat transfer equations [2,3]:

$$\nabla \vec{V} = 0 \tag{1}$$

$$\rho_f \left(\vec{V} \cdot \nabla \vec{V} \right) = -\nabla p + \nabla \cdot \left(\mu_f \nabla \vec{V} \right) \tag{2}$$

$$\rho_f c_{pf} \left(\vec{V} \cdot \nabla T_f \right) = k_f \nabla^2 T_f \tag{3}$$

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Additionally, there is also an equation for solid regions

$$k_s \nabla^2 T = 0 \tag{4}$$

Where $\vec{V}$ is the velocity of the fluid, p refers to the pressure of fluid regions, T_f , T_s are the temperatures of the fluid and solid respectively, ρ_f , c_{pf} , μ_f , k_f represent the density, specific heat, dynamic viscosity, and thermal conduction of the liquid, and k_s is the thermal conduction of the solid.

Equation 1 expresses that the volume of liquid flowing into the MCHS is the same as the volume of liquid flowing out, effectively saying that the liquid flows through the medium.

Equation 2 expresses the pressure at the end of the channel on the left as a function of pressure at the start of the channel($-\nabla p$) and the pressure lost to frictional and other internal forces ($-\nabla \cdot \left(\mu_f \nabla \vec{V}\right)$)

Equation 3 expresses that the thermal energy leaving the system via the outflow is the same as the energy transferred into the fluid from the solid.

Equation 4 represents the heat transfer by convection within the solid, which should be 0.

Additionally, many texts use Reynold's number($\Re$) as a variable, it effectively represents the how turbulent the flow of fluid is, with higher numbers representing more turbulent flows.

2.3. Performance and limitations of the conventional rectangular MCHS

The most common configuration is "straight parallel microchannels", while this design is easy to model and mass produce, it suffers from a few critical drawbacks: development of a thermal boundary layer, flow maldistribution, and loss of pressure along the channel. As the flow is largely laminar, a thermal boundary can develop along the surface where the fluid meets the channel's edges, this reduces the temperature differential and increases thermal resistance because the parts of the channel near the center don't actually carry heat away. Additionally, inconsistencies in the production tolerances can cause flow maldistribution between each channel which can affect temperature uniformity and cause "hot spots" where there is less flow further decreasing its reliability. Finally, the linear nature of the channels causes the pressure to drop throughout it, meaning a stronger pump that consumes more energy is required, this is especially noticeable in longer or thinner channels.

In general, we can gauge the efficiency of the microchannel heat sinks with 3 factors: thermal resistance, pressure drop, and temperature uniformity. Thermal resistance gives a value depending on how quickly heat can be transferred out of the system, the smaller the number, the more efficient. Pressure drop represents the amount of energy required for the pumps to run, the lower the number, the better. Temperature uniformity represents how uniformly the heat is transferred out (higher numbers represent "hot spots" with a high difference from average temperature), the lower the number, the better.

3. Strategies and design schemes for performance improvement

3.1. Non-uniform cross-sectional designs

This method includes both changing the cross-sectional shape of the channel or changing the dimensions of the channel along the length. The simplest change that can be applied to the heat sink is to adjust the aspect ratio of the channel for the same cross-sectional area. This method focuses on increasing surface area so that there's more surface area for heat exchange, however, the drawback to this design is that the same increase in surface area can cause more water to "stick" and therefore increase pressure drop. Wang et al. [3] created a simulation to record the effects that changing the aspect ratio has on thermal resistance. They found that changing the height/aspect ratio across the length causes a lower thermal resistance due to larger surface area to transfer heat, but also an increase in pressure drop. Ultimately, they determined the best aspect ratio to be between 8.904 and 11.442. Another change that has less information on it is changing the cross sectional shape of the MCHS. This mainly focuses on changing the geometry of thermal boundary layers and restricting different currents to achieve different albeit not necessarily better results. Fig. 2 displays some of the most commonly used shapes: rectangular, triangular and trapezoidal.

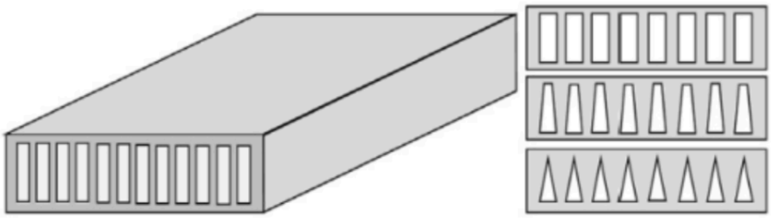

Figure 2. Commonly used cross sections for microchannel heat sinks [3]

Wang et al. [3] additionally conducted a simulation of different cross-sectional shapes in the same study, testing a rectangular, trapezoidal, and triangular cross-section. For the same hydraulic diameter, they generally found triangular cross sections to provide the least pressure drop, but also the highest thermal resistance. On the other end of the spectrum, rectangular cross-sections seem to provide a lower thermal resistance in exchange for a higher pressure drop and in between the two lies the trapezoidal cross-section. Hasan et al. [8] simulated many different cross-sectional shapes using an effectiveness index, which represents how much heat is being transferred out of the system and a performance index, which shows the efficiency of the heat sink via a ratio between the pressure drop and heat transfer. The results show that, for lower thermal conductivity ratios, trapezoidal cross sections have the highest performance index, but circular cross sections have a higher performance index at higher thermal conductivity ratios, and always have a higher efficiency index. The last method is a tapering width or height, the goal of this design is to increase the velocity of the fluid near the end of the MCHS so it can absorb more heat and level out the temperature gradient of the MCHS. Fig 3 provides a visual comparison between a standard MCHS channel against a tapered channel design. This method works because if you reduce the cross sectional area of a pipe, the fluid inside must flow faster for the same volume.

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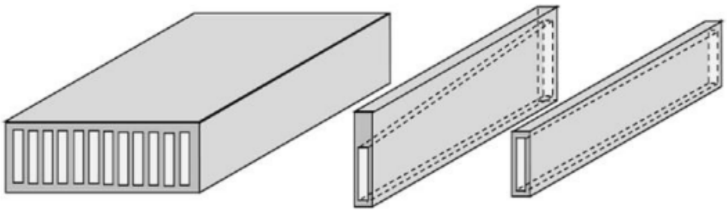

Figure 3. Diagram of a standard channel and a tapered channel [4]

Hung et al. [9] experimented with a tapering design with the coolant flowing from a larger inlet into a smaller outlet. They recorded both the velocity of the fluid as well as the temperature across the heat sink and found that a channel with a constricting width significantly increased the velocity of the fluid. Additionally, this same design flattened out the temperature gradient of the heat sink with the curve being largely the same near the beginning, but maintaining consistent lower temperature further into the channel. Wang et al. [3] also performed experiments with a cross sectional area that changes along the height and found that, while the thermal resistance for a cross sectional design that is more triangular is higher, it drastically decreases the pressure drop.

Overall, changing the cross-sectional shape of the channel offers a simple way to adjust pressure drop and heat transfer with a general rule of thumb being that for a larger edge to area ratio, the heat transfer rises while pressure drop also increases. Additionally, tapering the channel offers a simple and effective solution to squeeze more value out of the same flowrate taking advantage of basic fluid mechanics to change velocity.

3.2. Wavy/sinusoidal channels: as the names implies, the channel has periodic changes in its direction

The main functioning principle of sinusoidal channels is that the changes in the flow of the liquid induces a secondary current known as “dean vortices”. These currents work across a cross sectional area of the liquid and causes turbulence that breaks up the thermal boundary layer and in turn, decreases thermal resistance (allows you to use the entire channel for conducting heat instead of just the boundaries). Fig. 4 shows the general structure of one of these channels.

Mohammed et al. [1] performed a numerical simulation of heat transfer enhancement in wavy MCHS. The results of the simulation indicated that the temperature decrease increased as the amplitude of the waves increased up to a certain point. The running theory for this is that after a certain amplitude, poor fluid mixing starts to arise as a problem. However, these improvements in thermal resistance comes with the drawback of consistently higher pressure drops for larger amplitudes compared to smaller ones.

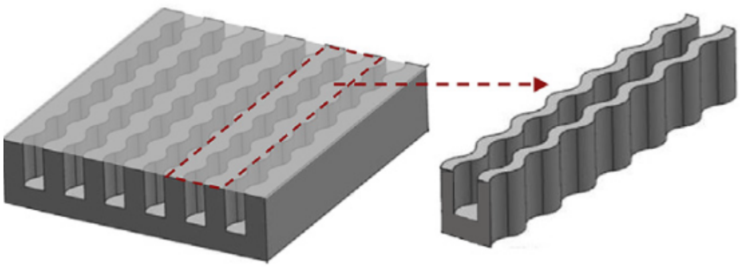

Figure 4. Model of a wavy channel [1]

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Ermagon et al. [10] produced a MCHS with wavy channels that used a hydrophobic surface texture in an effort to reduce the increase in pressure drop caused by traditional wavy channels. The method used to produce a hydrophobic effect are longitudinal grooves along the channel to create air gaps and reduce contact area between the surface and water. However this is noted to have the drawback of reducing surface area for heat transfer since having an air cushion increases thermal resistance. Overall, despite the increase in thermal resistance, there appeared to be a 47.3% increase in the "goodness factor" criterion indicating better performance compared to non-hydrophobic wavy channels.

Sui et al. [11] investigated the flow patterns in order to further understand the mechanics of the mixing. They found that the Jean vortices become more chaotic as the Reynolds number increases, at a certain threshold, the vortices become so turbulent that it increases the pressure drop. Additionally, the amplitude of the channel affects this heavily, as the higher the amplitude of the channel, the lower threshold is to cause turbulent flow.

Zhou et al. [12] focused more on the performance of the wavy channels compared to straight microchannel heat sinks. They found that the effectiveness of wavy channels compared to straight channels is heavily dependent on amplitude and frequency which increases with either generally increasing pressure drop while reducing thermal resistance. However, as these variables reach more extreme values, turbulence decreases the efficiency of the system, ultimately, the group found that the heat transfer of wavy channels can be up to 2.8 times the heat transfer of a similar straight channel at.

All in all, sinusoidal channels trade can decrease the thermal resistance of the channel at the cost of increased pressure drop. With the main working mechanic behind it being dean vortices that break up the thermal boundary layer.

3.3. Double-layered/multi-layered counterflow designs: essentially multiple layers of MCHS stacked on top of each other with flows in opposite directions

The advantage to this design is that we achieve more uniform temperatures with multiple layers. Fig. 5 demonstrates a two layered variant of this design with the arrows indicating flow direction of the fluid. The working mechanism behind this design is that, since with a regular MCHS, the thermal resistance increases as the flow travels through the channels (the liquid heats up), we introduce a second layer that decreases the thermal resistance near the tail end of the channels in the first layer, essentially cancelling out the gradient in thermal resistance of the two channels. This effect can further smooth out the temperature gradient with more layers, but the principle behind it remains largely the same. Hung et al. [4] modelled a double-layered counterflow design and found that the temperature graphed to length along the channel becomes more of a bowed out shape instead of an increasing curve, on top of that, the delta temperature was overall higher along the entire channel compared to the single layered model. Unfortunately, this also comes with the drawback that these are considerably more complex to manufacture as it's also important to prevent cross layer leakage when manufacturing. Vafai et al. [5] tested a similar double-layered model through a computational model and found that while the complexity of the system is increased, the tradeoff for much lower thermal resistance and thus, a lower needed pressure differential is worth considering. Overall, the conclusion was that multi-layered MCHS are a significant improvement compared to traditional one-layered models.

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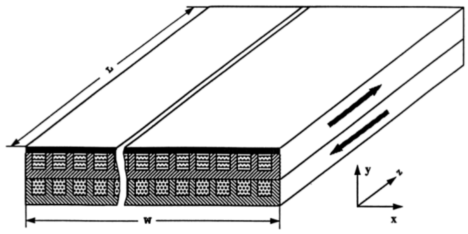

Figure 5. Diagram of a double-layered microchannel heat sink with a counterflow design [5]

To further improve the performance of double-layered MCHS, a great deal of effort has been put into the parameter examination and structure optimization. Wang et al. [13] investigated a combination of a double-layered counterflow design and wavy sinusoidal design using porous vertical ribs. They found that traditional double-layered MCHS had a non-uniform temperature distribution in a vertical cross section of the heat sink with there being a very large temperature differential between the temperature of the water and the temperature of the ribs. The graphs suggest a significant decrease in thermal resistance as well as pressure drop, with the thermal resistance being greatly affected by if the channel is wavy or not, and the pressure drop being affected by if the ribs is porous or not. Wong et al. [14] conducted an investigation to determine the benefits and drawbacks of a tapering design for double layered heat sinks with varying heights. While it was previously known that tapering designs offer a lower thermal resistance in exchange for higher pressure drop, there weren't numerical studies done on the double layered variant worked on in this study. However, after analysis, they concluded that this new design wasn't sustainable compared to the conventional straight double-layered MCHS when hydraulic performance/pressure drop was taken into account.

In summary, Multi-layered designs effectively stack two heat sinks on top of each other for better performance, with decreased overall temperatures and more even heat distribution in exchange for a slightly harder to manufacture design. This is also often used in conjunction with other methods of improving performance as it almost never interferes with how the other designs function.

3.4. Porous microchannel structures: exactly what it sounds like, water permeable materials with high surface area

These structures may be implemented in many ways, with hydraulic performance varying depending on the method, however, no matter the method, this structure significantly decreases thermal resistance as it drastically increases surface area available for heat exchange. One method that can be used to implement this is to fill the channels with a porous material, unfortunately, while this increases heat transfer area, it also increases the pressure differential as the pump is now forcing liquid through a porous substrate which gives the liquid a lot of surface to generate friction thus increasing resistance. Another method that may be used is replacing some amount of the ribs in between the channels with a porous material; this method decreases thermal resistance by breaking up the thermal boundary while also decreasing hydraulic stress, as there is less material for the liquid in the main channel to "stick" to.

Wan et al. [15] tested a new type of miniature porous MCHS using a stainless wire mesh as the porous substrate. This design was found to have a heat transfer capacity that was 15 times or 30 times the heat transfer capacity for a smooth MHCS with water and air as the fluid respectively. Chuan et al. [16] designed a new configuration MCHS, in which the solid ribs are replaced by porous ones. The results showed that the porous ribs design can significantly reduce pressure drop,

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with a maximum 47.9% improvement compared with the conventional solid MCHS. The mechanism behind this improvement is demonstrated that the porous material allows the liquid near the boundaries to "slip" or have a nonzero velocity, which in turn causes a lower drop in pressure. Gong et al. [7] also tested a configuration of MCHS with a portion of the ribs being replaced with porous ones with the ratio of porous rib to solid rib. They found that for all ratios, the thermal resistance and pressure drop were significantly reduced compared to the standard, solid ribbed MCHS. However, they also found that thermal resistance starts to increase after a certain ratio of rib is replaced with porous material, with this information, they found that 0.2 is an optimal ratio of porous and solid material in order to optimize performance. Wang et al. [13] proposed a double-layered microchannel heat sink coupling wavy and porous vertical ribs together. The superiority of this design lies in the enhanced heat transfer by the Dean vortex from the wavy rib and the pressure drop caused by the porous rib. They also found that the new design offers an optimal wavelength and optimal amplitude of units to achieve the lowest thermal resistance with a fixed pumping power of 0.05 W. Ghahremannezhad et al. [17] tested a similar double-layered microchannel heat sink with porous ribs. They focused more on performance compared to traditional porous microchannel heat sinks, collecting information on statistics. They found that this design provided a 45.3-48.5% decrease in needed pumping power while providing a tradeoff of an increase of only 14.8-16.2% in thermal resistance.

In summary, porous microchannel structures offer a powerful solution for addressing the inherent thermal-hydraulic trade-off in microchannel heat sinks by leveraging the substantial specific surface area and the fluid slip effect of porous media.

3.5. Bionic designs: designs that mimic naturally occurring structures in nature and often fractal-like, with self-recursive features

As an effective strategy for thermal management system optimization, bionic design capitalizes on nature's evolutionary principles. By emulating highly efficient, bio-inspired structures (e.g., fractal distribution systems and drag-reducing surface morphologies), this approach seeks to endow engineered systems like microchannel heat sinks with optimized thermal performance, notably in terms of temperature uniformity, heat transfer efficiency, and pressure drop characteristics. Bionic designs are specifically designs that mimic structures in nature, the reason behind this is that, due to evolutionary pressures, fluid distribution systems in nature are highly optimized and thus, mimicking them can help optimize our own designs.

Fig. 6 demonstrates an example of a radial design that incorporates a self-recursive layout to improve temperature uniformity. The main appeal of the self-recursive designs is the uniformity of the fluid distribution and thus temperature uniformity. Additionally, the thin channels also increase surface area, further decreasing thermal resistance. This design isn't without drawbacks however, the central area is often vulnerable to reflux and dead zones, decreasing the efficiency. On the production side, the self-recursive nature of these designs makes manufacturing difficult, as the design is very detailed and delicate. Xu et al. [19] tested a fractal-like multilayer MHCS design for 3-dimensional integrated circuits. This design opts to interweave bifurcating channels between each layer of circuitry to increase heat transfer. It was found to generally provide a lower pressure drop, lower maximum temperature, as well as a more uniform temperature distribution. Kumar Samal et al. [20] designed a radial tree-branching microchannel heat sinks. The results show that overall thermal resistance can be decreased by 7.2 % via the channel's deep dispersion design. Besides, the maximum substrate temperature can also be reduced by 4.5K compared to conventional designs.

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This work also found that channel deep-dissipation design has 40.5 % lower voltage drop and 71 % higher COP than conventional designs.

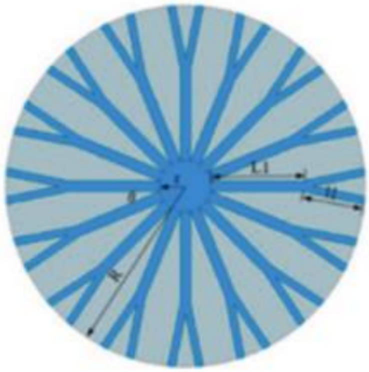

Figure 6. A microchannel heat sink with a self-recursive radial design [18]

Another form of bionic designs that are often considered is changing the surface morphology of the boundaries to closer match the physiology of shark skin or other surfaces that promote fluid flow. This provides an avenue to reduce pressure drop while not giving up other important factors compared to alternatives such as hydrophobic surfaces which sacrifice thermal conductivity. The main drawback of this method is that macroscopic structures are difficult to produce with traditional manufacturing, causing this method to increase the cost of production. Ghouchi. et al [21] introduced a different configuration of fins/ribs in a pin-rib configuration inspired by shark scale geometry. The results they found were that the temperatures were reduced by up to 5k from the baseline, however it also decreased the temperature uniformity index by 9.96% at 0.3m/s of flowrate. Lan et al. [22] designed a variant of ribbed flat-place heat sinks with the configuration that resembles a placoid scale shape. While a more detailed breakdown of why these shapes work so efficiently isn't available, the basic idea is to introduce turbulence into the flow to disrupt development of a thermal boundary layer. With this design, they were able to achieve a 10% increase in heat dissipation capacity.

Accordingly, bionic design harnesses the wisdom of nature as a source for engineering innovation, opening a promising avenue for addressing increasingly complex thermal management challenges. It reveals that highly efficient and sustainable solutions may already exist within nature's evolutionarily optimized blueprints.

4. Conclusion and future perspectives

This review has systematically examined five categories of innovative designs emerging to transcend the limitations of conventional parallel microchannel heat sinks (MCHS): non-uniform cross-sections, wavy channels, multi-layer counter-flow configurations, integration of porous media, and bio-inspired geometries. The analysis reveals that all these strategies aim to optimize the core "trade-off " of thermal resistance, pressure drop, and temperature uniformity, yet none is exempt from its inherent compromises. Overall, the evolution from singular designs towards hybrid architectures (e.g., wavy-porous-multi-layer structures) represents the most prominent current trend, offering the most potential for comprehensive performance breakthroughs through synergistic effects.

However, translating these promising laboratory achievements into widespread commercial application faces severe challenges. The primary obstacle lies in manufacturing complexity and the associated escalating costs; as intricate three-dimensional structures pose significant challenges for traditional microfabrication techniques. Secondly, long-term reliability and stability remain questionable; potential failure modes, including clogging and corrosion of porous structures, failure of micro-fine channels, and degradation of surface coatings, have not been sufficiently validated. Furthermore, most studies lack a system-level integration assessment. Optimizing the heat sink in isolation while neglecting its compatibility with system components such as pumps and piping may prevent its full practical efficacy from being realized. Finally, limitations in theory and modeling of complex flow and heat transfer phenomena also constrain precise design and optimization capabilities to some extent.

Looking ahead, overcoming these bottlenecks requires interdisciplinary collaborative efforts. Research should focus on the following directions:

(1) Embrace Advanced Manufacturing: Employ high-precision additive manufacturing (3D printing) technology offers a revolutionary solution for realizing complex, monolithic structures and reducing costs.

(2) Implement Intelligent Design: Utilize machine learning and artificial intelligence to process high-dimensional parameters, efficiently explore the design space, and shift from "empirical trial-and-error" to "intelligent prediction" to accelerate the R&D process.

(3) Focus on Reliability and Multifunctionality: Strengthen research on long-term durability, anti-clogging performance, and failure mechanisms, and explore the integration of sensing functions within the heat sink for developing intelligent thermal management.

(4) Explore System-Level Co-Design and Two-Phase Flow: Transition from a "device-level" to a "system-level" co-design mindset to maximize overall energy efficiency. Concurrently, researching the application of two-phase flow within these advanced structures will be an inevitable direction for addressing ultimate heat dissipation demands.

In conclusion, the development of the next generation of MCHS will result from a multidimensional convergence of materials, manufacturing, design, and system integration. By addressing the aforementioned challenges and exploring these future directions, we can anticipate the development of efficient, reliable, and compact thermal management solutions that truly meet the demands of future ultra-high-heat-flux electronic devices.

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