

# ***Research on the Optimization Design of Thermal Resistance and Pumping Power of Microchannel Heat Sinks (MCHS)***

**Jiayi Yu**

*School of Military and Political Basic Education, National University of Defense Technology,  
Changsha, China  
13940807743@163.com*

**Abstract.** Microchannel heat sinks (MCHS), with their outstanding heat dissipation efficiency and compact structural design, have become a crucial technology to address the thermal management challenges posed by high-power density devices. They are widely applied in fields such as electronic equipment, lasers, aerospace, and new energy, significantly advancing enhanced heat transfer technologies. The fundamental principle lies in utilizing fluid flow within microscale channels to achieve efficient heat exchange and dissipation. Their performance is primarily evaluated based on key indicators such as thermal resistance, pressure drop, and heat transfer coefficient. This paper systematically reviews the working principles of MCHS, core design parameters (such as channel shape and size), and optimization strategies for thermal resistance and pumping power (pressure drop). Methods for enhancing MCHS heat transfer efficiency, including filling channels with porous materials or introducing specific microstructures (such as ribs and cavities), are discussed. The current research status and development trends are analyzed in depth. This study aims to provide theoretical references for the optimized design and application of MCHS and to prospect its future development in high-performance thermal management systems.

**Keywords:** Microchannel Heat Sink, Thermal Resistance, Pumping Power, Heat Transfer Enhancement

## **1. Introduction**

Microchannel heat sinks (MCHS), as an efficient cooling technology, are widely applied and have demonstrated remarkable effectiveness in the thermal management of electronic devices. By leveraging forced convection heat transfer of fluids at the microscale, MCHS effectively addresses the heat dissipation challenges posed by high-power density devices, significantly enhancing device performance, reliability, and lifespan. With the continuous advancement of electronic technologies toward higher integration levels and power densities, the application prospects of MCHS are becoming increasingly promising.

In the design and optimization of MCHS, thermal resistance, and pumping power are the core parameters used to evaluate performance, jointly determining the balance between cooling efficiency and energy consumption. Current research, both domestically and internationally,

primarily focuses on three directions: (1) innovations in microchannel structures (such as geometric configuration design[1-5]), (2) regulation of flow characteristics (such as multiphase flow and turbulence enhancement), and (3) material optimization (such as functional material filling[6-9]). Typical examples include: Usman Ghani et al.[1] enhanced heat transfer by inducing secondary flow and turbulence through the introduction of secondary channels; Surojit Saha et al.[2] found that a 15° right triangular groove maximizes the Nusselt number; Haiwang Li et al.[3] demonstrated that cavities within microchannels can improve heat transfer by disrupting the boundary layer and triggering jet and throttle effects; Anru Yan et al.[4] verified that a double-layer reflux structure exhibits superior cooling performance compared to pin-fin structures; Zhang et al.[6] showed that porous copper composite heat sinks can reduce pumping power under specific aspect ratios; Wei et al.[7] confirmed the synergistic enhancement effect of porous ribs combined with phase change microcapsule suspensions; Li et al.[8] achieved a 44.1% reduction in accumulated thermal resistance of embedded heat sinks with porous materials through structural optimization; Bai et al.[9] revealed a positive correlation between particle size in porous layers and heat transfer performance in single-phase flow.

Although the aforementioned optimization strategies have significantly improved the heat dissipation performance and energy efficiency of MCHS, current research still faces challenges such as the trade-off between thermal resistance and pumping power, manufacturing process complexity, and long-term operational reliability. Future breakthroughs will rely on the deep integration of new material development, novel process integration, and multiphysics coupling simulation technologies. Based on this, the present paper systematically reviews the research progress of MCHS by: (1) elucidating its working principles and key design parameters; (2) analyzing the influence mechanisms of channel cross-sectional geometries (rectangular, trapezoidal, triangular); (3) evaluating the heat transfer enhancement pathways of internal microstructures (grooves, cavities, ribs, etc.); and (4) exploring optimization strategies for porous material filling.

The overall structure of this paper is as follows: It begins by discussing the application value of MCHS in electronic devices and high heat flux scenarios; then elaborates on the central role of thermal resistance and pumping power in performance optimization, while comparing domestic and international research developments; finally, it summarizes the current challenges and future directions, providing theoretical support for the design of high-performance MCHS.

## 2. Working principles and design parameters of microchannel heat sinks

### 2.1. Working principles

The working principle of MCHS is illustrated in Figure 1. Fluid is injected from the inlet and flows through multiple microscale channels where convective heat transfer occurs, carrying heat away. The heat is conducted through the substrate to the working fluid inside the microchannels. These fluids, typically liquids, flow within the microchannels in close contact with the heat-dissipating components, thereby absorbing heat.

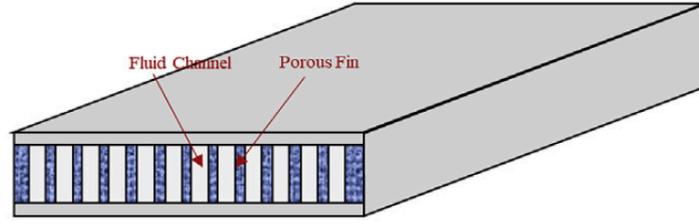


Figure 1. Schematic diagram of the working principle of MCHS

As shown in Figure 1, the structure of MCHS consists of fluid channels and porous fins. To simplify the calculations, the following assumptions are made: the cooling working fluid is viscous, incompressible, and in steady-state laminar flow; the material toughness parameters are unaffected by temperature variations; viscous dissipation of the fluid, natural convection, and radiative heat transfer are neglected; and a no-slip boundary condition is assumed at the solid-liquid interface. The governing equations are solved using the finite volume method, with pressure–velocity coupling handled by the SIMPLEC algorithm. The momentum and energy equations are discretized using the QUICK scheme. The solution is considered converged when the residuals of the equations are less than  $10^{-6}$ . Based on the above assumptions, the governing equations for the fluid domain are as follows:

$$\nabla \cdot \mathbf{u} = 0 \quad (1)$$

$$\rho (\mathbf{u} \cdot \nabla \mathbf{u}) = \mu \nabla^2 \mathbf{u} \quad (2)$$

$$\rho C_p \mathbf{u} \cdot \nabla T_f = k_f \nabla^2 T_f \quad (3)$$

The energy equation for the solid fin is:

$$k_s \nabla^2 T_s = 0 \quad (4)$$

Where  $\mathbf{u}$ ,  $T_f$ ,  $p$ ,  $\rho$ ,  $\mu$ ,  $k_s$ ,  $C_p$ , and  $k_f$  represent the velocity vector, fluid temperature, pressure, fluid density, dynamic viscosity, specific heat capacity at constant pressure, and Thermal conductivity of the fluid, respectively;  $k_s$  is the thermal conductivity of the solid material;  $T_s$  is the wall temperature, K .

## 2.2. Key design parameters

The design parameters of microchannel heat sinks primarily fall into the following categories: (1) geometric parameters; (2) material properties; (3) fluid parameters; (4) thermal performance parameters; (5) manufacturing and process parameters; and (6) operating conditions. These parameters are interrelated and must be considered comprehensively during the design process to achieve optimal performance. The general influences of these parameters on performance are outlined as follows.

(1) Geometric Parameters: Smaller dimensions can increase the surface-area-to-volume ratio, thereby enhancing heat transfer efficiency, but may also lead to higher pressure drops. Larger

dimensions, on the other hand, can reduce pressure drop but may compromise heat transfer performance. Longer channels increase the heat transfer area and improve cooling effectiveness, yet they also result in greater pressure losses. Shorter channels can reduce pressure drop but may limit thermal dissipation. Channel shape is another sensitive factor affecting performance; non-circular channels (e.g., rectangular or trapezoidal) typically offer a higher surface-area-to-volume ratio than circular ones, thereby improving heat transfer efficiency. Smaller channel spacing and wall thickness increase channel density and enhance cooling capacity, but they may also introduce greater manufacturing complexity and pressure drop.

(2) Material and Fluid Parameters: Materials with high thermal conductivity can enhance the overall thermal performance of the heat sink, thereby improving heat dissipation. Materials with high specific heat capacity and density can store more heat, which contributes to a more uniform temperature distribution. High thermal conductivity fluids significantly improve heat transfer efficiency and thermal capacity. Higher fluid velocity and flow rate can increase the heat transfer coefficient and reduce thermal resistance but at the cost of increased pressure drop and pumping power. Fluids with low viscosity reduce flow resistance, thereby lowering pressure drop.

(3) Thermal Performance Parameters: High heat flux requires a higher heat transfer coefficient and a larger heat dissipation area. Low thermal resistance improves cooling efficiency and reduces the temperature of the heat source. A high heat transfer coefficient enhances the heat exchange efficiency between the fluid and the channel walls. However, a high-pressure drop increases pumping power demands, thereby reducing system efficiency. Uniform temperature distribution helps prevent local overheating and enhances system reliability.

(4) Manufacturing and Process Parameters: Precision manufacturing techniques (such as photolithography and etching) enable the fabrication of smaller and more complex channel structures, thereby enhancing heat dissipation performance. Lower surface roughness can reduce flow resistance and decrease pressure drop. Effective packaging minimizes contact thermal resistance, improving the overall cooling efficiency.

(5) Operating Conditions: Lower inlet temperature ( $T_{in}$ ) and ambient temperature ( $T_{amb}$ ) can enhance heat dissipation performance. Higher cooling demands require increased heat transfer coefficients and larger heat dissipation areas.

During the design process, these parameters must be comprehensively considered to balance heat transfer efficiency, pressure drop, and temperature uniformity in order to achieve optimal performance.

### 3. Strategies for optimizing thermal resistance and pumping power

#### 3.1. Geometric design of microchannel cross-sections

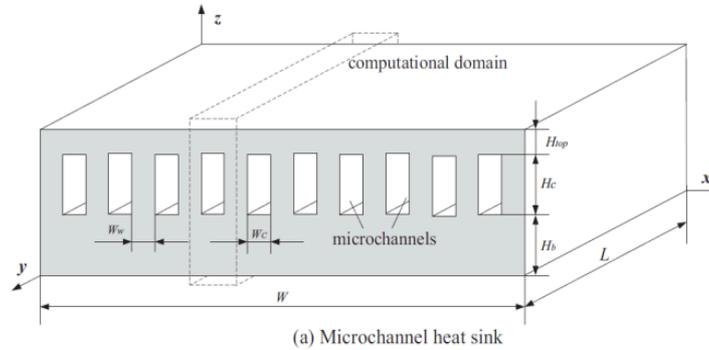


Figure 2. Structure of the MCHS with various channel elements

Figure 2 presents a structural schematic diagram of a rectangular cross-section microchannel heat sink. The basic dimensions of the heat sink are length  $\times$  width ( $L \times W$ ), with the height from the microchannel bottom surface to the heat sink bottom surface denoted as  $H_b$ , the channel height as  $H_c$ , and the total height of the heat sink as  $H_b + H_c$ . The channel width is  $W_c$ , and the wall thickness between adjacent channels is  $W_w$ , which functions similarly to fins. The top cover of the heat sink can be made from glass or metal materials, enclosing the flow passage. The entire bottom surface of the heat sink serves as the heating surface, with the shaded area in the diagram representing the solid metal. As a reasonable simplification, it is assumed that the flow and heat transfer conditions within each channel are identical. Therefore, based on the structural repetition and symmetry, a single channel is typically chosen for study.

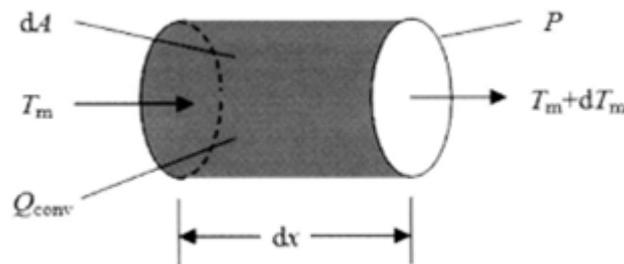


Figure 3. Internal flow within a differential volume element

Considering the internal flow within the control volume element shown in Figure 3, the control volume length is  $dx$ , the wetted perimeter is  $P$ , and the surface area is  $dA = Pdx$ . The average fluid temperature entering the control volume is  $T_m$ , and the average temperature leaving is  $T_m + dT_m$ . According to the conservation of energy, the convective heat transfer of the fluid passing through this control volume is:  $Q_{CONV} = C_{pf}q_m dT_m$  where  $q$  represents the mass flow rate through the control volume. The total convective heat transfer from the inlet to the outlet can be obtained by integrating the above expression over the entire flow length. The local convective heat flux density within the internal flow can be expressed as:  $\mu_{conv} = h(T_s - T_m)$

When heat is transferred from the wall to the fluid,  $T_m$  increases with  $x$ ; conversely, when heat transfers from the fluid to the wall,  $T_m$  decreases with  $x$ , until  $T_s = T_m$ .

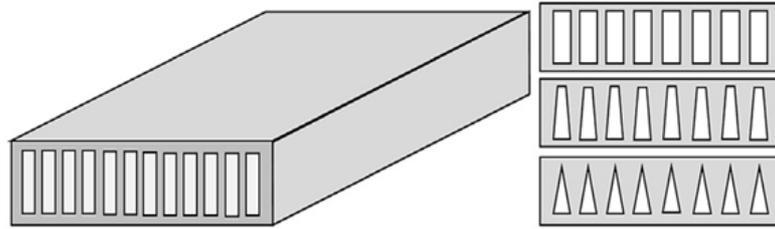


Figure 4. MCHS with various cross-section shapes

Figure 4 illustrates microchannel heat sinks with three different channel shapes, where the MCHS with rectangular channels exhibits better performance than that with trapezoidal channels, which in turn outperforms the MCHS with triangular channels. Additionally, increasing the channel aspect ratio and decreasing the hydraulic diameter can lead to lower thermal resistance, albeit accompanied by greater pressure loss.

### 3.2. Design of internal or surface microstructures within channels

This section discusses research on enhancing turbulent heat transfer efficiency and reducing thermal resistance by adding microstructures (such as micropillars and ribs) on the internal surfaces of channels. To investigate the effect of micro-rib distribution patterns on the heat dissipation capacity of rectangular microchannels, two simplified physical models of rectangular microchannel heat sinks with different distribution patterns—parallel-sidewall distribution and staggered distribution—are illustrated in Figure 5-6.

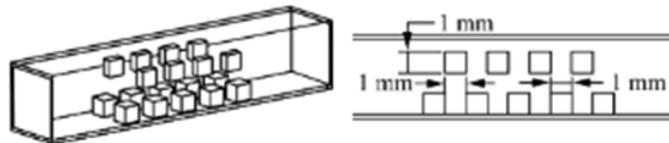


Figure 5. III lateral wall distribution

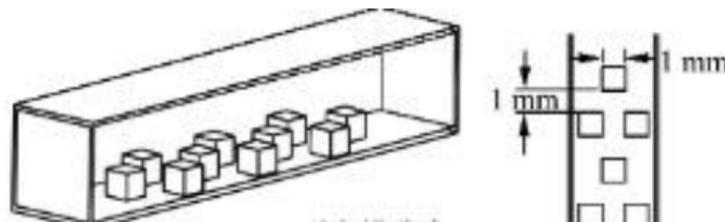


Figure 6. III alternating distribution

The channel inlet is set as a velocity inlet boundary condition, and the channel outlet as a pressure outlet boundary condition. The channel bottom surface is assigned a constant heat flux boundary condition, while the other walls are considered adiabatic boundaries. The effect of gravity is taken into account. The flow characteristics and heat transfer performance of the fluid within the channel are investigated under the conditions of an inlet velocity  $V=0.2$  m/s, inlet fluid temperature

$T=293.15\text{ K}$ , and the constant heat flux density at the bottom surface  $q = 10\text{ W/cm}^2$ . Figure 4 presents the flow streamlines for three types of rectangular microchannels. The fluid inside the channel is divided into two parts: one part is the main flow between the top of the micro-ribs and the upper wall, while the other part is the secondary flow in the region near the micro-ribs. The fluid flow inside the channel is influenced by the micro-ribs, causing a change in the flow direction, leading to a more pronounced fluctuating flow near the micro-ribs. In the Type II microchannel, the height of the sidewall micro-ribs is  $0.5\text{ mm}$ , and the fluid above the channel also changes its flow direction due to the micro-ribs. The Type III microchannel has a staggered distribution of micro-ribs on the bottom surface, creating more vortices on the backside of the micro-ribs. Figure 4 illustrates the flow streamlines in microchannels with different micro-rib distribution patterns ( $V = 0.2\text{ m/s}$ )

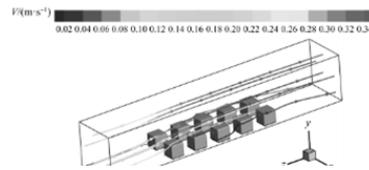


Figure 7. Rectangular microchannels

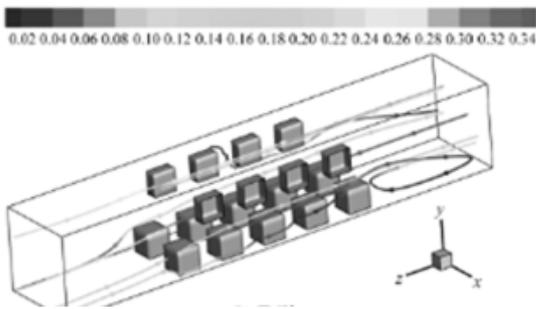


Figure 8. Rectangular microchannels

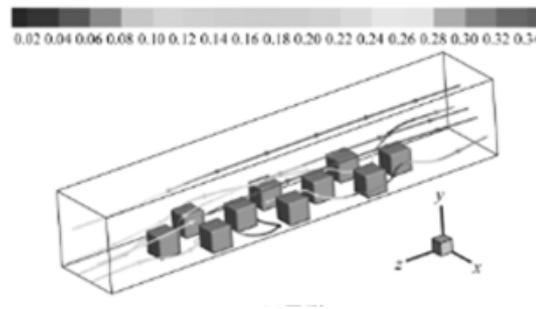


Figure 9. Rectangular microchannels

Figure 7-9 shows velocity contour maps at different cross-sections of rectangular microchannels with varying micro-rib distributions at a velocity of  $V = 0.2\text{ m/s}$ . The cross-section at  $X = 1.1\text{ mm}$  is perpendicular to the bottom micro-ribs. As seen in Figure 5, vortices form on the leeward side of the micro-ribs. The high-velocity region in the Type II microchannel is larger than that in Type I, while the high-velocity region in the Type III microchannel decreases, accompanied by a reduction in vortex intensity near the micro-ribs. The cross-section at  $X = 3.5\text{ mm}$  is perpendicular to the sidewall micro-ribs. Vortices form on the leeward side of the sidewall micro-ribs in the Type II microchannel, increasing the turbulence in the upper fluid region and thereby enhancing the heat transfer between the fluid and the micro-ribs. In the Type III microchannel, the vortex intensity at the outlet decreases, but the vortex region expands, driving more fluid to participate in heat transfer with the micro-ribs and the bottom surface, thus improving heat transfer performance. Usman Ghani et al.[1] enhanced heat transfer by adding secondary channels in heat sinks, which induce secondary flows and thus promote turbulence. As shown in Figure 8, Surojit Saha et al.[2] found that the Nusselt number is highest for right-angled triangular grooves with a  $15^\circ$  angle and lowest at  $75^\circ$ . The substrate temperature is lowest for the  $15^\circ$  groove, indicating superior heat transfer efficiency. Haiwang Li et al.[3] demonstrated that cavities within microchannels significantly improve heat transfer by disrupting and reestablishing the boundary layer, as well as through jetting and throttling effects. Furthermore, cavities with smaller expansion angles and streamlined edges maximize heat

performance improvement. Anru Yan et al.[4] verified that although pin-fin structures enhance heat transfer by altering the coolant flow and promoting turbulence, the presence of stagnant regions behind the pins—where coolant cannot pass—creates large cavities that severely reduce heat dissipation capacity. In contrast, double-layer reflux microchannel heat sinks exhibit superior cooling performance.

### 3.3. Porous material filling

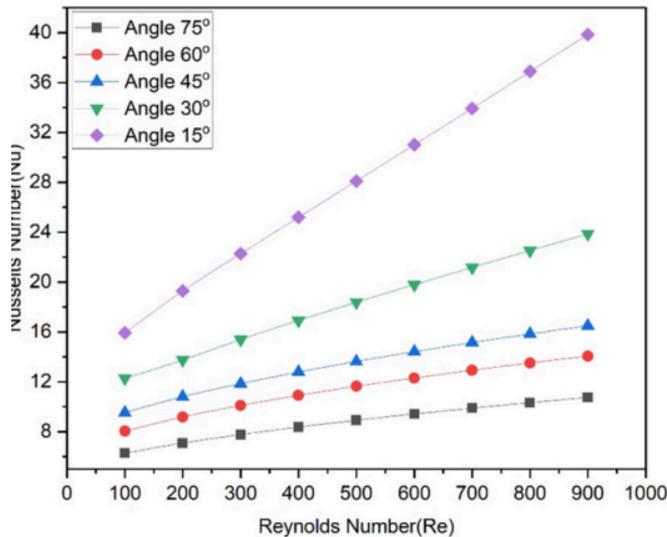


Figure 10. Reynolds number

Filling microchannels with porous media can effectively enhance heat transfer performance; however, it is necessary to balance this improvement against the increased fluid flow resistance caused by the porous structure.

As shown in Figure 11. The larger the inlet Reynolds number (Re), the smaller the equivalent thermal resistance of the heat sink, and when the inlet Re is smaller, increasing the Re significantly reduces the equivalent thermal resistance. For heat sinks with larger inlet Re numbers, the optimal aspect ratio of the heat sink unit's end face is smaller. The heat flux density has minimal impact on the heat sink's optimal configuration. As the volume fraction of the porous region increases, the optimal aspect ratio and the optimal number of channels on the heat sink unit's end face decrease. The smaller the porosity, the larger the optimal aspect ratio of the heat sink unit's end face, and the smaller the equivalent thermal resistance of the heat sink's optimal configuration. The single-degree-of-freedom optimization of the heat sink unit's end-face aspect ratio can reduce the equivalent thermal resistance. Further relaxing the constraints on the overall length-to-width ratio of the heat sink, the two-degree-of-freedom optimization can further reduce the equivalent thermal resistance. For heat sinks with a rectangular bottom surface, the fluid should flow into the short side of the rectangle and exit through the opposite short side for better cooling performance.

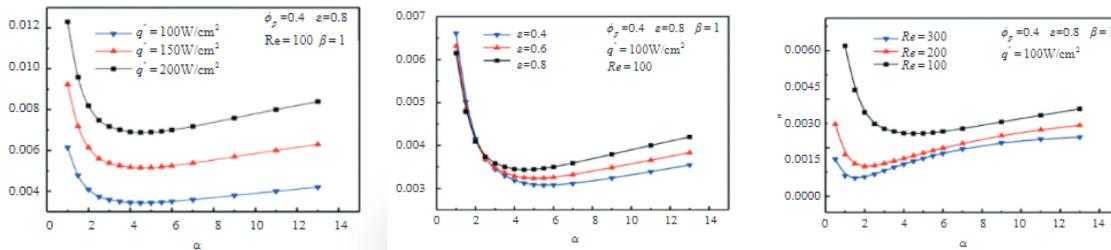


Figure 11. Relationship between Reynolds number and thermal resistance

Zhang et al.[5] studied a porous copper microchannel composite heat sink, as shown in Figure 12. They found that the maximum thermal resistance decreased with the increase in the aspect ratio of the heat sink unit's end face, but increased as the overall length-to-width ratio of the heat sink increased. When both the aspect ratio of the heat sink unit's end face and the overall length-to-width ratio of the heat sink were relatively small, the consumed pump power was lower. Wei et al.[6] showed that both porous ribs and phase-change microcapsule suspensions (Figure 13) can improve the comprehensive performance of microchannel heat sinks. The phase-change microcapsule suspension in porous rib microchannel heat sinks demonstrated a 14% improvement in comprehensive performance compared to water in solid rib microchannel heat sinks. Specific parameters are shown in Table 1. Li et al.[7] demonstrated that embedding porous materials in rectangular microchannel composite heat sinks optimized the structure, reducing the heat sink's equivalent thermal resistance by 44.1% compared to the initial value. Further optimization reduced the minimum equivalent thermal resistance by an additional 14.8% compared to the first optimization. Li [8] used a metal foam and columnar fin composite structure (Figure 14) to significantly improve the effective thermal conductivity of the heat sink. The performance was improved by approximately 266.6% compared to conventional columnar fin heat sinks and by 36.3% compared to metal foam alone. Bai et al.[9] found that under single-phase flow conditions, the heat transfer performance of a porous layer with the largest particle size was the best, showing an approximately 30% improvement in heat transfer coefficient compared to smooth channels. However, the friction coefficient of the porous composite channel was higher than that of smooth channels.

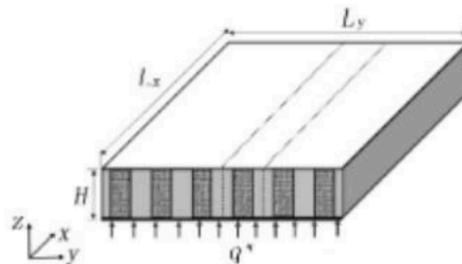


Figure 12. Porous copper microchannel composite heat sink

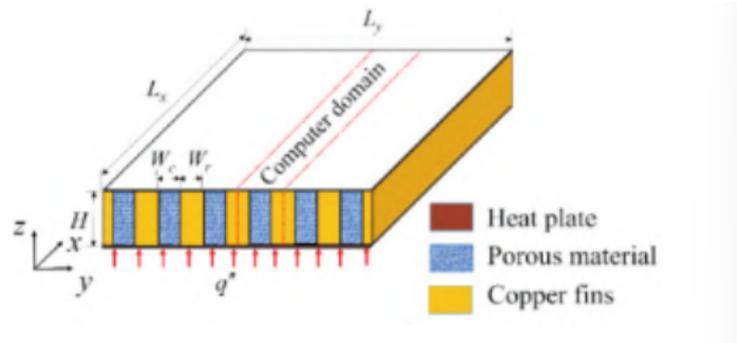


Figure 13. Schematic of microchannel heat sink with embedded porous materials

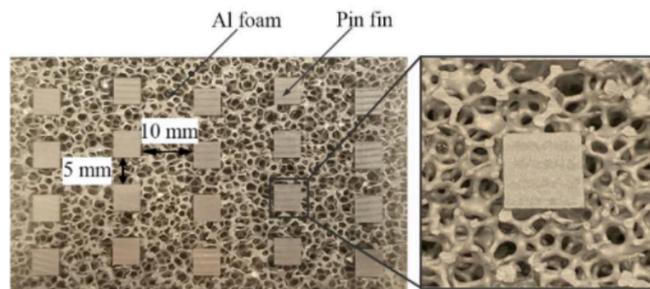


Figure 14. Close-up view of the metal foam-pillar fin connection

## 4. Conclusion and outlook

### 4.1. Conclusion

(1) Core Performance and Design Trade-offs: Microchannel heat sinks (MCHS) achieve efficient heat dissipation through forced convection of fluids within microchannels. Their performance is determined by thermal resistance, pumping power (pressure drop), and heat transfer coefficient. Optimization must consider geometric parameters (channel shape/size/aspect ratio), material properties (thermal conductivity), fluid characteristics (velocity/viscosity), and operational conditions (Reynolds number/heat flux) to balance cooling efficiency and energy consumption.

(2) Key Influence of Channel Configuration: Rectangular channels exhibit optimal heat transfer performance due to their high surface-to-volume ratio (superior to trapezoidal and triangular channels). Increasing the aspect ratio or reducing the hydraulic diameter can lower thermal resistance but significantly increase pressure drop. A combination of channel dimension optimization and staggered arrangement design is necessary to jointly regulate heat transfer and flow resistance.

(3) Microstructure and Porous Material Enhancement Mechanisms: Microstructure design (such as micro-ribs/cavities): Inducing secondary flow and disrupting the boundary layer enhances turbulent heat transfer, but excessive increase in flow resistance should be avoided.

(4) Porous Material Filling (e.g., Metal Foam): Using materials with a high surface area enhances heat exchange. Optimizing porosity and permeability can reduce thermal resistance by up to 44.1%. Combining phase change materials (e.g., microcapsule suspensions) can further improve overall performance.

## 4.2. Outlook

In the future, the performance of MCHS can be further optimized through the following approaches:

(1) **Integration of Novel Materials:** Development of high thermal conductivity materials (such as graphene, MXene) as channel coatings or filling phases, optimized through directional alignment techniques to improve thermal conductivity along the vertical heat flow direction and reduce interface thermal resistance. Combining micro/nanostructures (such as nanowire arrays) to expand the heat transfer area and promote phase-change processes (e.g., nucleate boiling) could achieve an 80% increase in critical heat flux (CHF).

(2) **Miniaturization and Composite Cooling Technologies:** Advancing microchannel widths to the 10–100  $\mu\text{m}$  scale and using processes like Deep Reactive Ion Etching (DRIE) to achieve high aspect ratio ( $>10:1$ ) structures can enhance heat transfer capabilities by 3–5 times per unit area. Development of microchannel-boiling/spray composite cooling, triggering efficient phase-change heat transfer through surface modifications (e.g., porous coatings).

(3) **Intelligent Optimization and Multi-field Collaborative Design:** Constructing CNN/GNN models to quickly predict the impact of channel geometric parameters on heat transfer (Nu number) and pressure drop. Combining multi-physics simulations to achieve thermo-fluid-structural coupled optimization design. Developing real-time control systems and fault prediction algorithms to enhance long-term operational reliability.

## References

- [1] Ghani, U., Wazir, M. A., Akhtar, K., Wajib, M., & Shaikat, S. (2024). Microchannel heat sinks—A comprehensive review. *Electronic Materials*, 5, 249–292.
- [2] Saha, S., Alam, T., Siddiqui, M. I. H., Kumar, M., Ali, M. A., Gupta, N. K., & Dobrotă, D. (2022). Analysis of microchannel heat sink of silicon material with a right triangular groove on the sidewall of passage. *Materials*, 15, 7020.
- [3] Li, H., Li, Y., Huang, B., & Xu, T. (2020). Numerical investigation on the optimum thermal design of the shape and geometric parameters of microchannel heat exchangers with cavities. *Micromachines*, 11, 721.
- [4] Yan, A., Liu, X., Wang, X., & Wang, Z. (2022). Design and analysis of microchannels for heat dissipation of high-energy VCSELs based on laser 3D printing. *Applied Sciences*, 12, 10205.
- [5] Zhang, Q., Li, W., Xi, K., Xie, Z., & Meng, F. (2022). Design of the minimum thermal resistance configuration for porous copper microchannel composite heat sinks. *Journal of Naval University of Engineering*, 34(03).
- [6] Wei, X., & Chen, W. (2022). Heat transfer analysis of porous rib microchannels with phase change microcapsule suspension. *Low Temperature and Superconductivity*, 50(04).
- [7] Li, W., Xie, Z., Xi, K., Guan, X., & Ge, Y. (2022). Configuration optimization of embedded porous material rectangular microchannel composite heat sinks. *Ship Electronic Engineering*, 42(01).
- [8] Li, Y. T. (2022). Heat transfer characteristics and structural optimization of metal foam heat sinks. (Doctoral dissertation, China University of Petroleum, East China).
- [9] Bai, P. (2010). Manufacturing and heat transfer performance study of porous microchannel enhanced heat transfer structures. South China University of Technology.