

Summary and Prospects of Key Technologies in Chip Thermal Analysis

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Abstract: This paper systematically reviews the research progress in chip cooling technologies, focusing on the technical mechanisms, performance characteristics, and current applications of air cooling, microchannel cooling, and two-phase cooling. Air cooling remains the fundamental solution for high-power chip thermal management due to its well-established technology and cost-effectiveness. However, its cooling capacity is limited by the physical properties of air and convective heat transfer efficiency. Microchannel cooling significantly enhances heat transfer performance through microscale forced convection, and its compact structure and compatibility with chip integration make it a current research hotspot. Two-phase cooling leverages the latent heat of phase change to surpass the heat transfer limits of single-phase cooling; however, flow boiling instability leads to heat transfer deterioration and reliability issues, restricting its large-scale application. Additionally, this paper explores the optimization potential of bionic microchannels and intelligent microchannel technologies. The former optimizes thermal-fluid distribution through biomimetic topological structures, while the latter employs thermally responsive materials for dynamic heat dissipation control, offering novel approaches to overcoming existing technological bottlenecks. This review aims to systematically outline the evolution of thermal management technologies and provide a reference for innovative design and engineering optimization in chip thermal management.

Keywords: electronic chips, thermal management, air cooling, microchannel cooling, two-phase cooling

1. Introduction

With the rapid advancement of electronic device performance and the acceleration of miniaturization trends, the integration density and power density of modern electronic chips continue to increase. However, this technological evolution leads to a sharp rise in heat generation during chip operation. Without efficient cooling solutions, chip temperatures will rise significantly, severely impacting electrical performance, long-term reliability, and lifespan. Studies have shown that when chip temperatures exceed 70–80°C, every 1°C increase results in approximately a 5% decrease in reliability, with failure rates rising exponentially with temperature [1]. Mithal et al. [2] further pointed out that reducing chip temperature by just 1°C can lower failure rates by up to 4%. More critically, around 55% of electronic device failures are attributed to thermal management failures, highlighting the central role of thermal management in high-performance electronic system design [3].

To address chip thermal management challenges, cooling technologies have become a major research focus in academia and industry, leading to the development of various cooling solutions. Nair et al. [4] emphasized the continued importance of air cooling in high-power chip heat dissipation due to its maturity and cost-effectiveness, systematically analyzing its application potential and future development trends. Cheng et al. [5] focused on microchannel evaporative cooling technology, explaining its heat transfer mechanisms and engineering challenges. Chen et al. [6] reviewed the development paths of electronic chip thermal management from three perspectives: embedded cooling, enhanced heat transfer in microchannels, and two-phase flow boiling heat transfer. Additionally, Bhatasana et al. [7] explored the regulatory mechanisms of phase change materials under transient thermal shock scenarios. Despite the advantages of these technologies, further breakthroughs are needed to address future demands for higher thermal loads, as conventional cooling technologies approach their physical limits.

This paper aims to systematically review recent research advancements in chip thermal management, with a focus on analyzing the principles, influencing factors, and optimization strategies of three mainstream cooling technologies: air cooling, microchannel cooling, and two-phase cooling. Furthermore, potential emerging technologies for enhancing thermal management capabilities are discussed to provide theoretical foundations and practical references for innovation and optimization in chip thermal management.

2. Analysis of Chip Thermal Management Cooling Technologies

2.1. Air Cooling Technology

Air cooling is a heat transfer technique based on air convection, where heat generated by the chip is dissipated into the surrounding environment via natural or forced convection. While natural convection is simple and reliable, its cooling capacity is significantly lower than that of forced convection. Studies have shown that the cooling capacity of forced convection is approximately 5 to 10 times greater than that of natural convection [8]. However, traditional air cooling faces challenges in high-power chip applications due to the low thermal conductivity of air and significant turbulence-induced noise. To overcome these limitations, researchers have explored geometric modifications to heat sinks to enhance air cooling performance. Common approaches include adding fin structures and adjusting fin shape, height, width, number, and arrangement to optimize heat dissipation.

For chip air cooling optimization, significant advancements have been achieved through structural improvements, material composites, and geometric parameter adjustments. Pouryoussefi et al. [9] compared the heat dissipation performance of parallel plate fins with additional circular pin fins. Their experimental setup, shown in Figure 1(a), demonstrated that under identical free-stream airflow conditions, the thermal resistance of heat sinks with circular pin fins was reduced by approximately 37.7% compared to traditional structures, highlighting the positive impact of localized flow disturbance on heat transfer enhancement. Bayrak et al. [10] investigated the thermal and hydraulic characteristics of inserting aluminum foam into air-cooled pin-fin heat sinks. Using experimental and numerical simulations, they examined factors such as fin arrangement, fin shape, slot width and height, and aluminum foam porosity density over a Reynolds number range of 500–3500. Their fin structure and arrangement schematic, shown in Figure 1(b), revealed that composite fin structures (CF) in staggered arrangements exhibited superior heat transfer performance and thermal performance factors. The Nusselt number (Nu) of CF heat sinks was 1.58 times higher than that of solid cylindrical fin heat sinks (SCF), with an 83% increase in thermal performance factor. Additionally, they suggested that slotted solid cylindrical fins (SSCF) and CF structures could serve as integrated heat sink (IHS) alternatives within specific Reynolds number ranges. Kim [11] investigated flat-plate fin heat sinks under natural convection conditions, as shown in Figure 1(c). By altering fin thickness distribution

along the vertical flow direction, they found that non-uniform thickness designs could reduce thermal resistance by up to 10%. However, the reduction diminished with decreasing heat flux or heat sink height, revealing the coupling effects between fin geometric parameters and thermal environment conditions.

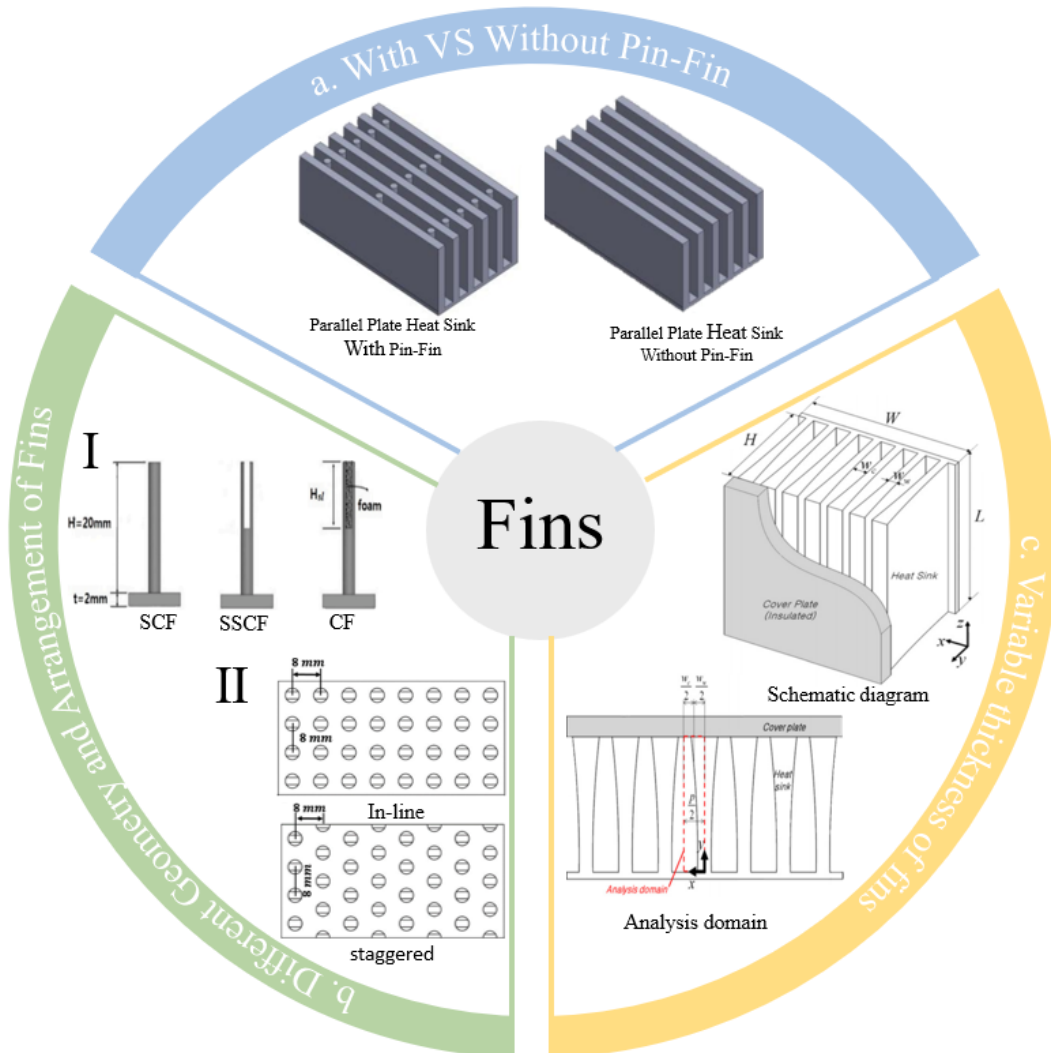


Figure 1: (a) Schematic diagram of a parallel plate heat sink with and without circular pin fins [9]. (b) Structural design and arrangement of three types of fins [10]. (c) Schematic diagram of a heat sink with variable fin thickness [11].

2.2. Microchannel Cooling Technology

With the continuous increase in the power density of integrated circuits, the heat flux density of modern chips has reached unprecedented levels of 10^6 W/m^2 , pushing traditional air cooling technologies to their physical limits [12]. Since the groundbreaking concept proposed by Tuckerman and Pease in 1981 [13], microchannel heat sink technology has utilized its unique microscale structure design. This design leverages high-density flow channel networks to significantly increase the heat transfer contact area, while requiring only a small amount of cooling fluid to achieve efficient heat dissipation. It has shown considerable advantages in the compact spaces of electronic devices [14]. To further enhance the heat transfer performance of microchannel heat sinks, researchers have

conducted systematic innovations by optimizing multi-scale structures and the geometry of microchannels.

Wang et al. [15] conducted a numerical study on the flow and heat transfer characteristics of rectangular, trapezoidal, and triangular microchannel heat sinks, analyzing the impact of geometric parameters on the performance of heat sinks. Their experimental setup is shown in Figure 2(a). The results indicated that under conditions of identical porosity, channel number, cross-sectional area, and hydraulic diameter, the rectangular structure exhibited the lowest thermal resistance, followed by the trapezoidal, and the triangular structure had the highest thermal resistance. Additionally, the thermal resistance and pressure drop of rectangular microchannel heat sinks showed a strong sensitivity to changes in channel number. Increasing the channel number reduced thermal resistance but led to a higher pressure drop, necessitating the determination of the optimal range for the number of channels under fixed power consumption. Jing et al. [16] conducted a systematic study on the heat transfer characteristics of staggered double-layer microchannel heat sinks, with the structure shown in Figure 2(b). They explored the effects of factors such as inlet velocity, channel offset, vertical rib thickness, and aspect ratio on thermal resistance. The results showed that the vertical rib thickness had a threshold effect on the channel offset. When the rib thickness was below a critical value, thermal resistance increased monotonically as the offset increased. However, when the rib thickness exceeded the critical value, thermal resistance first decreased and then increased in a nonlinear manner. Additionally, the correlation between thermal resistance and aspect ratio showed both positive and negative dependencies, and an increase in inlet velocity could systematically reduce thermal resistance. Shi et al. [17] conducted a multi-objective optimization design study on microchannel heat sinks with integrated secondary flow channels, with the structure shown in Figure 2(c). The study found that the width ratio of the main and secondary channels had a dominant effect on thermal resistance and pumping power. Increasing the width ratio reduced pump power but increased thermal resistance. The effect of the half-gap ratio (β) was weaker, and increasing the tangent value of the channel angle (γ) simultaneously degraded both indicators. Ultimately, significant improvements in overall performance were achieved through multi-parameter collaborative optimization.

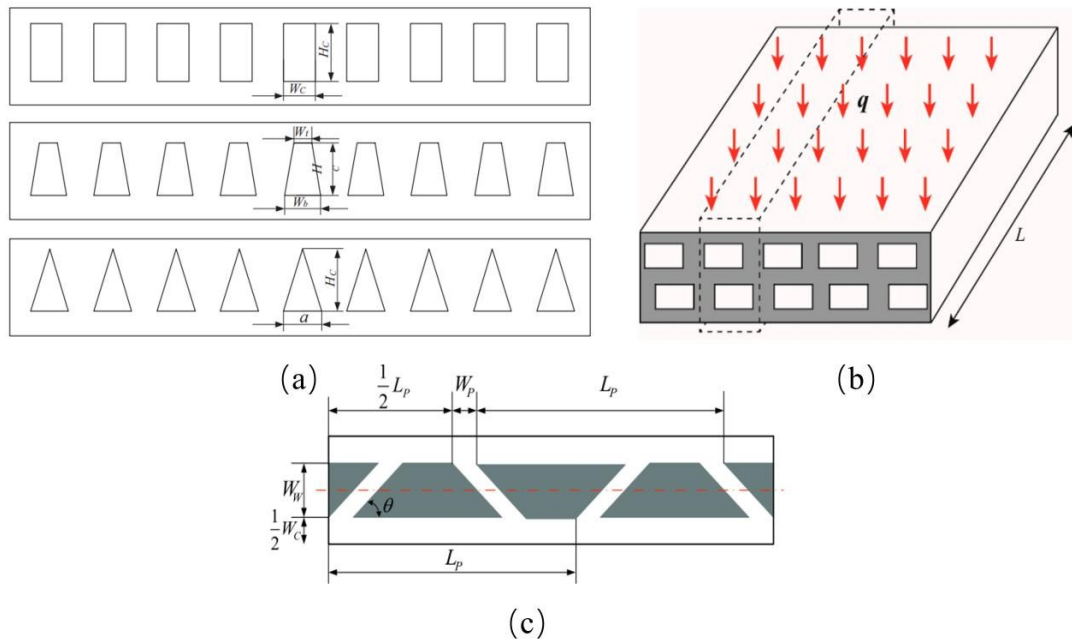


Figure 2: (a) Schematic diagram of three different microchannel structures [15]. (b) Schematic diagram of a staggered double-layer microchannel heat sink structure [16]. (c) Schematic diagram of a secondary flow channel structure [17].

2.3. Two-Phase Cooling Technology

Cooling technologies can be classified into single-phase and phase-change categories based on whether the cooling medium undergoes a phase change. Compared to single-phase cooling, phase-change cooling significantly enhances the heat transfer coefficient and cooling efficiency by utilizing the latent heat effect of the cooling medium. This provides a unique advantage in managing the thermal needs of high-power density electronic devices [18]. Among the current two-phase cooling technologies for electronic devices, water and dielectric fluids are two typical cooling media. Water, with its high heat flux carrying capacity and high specific heat, is suitable for high-heat-load scenarios. However, its non-dielectric properties pose a leakage and conductivity risk, and under standard atmospheric pressure, its saturation temperature is relatively high (100°C), which can lead to increased boiling wall temperatures. Dielectric fluids such as HFE-7000, FC72, and R245fa, although having lower specific heat and latent heat, offer low saturation temperatures and chemical inertness, effectively avoiding the risk of circuit short circuits caused by fluid leakage. Notably, environmentally friendly refrigerants such as R1234ze(E) and R1233zd(E), which maintain good thermal performance while having a global warming potential (GWP) of less than 1, have become an important research direction for replacing the traditional refrigerant R134a [19].

Although two-phase cooling technology offers excellent heat dissipation potential, flow boiling instability and complex heat transfer mechanisms remain key bottlenecks in practical applications. To address this, researchers have systematically explored instability suppression and heat transfer enhancement. Prajapati et al. [20] summarized the main triggers of instability in microchannel flow boiling, which include bubble blockage, rapid growth, flow reversal, excessively high inlet subcooling, interactions between parallel channels, upstream compressibility, and oscillatory flow. Yu et al. [21], based on a classification framework of active and passive control strategies, systematically reviewed active control methods such as seed bubble injection, nanoparticle fluid applications, and artificial nucleation site preparation, as well as passive control methods like inlet throttling and channel geometric expansion. Further research by Szczukiewicz et al. [22] used micro-throttling holes with different expansion ratios at the inlet to successfully suppress flow boiling instability without throttling. Their experimental setup, shown in Figure 3(a), demonstrated that micro-throttling holes with expansion ratios of 2 and 4 could effectively adjust the fluid flow distribution, eliminating flow pattern oscillations while maintaining stable system operation. Ghosh et al. [23] employed a chemical oxidation method to create copper oxide nanostructures on the inner walls of copper-based microchannels. Their experimental setup and copper oxide nanostructure characterization are shown in Figure 3(b). Comparative studies revealed that under similar conditions of average pressure drop and fluctuation amplitude, the heat transfer performance of the nanostructure channels (NSM) significantly outperformed that of regular channels (PWM). This enhancement mechanism was attributed to the formation of a stable capillary-fed liquid film evaporation zone in the annular region of the superhydrophilic nanostructures on the wall. This region could not be maintained in regular channels, and the nanostructures effectively suppressed wall temperature fluctuations by sustaining liquid film evaporation and fluid replenishment. Song et al. [24] developed three configurations of rectangular radial expansion multi-microchannel heat exchangers with cold plate-cover plate combinations, as shown in Figure 3(c). The experiments showed that this design effectively suppressed reverse flow in two-phase flow and eliminated dry-out phenomena, with the slotted cold plate and seamless cover plate combination configuration exhibiting the best overall performance.

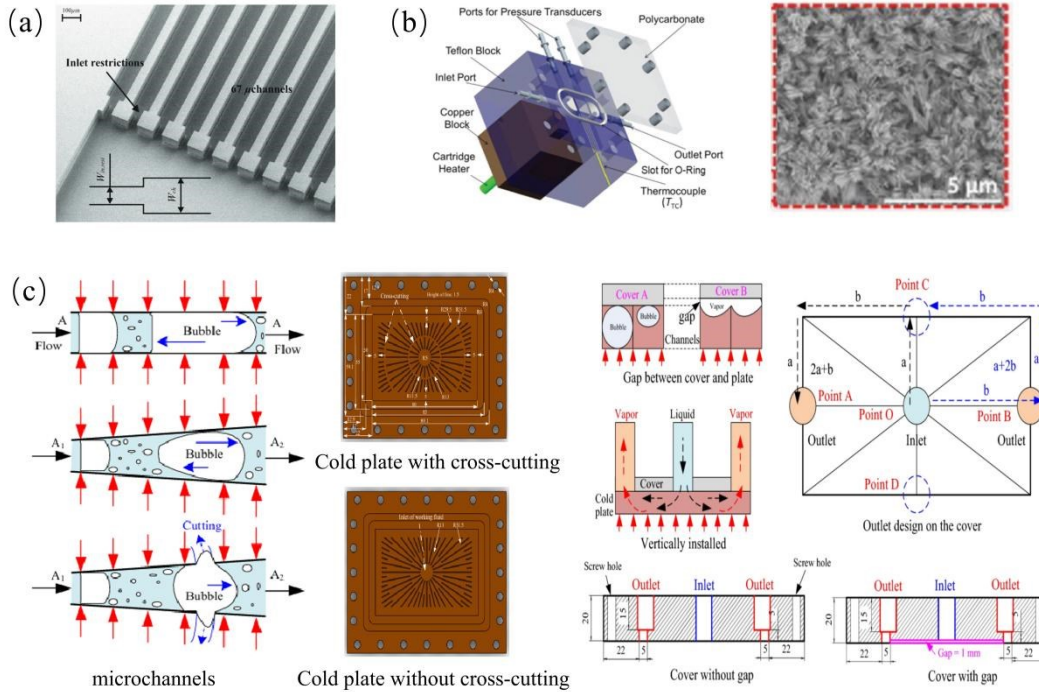


Figure 3: (a) Schematic diagram of a channel structure with an inlet restrictor [22]. (b) Experimental setup and electron microscopy image of copper oxide nanostructures [23]. (c) Structural design diagrams of different microchannels, cold plates, and cover plates [24].

3. New Technologies for Thermal Management Cooling

3.1. Bionic Microchannel Technology

In the development of cooling technologies, researchers have effectively enhanced the heat flux density capacity by introducing methods such as fin arrays, micro-pin rib structures, and asymmetric channel designs. However, these structural reinforcement techniques often lead to a significant increase in flow resistance, which results in higher pumping power and reduced system stability, creating an inherent contradiction between heat transfer performance and flow losses. Inspired by efficient mass and heat transfer systems in nature, biomimetic design offers a new approach to solving this contradiction. By simulating multi-level fractals, channel topology optimization, and flow-heat transfer synergy mechanisms found in biological systems, it is possible to achieve directed transport and uniform distribution of heat flux density while reducing flow resistance. This provides a solution for the thermal management of high-power density electronic devices, combining low energy consumption and high stability.

In bionic technology research within the field of heat dissipation, plants and marine organisms have become the primary biomimetic models due to their unique heat transfer and flow regulation mechanisms. Over long periods of evolution, plants have developed highly efficient heat dissipation structures, such as the fractal network of leaf veins [25] (Figure 4(a)) and the branching structure of tree branches [26] (Figure 4(b)), which optimize heat flow distribution through multi-level branching, achieving efficient heat dissipation with minimal energy consumption. Marine organisms, on the other hand, have significantly reduced flow resistance through special surface structures. For example, the grooved structure on the skin of sharks [27] (Figure 4(c)) allows water to flow in a specific direction, reducing lateral flow fluctuations and minimizing turbulence, which in turn reduces flow resistance [28]. Additionally, spider webs and honeycomb structures, due to their unique topological configurations, have also become current hotspots in biomimetic research. However, the application

of biomimetic technology still faces challenges such as cross-scale manufacturing, lack of dynamic response mechanisms, and multi-objective optimization conflicts. Further breakthroughs are required to overcome these technical bottlenecks and enable broader applications [29].

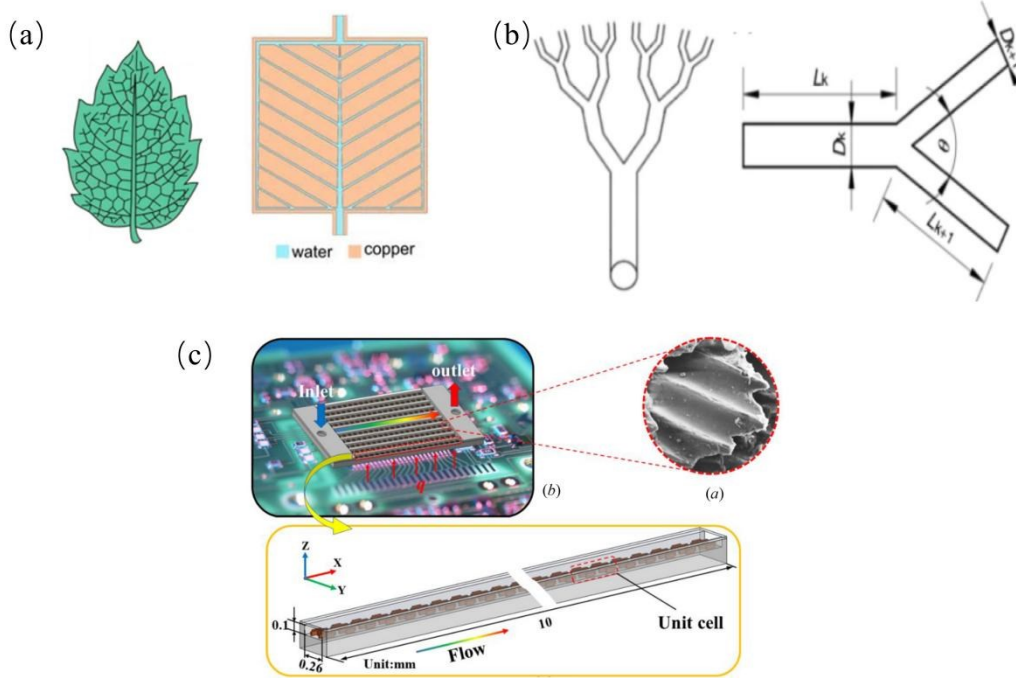


Figure 4: (a) Schematic diagram of a biomimetic leaf vein microchannel [25]. (b) Schematic diagram of a biomimetic tree branch microchannel [26]. (c) Schematic diagram of a biomimetic shark skin microchannel [27].

3.2. Intelligent Microchannel Heat Exchanger Technology

In microelectronic chip thermal management, localized overheating caused by non-uniform heat flux distribution poses a critical challenge to device reliability. Studies have shown that the heat flux in localized hotspot regions can exceed the average value by more than ten times, potentially leading to thermal stress failure [30]. While conventional microchannel heat sinks can enhance overall heat dissipation, their fixed geometric structures are unable to adapt to dynamic thermal load variations, limiting their effectiveness in suppressing temperature rise in random hotspots. To address this challenge, Chu et al. [31] proposed an intelligent microchannel heat exchanger based on shape memory alloy (SMA), with its core innovation being the integration of a thermally responsive vortex generator (SMA-VG). When a localized hotspot increases the fluid temperature, the SMA-VG coils contract due to the shape memory effect, reducing coil spacing to enhance flow disturbances. This mechanism drives the mixing of high-temperature fluid near the walls with the mainstream low-temperature coolant, thereby improving local heat transfer efficiency. Compared to fixed vortex generators, this structure dynamically optimizes heat transfer performance by adaptively adjusting turbulence intensity, offering a novel approach to regulating random hotspots. Future research could further explore the integration of artificial intelligence (AI) with thermal management systems. For instance, real-time thermal field monitoring could enable dynamic adjustment of coolant flow rate and velocity, forming a closed-loop thermal management framework.

4. Conclusion

This paper systematically reviews the three mainstream cooling technologies in chip thermal management—air cooling, microchannel cooling, and two-phase cooling—analyzing their heat transfer mechanisms, current research progress, and technical challenges. Additionally, the optimization potential of two emerging technologies, biomimetic microchannels and intelligent microchannels, is discussed. The main conclusions are as follows:

(1) Air cooling technology, despite its limited cooling capacity, remains widely used for high-power chip cooling due to its economic viability and maturity. Modifying the geometric shape of heat sinks can effectively improve air cooling efficiency.

(2) Microchannel cooling technology offers significantly higher heat dissipation performance than air cooling. Its efficient heat transfer capability, compact size, and ease of integration make it highly advantageous for chip cooling. Further enhancement of microchannel heat dissipation can be achieved through multi-scale structural optimization.

(3) Two-phase cooling technology leverages the latent heat of phase change in the cooling medium to significantly enhance heat exchange efficiency. However, the instability of flow boiling and the complexity of the heat transfer mechanism remain key challenges in practical applications. Therefore, suppressing flow boiling instability and strengthening heat transfer performance remain focal points of two-phase cooling research.

(4) Biomimetic microchannel technology and intelligent microchannel technology, as two emerging approaches, are being actively explored to enhance thermal management capabilities. Through biomimetic topology optimization and the application of shape memory alloys, these technologies hold promise for further improving heat dissipation performance.

References

- [1] Yu, Z.-Q., Li, M.-T., & Cao, B.-Y. (2024). *A comprehensive review on microchannel heat sinks for electronics cooling*. *International Journal of Extreme Manufacturing*, 6(2).
- [2] Mithal, P. (1996). *Design of experimental based evaluation of thermal performance of a flipchip electronic assembly*. *ASME EEP Proceedings*, 18, 109–115.
- [3] Ghandouri, I. E., Maakoul, A. E., Saadeddine, S., & Meziane, M. (2022). *A comprehensive review of methods used to improve the thermal performance of heat sinks in natural convection*. *Heat and Mass Transfer : Wärme- Und Stoffübertragung*, 59(5), 825–849.
- [4] Nair, V., Baby, A., M.B., A., S., I., Murali, M., & Nair, M. B. (2024). *A comprehensive review of air-cooled heat sinks for thermal management of electronic devices*. *International Communications in Heat and Mass Transfer*, 159.
- [5] Cheng, L., & Xia, G. (2023). *High Heat Flux Cooling Technologies Using Microchannel Evaporators: Fundamentals and Challenges*. *Heat Transfer Engineering*, 44(16-18), 1470–1497.
- [6] Chen, H., Zhang, T., Gao, Q., Lv, J., Chen, H., & Huang, H. (2025). *Thermal management enhancement of electronic chips based on novel technologies*. *Energy*, 316.
- [7] Bhatasana, M., & Marconnet, A. (2025). *Die level thermal management of microelectronics using phase change materials*. *Applied Thermal Engineering*, 261.
- [8] DU, P., ZHOU, Q., ZHENG, H., ZHANG, Y., LI, J., & LI, Y. (2023). *Research progress of microchannel cooling technology for high-density microsystems*. *Microelectronics & Computer*, 40(1), 87-96.
- [9] Sam Pouryoussefi, & Yuwen Zhang. (2015). *Experimental Study of Air-Cooled Parallel Plate Fin Heat Sinks with and without Circular Pin Fins between the Plate Fins*. *Journal of Applied Fluid Mechanics*, 8(3), 515–520.
- [10] Bayrak, F. T., Toprak, B. İ., Solmaz, İ., & Bayer, Ö. (2025). *The influence of slotted solid cylindrical fin with aluminum foam insert on the thermal and hydraulic characteristics of air-cooled pin-fin heat sink*. *International Communications in Heat and Mass Transfer*, 162, 108595.
- [11] Kim, D. K. (2012). *Thermal optimization of plate-fin heat sinks with fins of variable thickness under natural convection*. *International journal of heat and mass transfer*, 55(4), 752-761.
- [12] Dewan, A., & Srivastava, P. (2015). *A review of heat transfer enhancement through flow disruption in a microchannel*. *Journal of Thermal Science*, 24(3), 203–214.
- [13] Tuckerman, D. B., & Pease, R. F. W. (1981). *High-performance heat sinking for VLSI*. *IEEE Electron Device Letters*, 2(5).

- [14] Du, L., & Hu, W. (2023). An overview of heat transfer enhancement methods in microchannel heat sinks. *Chemical Engineering Science*, 280, 119081.
- [15] Wang, H., Chen, Z., & Gao, J. (2016). Influence of geometric parameters on flow and heat transfer performance of micro-channel heat sinks. *Applied Thermal Engineering*, 107, 870-879.
- [16] Jing, D., & He, L. (2018). Thermal characteristics of staggered double-layer microchannel heat sink. *Entropy*, 20(7), 537.
- [17] Shi, X., Li, S., Mu, Y., & Yin, B. (2019). Geometry parameters optimization for a microchannel heat sink with secondary flow channel. *International Communications in Heat and Mass Transfer*, 104, 89-100.
- [18] Zhang, T., Wen, J. T., Peles, Y., Catano, J., Zhou, R., & Jensen, M. K. (2011). Two-phase refrigerant flow instability analysis and active control in transient electronics cooling systems. *International Journal of Multiphase Flow*, 37(1), 84-97.
- [19] Hoang, C. H., Rangarajan, S., Manaserh, Y., Tradat, M., Mohsenian, G., Choobineh, L., Ortega, A., Schiffres, S., & Sammakia, B. (2021). A Review of Recent Developments in Pumped Two-Phase Cooling Technologies for Electronic Devices. *IEEE Transactions on Components, Packaging and Manufacturing Technology*, 11(10).
- [20] Prajapati, Y. K., & Bhandari, P. (2017). Flow boiling instabilities in microchannels and their promising solutions—A review. *Experimental Thermal and Fluid Science*, 88, 576-593.
- [21] Tongpu, Y. U., Jinliang, X. U., & Guohua, L. I. U. (2016). Controlling strategies for flow boiling instability in microchannels. *Journal of Anhui University of Technology (Natural Science)*, 33(4), 332-342.
- [22] Szczukiewicz, S., Borhani, N., & Thome, J. R. (2013). Two-phase flow operational maps for multi-microchannel evaporators. *International Journal of Heat and Fluid Flow*, 42, 176-189.
- [23] Ghosh, D. P., Sharma, D., Mohanty, D., Saha, S. K., & Raj, R. (2019). Facile fabrication of nanostructured microchannels for flow boiling heat transfer enhancement. *Heat Transfer Engineering*, 40(7), 537-548.
- [24] Mengjie, S., Chaobin, D., & Eiji, H. (2020). Experimental investigation on the heat transfer characteristics of novel rectangle radial microchannel heat exchangers in two-phase flow cooling system for data centers. *Journal of Thermal Analysis and Calorimetry*, 141(1), 199-211.
- [25] Wang, J., Qi, S., & Xu, Y. (2024). Numerical investigations of the thermal-hydraulic characteristics of microchannel heat sinks inspired by leaf veins. *Energies*, 17(2), 311.
- [26] Wu, M., Shen, S., Yang, X., Dong, W., Song, F., Zhu, Y., & Wang, Z. (2023). Advances in the enhancement of bionic fractal microchannel heat transfer process. *Journal of Thermal Analysis and Calorimetry*, 148(23), 13497-13517.
- [27] Shen, X., Zhai, Y., Guo, W., Chen, W., & Wang, H. (2023). Optimization and thermodynamic analysis of rib arrangement and height for microchannels with sharkskin bionic ribs. *Numerical Heat Transfer, Part A: Applications*, 84(1), 54-70.
- [28] Dean, B., & Bhushan, B. (2010). Shark-skin surfaces for fluid-drag reduction in turbulent flow: a review. *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences*, 368(1929), 4775-4806.
- [29] Yin, L., Jiaqiang, E., Tu, Y., & Luo, W. (2025). Biomimetic microchannel structures and their topological optimization: A review. *International Communications in Heat and Mass Transfer*, 163, 108689.
- [30] Viswanath, R., Wakharkar, V., Watwe, A., & Lebonheur, V. (2000). Thermal performance challenges from silicon to systems. *Intel Technology Journal*, 4(3), 1-16.
- [31] Chu, X., You, H., Tang, X., Zhou, W., Li, X., Yuan, D., & Zhou, S. (2021). Smart microchannel heat exchanger based on the adaptive deformation effect of shape memory alloys. *Energy Conversion and Management*, 250, 114910.