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Research Progress on the Structure and Optimization Design of Microchannel Heat Exchangers

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Abstract. Electronic chips are becoming more and more integrated, so the heat they produce is getting much denser, and effectively dissipating heat has become a key technical problem that limits the performance and reliability of electronic devices; microchannel heat sinks are a revolutionary cooling technology, and because they have the advantages of compact structure and high heat transfer efficiency, they have become a research focus for cooling high-power electronic devices, this paper systematically explains the working principle of microchannel heat sinks, analyzes the key factors affecting their performance including the characteristics of working fluids, the geometric parameters of microchannels and material selection, on this basis, it details the methods to improve the performance of microchannel heat sinks through innovative structural design, working fluid optimization and integrated design, finally, it looks forward to the future research directions and development trends of microchannel heat sinks including multi-functional integration, the application of new materials and intelligent design, and this review aims to provide a theoretical reference for the further research and technological innovation of microchannel heat sinks.

Keywords: Microchannel heat sink, New configuration, AI chip, Intelligent manufacturing

1. Introduction

Now more and more modern electronic devices are becoming more integrated, running faster and getting smaller; because of this, the heat produced by electronic chips is growing very fast. Research shows that more than half of integrated circuit failures are caused by heat problems, and if the junction temperature of electronic components drops by 10°C, their failure rate will be reduced by half [1]. This means that good heat management is very important to keep electronic devices working well and reliably. Traditional air cooling technology can't meet the heat dissipation needs of chips that produce a lot of heat, because air has low thermal conductivity and specific heat capacity. So liquid cooling technology, especially microchannel heat sink technology, has appeared at the right time and quickly become a key research topic in the field of electronic heat dissipation [2].

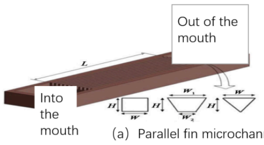
Microchannel heat sinks were first put forward by Tuckerman and Pease in 1981; they use very small channel structures to greatly increase the area for heat transfer, so they can dissipate heat very efficiently [3]. In recent years, with the rapid development of technologies like artificial intelligence, 5G (fifth-generation mobile communication technology) and the Internet of Things, the need for good heat dissipation solutions has become more urgent. In the field of electric vehicles and hybrid electric vehicles, microchannel heat sinks can be used in battery heat management systems to prevent batteries from overheating and improve battery performance and service life [4].

This paper aims to systematically sort out the research progress of microchannel heat sink technology, analyze its working principle, factors affecting performance and improvement methods, and look forward to its future development direction, so as to provide systematic reference for further research and application of this technology. By deeply analyzing the technical characteristics and development trends of microchannel heat sinks, it is hoped to promote the innovation and breakthrough of heat dissipation technology for electronic devices.

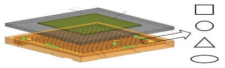
2. Working principle of microchannel heat sinks

Microchannel heat exchangers are divided into single-phase microchannel heat exchangers and two-phase microchannel heat exchangers, and their working principles are divided into single-phase fluid cooling principle and two-phase fluid cooling principle. Among them, single-phase microchannel heat exchangers are made of oxygen-free copper and based on single-phase cooling, realizing heat transfer through forced convection of single-phase fluid. Compared with single-phase microchannel heat exchangers, two-phase microchannel heat exchangers take away energy through the vaporization of cooling fluid.

Figure 1 shows the structural schematic diagram of the microchannel heat sink. The structures of microchannels are divided into parallel fin microchannel heat exchangers, micro-needle rib channel heat exchangers, and complex microchannel heat exchangers. The parallel fin microchannel has an elongated structure with regular rectangular strips distributed in the middle. The front and rear sides of the rectangular strips are the inlet chamber and the outlet chamber. The fluid first flows in from the inlet chamber, passes through the rectangular channel with length L (L < total L), and then flows out from the outlet chamber, thereby taking away heat. Compared with the parallel fin microchannel heat exchanger, the structure of the micro-needle rib channel heat exchanger is more complex. The upper part of the bottom plate is composed of dense columns, and the column shapes include rectangular, circular, triangular, elliptical, etc. The spacing between two columns is called the micro-needle rib channel. The fluid first flows in from the inlet, obliquely flows out from the outlet through the irregular micro-needle rib channels. This process can reduce the thickness of the heat sink boundary layer and improve the heat dissipation capacity of the microchannel heat sink. The complex microchannel heat exchanger combines parallel fins with micro-needle ribs, and its core working principle is to integrate the strong convection characteristics of parallel fins and the heat transfer advantages of two-phase microchannels. Parallel fins increase the heat transfer area, and the liquid in the two-phase microchannels takes away a lot of heat through vaporization. The two cooperate to achieve efficient heat exchange.



(a) Parallel fin microchannel heat exchanger



(b) Micro-needle rib heat exchanger

Figure 1. Structural schematic diagram of microchannel heat sinks [5,6]

3. Key factors affecting the performance of microchannel heat sinks and methods to improve their performance

Researchers have come up with new types of microchannel structures. For example: wavy microchannels, grooved microchannels, micro-needle rib channels with different shapes, rib-column arrays, double-layer microchannels, secondary flow microchannels, porous microchannels, and bionic microchannels. But these new structures only make the fluid transfer heat better. They can't solve two big problems: first, the fluid needs to overcome high pressure to flow (this is called high pressure drop); second, the overall temperature difference of the microchannel is large. These two problems are caused by the long path that the fluid has to flow in the microchannels. However, there is a manifold microchannel (MMC) structure. It has many channels, and these channels are arranged in a staggered way (not in a straight line next to each other). This MMC structure can reduce the overall heat transfer resistance (make heat transfer smoother) and also make the fluid transfer heat better.

3.1. Influence of microchannel parameters on performance

Scientists study key size-related features of microchannels. These features are channel depth, channel width, number of channels, fin thickness, manifold thickness, manifold inlet-outlet width ratio, manifold area, and manifold cross-sectional area ratio. Scholar Luo Yang [7] and others studied these size features in MMC heat sinks. They found that making the channel width (We) and fin width smaller can lower the average temperature of the heat sink's wall. This then slows down the fluid from getting hotter as it absorbs heat. At the same time, J. H. Ryu [8] and others studied three things: thermal resistance (R), volumetric flow rate (Q), and channel depth (H). They found that channel depth (H) and thermal resistance (R) have a quadratic function relationship. When the channel depth (H) is about 150 nanometers, the thermal resistance is the smallest. And at this point, the heat transfer effect is the best. Channel width (We) and thermal resistance (R) have a quadratic function relationship. Fin thickness (Ww) and thermal resistance (R) have an exponential function relationship. When the value of channel width (We) and fin thickness (Ww) match a certain point, we get the best channel width and best fin thickness. This best value is about 15 nanometers. At this value, the thermal resistance is the lowest, and the heat transfer effect is the best. Besides, the inlet-outlet width ratio (y) also affects how well the microchannel transfers heat. This ratio and thermal resistance (R) are inversely proportional. This means the bigger the inlet-outlet width ratio is, the smaller the thermal resistance becomes. But the heat transfer coefficient also becomes smaller.

3.2. Manifold Microchannel (MMC) structure

As shown in Figure 2a, we cut the traditional long channel into many small parallel short channels. This MMC structure makes it much easier for fluid to flow (it lowers flow resistance) and also slows down the temperature rise along the channel. Computer simulation tests show that the improved MMC design can not only lower the highest temperature of the heat sink, but also make the temperature on the heat sink surface more even. This then reduces the heat-related stress on the heat sink.

Manifold microchannels have different cross-sectional shapes, like round, square, triangular, trapezoidal and so on, as shown in Figure 2b. These different shapes can add more microchannels, and this can make the heat transfer effect better. But when the heat transfer effect gets better, it also becomes harder for fluid to flow through the manifold microchannels (this means higher pressure drop). Finally, this causes the fluid in the microchannels to absorb more heat and get hotter, makes the fluid and the thin fluid layer on the heat sink surface (boundary layer) change in a bad way, and also makes the heat transfer ability weaker. To fix this problem,

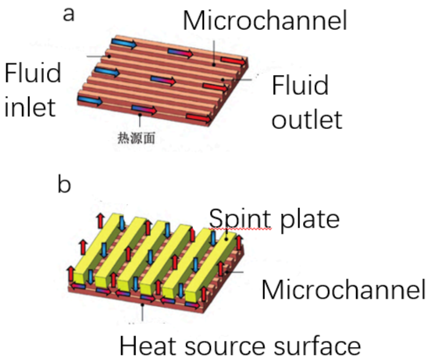


Figure 2. Flow schematic diagram of microchannel heat sinks: a traditional microchannel heat sink and b manifold microchannel heat sink [9]

Researchers did a lot of experiments on manifold parameters. Manifold parameters include pressure drop difference, how fluid flows in channels, the ratio of combined manifold width to split manifold width, manifold aspect ratio, and changes in manifold depth. First, M. Mohammadi and his team [3] studied how triangular manifolds affect fluid speed and the manifolds themselves when the Reynolds number is low. At the same time, S. H. Choi and his team [10] found the best width ratio by using computer simulations to study this ratio. When the width ratio is about 4, the cooling fluid spreads out best in the Z-type MMC heat sink. Besides, different manifold widths and depths affect how evenly fluid flows. R. M. Kumaran and his team [11] found through computer simulations that the wider the manifold is, the more uneven the fluid flow becomes. Researchers also found that the manifold width ratio affects the manifold's length and width. S. S. Sehgal and his team [12] did three groups of experiments and made related function graphs. They studied how MMC heat sinks transfer heat and how fluid flows when the ratio values are 2.5, 3.0, and 3.75. The results showed that when the ratio drops from 3.0 to 2.5, or from 3.75 to 3.0, the total pressure drop percentage of the manifold goes up. In short, different researchers did different experiments on different manifold parameters. They found how these parameters affect heat transfer efficiency. But they did not control all variables in their experiments. Now, researchers need to combine these experiments. They should study how one manifold parameter affects heat transfer efficiency when other manifold parameters are fixed.

Channel-coupled manifold structures are mainly divided into two types. The first type is continuous manifolds. These manifolds have channels arranged in many ways to form different paths, so fluid can flow in or out through multiple inlets and outlets. The second type is hierarchical manifolds. These are made of multiple layers. The deeper the fluid goes into the layers, the smaller the channel's diameter and length become. The more layers the manifold has, the more evenly fluid flows. As researchers studied manifold structures, they found many things can make manifolds work poorly. These things include bad manifold design, channel size parameters, number of channels, how much fluid flows each second, and changes in the cooling fluid's thickness. To solve these problems, researchers focused on improving manifold structures. The most typical improved structure is the parallel rectangular manifold, as shown in Figure 3a. L. Boteler and his team [13] did computer simulations on microchannel MMCs and found this design makes fluid flow easier (lowers pressure drop) and makes fluid spread more evenly in channels. But this design has more parallel flow paths. This makes the pressure drop uneven in the manifold, so the manifold works worse. To solve this problem, some researchers proposed a Z-type manifold arrangement. This arrangement is simpler and easier to make. So the conical manifold structure became a good replacement for the parallel manifold structure, as shown in Figures 3a and 3b. The working principle of this structure is that the space for fluid to flow gets smaller and smaller along the inlet. On the contrary, the space for fluid to flow gets bigger and bigger along the outlet. This solves the problem of uneven fluid distribution, as shown in Figure 3c. After solving this problem, uneven fluid distribution still happens in real uses. So solving the uneven temperature and hot spots on the chip surface (caused by uneven fluid distribution) has become a key research focus for researchers. To reduce (but not get rid of) uneven fluid flow under single-phase conditions, some researchers changed how manifold channels are arranged. This improves uneven fluid flow and uneven wall temperature. R. Mandel and his team [14] studied three arrangements: Z-type, C-type, and H-type, as shown in Figures 3d, 3e, and 3f. The results showed that under single-phase conditions and low fluid flow rates, the Z-type manifold makes fluid flow more evenly than the C-type. But at high fluid flow rates, the C-type manifold is better than the Z-type. Both under single-phase and two-phase conditions, the H-type manifold can make fluid flow very evenly. Later, to study the heat sink characteristics of microchannel MMCs, researchers used a method. The principle of this method is to optimize how materials are placed in the 3D space. They do this based on given load conditions, boundary conditions, material features, and performance goals. Then they find the best parameter values for MMC heat sinks to optimize material placement. Topology optimization [15] is one method to find these best parameters. Common topology optimization methods include the homogenization method, level set method, density method, and genetic algorithm. S. Ozguc and his team [16] used a multi-objective optimization method to balance pressure drop and thermal resistance. To get a better balance, they reduced the overall pressure drop by lowering the thermal resistance. Now, the key to making multi-objective optimization work is to choose the right functions and set the right weight ratios for different objective functions. This ensures the optimization goal is correct.

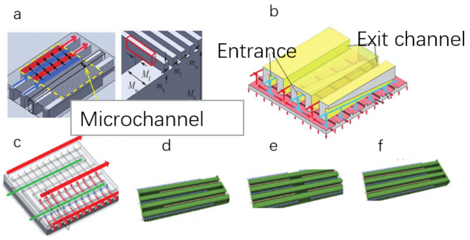


Figure 3. Parallel rectangular manifold a and conical manifold b; Schematic diagram of conical manifold principle c; Different manifold channel arrangements d, e, and f [14]

3.3. Conical flow channel design

We can change the channel's width or height little by little as the fluid flows (making it narrower or wider). This changes how fast the fluid moves and makes the temperature more even. Studies show that when the pump power stays the same, changing how much the channel narrows is a good way to make heat transfer better. Now, to change the channel narrowing ratio, we can start by changing the shape of the channel's cross-section and its aspect ratio. Hasan and his team [17] studied how different cross-section shapes (rectangle, circle, trapezoid) affect microchannel heat dissipation. They found that microchannels work best at dissipating heat when their cross-sections are circular or square. At the same time, as shown in Figures 4a and 4b, some researchers studied how fluid flows and transfers heat in narrowing channels. These channels are designed like animal blood vessels and leaf veins in nature. Duryodhan and his team [18] compared two types of microchannels with rectangular variable cross-sections: ones that get wider and ones that get narrower. They found that when the heat flux density is constant, the narrowing microchannels transfer heat much better than the widening ones. Also, both narrowing and widening microchannels need less pump power than microchannels with a fixed width. Kumar and his team [19] made a double-layer microchannel heat sink with tapered variable cross-sections. They studied how the nanofluid in this heat sink affects electronic chips. They concluded that this double-layer tapered microchannel heat sink transfers heat better than straight microchannels with no tapering.

Besides the methods above, to solve the problems of too much pump power and uneven temperature in microchannels, researchers put forward three kinds of designs. The first design makes the channel's cross-sectional area narrow first, then widen, as shown in Figure 4c. The second design uses many different cross-sectional area combinations and adds sudden narrowing and sudden widening structures. They found that under the sudden widening structure, the pressure in the microchannel will go back up little by little. Under the sudden narrowing structure, the pressure in the microchannel will go down little by little. When two wide channels are connected with a narrow channel, the overall heat transfer performance of the microchannel gets much better. The third design adds many sudden widening and sudden narrowing structures to the channel's cross-section. This method adjusts the channel narrowing ratio, and it makes both the heat transfer performance and pressure drop of the microchannel heat sink better. As research progresses, researchers have used these structures in many situations to improve heat dissipation. Hasan [20] studied sudden widening and gradual widening of microchannel cross-sections. Both methods can lower the pressure drop and make heat transfer more efficient.

In short, when it comes to actively changing the flow channel's cross-section and structure, researchers can make heat transfer better and reduce pump power needs in two main ways. First, use efficient cross-section shapes like circles and squares, and designs like bionic narrowing structures, wavy walls, and tapered variable cross-sections. Second, use channel configurations such as "narrow-then-widen", combinations of sudden narrowing/sudden widening, and multi-section variable cross-sections. These configurations can improve heat dissipation efficiency, adjust pressure distribution, and make temperature more even. These structural methods have been tested in many heat dissipation scenarios and show good application potential. They also point out a clear direction for designing high-performance, low-energy microchannel heat sinks in the future.

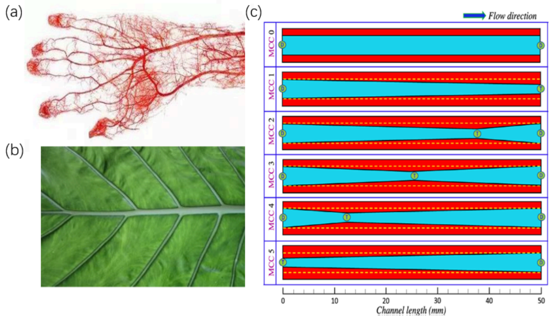


Figure 4. Typical heat sink structure designs: (a) and (b) bionic structures; (c) converging-diverging structure [17,21]

3.4. Turbulence promoting structures and composite designs

We can put small structures like micro-ribs, cavities, or fins inside microchannels. These structures are called turbulence promoting structures. They can disturb the thin fluid layer (flow boundary layer) and thin heat layer (thermal boundary layer) on the channel wall again and again. This makes the fluid mix better and transfers heat more effectively. For example, the combined structure of rectangular ribs and rectangular cavities has been tested. It can enhance heat transfer without making the fluid rub against the channel wall much more (this rub is called friction factor) when the Reynolds number is low. Even though this design makes the channel transfer heat better, it also makes the fluid flow harder (higher pressure drop) and uses more pump power. So in recent years, researchers have stopped focusing only on optimizing single structures. Instead, they have started to study how to make multiple structures work together, how to control fluid flow intelligently, and how to design structures based on specific working needs.

Adding fillets (rounded corners) inside microchannels can help rebuild the boundary layer and make fluid mix better. This improves the heat transfer performance of microchannels. Derakhshanpour and his team [22] studied how to optimize semicircular and semi-elliptical sidewall ribs. They used fluid mechanics principles—these principles help stop fluid from separating from the wall and help rebuild the boundary layer early. Based on these principles, they designed a new microchannel that combines fillets and rib structures. Zhou and his team [23] used computer simulations and real experiments to study fins. They found that fins of different shapes have different effects on microchannel heat transfer. Compared with square and circular fins, irregular droplet-shaped fins can make fluid flow much easier (lower flow resistance) and improve the overall heat transfer performance. But research on fins still has some limits. How much they improve performance depends a lot on the Reynolds number. For example, when the Reynolds number is low, the fins may not disturb the fluid enough. On the contrary, when the Reynolds number is high, the fins may make the pressure drop too big. Besides fin structures, grooved structures can also improve channel heat transfer. They do this by increasing the area for heat transfer and reducing flow resistance. Fan Xiangguang and his team [24] used computer analysis to study triangular, circular, and rectangular grooved microchannels. They looked at how the fluid flows and how heat transfers in these channels. They found that each groove shape has different heat transfer performance. Triangular grooves transfer heat best, but they also cause a large pressure drop. For circular grooves, the higher the Reynolds number, the better the heat transfer. Rectangular grooves have the worst heat transfer performance. Pan and his team [25] studied how fan-shaped grooves affect microchannel heat transfer. They looked at how much the grooves are offset, how much they overlap, and how they are arranged. They found that fan-shaped groove structures can significantly improve heat transfer capacity and reduce fluid flow resistance. Also, different arrangements of fan-shaped grooves can make fluid mix more evenly, so heat transfers more evenly too. Fin structures in microchannels can enhance heat transfer, but they also increase fluid resistance. Grooved structures can reduce flow pressure drop and resistance, but they do not improve heat transfer much. Even though grooved structures can make fluid mix better with low resistance, the improvement in heat transfer is weak. So grooved structures are usually used when we want high efficiency, not when we need extremely good heat transfer. To balance the strong disturbance of fins and the low resistance of grooves, researchers have combined fin and groove structures into one channel. This combination can enhance convective heat transfer well. Wang and his team [26] designed a new microchannel heat exchanger. It has different groove structures and straight rib structures. They used computer simulations to study this design. They also used artificial neural networks and multi-objective genetic algorithms to find the best size for the fins. They found that the microchannel with rectangular straight rib structures not only transfers heat better. Compared with channels without ribs, its heat enhancement efficiency is about 10% higher. Also, its Nusselt number (a number that shows heat transfer ability) and friction factor are at the best values. In addition, they analyzed grooves and fins of different shapes with computer simulations. The results show that when the Reynolds number (Re) is less than 500, rectangular fins make the channel dissipate heat best. But when Re is more than 500, elliptical fins and diamond fins work better. This study tells us that in this composite structure, fins are the main parts that disturb the fluid flow and create small secondary flows. Grooves are the parts that let fluid circulate with low pressure loss and keep the small vortexes stable. The biggest problem with this structure is that the design work becomes much more complicated, and it is harder to make the structure in real production. To make static structures work even better, some researchers have added periodic local turbulence promoting structures inside microchannel heat sinks. These structures change the direction and speed of the fluid. They disturb the flow and thermal boundary layers, so the heat sink transfers heat better. The periodic local turbulence promoting structure is made of two parts: cavities on the microchannel side walls and pin fins in the middle of the channel. These parts make the fluid form local chaotic heat flow, which improves heat transfer performance. Chen Zhuo and his team [27] studied how free-oscillating square cylinders in microchannels disturb the fluid. Compared with fixed square cylinders, free-oscillating square cylinders can make the fluid flow more sideways (transverse flow). This improves heat transfer characteristics. They can also keep the fluid mixing well sideways in a wider range of Reynolds numbers. In theory, these cylinders have a higher energy efficiency ratio, and they have the potential to eliminate local hot spots on the chip. But at present, this kind of research is still in the early stage—either just proving the idea is possible or doing preliminary computer simulations. There is no clear guide on how to design these periodic local turbulence promoting structures.

In short, when it comes to designing microchannel structures to enhance heat transfer and control fluid flow, researchers have come up with several types of structures. First, rib structures—they can actively disturb the fluid and increase heat transfer area, but they have clear costs like higher pressure drop. Second, structures that guide high-speed fluid to hit specific wall areas. Third, grooved structures—they make fluid mix with low resistance, but they do not improve heat transfer much. Fourth, rib-groove composite structures—they are designed to make ribs and grooves work together. These structures show that the design idea has changed from single-function parts to systematic units that manage fluid flow. Fifth, periodic local turbulence promoting structures—they are made to break through the performance limits of static structures. As research goes deeper, experiments have proven that these structures can make fluid mix better and transfer heat more effectively. They point out a new research direction for enhancing fluid heat transfer in the future.

3.5. Multi-layer stacked design

Although traditional single-layer microchannel heat sinks are widely used because their making process is mature, the fluid still has to overcome large pressure loss when flowing through the single-layer channel. In addition, when the fluid flows in the microchannel, it keeps exchanging heat with the outside. Its own temperature will also go up. This makes the temperature difference between the cooling fluid and the object being cooled smaller. Then the heat transfer effect towards the fluid direction gets worse, and the temperature of the single-layer microchannel heat sink becomes more uneven. To solve this problem, we can build a 3D flow network, like a two-layer stacked or three-layer stacked microchannel. This can greatly increase the area for heat transfer. It can also make the overall temperature more even by optimizing how the flow channels are arranged. Studies have given guiding rules for optimizing the channel aspect ratio and number of channels under different layers, so we can get the best performance. For example, to fix the flaws of single-layer microchannel heat sinks, Vafai and Zhu [28] proposed a 3D stacked design model — a two-layer microchannel heat sink, as shown in Figure 5. They studied this two-layer microchannel by using both computer simulations and real experiments. They found that when the total pump power stays the same, the two-layer microchannel heat sink can not only make the temperature change of the base plate smaller, but also lower the inlet pressure drop and the noise of the microchannel. Based on the two-layer microchannel heat sink design by Vafai and Zhu [29], many researchers have done a lot of research on its cooling performance. They hope to prove that the two-layer microchannel heat sink cools better than the single-layer one. Wei and his team [30] used computer simulations to compare the heat dissipation performance of the two-layer microchannel heat sink under the channel hydraulic diameter. The results show that the two-layer microchannel heat sink has a much better heat dissipation advantage than the single-layer one.

However, high heat flux density heat sources will make cooling devices get hotter. For ordinary two-layer microchannels, the middle layer is isolated. So the heat load cannot be effectively carried away by the upper cooling fluid. This means the upper cooling fluid is not used well. How to make the best use of the upper cooling fluid through better configuration design, and thus improve the heat dissipation performance of the two-layer microchannel heat sink, has become a problem that needs to be solved now.

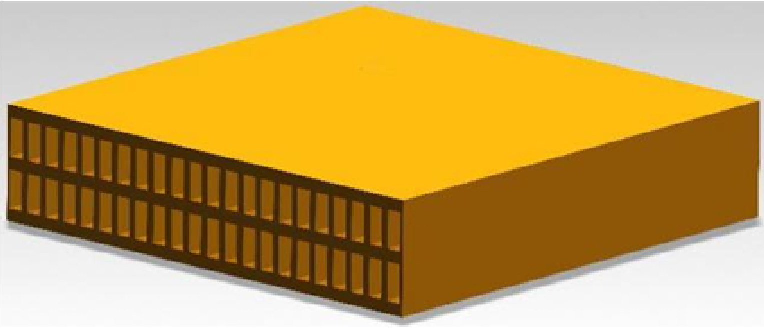


Figure 5. Straight two-layer microchannel heat sink [28]

4. Conclusion and prospect

This paper says that the design of microchannel structures for better heat transfer has changed. It has moved from the early stage of trying different shapes randomly to the stage of designing based on what the structure needs to do — and this design is based on how fluid flows and how heat transfers. By doing deep research on fins, grooves, and structures that combine fins and grooves, we have slowly found out the fixed relationship between three things: how much the structure disturbs the fluid, how hard the fluid flows, and how stable the small fluid vortexes are. The study of periodic structures and dynamic structures shows that the next generation of high-performance heat management technology will develop in one direction. That direction is to control fluid flow in a smart way, and this control covers space and time (this is called four-dimensional spatiotemporal active intelligent regulation). But current research still has some limits. Future work needs to focus on making breakthroughs in these four areas:

(1) From local optimization to full-field synergy: We need to stop only trying to make the global average Nusselt number (a number that shows heat transfer ability) higher. Instead, we should pay more attention to making the fluid flow field and temperature field work together evenly. This will improve the overall efficiency of heat management.

(2) Promote the development of dynamic and intelligent structures: We should combine three things — how fluid and structures interact, smart materials, and advanced manufacturing technologies. With these, we can develop technologies that make heat transfer better. These technologies can be active or semi-active. They can adapt to changes in working conditions, have a long and reliable service life, and use little power.

(3) Deepen two-phase flow and system-level research: First, we need to make rules for classifying and designing heat exchangers that fit different scenarios. Second, we need to develop full-set heat management solutions for high-power electronic devices. These solutions should solve the problems of uneven heat and "hot spots" on real chips.

(4) Focus on manufacturing feasibility and comprehensive evaluation: While we try to make performance better, we also need to include many factors in the overall evaluation system. These factors are the manufacturing process, precision, reliability, and cost of complex structures. This will help the technology move towards real-world use.

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