OPEN ACCESS
IOP Publishing | IMMT

International Journal of Extreme Manufacturing

Int. J. Extrem. Manuf. **6** (2024) 022005 (30pp)

https://doi.org/10.1088/2631-7990/ad12d4

Topical Review

A comprehensive review on microchannel heat sinks for electronics cooling

Zhi-Qiang Yu[1], **Mo-Tong Li**[1] and **Bing-Yang Cao***

Key Laboratory for Thermal Science and Power Engineering of Ministry of Education, Department of Engineering Mechanics, Tsinghua University, Beijing 100084, People's Republic of China

E-mail: caoby@tsinghua.edu.cn

Received 15 May 2023, revised 2 September 2023
Accepted for publication 27 November 2023
Published 11 January 2024

Abstract

The heat generation of electronic devices is increasing dramatically, which causes a serious bottleneck in the thermal management of electronics, and overheating will result in performance deterioration and even device damage. With the development of micro-machining technologies, the microchannel heat sink (MCHS) has become one of the best ways to remove the considerable amount of heat generated by high-power electronics. It has the advantages of large specific surface area, small size, coolant saving and high heat transfer coefficient. This paper comprehensively takes an overview of the research progress in MCHSs and generalizes the hotspots and bottlenecks of this area. The heat transfer mechanisms and performances of different channel structures, coolants, channel materials and some other influencing factors are reviewed. Additionally, this paper classifies the heat transfer enhancement technology and reviews the related studies on both the single-phase and phase-change flow and heat transfer. The comprehensive review is expected to provide a theoretical reference and technical guidance for further research and application of MCHSs in the future.

Keywords: microchannel heat sink, thermal management of electronics, microscale heat transfer, heat transfer enhancement

1. Introduction

The advent of the semiconductor device in 1948 promoted technological innovations and caused revolutionary progress in many fields. With the rapid development and progress of microelectronic systems, micro-electro-mechanical system (MEMS), super-large-scale integration and their related manufacturing technologies, in particular the rise of third-generation semiconductor materials (such as SiC and GaN), electronic chips and devices tend to be more multi-functional, multi-integrated, high-power and miniaturized. The Taiwan Semiconductor Manufacturing Company has officially announced the mass production of 3 nm chips in December 2022 and will implement 2 nm chips in 2024. In the meantime, Intel plans to mass-produce its 20 Å chips in 2024, and its nanoscale 18 Å process has already been in trial production. It is predicted that manufacturing process technology could reach 0.1 nm in 2050. As the size of the chip and transistor continues to shrink, it becomes more and more difficult to maintain Moore's law.

[1] These authors contributed equally.
* Author to whom any correspondence should be addressed.

Original content from this work may be used under the terms of the Creative Commons Attribution 4.0 licence. Any further distribution of this work must maintain attribution to the author(s) and the title of the work, journal citation and DOI.

© 2024 The Author(s). Published by IOP Publishing Ltd on behalf of the IMMT

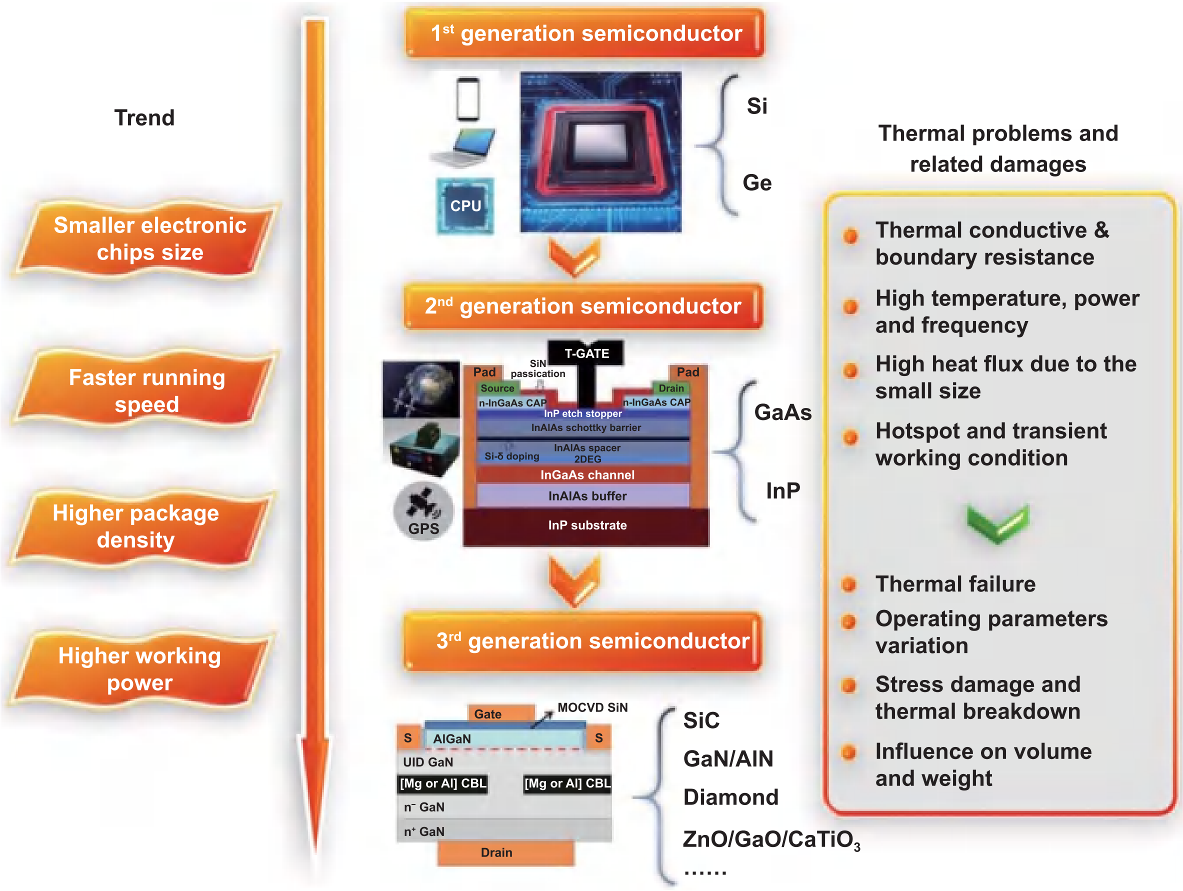

Figure 1. Development trends of chip performance and related thermal problems.

There will be a sharp increase in the heat production and heat flux in the chips caused by factors including smaller size, faster running speed, higher package density and higher working power, which will necessarily lead to temperature rise. When the rated temperature of chips and electronic devices is exceeded, many negative effects, even damage, will appear [1–5] (figure 1), such as:

(1) Thermal failure: when the chip works above the temperature of 70 °C–80 °C, its reliability will decrease by 5% every 1 °C increase in temperature, and the chip failure rate increases exponentially along with the rise in temperature. In addition, exceeding the operating temperature accounts for 55% of the chip failure factors.

(2) Operating parameters' variation: the parameters of the electronic device itself will change with temperature. For example, the switching delay time of an insulated gate bipolar transistor increases with the rise in the device junction temperature.

(3) Stress damage and thermal breakdown: different materials in a device have different thermal expansion coefficients, while the excessively high junction temperature will cause serious thermal stress in the chip, resulting in solder bending, bonding wire loss, and other problems. Furthermore, the high temperature will lead to thermal breakdown and even irreversible thermal melting damage.

(4) Influence on volume and weight: the industry pays more attention to the electrical design than the heat dissipation system, thus lacking thermal enhancement theory and neglecting the improvement of heat dissipation efficiency. Nevertheless, an unreasonable heat dissipation system often makes the whole equipment heavy and oversized, which is against the development tendency of electronic devices.

Heat production in electronics is characterized by heat concentration [6], limited heat dissipation area, multiple application conditions [7], complex and variable environments, interdisciplinarity [8], and multi-physical field coupling [9]. At present, the commonly used approaches in the area of electronics thermal management include air cooling [7], thermoelectric cooling [10–13], immersed liquid cooling, phase-change cooling, heat pipe [14–16], spray cooling and microchannel cooling [17]. The heat dissipation capacities of these common cooling methods under normal circumstances are shown in figure 2. With the rapid development of electronic technology, the heat flux generated by the new generation of microelectronic devices has reached 1500 W·cm^{-2} [10, 11, 14], while the maximum heat flux dissipated by the air-cooling system is about 100 W·cm^{-2} [7]. It means that the air-cooling approach can no longer meet the current and future high heat flux dissipation requirements. The heat dissipation capacity of the heat pipe is generally less than 200 W·cm^{-2} due to the

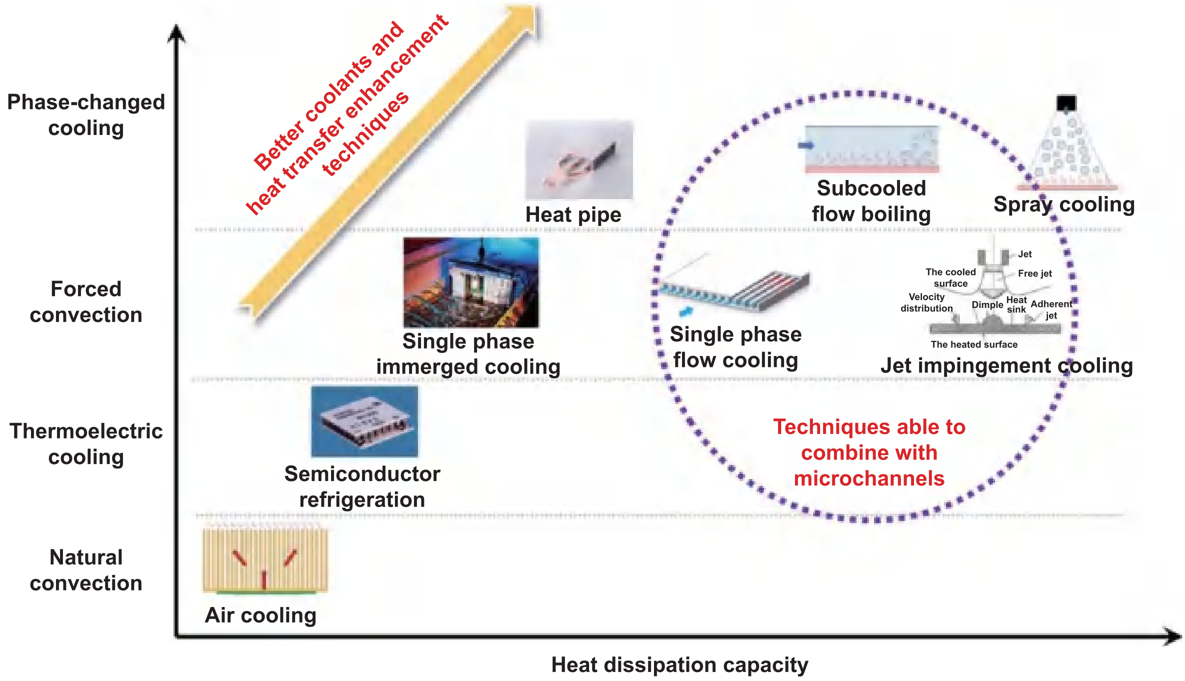

Figure 2. The roadmap of common cooling methods in electronics.

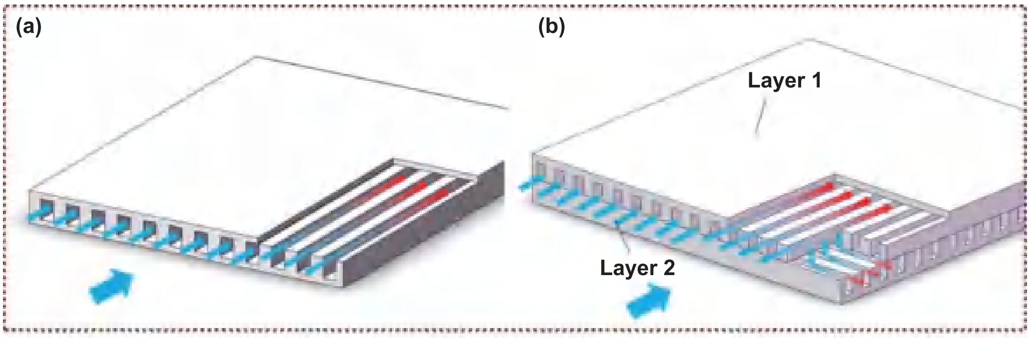

Figure 3. Schematic of parallel MCHS. (a) Schematic parallel microchannels. (b) Double-layer parallel microchannel.

limitation of capillary force. According to the current state and future trend, spray cooling and microchannel cooling are very likely to solve the thermal management problem. For spray cooling, accelerating the droplets will demand large space and high pumping power, which is contrary to the trend of miniaturization of electronic devices. As micromachining technology has developed, the microchannel heat sink (MCHS) has become a superior way to solve the heat dissipation problem of electronics, which has the advantages of large specific surface area, small size, coolant saving and high heat dissipation capacity.

The MCHS was first proposed by Tuckerman and Pease [18] in 1981. The first design is the parallel microchannel (figure 3). The authors processed rectangular channels on a 10 mm × 10 mm silicon wafer, with a single channel 0.302 mm × 0.05 mm × 10 mm in size. The MCHS cooled by water can dissipate a heat flux up to 790 W·cm^{-2} at a volume flow of 8.6 cm^3·s^{-1} when the temperature rise is 70 °C. Its thermal performance was ahead of the known cooling methods at that time, which fully shows the huge potential of microstructure heat dissipation.

The microscale flow and heat transfer phenomenon is always the hotspot of electronics thermal management. There are two main ways to classify microchannels. One is according to the channel hydraulic diameter. Generally speaking, a channel with a hydraulic diameter of 10–1000 μm is a microchannel, while some other researchers refer to channels with hydraulic diameters of 10–200 μm as microchannels. The other is based on the ratio of buoyancy to surface tension. Most studies adopt the former, especially the principle proposed by Kandlikar and Grande [19].

As the characteristic scale of the channel is getting smaller, some new phenomena and rules will appear in the process of fluid flow and heat transfer, which are quite different from the conventional-scale heat sinks. Some factors that can be ignored in conventional conditions, such as viscous force,

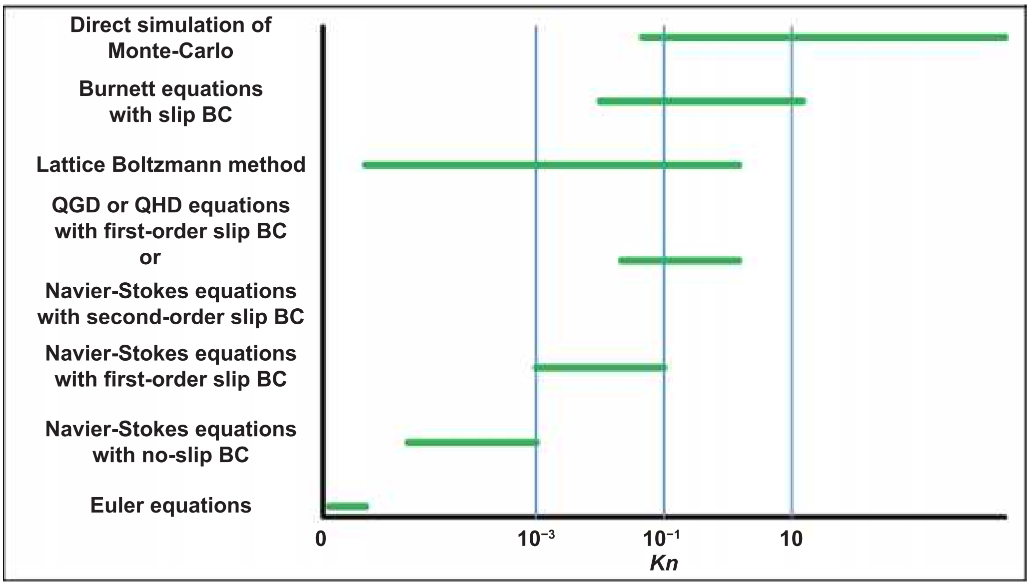

Figure 4. Flow calculation model defined by *Kn* number.

surface tension, friction and capillary force, may have significant effects on microchannel flows. The scale effect can be divided into two regimes. One is that the scale of the research object is equivalent to that of the mean free path of molecules. At this point, the continuum assumption is no longer valid, and the basic law of flow and heat transfer needs to be studied and described at a molecular level. The other is that the scale of the research object is much larger than that of the molecular mean free path, and, thus, there is no fundamental change in the mechanism. The continuum hypothesis and all the basic laws applicable to the conventional conditions are still valid. The reduction of scale only influences the relative importance of various factors. As for the research on MCHSs, the Knudsen number is generally the criterion to determine whether the continuum assumption is applicable (figure 4).

Fedorov and Viskanta [20] developed a three-dimensional model to study the flow and heat transfer process in MCHSs. It was calculated by the Navier–Stokes equations of incompressible laminar flow. They implemented this model to analyze the velocity and temperature field and compared the predicted thermal resistance and friction factors with the corresponding experimental data to verify the validity of the theoretical model. This work provides important practical guidance for the application of MCHSs. Qu and Mudawar [21] also demonstrated the accuracy of the three-dimensional model governed by the Navier–Stokes equations. At present, for research on MCHSs, the scale effect involved belongs to the second regime. That is, the liquid flow in microchannels is mainly in the continuous flow zone, and it is reasonable to neglect the influence of boundary conditions such as velocity slip or temperature jump. The continuum assumption, the Naiver–Stokes equations and the Fourier law are still applicable.

With the progress in modern electronic technology, MEMS and microscale heat transfer theory, the MCHS has drawn a lot of attention in industry and academia. This approach has been widely used in the fields of electronics, aerospace, refrigeration, chemical engineering and biological engineering. In this paper, recent progress in MCHSs is outlined from aspects including microchannel structures and optimization design, working coolant, phase-change flow and heat transfer, microchannel materials, and other influencing factors. The development trends and prospects will also be mentioned in the last section.

2. Microchannel structure and optimum design

Many researchers have carried out extensive and in-depth studies on MCHSs and analyzed the flow and heat transfer in different structures [22–25]. The parallel straight channel is the original structure first proposed by Tuckerman and Pease, and was adopted in the early-stage studies for a long time. With continuous development of MEMS, MCHSs began to adopt a variety of shapes (figure 5). There is relatively large optimization potential to explore the thermal enhancement methods for MCHSs by designing channel layout, channel surface microstructures, channel sections, geometric parameters and so on. Table 1 summarizes the advantages and drawbacks of microchannel geometries and optimization methods involved in MCHSs, and detailed information will be introduced in the following section.

2.1. Single and simple structure

MCHSs with different channel sections will have different heat dissipation performances [26–28]. Early studies generally investigated the microchannel sections such as rectangular, trapezoidal and circular channel section shapes (figure 6).

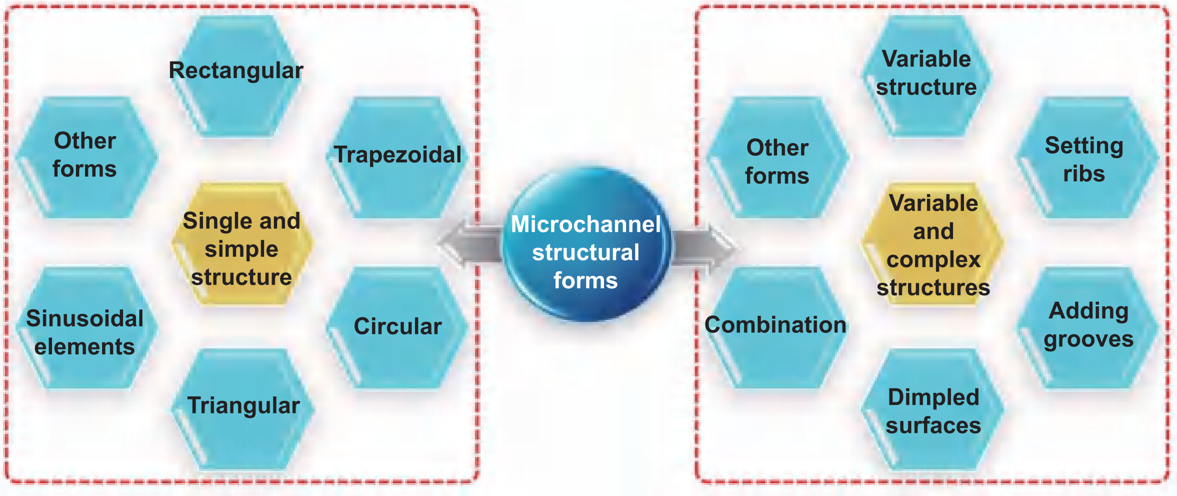

Figure 5. Various structural forms of microchannels.

Table 1. Microchannel geometry and optimization design of MCHS.

Microchannel geometry	Optimization method	Advantages	Drawbacks
Conventional structures (like different section shapes, ribs, grooves, wavy shapes, etc)	Comparison one by one	• Evaluating the performance accurately • No analytical method used	• Unable to confirm optimal solution • Hard to reflect the interrelation of multiple influencing variables
	Single-objective optimization	• Obtaining locally optimal value • Getting the empirical formula for analysis and prediction	• Only one objective concerned • Unable to confirm the overall performance
	Multi-objective optimization	• Obtaining locally optimal value • Improving the overall performance simultaneously • Getting the empirical formula for analysis and prediction	• Large database required • Expensive computational cost • Sensitive to optimization settings
Unconventional structures (like biomimetic shapes, topological shapes, etc)	Comparison one by one	• Evaluating the performance accurately • No analytical method used	• Unable to confirm optimal solution • Hard to reflect the interrelation of multiple influencing variables
	Topology optimization	• High design freedom • More inspiring design • Bringing breakthrough in flow and thermal performance	• Sensitive to optimization settings • Hard to fabricate • Unclear mechanism • Expensive computational cost

Figure 6. MCHS with three different channel section shapes. (a) Rectangular. (b) Trapezoidal. (c) Circular.

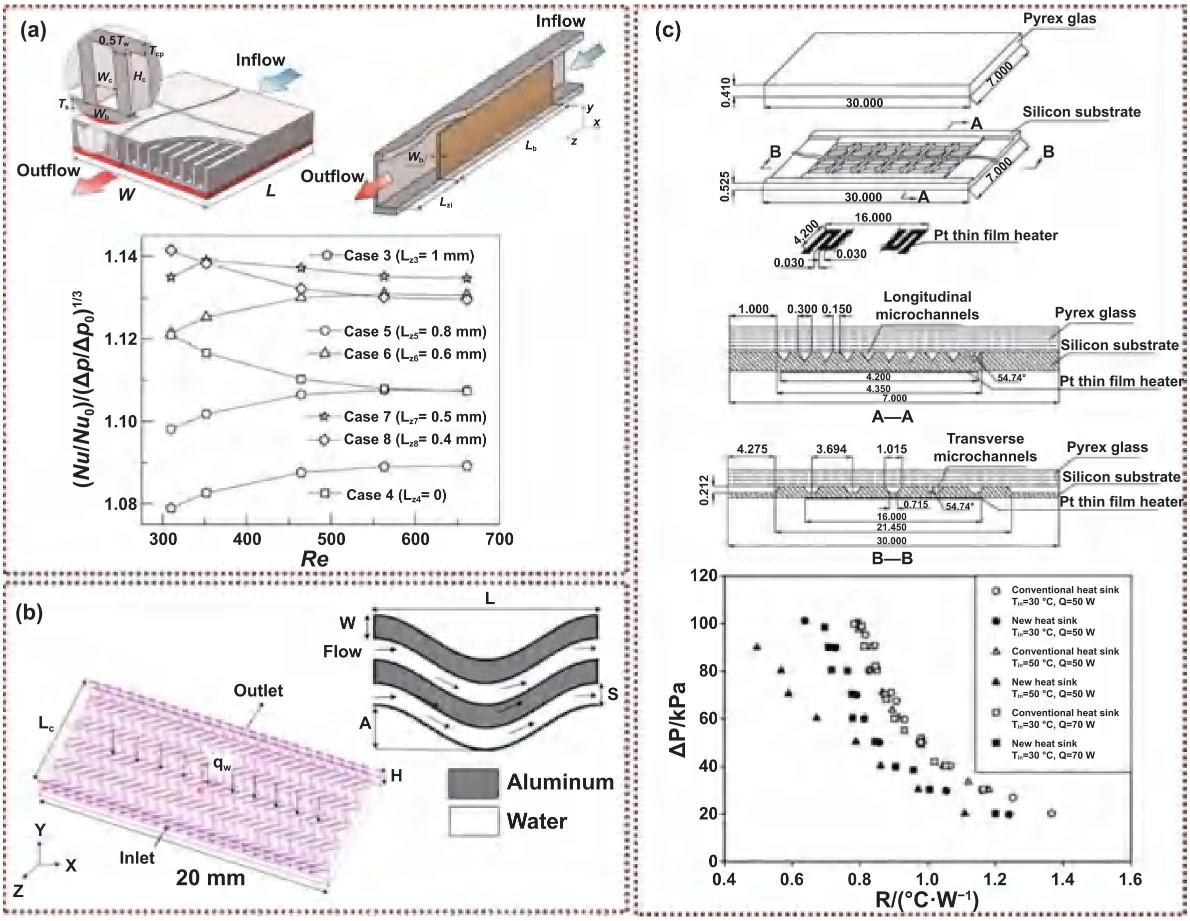

Figure 7. Research on the variable structures of MCHSs. (a) Microchannel with Y-type bifurcations. Reprinted from [38], © 2017 Elsevier Ltd. All rights reserved. (b) Microchannel with wavy shape along the flow direction. Reprinted from [39], Copyright © 2010 Elsevier Ltd. All rights reserved. (c) Microchannel with transverse channels. Reprinted from [40], Copyright © 2005 Elsevier Ltd. All rights reserved.

The heat transfer characteristics of single-phase forced convection in microchannels are closely related to the geometric parameters of channels, such as the hydraulic diameter and the depth to width ratio of the channel [29]. The optimal design can be obtained by adjusting the geometric parameters [30]. However, researchers fail to reach an agreement on the best-performing shape for a microchannel. Chen *et al* [31] believed that the triangular microchannel performed the best in heat transfer, followed by the trapezoidal microchannel, and the rectangular microchannel is the worst. Nevertheless, the results of Gunnasegaran *et al* [29] showed that the heat transfer efficiency in order from high to low is rectangular, trapezoidal and triangular microchannels. To further explore the influence of microchannel section shape, Wang *et al* [32] simulated MCHSs with different cross-section shapes and aspect ratios while maintaining the same cross-section area. They showed that the thermal resistance of the rectangular MCHS is the smallest, and that of the triangular MCHS is the largest. Meanwhile, in the rectangular MCHS with the same cross-section area, the channels with higher aspect ratio usually have lower thermal resistance. Considering that parallel and regular structures are relatively easy to manufacture, the rectangular MCHS with high aspect ratio is commonly used in related research. The divergence of these conclusions is probably due to the failure in variable control.

2.2. Variable and complex structures

Because of the rapid increase of heat flux in micro-devices, the simple structure of microchannel heat exchangers cannot meet the demand, and the research has gradually moved towards complex microchannel structures. There are many novel designs proposed to promote flow turbulence and heat exchange, such as ribs [33], grooves [34], nanofins [35] and some other complex structures [36].

Some researchers carried out research on heat transfer enhancement by changing the shapes of the channel wall, among which the typical designs include T-type, Y-type, wave-type, convergent-type, and periodically variable cross-section channels. Yagodnitsyna *et al* [37] studied the immiscible ionic liquid water in a T-type microchannel with a hydraulic diameter of 160 μm when the aspect ratio was 2 or 4. The results show that the rectangular microchannel with higher aspect ratio performs better. Shen *et al* [38] analyzed the influence of the positions of the internal vertical bifurcations placed in rectangular microchannels on pressure drop and heat transfer characteristics numerically (figure 7(a)).

Compared with the traditional long, straight microchannel, the microchannel with wavy shape along the flow direction will generate a Dean vortex inside, which disturbs the boundary layer and is beneficial to heat transfer. Mohammed *et al* [39] designed a corrugated MCHS (figure 7(b)). The simulation results indicate that the heat transfer performance of a corrugated microchannel is obviously better than that of a straight microchannel of the same length because of the increased heat transfer area. Although the pressure drop of a corrugated microchannel is greater, its loss is far less than the heat transfer enhancement effect. However, more efforts are needed to investigate the underlying mechanism of thermal transfer enhancement in wavy microchannels.

The change of the channel section along the flow direction can also enhance the flow and heat transfer. Dehghan *et al* [41] used the finite volume method to study the MCHS with converging channels and found that *Nu* increased gradually as the structure got thinner. The optimal width-tapered ratio is 0.5. When the pressure is limited below 3000 Pa, the pumping power is reduced by 75% compared with the straight channel, and the overall thermal efficiency remains unchanged. Chai *et al* [42] studied the flow and heat transfer characteristics in the periodically changeable cross-section microchannel and found that the heat transfer was significantly improved compared with the straight channel, while the increase in pressure drop was small. Xu *et al* [40] designed a new silicon-based MCHS (figure 7(c)), which added transverse microchannels across the traditional parallel straight channels. The substrate is blocked along the flow direction, and thus generates a developing thermal boundary layer similar to the flow inlet, which significantly improves the heat dissipation capacity of the heat sink. In addition, its pressure drop also decreases.

Metal ribs are widely used to enhance heat transfer in microchannels because of their high thermal conductivity and obvious effect on fluid disturbance. The common rib shapes include circle, oval, rectangle, diamond and triangle, and some like rectangular inclined ribs, sidewall misalignment ribs, staggered trapezoid ribs and V-shaped ribs are also in development.

There are many experimental and numerical studies focusing on the shapes, heights and arrangements of the ribs (figure 8(a)) and investigating the influence of these variables on thermal convection and pressure drop under different Reynolds numbers (*Re*) [33, 43–47]. Some researchers also find that if the ribs are not through the height of the channel (i.e. there is clearance between the top of the rib and the channel ceiling), the pressure drop may reduce without heat transfer worsening. Moores *et al* [45] conducted experiments on cylindrical rib MCHSs with rib height-to-diameter ratios ranging from 0.5 to 1.1 (figure 8(b)). It was found that when the ratio of tip clearance to section diameter is 0.05–0.1, the total pressure drop increases with the increase of clearance. When the ratio is greater than 0.1, the pressure drop is smaller than that without clearance. Mei *et al* [46] simulated the hydrodynamics and thermal properties under different ratios of channel height to rib height in microchannels with micro-pin-fin arrays, and concluded that when Reynolds number was 33–350, the channel with the ratio 1.1 or 1.2 performed better than that without tip clearance. The ribs can also combine with secondary oblique microchannels or other heat transfer enhancement techniques. Ghani *et al* [47] studied the flow and heat transfer characteristics of rectangular rib microchannels and secondary oblique microchannels with *Re* ranging from 100 to 500 by numerical calculation. Additional flow is injected through secondary channels to further enhance flow mixing, and these channels can provide a larger flow area to reduce the pressure drop caused by the ribs.

Optimizing structural parameters, arrangement patterns and tip clearance of ribs can all improve thermal diffusivity, though their thermal transfer enhancement mechanisms are different. However, adding ribs often induces higher pressure drop. In addition, variable control should be guaranteed when comparing ribs with different sectional shapes.

In 2008, Ridouane and Campo [50] conducted simulations and demonstrated that the microchannel with grooves had superior heat transfer performance. After that, the study of groove structure in rectangular microchannel gradually developed. Pan *et al* [48] introduced a fan-shaped groove structure into a straight microchannel with a rectangular section (figure 8(c)). The heat transfer performance of the microchannel with grooves proved to be better. There is an optimal groove deviation degree and the smaller the overlap degree of grooves is, the better the microchannel performs. Additionally, at a high flow rate of coolant, the groove-type microchannel with sparse front and dense rear arrangement will have better performance.

Unlike the needle rib, the dimpled structure often has a smaller heat transfer surface area, which will slightly weaken the heat transfer enhancement. However, its relatively smooth surface has little blocking effect on the working fluid, thus saving the pumping power [51]. Based on this, it is proposed to combine the dimpled surface and needle ribs to achieve high efficiency and low flow resistance simultaneously. For relatively low heat flux area, the dimpled structure can reduce the pressure drop as well as increase the heat transfer, and for the high heat flux, the needle rib can achieve considerable heat transfer enhancement. Li *et al* [49] designed an MCHS with cylindrical needle ribs and dimpled structures alternately arranged on the channel side wall (figure 8(d)). The researchers studied the influence of parameters such as the diameter of the needle rib, the height of the dimpled structure and the center distance between them, and the optimal combination of the parameters were obtained. The results show that the decrease of the center distance and the increase of the needle rib diameter are beneficial to heat transfer, and the needle rib diameter is the most important factor among the three variables, followed by the cell height.

These related studies show that the heat transfer enhancement is caused by two aspects: on the one hand, the change of microchannel sections and integrated barriers can interrupt the thermal boundary layer. The flow in microchannels is not fully developed, so as to enhance the thermal convection near the channel wall. The complex flow path can also promote the perturbation and mixing of the coolant. On the other hand, the heat transfer surface area is increased significantly by adding solid parts in the channel or breaking the continuous wall.

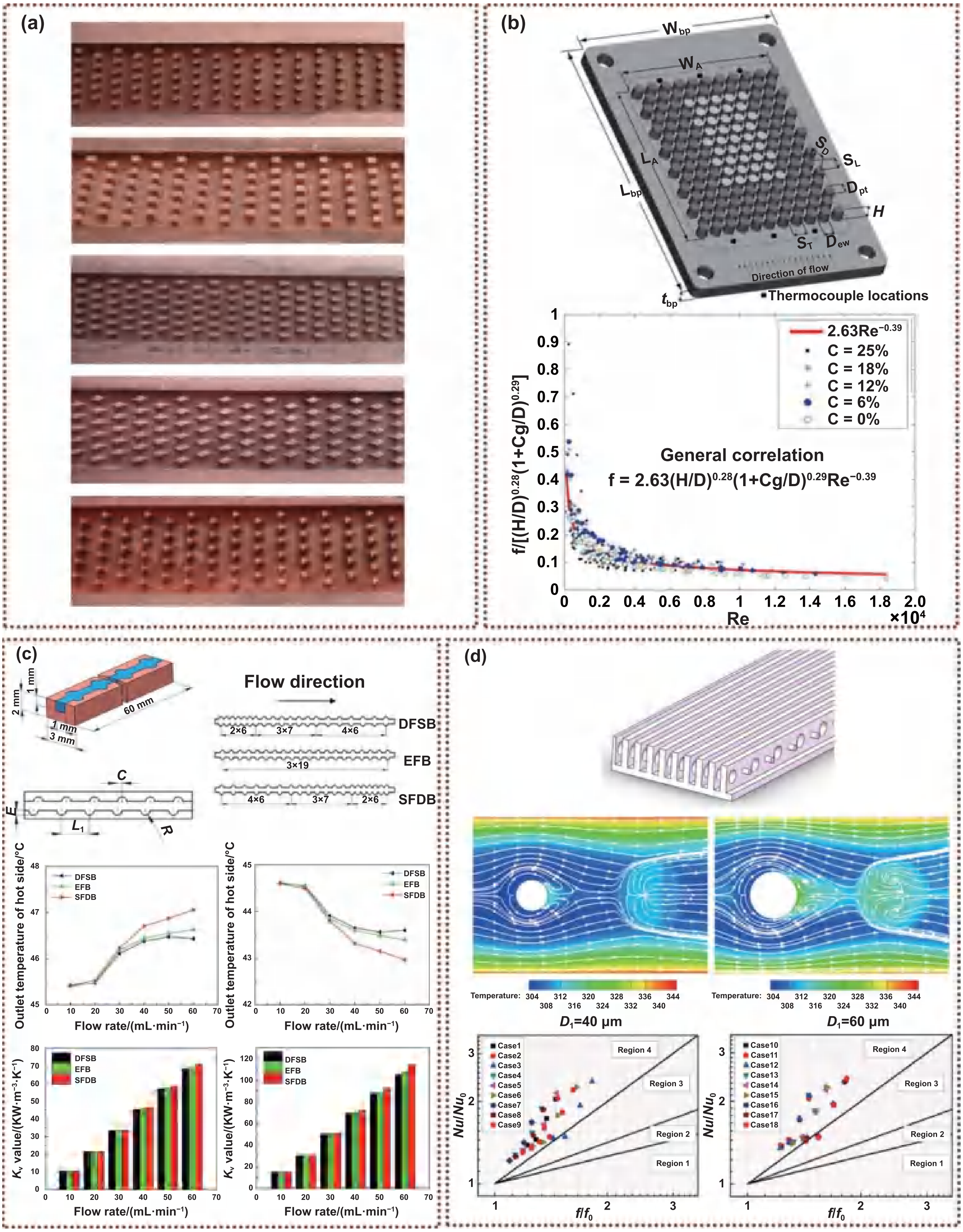

Figure 8. Research on the MCHS with ribs, grooves and dimpled walls. (a) Interleaved rib arrays with different sectional shapes. Reprinted from [43], © 2016 Elsevier Ltd. All rights reserved. (b) Microchannel with cylindrical ribs. Reprinted from [45], Copyright © 2009 Elsevier Ltd. Published by Elsevier Ltd. All rights reserved. (c) Microchannel with fan-shaped grooves. Reprinted from [48], © 2019 Elsevier Ltd. All rights reserved. (d) Microchannel with dimpled structures and needle ribs alternately arranged. Reprinted from [49], © 2017 Elsevier Ltd. All rights reserved.

A reasonable design should make full use of these advantages with an acceptable pressure drop.

2.3. Optimization design of microchannel structure

Although the MCHS has been regarded as an efficient thermal management method for electronic chips and devices, the simulation and experiment results reflect that it still has the potential to be improved. For example, the fluid temperature will rise along the flow direction, which will cause non-uniform temperature distribution and thermal stress inside the device. Furthermore, the high pressure drop in the microchannel is also challenging for the micropump.

A superior MCHS should dissipate more heat under lower pumping power. The thermal resistance, temperature distribution and pressure drop are all important criteria to evaluate the overall performance of an MCHS. Above all, the geometric structure of the microchannel plays the main role in affecting the flow and heat transfer of microchannels, and thus is the major optimized variable [52]. The optimization studies mainly focus on the aspect ratio, hydraulic diameter, shape of the channel and so on. The optimization objective is usually to minimize the thermal resistance, minimize the pressure drop or improve the temperature uniformity. Sometimes, researchers also optimize a combination of them, while Chen [53] set entropy generation rate minimization as the objective by neglecting the fluid temperature variation in the lateral direction.

It is essential to get the numerical expression of the optimization objective before implementing the optimization method. As the correlation between the objectives and variables is generally complex, an enormous dataset is required to analyze the mechanism and fit the empirical formula. The data here are mainly obtained by simulations or experiments, which demands high computational or experimental costs. Therefore, some researchers proposed to utilize machine learning (ML) to extend the prediction region of multi-variable problems based on limited data. The commonly used ML methods contain artificial neural networks [54], random forests, Gaussian process regression [55], extreme gradient boosting [56] and so on.

To date, there have been many optimization methods applied to microchannel design [57–61]. Hung *et al* [62] used the simplified conjugate-gradient method to optimize a double-layered MCHS. At the given pumping power conditions, they obtained optimal designs rapidly. Arie *et al* [63] optimized the manifold microchannel (MMC) with a multi-objective optimization method. This indicates that the manifolds also have potemtial for optimization. Shi *et al* [64] implemented the NSGA-II algorithm to optimize microchannels with secondary flow. Compared with the straight microchannel, the optimal design reduced the thermal resistance by 28.7% and, meanwhile, reduced the pumping power by 22.9%.

For conventional structures, the geometric parameters of the microchannel are the critical factors that influence its thermal transfer performance. Most studies only concentrate on these and try to optimize the geometry shape and parameters of the channel with different optimization methods. Nevertheless, some unconventional shapes also attract people's attention. Some biomimetic patterns such as leaf [65], snowflake and spiderweb [66] have been investigated and found to be efficient in heat transfer and temperature uniformity. With the introduction of topology optimization into solid–liquid heat transfer, many researchers have used topology algorithms and presented many pioneering topological structures of MCHSs, which show extraordinary performance in flow and heat enhancement. As shown in figure 9(a), Xia *et al* [67] obtained quite different optimal results with different inlets and outlets and different weights of objectives. They conducted topology optimization in a simplified 2D model. Gilmore *et al* [68], however, optimized 3D structures directly and obtained a rebuilding of the channel region (figure 9(b)). Considering the fabrication and feasibility, most studies focus on the 2D shape and validate it with the corresponding 3D structure. As the manufacturing process has developed, topology-optimized designs have been fabricated to verify their advantages experimentally (mainly by a stereolithography process [69] or computer numerical control carving [70] for metal). Unfortunately, the optimal results are sensitive to the parameters and objectives, so it is hard to determine which one is superior under different settings. In addition, it is still very difficult to fabricate such complex shapes in microscale, especially for semiconductor materials. More efforts should be devoted to advanced processes and experimental research.

3. Working fluid

Besides the microchannel structure, the working fluid also influences the performance of heat sinks directly. The working fluid is expected to have efficient thermal properties, good chemical stability, low viscosity and non-corrosiveness. It also needs to be non-volatile under the operating conditions and environmentally friendly to some extent. The working fluid will be outlined in this section (figure 10) [71–74].

3.1. Conventional working fluid

The most commonly used coolants in MCHSs are air, deionized water and organic liquids (e.g. R134a, R22 and HFE-7100). Air has poor thermal conductivity and heat capacity, which can only meet the thermal dissipation demand of low-power working conditions [75]. Liquid coolants such as water perform better in convective heat transfer, and thus are more economical and practical in MCHSs for high heat flux electronics [76–78]. When Tuckerman and Pease [18] first presented the concept of the MCHS, they used water as the coolant and dissipated a heat flux of 790 $W \cdot cm^{-2}$ with a temperature rise of 70 °C at a flow rate of 8.6 $cm^3 \cdot s^{-1}$.

3.2. Nanofluid

As the nanofluid attracts more and more researchers' interest, it has become an alternative coolant for thermal transfer enhancement. By adding solid nanoparticles in the base fluid, the thermal conductivity of the mixture can be improved

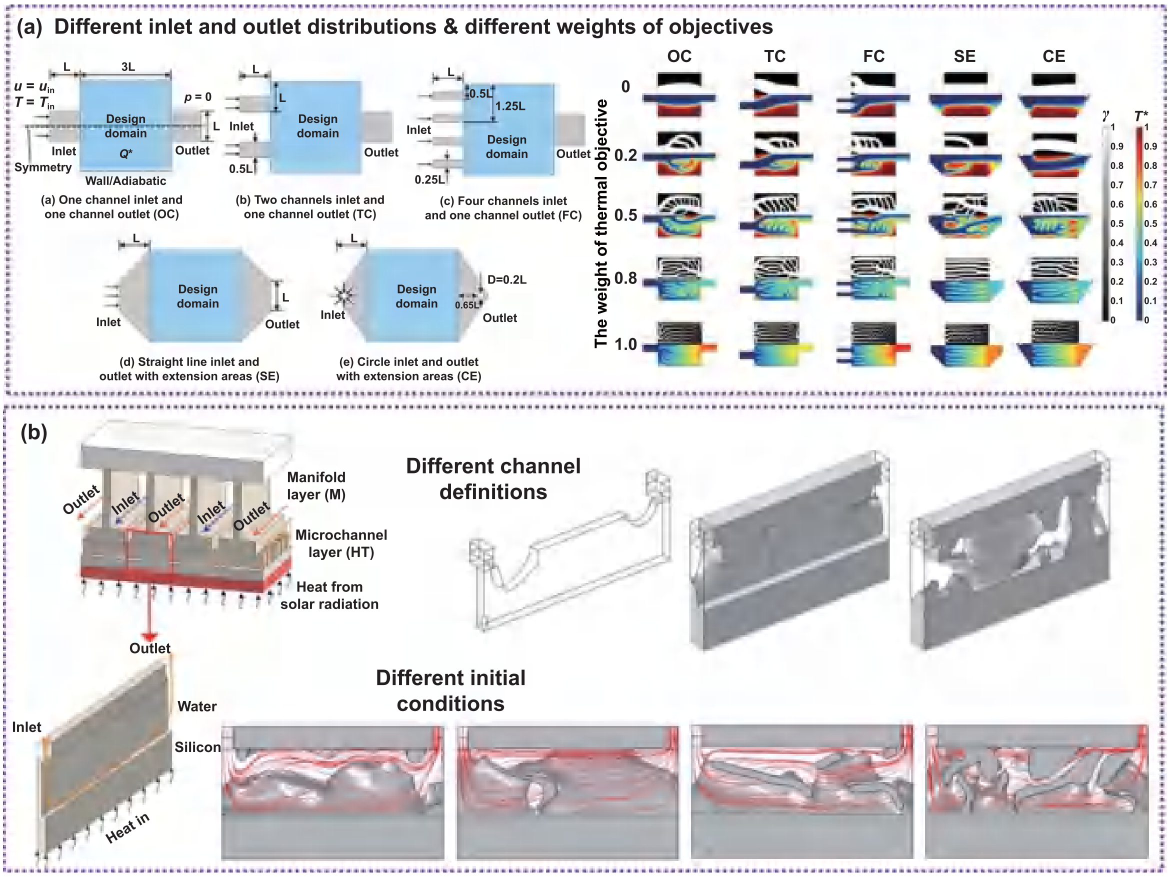

Figure 9. Topology optimization of the MCHS. (a) 2D optimal design. Reprinted from [67], © 2022 Elsevier Ltd. All rights reserved. (b) 3D optimal design. Reprinted from [68], © 2021 Elsevier Ltd. All rights reserved.

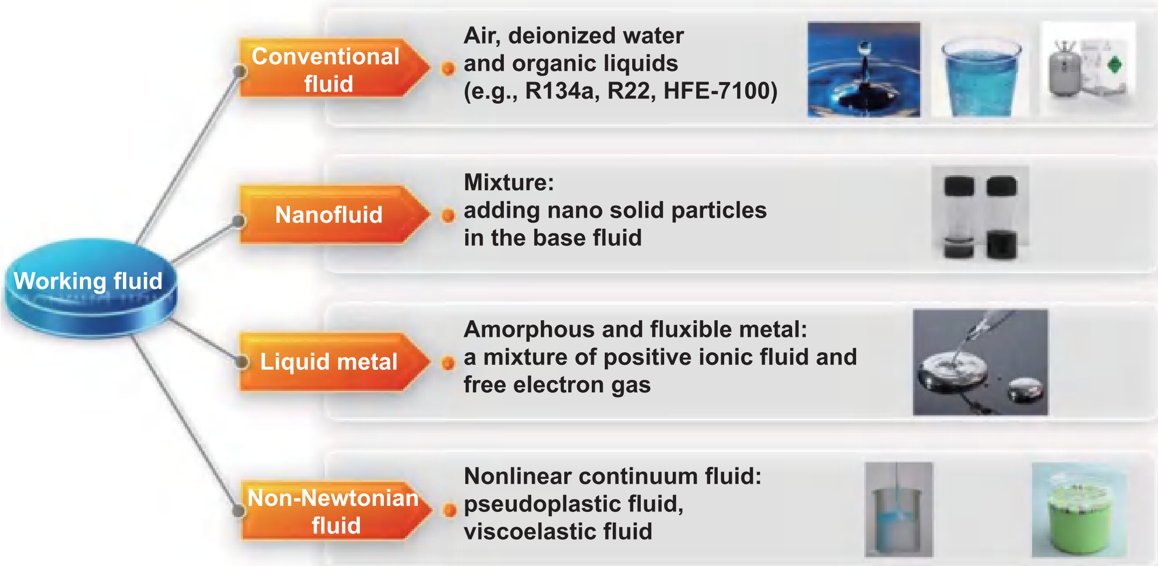

Figure 10. Working fluid in MCHSs.

dramatically, which can contribute to the heat dissipation [79–82].

According to related research, the thermal resistance will decrease and the extra pressure drop caused by the nanoparticles can be neglected when the nanofluid concentration is low, while the nanofluid with high particle volume fraction will weaken the heat transfer enhancement due to the significant increase in the viscosity [83–85]. Wu *et al*

[86] investigated the effectiveness of Al_2O_3/H_2O nanofluid on improving the overall performance of MCHSs. They found that Al_2O_3/H_2O nanofluid can efficiently reduce the thermal resistance and improve the uniformity of temperature distribution on the base surface. However, the pumping power required for the MCHS will increase rapidly as the particle volume fraction and inlet velocity increase. It should be noted that the nanofluid can enhance the heat transfer only when the pumping power is high enough, and thus, a moderate inlet velocity needs to be selected to save the pumping power.

Until now, many researchers have carried out simulations to study the MCHS cooled by a nanofluid. The research methods can be generally classified into two models: one considers the nanofluid as a two-phase mixture. The random motion of solid nanoparticles in the base fluid can enhance the heat transfer. The other is the single-phase model, which assumes that the fluid and nanoparticles are in thermal equilibrium without relative velocity. Many studies adopt the single-phase model to simplify the governing equation. When the particle volume fraction is low, the nanoparticles can be considered uniformly distributed in the base fluid, and the nanofluid can be supposed as a novel single-phase liquid, of which all the properties such as density, heat capacity, thermal conductivity and viscosity should be reevaluated by new models, such as the 3D porous media approach and the 3D solid and fluid coupling approach [87–90].

Most of the previous simulation studies had not been validated by experiment until 2007 [91]. Chein *et al* [92] first conducted experimental research on the MCHS using $CuO–H_2O$ mixtures, of which the CuO particle volume fraction was in the range of 0.2%–0.4%. After that, Ho *et al* [93] investigated the performance of MCHS cooling by Al_2O_3/water nanofluid. Azizi *et al* [94] evaluated the convective heat transfer coefficient and pressure drop of a cylindrical MCHS with a Cu–water nanofluid. They show that a high heat transfer coefficient is obtained using the nanofluid at 0.3 wt% without a large pressure drop. However, further increase in *Re* after reaching a certain value will lead to the reduction of thermal efficiency and heat transfer ability. This is because the nanoparticles move too fast to have sufficient contact time with the channel wall at a high flow rate and, therefore, fail to enhance the heat transfer between the heat sink and coolant. Therefore, it is essential to find the optimal flow rate for a nanofluid for the heat transfer process.

In conclusion, both experimental data and simulation analysis suggest that a nanofluid is a good alternative coolant in MCHSs since it can improve the thermal performance at a low volume fraction condition with an increase in pressure drop that is acceptable. However, the nanofluid is not stable enough and is prone to agglomeration and precipitation due to the high surface energy of nanoparticles. This may make block the channel and cause the system to break down. To improve nanofluid stability, on the one hand, it is meaningful to destroy the weak interaction between the particles. Mechanical agitation or ultrasonic oscillation can be applied to get a transiently stable fluid. Nevertheless, when the mechanical operation stops, the nanofluid tends to agglomerate again. Adding dispersant can solve the problem effectively and has become a favored method to improve the nanoparticle preparation. On the other hand, some approaches, such as surface coating modification or surface grafting modification, can modify functional groups in the particles and improve the surface wetting properties, which can inhibit chemical bond formation and make the nanofluid more stable. In addition, the shape and size of nanoparticles also affect the stability. To obtain a high-quality particle suspension, there is a need to reduce the particle size, lower the concentration, reduce the contact probability between particles and lighten the impact of gravity.

3.3. Liquid metal

Compared with water, liquid metal has a higher thermal conductivity. Therefore, metals with low melting points can be used as the coolant for the thermal management of electronic chips and devices [95]. For example, the thermal conductivity of gallium (Ga) is about 60 times more than that of water, and 1000 times more than that of air. Additionally, the liquid metal can be used in microchannels and thus can dissipate the heat effectively [96]. Therefore, it is appropriate to explore liquid metal for microchannel cooling.

In 1988, Smith's team [97] at Argonne Laboratories in the United States developed a liquid Ga cooling system to replace the traditional water cooling for the heat dissipation of optical elements in the Advanced Photon Source device, with a highest heat flux of 1400 $W\cdot cm^{-2}$. The results show that this method has a significant enhancement effect compared with water cooling.

In order to further improve heat transfer efficiency and promote the application of liquid metal, many researchers carried out experiments to verify the performance of liquid metal MCHSs. The study of Zhang *et al* [98] showed that a GaInSn-based microchannel cooling system can dissipate a heat flux of 300 $W\cdot cm^{-2}$ and heat power of 1500 W (figure 11). This indicates that GaInSn-based microchannel cooling can obtain much larger heat transfer enhancement and lower pressure losses than water-based microchannel cooling. Moreover, it was also found that heat capacity thermal resistance becomes a rather important factor for GaInSn-based microchannels, due to the high thermal conductivity and low heat capacity of GaInSn. Zhang *et al* [99] designed a vascularized liquid metal heat sink. The experiments indicated that vascularized liquid metal cooling can achieve 2000 W heat dissipation of a high-power laser diode array, with a maximum temperature of the heat sink top surface lower than 54 °C.

It is feasible to apply a liquid metal with a low melting point to the thermal management of electronics. A new concept, i.e. nano liquid metal, brings a new option for reliable coolants. However, the current theoretical achievements are still far away from being widely used in industry. There is still a need to select more kinds of liquid metal suitable for various working conditions and to summarize the empirical formula to predict the flow and heat transfer performance. Furthermore, there is a need to improve the manufacturing and packaging of liquid metal MCHSs.

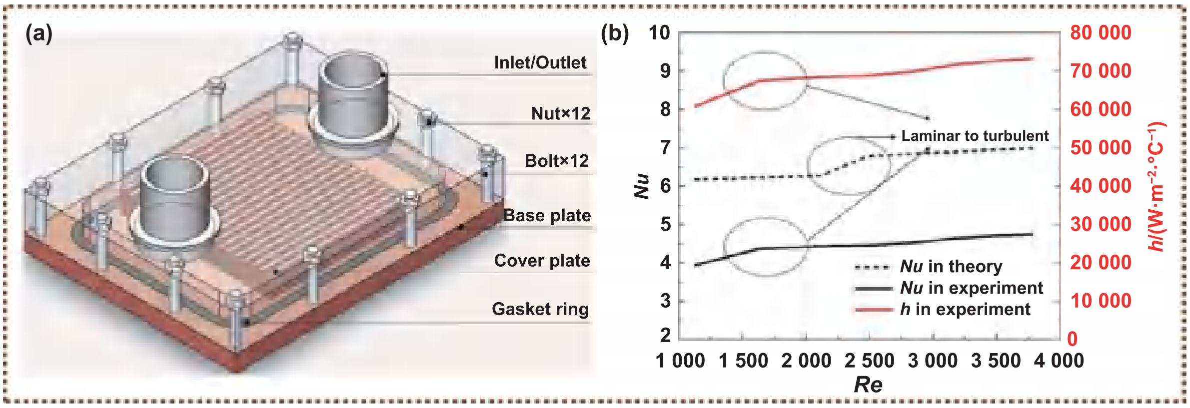

Figure 11. The design and experimental results of Zhang *et al*. (a) Structure of liquid metal-based rectangular MCHS. (b) Nusselt number and convection heat transfer coefficient of liquid metal-based rectangular MCHS. Reprinted from [98], © 2019 Elsevier Ltd. All rights reserved.

3.4. Non-Newtonian fluid

The heat transfer capabilities of Newtonian fluids are limited because of their poor thermal conductivity. It is hard to further improve the cooling efficiency of Newtonian fluids without changing the channel shape due to the fact that the flow in microscale structures is mostly laminar flow, and the heat transfer coefficient appears low. For the nanofluids mentioned above, the preparation is usually costly, and the nanoparticles tend to adhere to the wall of the microchannels, leading to high flow resistance [100–102]. Hence, some researchers introduce non-Newtonian fluids for microscale heat transfer. They find that, as a nonlinear continuum fluid, its inner nonlinearity effect will cause flow instability. This can produce turbulence contributing to the heat transfer [103]. In this section, two typical types of non-Newtonian fluids, i.e. pseudoplastic fluid and viscoelastic fluid, will be introduced.

3.4.1. Pseudoplastic fluid. A pseudoplastic fluid refers to one for which the flow conforms to the pseudoplastic flow law. The apparent viscosity of pseudoplastic fluid decreases with the increase of shear stress or shear rate in the momentum equation of a non-Newtonian fluid. This kind of fluid, without yield stress, has already been widely used in microscale heat transfer enhancement.

Li *et al* [104] used carboxyl methyl cellulose (CMC) aqueous solutions to cool a dimpled/protruded MCHS. The results reveal that when the CMC concentration is 2000 ppm, the shear-thinning effect is enlarged, and it is demonstrated that this can enhance the heat transfer efficiently. The authors attribute this to the transformation of viscosity that accelerates the separation of the secondary flow and vortex in dimpled/protruded microchannels. Ebrahimi *et al* [105] carried out simulations to study the shear-thinning effect on the thermal performance of an MCHS with longitudinal vortex generators. They find that compared with a Newtonian fluid, CMC aqueous solutions can achieve an enhancement of 6.82%–31.18% in heat transfer.

In brief, a pseudoplastic fluid can promote the heat transfer in both the steady and the unsteady state. The main reason is that the shear-thinning behavior can help produce secondary flow. However, at the same time, the flow resistance increases due to the large viscosity. Until now, the studies on MCHSs cooled by pseudoplastic fluids have generally been conducted by simulation or just by selecting a specific structure for the channel. More effort is still needed to explore the flow and thermal performance of microchannels with different shapes.

3.4.2. Viscoelastic fluid. Another commonly used non-Newtonian fluid is the viscoelastic fluid. It exhibits both viscous and elastic characteristics in the deformation process. Due to its specific properties, a viscoelastic fluid can enhance heat transfer by producing elastic turbulence at low *Re* [106]. In recent years, some researchers have conducted studies on viscoelastic fluid heat transfer in milli- and microchannels.

Whalley *et al* [107] proposed a serpentine channel with the characteristic scale of 1 mm and demonstrated the enhancement of heat transfer could reach 300% by producing elastic turbulence in this channel structure. Tatsumi *et al* [108] carried out experiments to study the thermal transfer performance of polyacrylamide in serpentine microchannels. They showed that *Nu* (Nusselt number) will rapidly increase with the increase of *Re*. They attributed the thermal enhancement effect to the flow instability generated by the normal stress. They also observed secondary flow and vortex structures in the flow.

To date, research on viscoelastic fluid cooling in microchannels has not been extensive. The mechanism of heat transfer enhancement and the relation between the heat exchange efficiency and the turbulent velocity field needs to be further clarified. It is still a prospect to take advantage of the optimized designs with conventional coolants and use a viscoelastic fluid instead to enhance the heat transfer significantly.

4. Phase-change flow and heat transfer

Although the single-phase cooling in microchannel can achieve a quite high heat transfer coefficient, it still has the disadvantage of uneven temperature distribution in the flow direction, which will affect the operating condition of the electronics. Phase change cooling, however, can solve the high temperature rise problem with a relatively low flow rate of coolant [109–112]. Single-phase cooling has been discussed above, and next, we will present an overview of the research on phase-change flow and heat transfer.

4.1. Gas–liquid phase change

Flow boiling can reach a considerably high heat transfer coefficient and better heat transfer capacity at a given flow rate. Due to the small size of the microchannel, the bubbles generated during the flow boiling in an MCHS will be limited in a narrow space and the surface tension, as well as the capillary force, plays a more important role in microchannels than in conventional channels. The effect of buoyancy is weakened instead. The relative magnitude of gravity, buoyancy force, inertial force, surface tension and capillary force affects the two-phase flow patterns in microchannels. Additionally, considering factors like size effect, surface effect, compressibility and rarefaction of the coolant, there are obvious differences between microchannel flow boiling and conventional pool boiling [113–116].

Qu and Mudawar [117] proposed a two-phase annular flow model to calculate the heat transfer coefficient in microchannels. The results show that the annular flow model can accurately describe the decreasing trend in the heat transfer coefficient with the increase of gas volume fraction in the low gas volume fraction region. Sur and Liu [118] studied the influence of channel size and surface phase velocity on air–water two-phase flow patterns and pressure drop in circular microchannels. Two-phase flow patterns were observed by high-speed camera, and four basic flow patterns were found: bubble flow, slug flow, wave flow and annular flow. Wei *et al* [119] studied the two-phase flow pattern of air and water flowing upwards in a vertical narrow rectangular channel by using a volume of fluid simulation model. The results show that the main flow patterns of two-phase flow in the narrow-slit channel are bubble flow, slug flow, turbulent flow and annular flow, and the void fraction distribution is quite different. In addition, since the Taylor bubble is located in the center of the groove and the slug flow is an intermittent flow, the void fraction of the slug flow is more evenly distributed in the center.

A study on the flow pattern of gas–liquid two-phase flow and the transition characteristics between different flow patterns can further reveal the characteristics of the friction resistance coefficient, liquid content, dryness, critical heat flux (CHF) and instability in the fluid flow and heat transfer process of two-phase flow. It can develop the theoretical research on the two-phase flow based on experimental results. However, due to the inherent complexity and diversity of the microscale boiling phenomenon and the limitations of current test methods, there may be many flow patterns that have not been discovered, and there is no unified standard on how to define and differentiate the existing flow patterns. These bring challenges for research on gas–liquid phase-change flow and heat transfer.

Unlike single-phase cooling, two-phase flow and heat transfer involve some specific concepts, including the mass flow rate of the two phases, the two-phase interfacial friction factor, the CHF, flow instability, the onset of nucleate boiling and dryness [120–124]. Li *et al* [125] performed saturated boiling experiments using water and studied the effect of surface wettability on the high aspect ratio microchannel. Their work indicateed that with the increase of the steam flow rate and heat flux, the heat transfer performance of the hydrophobic silicon wafer deteriorates seriously, while that of the superhydrophilic silicon wafer surface is relatively stable. Kim and Mudawar [126] summarized the prediction approaches for pressure drop and heat transfer, and introduced the thermal limit related to initial drying, premature CHF and two-phase critical flow. The research showed that the deeper microchannels can increase the maximum heat flux and reduce the pressure drop, but will have a negative impact on the bottom temperature.

The determination criterion for CHF has not reached an agreement in related studies, and the channel structure and working medium used in relevant experiments are not the same, so the empirical formulas gained by researchers are usually different. Park and Thome [127] found that, in the microchannels with large cross-section, CHF would slightly increase as the inlet temperature increased. However, this is not related to the degree of inlet subcooling in a small cross-sectional microchannel. In other studies, few of them declare that CHF is associated with the degree of inlet subcooling. In the work of Qu and Mudawar [128], they found that due to the backflow of vapor in the microchannel, on the one hand, the wetting of the incoming flow on the microchannel was hindered, while, on the other hand, the subcooling effect of the working medium on the microchannel almost disappeared, so that CHF was almost independent of the degree of inlet subcooling. In conclusion, there is still controversy on the mechanism of the experimental phenomenon of the flow boiling heat transfer process in microchannels.

Many studies have been conducted on the influencing factors in microchannel flow boiling instability [129, 130]. Zhang *et al* [131] observed by experiments that if the bubble nucleation in the microchannel was difficult and the fluid in the channel had a high superheat, once the bubble nucleation formed, a large amount of gas would lead to rapid bubble expansion. This will result in serious fluctuations of the pressure in the microchannel. Then, due to the evaporation of the liquid film on the wall, the temperature will rise rapidly. Flow instability can be reduced by using microchannels with a sufficient gasification core on the wall. Deng *et al* [132] proposed a reentrant porous microchannel with an Ω-shaped configuration (figure 12). The results show that nuclear boiling can occur under lower superheat conditions due to the significant increase of nucleation sites. In addition, whether the heat flow or the mass flow dominates the heat transfer performance is related to the transformation of the dominant heat transfer mechanism.

The enhancement of heat transfer caused by nuclear boiling is usually attributed to the rapid evaporation of the thin liquid film below the bubble and the strong mixing after the bubble

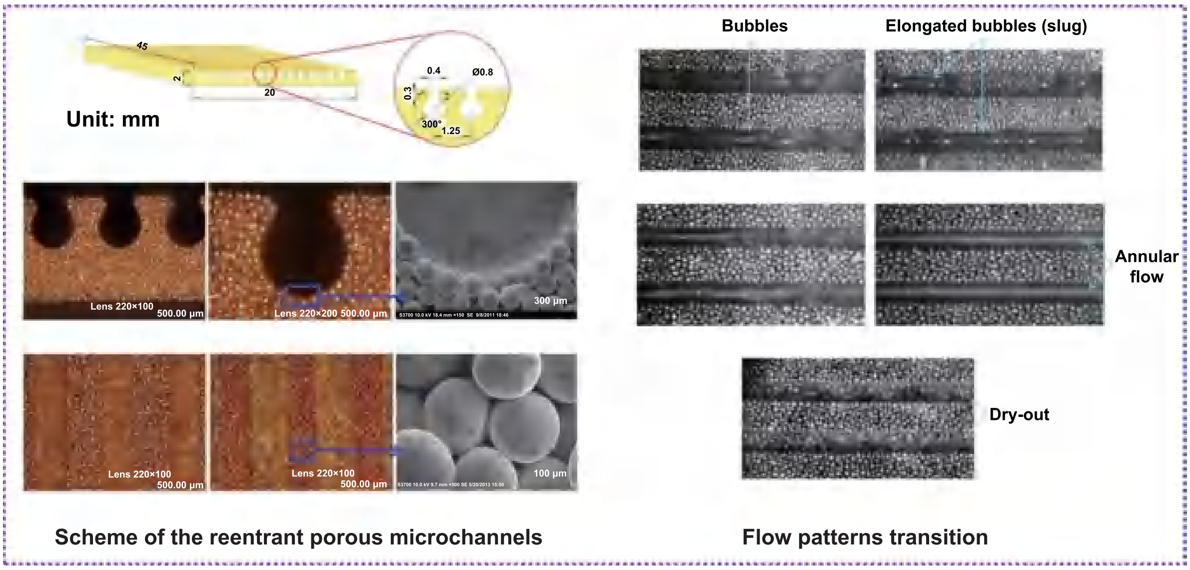

Figure 12. Phase change in the reentrant porous microchannel. Reprinted from [132], Copyright © 2015 Elsevier Ltd. All rights reserved.

leaves the nucleation site. In convective boiling, the heat transfer is enhanced by the improvement of two-phase velocity and thin liquid film evaporation on the wall. At present, no consensus has been reached on the dominant heat transfer mechanism in microchannel flow boiling. The heat transfer process is usually the result of the combination of single-phase convective heat transfer, thin liquid film evaporation, nuclear boiling, and surface droplet deposition, etc [133].

Although gas–liquid two-phase cooling has many advantages, it requires a high-pressure pump to drive the flow of bubbles. In addition, the non-condensable gas in the two-phase flow system may enter the micropump and cause gas blockages, and thus, there will be application limitations in the aerospace field where high reliability is required. In conclusion, the research on the internal mechanism and working characteristics of microchannel flow boiling is still in development, and the gas–liquid two-phase MCHS is far from being marketed widely.

4.2. Solid–liquid phase change

To further improve the cooling capacity, some people use solid-to-liquid phase-change materials (PCMs) as the coolant for their high latent heat and the small temperature change in the phase-change process. PCMs can remove more heat in a compact arrangement of electronics and require lower pumping power than general liquids. Therefore, they have been considered as an efficient way to maintain the equipment temperature environment over a long period of time [134–137]. This section will discuss the research and application of the commonly used PCMs (i.e. liquid metal, microencapsulated phase change material (MPCM) suspension and phase change emulsion) in MCHSs.

4.2.1. Microencapsulated phase change material (MPCM) slurry. The MPCM slurry has a relatively high latent heat, which is beneficial to store energy and for temperature control. The application of this liquid can avoid leakage of the phase change material and direct contact with the environment. Its performance is better in narrow channels and depends on the particle mass ratio of the slurry. The volume change of the coolant can also be neglected in application [138–140]. The study of Wu *et al* [141] indicated that the convective heat transfer coefficient of the slurry is as high as 47 000 $W \cdot m^{-2} \cdot K^{-1}$, which is greater than that of water.

At the same condition of *Re*, the MPCM slurry performs better in heat dissipation than a single-phase coolant. The heat transfer performance of the slurry can be increased by increasing the concentration of the phase-change material. Furthermore, phase-change particles with small diameters can enlarge the specific surface area and enhance the ‘micro convection effect’ between the particles and fluid, which can further enhance the heat transfer. However, the existing studies were conducted mainly based on the conventional scale channels, and more investigation is demanded for microscale channels. In addition, the preparation process for MPCM slurry is really difficult, and the polymer shell can be easily destroyed in the flow process [142–144].

4.2.2. Phase-change material emulsion. Nanoparticles of the phase-change material can be uniformly dispersed in the base liquid at high rotation speed and can form a phase-change material emulsion, which can store and transfer heat owing to the sensible heat of the base liquid and the latent heat of the phase-change particles [145–147].

The phase-change material emulsion has higher heat transfer efficiency due to the large specific surface area of the phase-change material particles, which has the advantages of high energy storage, low temperature rise, and low pumping power demand. It is also easy to prepare the emulsion [148]. Roy and Avanic [149] conducted an environmental analysis on the flow and heat transfer of n-octadecane ($C_{18}H_{42}$) in a circular duct. It showed that the heat exchanger capabilities of the phase change material emulsion and the MPCM suspension are nearly the same.

The phase-change materials are mainly alkanes and paraffin [150, 151]. Just like the MPCM slurry, the existing numerical simulation and experimental studies of phase-change material emulsions are mostly concentrated on the conventional scale, and there are not enough on MCHSs. In addition, the existing studies pay more attention to the preparation and physical properties of the phase-change emulsion rather than the phenomenona in MCHSs.

5. Microchannel materials

The microchannel material will have a direct effect on the manufacturing process and heat dissipation performance [152]. For instance, a solid with high hardness will be difficult to machine, and a low thermal conductivity of the heat sink base will be unfavorable for heat removal. According to the packaging of the thermal management system, it can be divided into embedded and external microchannels, which will be introduced separately in this section.

5.1. External MCHS materials

In the relevant research, the materials for external microchannels mainly include silicon, stainless steel, copper, aluminum and ceramics. The heat sink is fabricated separately and will not influence the design of the electronic layer, generally. Silicon is one of the most commonly used materials for MCHSs. Due to its superior properties, lithography and deep silicon etching can be used to produce high aspectratio and multi-shape channels or micro-fins. The silicon-based microchannel can be bonded to the chip by diffusion bonding, which can realize compact packaging. Li and Peterson [153] adopted a 3D conjugate heat transfer model to simulate and optimize the silicon-based microchannel. The optimal design improved the heat dissipation capacity to 20% higher than that of Tuckerman's design.

In 1994, Wang and Peng [154] used stainless steel instead of silicon and experimentally investigated the heat transfer and flow resistance characteristics of a rectangular MCHS. The experimental data are in good agreement with simulation results. Mudawar and Bowers [155] used stainless steel, and the hydraulic diameter they adopted was 902 μm. The experiments demonstrate that the MCHS can remove a heat flux of more than 3000 W$\cdot$cm^{-2} with subcooled water flow boiling. Copper is another important choice for MCHSs due to its low hardness, large thermal conductivity, rich sources and wear resistance. Qu and Mudawar [21] fabricated a rectangular MCHS from oxygen-free copper, fitted with a polycarbonate plastic cover plate. The pressure drop and temperature distribution tested in experiment agree with the simulation results very well, which verifies the reliability of numerical simulation. Zhang *et al* [156] designed an aluminum heat sink with a size of 15 mm in length and 12.2 mm in width and assembled it on a chip using thermal interface materials (TIMs) to reduce interfacial thermal resistance. Metal MCHSs are relatively easy to manufacture and are usually fabricated by mechanical cutting, laser cutting or a micro-electroforming process (with ultraviolet-lithogrophy electroforming micro molding technology). Although the metal has high thermal conductivity and is relatively low-cost, it is more suitable for a conventional heat sink rather than an MCHS since it is difficult to guarantee fabrication accuracy and roughness at microscale. Additionally, due to the mismatch of thermal expansion between metals and semiconductor materials, there will be serious thermal stress in high-power electronics.

Except for the materials mentioned above, a ceramic or glass cover plate can also be integrated in microchannels and set as a heat sink. Cacucciolo *et al* [157] even used soft materials to set up a soft-matter bidirectional pump. Combining with the micro-tubes, the cooling system can help cool the sensors and actuators for soft robots and wearable devices. This greatly expands the application area of microchannel cooling.

5.2. Embedded MCHS materials

Conventional packaging and system-level active heat dissipation technology can achieve heat dissipation of about 0.8 kW$\cdot$cm^{-2} at most, while the chip-level embedded passive heat dissipation technology in the near-junction area can meet a heat dissipation demand of 1 kW$\cdot$cm^{-2} [158]. The heat dissipation with higher chip heat flux requires the embedded active heat dissipation technology in the near-junction area of the chip, which is expected to achieve a heat dissipation of 1.4 kW$\cdot$cm^{-2} [159]. The material for an embedded microchannel is often the same as that of the electronic chip and device substrate. The commonly used materials include silicon, SiC, diamond and composite materials [160].

GaN epitaxial growth on silicon wafer is a technology developed in recent years. The silicon substrate is low-cost, easy to process and can be integrated with conventional silicon devices. However, due to the difference in crystal structure (Si is diamond structure while GaN is wurtzite structure), there will be a large lattice mismatch between GaN and Si. Serious problems will emerge when GaN is grown directly on silicon substrate, which cannot meet the requirements of device manufacturing. With the development of epitaxy technology, researchers have proposed a variety of methods to improve silicon-based epitaxy GaN. Methods such as AlN low-temperature growth insertion layers, superlattices and graphed substrates can improve the quality of GaN based on Si substrate. A typical embedded MCHS made of silicon is the work of Erp *et al* [161] published in Nature in 2020. They performed a co-design of the electronic and thermal dissipation system and fabricated both the electronic devices and microchannels on the same silicon wafer. The experiments demonstrate that the cooling structure can remove a heat flux up to 1700 W$\cdot$cm^{-2} using only 0.57 W$\cdot$cm^{-2} of pumping power. The performance cooling coefficient increases 50 times compared with straight microchannels. This is a breakthrough in MCHSs. They also presented the fabrication process of the co-design device (figure 13(a)).

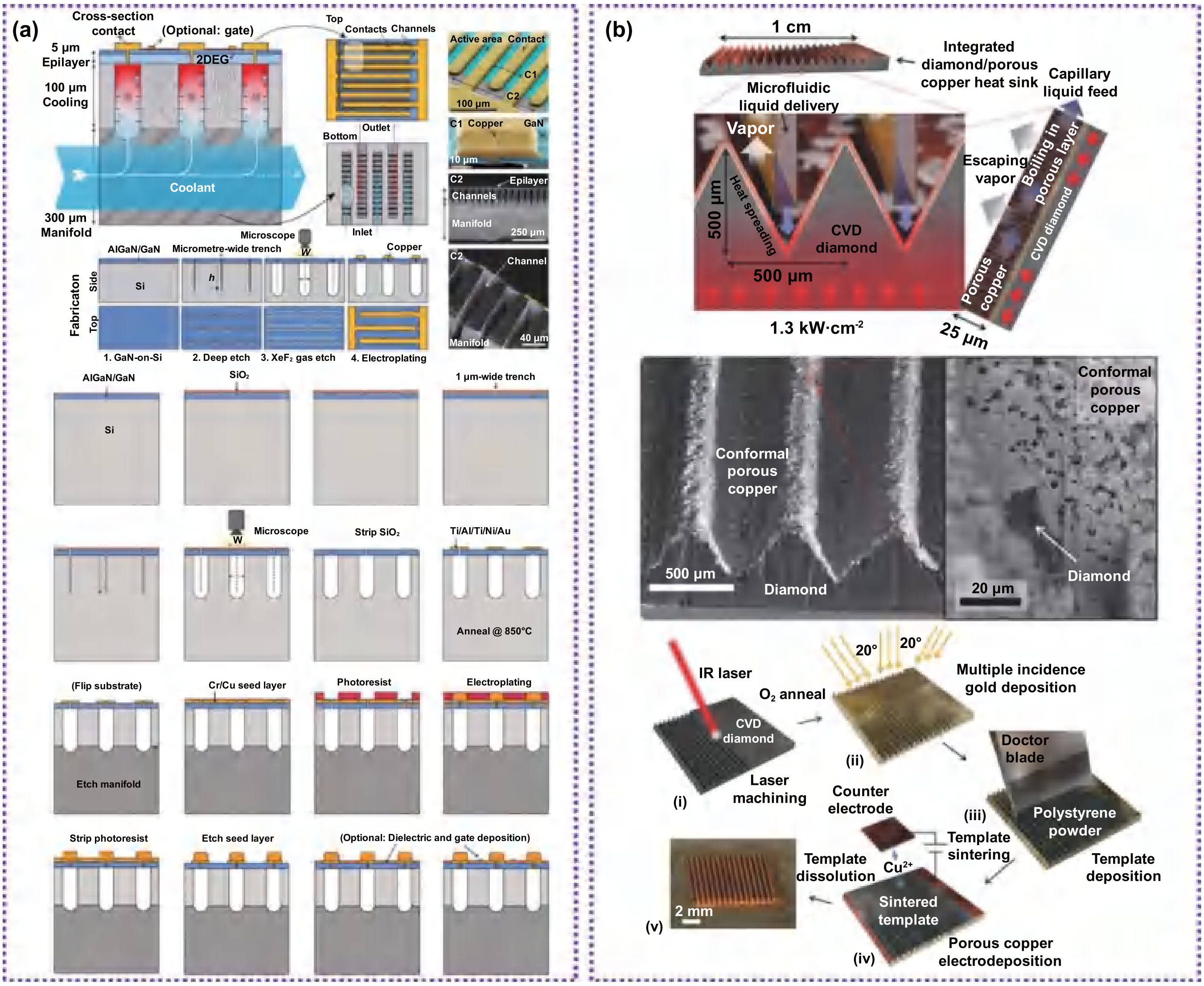

Figure 13. Different types of chip substrate and the corresponding MCHS. (a) Silicon. Reproduced from [161], Copyright © 2020, The Author(s), under exclusive license to Springer Nature Limited. (b) Diamond. [163] John Wiley & Sons. © 2017 WILEY-VCH Verlag GmbH & Co. KGaA, Weinheim.

Another commercially available substrate is SiC. Since the lattice mismatch between GaN and SiC is relatively small, this advantage and its excellent thermal and electrical conductivity make it an ideal GaN heterostructure epitaxial substrate, especially in high-frequency, high-pressure and high-temperature power devices. However, the oxide film and lattice mismatch on SiC will also introduce dislocation defects or cracks, which affect the quality of GaN and ultimately affect the performance of the device. Additionally, the high price of SiC also prevents it from being widely used in GaN heteroepitaxy. A similar growth technology can also be applied to SiC substrates, such as low-temperature AlN buffer layers, and graphed substrates. The technology of directly designing microchannels in SiC structure for on-chip microfluid heat dissipation has been proposed by Lockheed Martin's team, that is, using the back of a SiC substrate as the microchannel plate of the heat sink, and the fluid in the heat sink directly flows through the substrate below the chip heat source, so as to achieve the purpose of efficient heat exchange near the chip junction area. Based on a cylindrical needle-shaped microchannel heat dissipation structure, Ditri *et al* [162] used photolithography and physical etching technology to make a breakthrough in the manufacturing process of near-junction microchannels on GaN substrates (figure 13(b)). They also carried out a verification study of GaN monolithic microwave integrated circuit (MMIC) by this approach. The working fluid is a mixture of propylene glycol and water for single-phase heat dissipation, which has the capability to meet a heat flux of 1 kW·cm^{-2}. The thermal resistance is reduced by four times under the same power.

When diamond is used as the substrate for a GaN device, the key technologies are the diamond microchannel manufacturing, the seal with the silicon distribution plate and fluid control. Commonly used manufacturing processes include: (a) the Si substrate serves as drainage and sealing, and its bonding process uses SiO_2 vapor deposition bonding or solder direct bonding; (b) the Si substrate is designed with a multi-layer drainage structure to achieve an integrated microfluidic drive on the chip. Although the development of wafer-level diamond substrate GaN devices is slow and the etching of a diamond microchannel is extremely difficult, the superior heat conductivity of diamond and the active microfluidic heat dissipation bring great research potential and development value for the thermal management of ultra-high power density devices. First developed by the Raytheon research team, the technology for diamond microchannel design includes the support of an intra-chip embedded cooling program, that is, etching the microchannels in the diamond substrate near the junction area at the lower end of the gate area of GaN devices, and using silicon substrate for bonding sealing and microflow control. The fluid flows into the area of the diamond substrate below the active area of the chip to directly exchange the heat, at a heat flux of 1.25 $kW{\cdot}cm^{-2}$. Stanford University proposed an excellent diamond channel heat dissipation structure [163]. The chemical vapor deposition (CVD) diamond die is fabricated into a triangular shape by infrared (IR) laser micromachining, and then porous copper layers are electrodeposited on its surface. The integration process is shown in figure 13(b).

The Northrop Grumman AS research team proposed in-chip microflow heat dissipation technology based on a composite substrate. The approach is to fabricate rectangular microchannels in a conventional SiC substrate and grow a layer of diamond on the microchannel walls to enhance the thermal exchange between the liquid and the solid. The challenges are the design of the microchannels, the control of the interfacial thermal resistance between SiC and diamond and the growth of a high-quality diamond layer. Gambin *et al* [164] designed a microchannel below the heat source and pumped the working fluid by jet impingement. A silicon plate is used for bonding and sealing as well as microflow control. This design can reduce the difficulty of diamond layer growth in the microchannel of the SiC substrate, and effectively realize the manufacture of microchannels inside a composite substrate.

The embedded cooling technology is very innovative and pioneering. The application and technical approach depend on the substrate material, and it is expected more materials will be developed with high thermal conductivity integrated inside the chip. However, at present, the technique still cannot be used commercially. There is still disagreement about the on-chip microflow structure, microflow control and device manufacture. In addition, the embedded MCHS may affect the electronics fabrication and operation since the flow is too near the device. However, it has great application potential in the third-generation semiconductors, and will be a promising way to solve the bottleneck of heat accumulation in high-power devices.

6. Other influencing factors

The characteristic size of the microchannel is much smaller than that of the conventional channel. The factors (such as surface roughness and thermal property variations) which are often neglected in conventional-scale structures may play important roles in microchannels [165]. This section will focus on some other factors affecting the flow and heat transfer features in microchannels.

6.1. Surface roughness

In conventional channels, when the surface relative roughness is below 5%, it is unnecessary to consider the effect of roughness on the flow resistance, while in microchannels, limited by the small size and manufacturing techniques, the surface relative roughness generally exceeds 5% and the effect cannot be neglected. Therefore, the roughness will play an increasingly important role with decreasing channel scale. For example, the height of the roughness elements can reach 40 μm and the relative roughness can be 10%–20%, when fabricated by wire-electrode cutting. At this point, roughness needs to be taken into account.

Many researchers have devoted effort to studying the surface roughness in microchannels. The approaches they adopted include: (1) Direct simulation. This considers the roughness elements as macroscopic structures and simulates them directly. This method is accessible but not accurate. Moreover, the computation cost is really expensive. (2) The roughness-viscosity model. This considers the additional momentum transfer caused by roughness and explains it by means of an effective viscosity. In this model, the viscosity near the wall is considered as a constant which is proportional to *Re*, while, at the center of the tube, it diminishes to zero. (3) The porous media model [166]. This model divides the flow region into two parts: one is the central part where the conventional momentum equation applies. The other part is the rough layer where it introduces a friction factor and an empirical porous layer permeability. (4) Regular perturbation method [167]. This method considers the roughness as a perturbation, and the perturbation equation is expanded in Fourier series to solve for laminar flow in microtubes.

Koo and Kleinstreuer [168] analyzed the influence of the roughness in microconduits on heat transfer using the porous media model. They took the relative surface roughness as a key parameter and concluded that the impact of surface roughness on heat transfer was less than that on the momentum transfer. The most important factor affecting heat transfer performance for a given relative surface roughness is the thermal conductivity ratio between the rough layer and bulk fluid. Hetsroni *et al* [169] analyzed the pressure drop and the transition *Re* in circular, rectangular, triangular and trapezoidal microchannels with hydraulic diameters ranging from 1.01 μm to 4010 μm. In their work, the transition *Re* is in the range of 1800–2200 with relative roughness of 0.32%–7%. When the relative roughness grows, the friction factors will be larger, and the transition *Re* will decrease. Shen *et al* [170] and Steinke and Kandlikar [171] both investigated the flow and heat transfer performance in microchannels with roughness. The results reflect that the Nusselt number, friction factors and pressure drop are

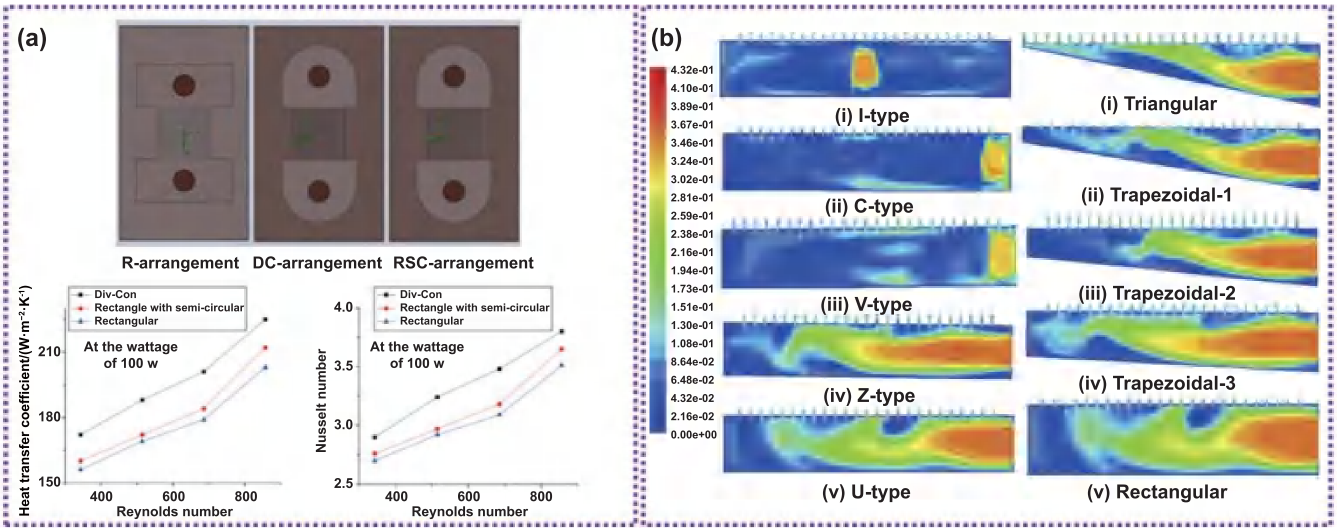

Figure 14. MCHS with different arrangements of inlet and outlet (a) effect of chambers on heat transfer coefficient. Reproduced from [172]. CC BY 4.0. (b) Effect of inlet and outlet configurations and inlet header shapes on temperature uniformity. Reprinted from [173], Copyright © 2013 Elsevier Ltd. All rights reserved.

significantly deviated from those calculated based on conventional theories.

The deviation of the friction in microchannels from that at conventional scale is due to the comprehensive effect arising from the non-ideal experiment condition, the measurement error and the decrease of characteristic length, etc. It remains to further confirm whether the flow and heat transfer laws in microchannels are in agreement with those at large scale.

6.2. Inlet and outlet design

Generally speaking, if not specifically pointed out, studies of the flow and heat transfer in conventional channels focus on the fully developed region. However, for the microchannel, in order to measure the pressure drop and temperature at the inlet and outlet, it is often necessary to set a relatively large static pressure chamber. At this point, the flow at the joint between the chamber and channel is not fully developed, which will induce inlet and outlet effects. Many researchers often ignore or use conventional empirical formula to estimate this effect.

Referring to the conventional channel theory, the length of the inlet section is related to the pipe diameter, *Re* and *Pr*. If the inlet effect is considered, different *Re* will lead to significantly different friction coefficients. Due to the surface effect, the development of the flow and heat transfer boundary layer in microchannels is relatively slow, and the length of the inlet section will be longer than conventional channels. Dahiya *et al* [172] studied three different arrangements of the inlet and outlet: rectangular (R), divergent (DC) and semicircle (RSC) (figure 14(a)). The results show that the DC-type arrangement has the highest heat transfer coefficient compared with the other two types when the Reynolds number is in the range of 342–857.

Furthermore, temperature uniformity is also an important factor in measuring the performance of a microchannel heat exchanger. In order to ensure uniform temperature, it is necessary to guarantee the uniformity of fluid distribution in microchannels. However, at the inlet, outlet and headers, the distribution of the fluid is non-uniform [174–176]. Kumaran *et al* [173] studied the influence of the header design and inlet/outlet structure on the flow distribution (figure 14(b)). The numerical results show that the triangular inlet header and trapezoidal outlet header can provide more uniform flow distribution. The C-type flow arrangement performs well, while the V-type flow configuration is poor. Xia *et al* [177] studied the effects of different inlet/outlet positions, headers and microchannel section shapes and concluded that the flow distribution of type Z was poor. The triangular inlet header can obtain a more uniform flow distribution. In addition to the above research, some researchers improved the uniformity of flow and temperature distribution by optimizing the MMCs. Tang *et al* [178] adopted the inlet chamber and inlet manifold modified with a tapered contracting structure when optimizing a self-similarity heat sink (SSHS). The research shows that the flow distribution and heat transfer performance are determined by the height of the overflow channel, but not by the width and length of it. When the rectangular inlet chamber and inlet manifold channel are replaced by a conical structure, the flow and temperature distribution inside the SSHS is more uniform.

6.3. Axial heat conduction

Considering the hydraulic diameter of the microchannel is really small, the width of the channel wall is often thick enough to guarantee structural strength in the manufacturing process. However, when the heat flux is really high, the axial thermal conduction along the channel wall cannot be neglected. In addition, there will be errors between the real and measured data due to the fact that the test positions are not so close to the microchannel wall.

In order to fully consider the influence of the axial thermal conduction effect, Maranzana *et al* [179] numerically studied the MCHS. The results show that axial thermal conduction can be ignored only when the ratio of axial thermal conduction to radial thermal conduction is less than 0.01, and axial thermal conduction is more obvious when *Re* is small. The work of Tiselj *et al* [180] indicates that when axial thermal conduction is considered, there is a singular point for the Nusselt number along the channel (where the average temperature of the fluid and the solid is the same), and this special point gradually approaches the outlet as the *Re* number increases.

To sum up, in the theoretical analysis, numerical calculation and experimental testing of MCHSs, the influence of surface roughness is a problem that needs to be further studied. The flow and heat transfer processes in the microchannel have obvious three-dimensional characteristics, so it is necessary to consider the influence of the axial thermal conduction effect, especially when the Reynolds number is relatively small.

7. Heat transfer enhancement technology

Due to the small characteristic size of microchannels, the Reynolds number of conventional fluids is generally in the range of laminar flow. In addition, the boundary layer developed along the flow direction also weakens the heat transfer process. Consequently, proposed new designs of MCHSs are needed to enhance the heat transfer. At present, efficient thermal management technology in microchannels can be divided into active and passive methods (figure 15). In terms of the active method, external energy is supplied to produce an unsteady flow, while the passive method is to enlarge the heat transfer surface [43–51], promote fluid mixing [181–183] or improve the thermal properties of coolants by optimizing the geometric structures [184] or use various working fluids [185].

7.1. Active method

7.1.1. Jet impingement cooling. In jet impingement cooling, the rapidly flowing working fluid impacts on the heat surface directly with a short flow distance. The boundary layer formed in the central impinging area is very thin. Additionally, according to the field synergy principle presented by Guo [186], the best synergy between velocity field and temperature gradient field is attained when the flow impinges on the heat surface vertically and thus enhances the convective process. The jet impingement flow is thereby considered as a promising research hotspot in the field of electronic cooling [187–189].

The external impact generated by jet impingement can promote the flow mixing and disturb the boundary layer to improve the heat transfer efficiency. Zhuang *et al* [190] designed a microchannel heat exchanger with jet nozzles, and tested the local heat transfer coefficients at a stagnation point and in parallel flow regions experimentally. They showed that the cooling efficiency will be enhanced by accelerating the impingement, but the pressure drop will increase significantly.

The techniques combining any two of the jet impingement, dimpled surface and microchannel will perform better in heat transfer than adopting any one of the three. Therefore, many people propose the composite microchannel. Huang *et al* [191] carried out simulations on a MCHS with impinging jets (MIJs) and different dimple structures (figure 16(a)) using Ansys Fluent. They indicate that MIJs with convex dimples have the best thermal transfer performance, and the other three structures (i.e. MIJs without dimples, with concave dimples and with mixed dimples) have little difference in heat exchange.

Pin-fins can also enhance the heat exchange. Wan *et al* [192] integrated the jet impingement into a pin-fin roughened plate. As shown in figure 16(b), they compared the flow and thermal characteristics of the inline and staggered pin-fin plates. A pin-fin roughened plate performs better than one without pin-fins due to the enlargement of the heat transfer area and turbulence enhancement. In addition, the inline pin-fin roughened plate can promote the production of a large-scale vortex in the main flow, which can help dissipate more heat from the solid surface.

Any two or more of the techniques mentioned above can be combined into the thermal enhancement design, and at the same time, will increase the pumping power. Consequently, the key objective is to improve the heat transfer efficiency and temperature distribution uniformity as well as reduce the pressure drop. Moreover, it is hard to obtain analytical solutions for the jet impingement, and most researchers therefore investigate it by experiment and simulation. Nevertheless, there are so many influencing factors in experiments that the empirical correlations proposed at different working conditions fail to reach an agreement and cannot be universally applied. Simulations, however, can be implemented under the ideal conditions and supplement the experimental studies on jet impingement.

7.1.2. Pulsating flow. Pulsating flow can destroy the development and reduce the thickness of the flow and thermal boundary layer. By introducing time-pulsating fluid into the microchannel, the unstable flow near the microchannel wall can improve the overall heat transfer efficiency. Compared with steady flow, the pulsating flow in a microchannel has more complex characteristics. The related parameters such as pulsation frequency, amplitude, period, and the geometric structure of the microchannel will all have an impact on the heat dissipation performance [195].

Nishimura *et al* [196] studied the influence of pulsating flow on the flow and mass transfer of non-Newtonian fluid in microchannels with corrugated and special periodic structures. The results show that the corrugated and specific periodic channels can generate secondary flow at the channel bend, and thus perform better in mass transfer. By oscillating the fluid, laminar flow at this point has a stronger mass transport capacity than turbulent flow. Nandi and Chattopadhyay [197] carried out a series of numerical simulation studies and found that the improvement of heat transfer performance of pulsating inlet flow depended on the amplitude and frequency of pulsation. When *Re* exceeds a certain value, the fluctuating inlet flow at all amplitudes predominates the viscous force, making the shear layer roll up near the wall and the flow unstable. In

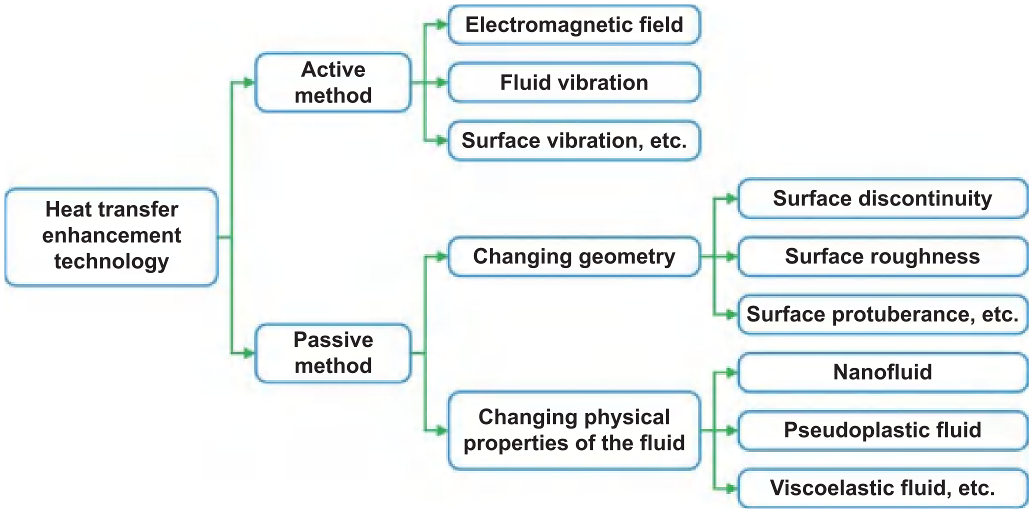

Figure 15. Classification of heat transfer enhancement technology in microchannels.

addition, when *Re* is small, the pulsation effect is significant, but when *Re* is large, the effect of the pulsating inlet on heat transfer can be neglected.

The pulsating inlet can improve the heat transfer performance under specific conditions and shows great potential in engineering applications. However, as an effective heat transfer enhancement technology, fluid pulsation has many influencing factors due to its complex mechanism, and more effort should be devoted to the relevant research. For example, under the interaction of multiple factors, systematic research needs to be carried out to determine the best working conditions. In addition, a pulsating device is essential for pulsating flow, and its performance directly determines the characteristics of the pulsating fluid, thus affecting the overall heat dissipation capacity. Research with different operating conditions and environments needs to be conducted.

7.2. Passive method

Passive enhanced heat transfer technology refers to carefully designed channel geometry (such as the non-straight microchannel, and the construction of the turbulence structure, discussed specifically in section 2.1), setting the obstacles in the channel structure (such as ribs, surface modification and surface extension, discussed specifically in section 2.2) and working fluid selection (such as the introduction of non-Newtonian fluid, discussed specifically in section 3). It can enhance the heat transfer capacity by increasing the thermal conductivity of coolants, interrupting the boundary layer, inducing the generation of secondary or unstable flow, accelerating the transition from laminar to turbulence, or increasing the velocity gradient near the heating surface [198, 199]. The passive method does not require additional external components or power input, and thus is more reliable in complex systems. Some passive enhanced heat transfer methods have been introduced in the previous sections. Here, research on the porous media microchannel and MMC will be discussed.

7.2.1. Porous media microchannel. Porous media can provide an extremely large convective heat transfer surface, and the complex foam structures can also promote fluid mixing. Turbulence will occur even at low flow rates. The related research also verifies that porous media are effective materials to enhance single-phase convective heat transfer [200–203].

Hsieh *et al* [204] studied the effects of porosity, pore density and air flow rate on the heat transfer characteristics of a porous foam aluminum heat sink experimentally. Their results indicated that the Nusselt number increases with the increase of hole density, which the researchers believed was due to the increase of heat dissipation area. Ghahremannezhad and Vafai [193] experimentally studied the strengthening effect of porous substrate materials (figure 16(c)) on the heat transfer performance of MCHS, and established an optimization design method based on thermal resistance and pumping power. The results showed that with the increase of porosity, the thermal resistance increases and the pumping power decreases, but the pumping power decreases much more significantly than the thermal resistance increases. In addition, as the thickness of porous substrate increases, the effect of porosity becomes greater. This study showed that porous substrate materials have great potential in improving heat dissipation and hydraulic performance.

The existing studies indicate that the porous foam metal, as an internal insert, can effectively destroy the boundary layer within a certain range. The enlarged heat transfer surface area also plays an important role in improving the cooling efficiency. At the same time, it can also achieve a higher heat transfer coefficient than other conventional heat sinks under a low pressure drop [205, 206]. However, as the porous foam metal has been an emerging material in recent years, the related research on it is still in development, and more theoretical results are expected in the future. In addition, due to the limitation of foam metal preparation, it is difficult to connect the porous media well with the heating surface. The existing research adopts self-welding or directly inserting porous

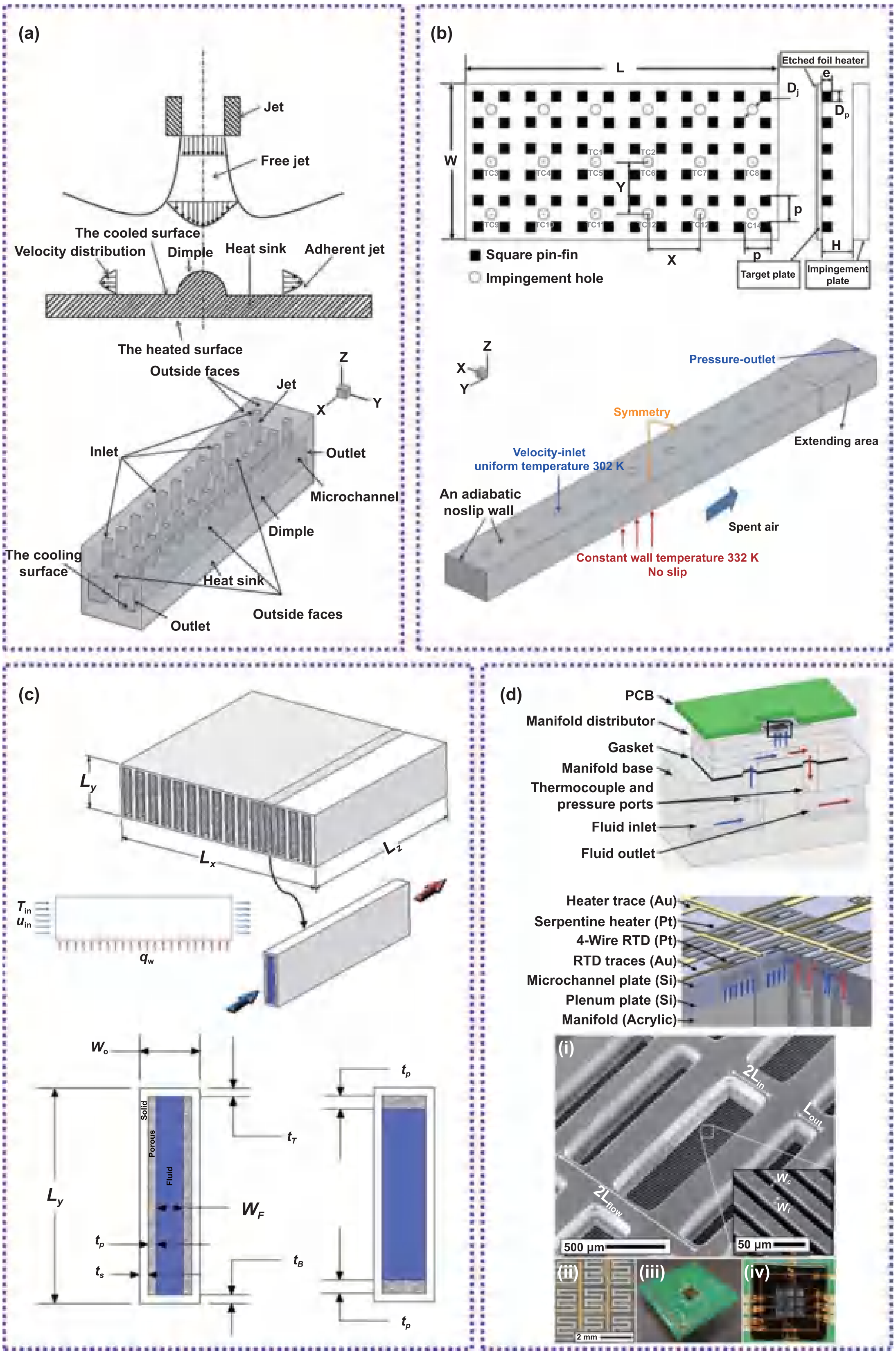

Figure 16. Research on heat transfer enhancement of MCHS. (a) Microchannel with impinging jet and dimple structure. Reprinted from [191], © 2017 Elsevier Ltd. All rights reserved. (b) Microchannel with multiple impinging jet and pin-fin. Reprinted from [192], Copyright © 2015 Elsevier Ltd. All rights reserved. (c) Microchannel with the proposed porous structure. Reprinted from [193], © 2018 Elsevier Ltd. All rights reserved. (d) Manifold microchannel. Reprinted from [194], © 2017 Elsevier Ltd. All rights reserved.

media, which will inevitably increase the contact thermal resistance. The MCHS with porous foam metal will develop greatly if these problems can be solved,

7.2.2. Manifold microchannel (MMC). Although porous media can have a relatively high heat transfer coefficient, they are not suitable for cooling large-size electronic chips or devices due to the huge flow resistance. Consequently, in addition to the heat transfer performance, reducing the pressure drop should be taken into account in the optimization of microchannel structures. The manifold, acting as a coolant distributor, can shorten the flow distance in the microchannel and reduce the pressure drop substantially. Furthermore, when the coolant flows through the manifolds, it will impinge on the substrate surface directly and heighten the heat exchanger at the impingement point. Considering this, many researchers have proposed the concept of the MMC [207–210].

Arie *et al* [211] implemented the manifold MCHS into an air–water heat transfer system and found that compared with wavy fins, the manifold MCHS manufactured by 3D printing could dissipate up to 60% higher heat flux. As shown in figure 16(d), Drummond *et al* [194] fabricated an embedded manifold MCHS and conducted two-phase experiments with HFE-7100. Under a pumping pressure of 162 kPa, the manifold MCHS can dissipate a heat flux as high as 910 $W{\cdot}cm^{-2}$. Jung *et al* [212] also fabricated an embedded manifold MCHS and demonstrated that, at a flow rate of 0.104 $l{\cdot}min^{-1}$ and a heat flux of 251.74 $W{\cdot}cm^{-2}$, the thermal resistance of single-phase water cooling could drop to 0.58 $^{\circ}C{\cdot}W^{-1}$, with a pressure drop of only 2.36 kPa. This manifold MCHS exhibited excellent heat transfer capability. However, the microchannel and the multi-manifold plate are usually designed and manufactured separately and then combined through a bonding process. This process will greatly increase the complexity and cost of chip manufacturing. Fortunately, single-chip integrated MMC technology is a great breakthrough in solving this problem and thus generates the embedded MMC heat sink. Using this technology, embedded 3D manifold channels can be integrated and co-manufactured with the chip in a single wafer. The manufacturing processes are as follows: first, a narrow slit is etched into a silicon substrate coated with a layer of GaN semiconductor, where the depth of the slit corresponds to the depth of the channel that will be created. Second, isotropic gas etching is used to widen the gaps in the silicon to the final width of the microchannel. Finally, the openings at the top of the microchannel are sealed with copper, and then electronic devices can be manufactured in the GaN layer. Unlike previous methods for manufacturing MMCs with an extra bonding process, this method can produce microchannels and manifolds together.

Active heat transfer enhancement methods can significantly improve the heat transfer efficiency but require external control modules, which makes them complex and high-cost. Passive enhancement methods, despite their reliability and convenient integration in electronic devices, will also have some limitations in practice, for example, the complex micro-structures will increase the flow resistance and are hard to manufacture. In short, there are both advantages and disadvantages of active and passive enhancement technology. Engineers should select appropriate approaches to enhance heat exchange based on the operating conditions.

8. Conclusions and outlook

Since the concept of the MCHS was first proposed by Tuckerman and Pease [18], many researchers have conducted a large amount of theoretical, numerical and experimental studies on it and demonstrated the MCHS to be an effective way to solve the thermal management problem of high-power electronic chips and devices. This paper introduces the application of MCHSs with different structures, cooling fluids and materials, and also emphasizes the research focused on microchannel heat dissipation, such as optimized design, phase-change heat transfer and heat transfer enhancement. It also highlights the key problems and difficulties of microchannel heat dissipation. All these can provide a theoretical reference and technical guidance for further research and application. The development outlook of MCHS is shown in figure 17 and will be discussed in detail below.

With the rapid development of the high-power and high-heat-flux electronics industry, the heating power of electronic chips and devices is bound to increase continuously, and its thermal management technology will face greater challenges [213, 214]. The development of existing heat dissipation technologies ranges from passive to active, from natural convection, forced air cooling to forced liquid cooling, and from single-phase heat dissipation to multiphase heat dissipation. New and efficient heat dissipation technologies and methods urgently need to be developed, along with methods for dissipating significantly increasing heat flux.

The MCHS requires a complete loop system and the supporting equipment is relatively expensive and large in size. This limits the application of MCHSs in some circumstances to a certain extent. In recent years, with the progress of nanomachining technology, the nanochannel heat sink has come into people's attention. Compared with a microchannel, the ratio of surface area to volume of a nanochannel is larger, so the heat transfer area under the same volume is larger. Additionally, the capillary force is dominant in the filling process in a nanochannel. The nanochannel heat sink device is relatively simple and has higher heat dissipation efficiency. However, there is a lack of studies on the capillary filling process in a nanochannel. Due to the numerous factors affecting the filling process (including the dynamic contact angle, bubble and electro-viscous effect), the mechanism is still unclear, and the main influencing factors are still controversial. In addition, the fitting slopes of the simulation and experimental results are lower than the theoretically predicted value, and no model so far has accurately predicted the capillary filling process. The difficulties above should be overcome in future research.

For external MCHSs, the thermal interface material (TIM) between the chip and heat sink is unavoidable. Although many researchers are exploring TIM with high thermal conductivity,

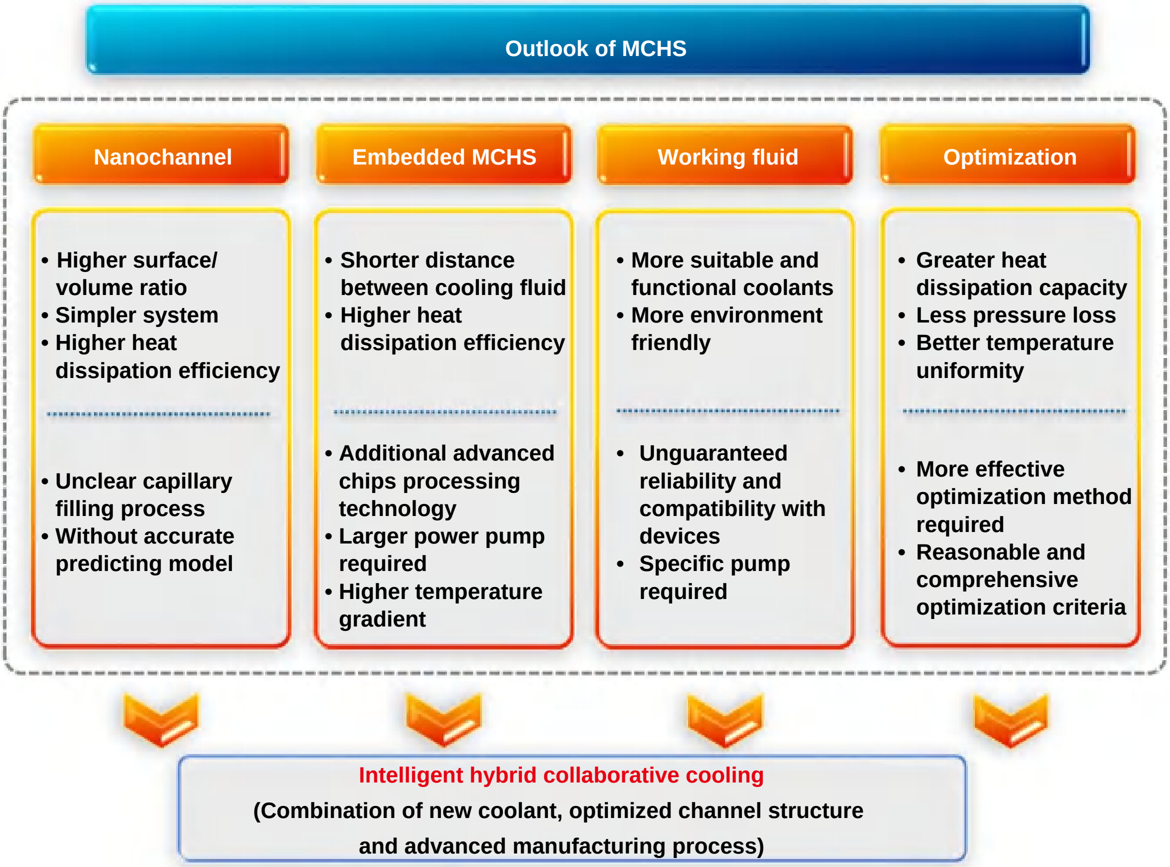

Figure 17. The development outlook for the MCHS.

the current TIM layer still retains high thermal resistance, so it becomes the main heat dissipation bottleneck of external MCHSs. For embedded MCHSs, the microfluid cooling channel is integrated into the chip without the use of a TIM layer, so that the distance between the cooling fluid and the heat source of the chip is greatly reduced, and its cooling efficiency is very high. Therefore, it has become a promising method to improve the performance of chip thermal management. However, the cooling system of the embedded MCHS requires many additional chip manufacturing processes, such as backside lithography, etching and bonding. Another major disadvantage is that the pressure drop increases sharply with the increase in the length of the channel, which means that a more powerful pump is required. This brings more energy consumption and costs, and creates potential mechanical stresses on the chip. Furthermore, the high temperature gradient on the chip may cause thermal–mechanical stress and even local warping for thin chips. Therefore, the future development direction of embedded MCHSs is to improve the chip manufacturing process, to ensure the efficiency and reliability of the chip working conditions, and to increase the reliability and stability of system operation.

As for the working fluid in MCHSs, different coolants have different characteristics and application environments. Water-soluble liquids are not electrically insulated and cannot contact the chip directly, which makes the entire cooling system complex. Although a dielectric fluid can effectively solve the problem, its heat transfer capacity is relatively low. Nanofluids perform well in heat transfer, for example, magnetic nanoparticles can be regulated by an external magnetic field to achieve better heat transfer. However, nanofluids require higher pumping power, and particle agglomeration, volume concentration and other instability phenomena can all weaken the heat transfer. Researchers should devote more efforts to determine the mechanism of the phenomena and find ways to avoid them fundamentally. Compared with aqueous coolants, liquid metals promise better properties and less flow resistance. However, at present, the practical temperature range of liquid metals still needs to be further extended. In addition, the costs and compatibility with common packaging materials are also critical barriers preventing liquid metals from being widely used. As for MCHSs with phase-change flow and heat transfer, when the working fluid is boiling, the bubbles may cause a ‘gas plug’ and ‘backflow’, which will lead to unstable flow. These possible phenomena can worsen the heat transfer, affect the system safety and cause other problems. With the rapid development of new cooling medium and intelligent technology, the cooling of electronics in the future should be combined with intelligent control for different situations, so as to achieve efficient and economical heat dissipation. Intelligent hybrid collaborative cooling with new cooling medium is predicted to be a future trend of microchannel cooling.

The MCHS in future is expected to have greater heat dissipation capacity, less pressure loss, and better temperature uniformity. Although various structures have been proposed by reserachers, all the existing types of microchannel structures have some disadvantages. For example, continuous microchannels will create large temperature differences along the flow and the heat transfer efficiency is often relatively low. Discontinuous microchannels can enhance disturbance and thin the boundary layer, but will increase pressure loss when the structural parameters are not designed properly. Elementary geometric optimization of the channel structure can no longer meet the rapidly growing heat dissipation demand. Therefore, it is necessary to design a composite structure MCHS that can strengthen heat transfer and reduce flow resistance at the same time by adopting the advantages of various structures and advanced optimization algorithms. At present, the most widely used optimization design methods include the minimum entropy production principle, the entransy dissipation extreme principle and topology optimization. In particular, topology optimization has been rapidly developed and well applied in recent years, and it is expected to play an increasingly important role in the optimization design of MCHSs. In addition, based on the current research, it is still necessary to further study the flow and heat transfer phenomena of fluids in microchannels, improve understanding of the heat transfer enhancement mechanism and factors affecting flow resistance, and find effective optimization approaches. It is also necessary to propose certain criteria to evaluate the performance of MCHSs comprehensively.

In conclusion, the research on MCHSs is still under development. The mechanisms of some heat transfer enhancement methods are still not very clear, and there is no consistent conclusion on the optimal size and shape of the microchannel. Furthermore, the manufacturing techniques to integrate MCHSs into the electronic packaging are far from mature. However, with the development of modern microelectronic and MEMS technology, these problems are expected to be overcome. The introduction of new concepts of heat transfer enhancement, efficient liquid cooling technology, and the preparation of new materials will bring opportunities to enhance the comprehensive performance of microchannel thermal management. These also point out the development directions for research and application of MCHS technology in the field of electronic chips and devices. We believe that significant progress will be made in the near future.

Acknowledgments

This project was supported by the National Natural Science Foundation of China (Grant Nos. U20A20301, 51825601).

Conflict of interest

The authors declare that they have no conflict of interest.

ORCID iDs

Mo-Tong Li https://orcid.org/0000-0002-9895-9935
Bing-Yang Cao https://orcid.org/0000-0003-3588-972X

References

[1] Vinodhan V L and Rajan K S 2014 Computational analysis of new microchannel heat sink configurations *Energy Convers. Manage.* **86** 595–604

[2] Abo-Zahhad E M, Hachicha A A, Said Z, Ghenai C and Ookawara S 2022 Thermal management system for high, dense, and compact power electronics *Energy Convers. Manage.* **268** 115975

[3] Xu J L, Zhou J J and Gan Y H 2005 Static and dynamic flow instability of a parallel microchannel heat sink at high heat fluxes *Energy Convers. Manage.* **46** 313–34

[4] Bahiraei M and Heshmatian S 2017 Application of a novel biological nanofluid in a liquid block heat sink for cooling of an electronic processor: thermal performance and irreversibility considerations *Energy Convers. Manage.* **149** 155–67

[5] Radwan A and Ahmed M 2017 The influence of microchannel heat sink configurations on the performance of low concentrator photovoltaic systems *Appl. Energy* **206** 594–611

[6] Sun B and Huang X Y 2021 Seeking advanced thermal management for stretchable electronics *npj Flex. Electron.* **5** 12

[7] Khalaj A H and Halgamuge S K 2017 A review on efficient thermal management of air- and liquid-cooled data centers: from chip to the cooling system *Appl. Energy* **205** 1165–88

[8] Qin Y X, Qin B C, Wang D Y, Chang C and Zhao L-D 2022 Solid-state cooling: thermoelectrics *Energy Environ. Sci.* **15** 4527–41

[9] Bahiraei M and Heshmatian S 2018 Thermal performance and second law characteristics of two new microchannel heat sinks operated with hybrid nanofluid containing graphene-silver nanoparticles *Energy Convers. Manage.* **168** 357–70

[10] Lin X H, Mo S P, Jia L S, Yang Z, Chen Y and Cheng Z D 2019 Experimental study and Taguchi analysis on LED cooling by thermoelectric cooler integrated with microchannel heat sink *Appl. Energy* **242** 232–8

[11] Meng Y, Zhang Z Y, Wu H X, Wu R Y, Wu J H, Wang H L and Pei Q B 2020 A cascade electrocaloric cooling device for large temperature lift *Nat. Energy* **5** 996–1002

[12] Ma R J, Zhang Z Y, Tong K, Huber D, Kornbluh R, Ju Y S and Pei Q B 2017 Highly efficient electrocaloric cooling with electrostatic actuation *Science* **357** 1130–4

[13] Cui H, Zhang Q, Bo Y W, Bai P J, Wang M Y, Zhang C Y, Qian X S and Ma R J 2022 Flexible microfluidic electrocaloric cooling capillary tube with giant specific device cooling power density *Joule* **6** 258–68

[14] Wang X L, Yang J X, Wen Q W, Shittu S, Liu G M, Qiu Z N, Zhao X D and Wang Z Y 2022 Visualization study of a flat confined loop heat pipe for electronic devices cooling *Appl. Energy* **322** 119451

[15] Xin F, Ma T and Wang Q W 2018 Thermal performance analysis of flat heat pipe with graded mini-grooves wick *Appl. Energy* **228** 2129–39

[16] Zhou G H, Li J and Jia Z Z 2019 Power-saving exploration for high-end ultra-slim laptop computers with miniature loop heat pipe cooling module *Appl. Energy* **239** 859–75

[17] Shao L-L, Yang L and Zhang C-L 2010 Comparison of heat pump performance using fin-and-tube and microchannel

heat exchangers under frost conditions *Appl. Energy* **87** 1187–97
[18] Tuckerman D B and Pease R F W 1981 High-performance heat sinking for VLSI *IEEE Electron Device Lett.* **2** 126–9
[19] Kandlikar S G and Grande W J 2003 Evolution of microchannel flow passages–thermohydraulic performance and fabrication technology *Heat Transfer Eng.* **24** 3–17
[20] Fedorov A G and Viskanta R 2000 Three-dimensional conjugate heat transfer in the microchannel heat sink for electronic packaging *Int. J. Heat Mass Transfer* **43** 399–415
[21] Qu W L and Mudawar I 2002 Experimental and numerical study of pressure drop and heat transfer in a single-phase micro-channel heat sink *Int. J. Heat Mass Transfer* **45** 2549–65
[22] Zhai Y L, Li Z H, Wang H and Xu J X 2017 Thermodynamic analysis of the effect of channel geometry on heat transfer in double-layered microchannel heat sinks *Energy Convers. Manage.* **143** 431–9
[23] Chen L, Deng D X, Ma Q X, Yao Y X and Xu X H 2022 Performance evaluation of high concentration photovoltaic cells cooled by microchannels heat sink with serpentine reentrant microchannels *Appl. Energy* **309** 118478
[24] Stroock A D, Dertinger S K W, Ajdari A, Mezic I, Stone H A and Whitesides G M 2002 Chaotic mixer for microchannels *Science* **295** 647–51
[25] Gau H, Herminghaus S, Lenz P and Lipowsky R 1999 Liquid morphologies on structured surfaces: from microchannels to microchips *Science* **283** 46–49
[26] Ghodoossi L 2005 Thermal and hydrodynamic analysis of a fractal microchannel network *Energy Convers. Manage.* **46** 771–88
[27] Vinodhan V L and Rajan K S 2015 Fine-tuning width and aspect ratio of an improved microchannel heat sink for energy-efficient thermal management *Energy Convers. Manage.* **105** 986–94
[28] Wu J M, Zhao J Y and Tseng K J 2014 Parametric study on the performance of double-layered microchannels heat sink *Energy Convers. Manage.* **80** 550–60
[29] Gunnasegaran P, Mohammed H A, Shuaib N H and Saidur R 2010 The effect of geometrical parameters on heat transfer characteristics of microchannels heat sink with different shapes *Int. Commun. Heat Mass Transfer* **37** 1078–86
[30] Yilmaz A, Büyükalaca O and Yilmaz T 2000 Optimum shape and dimensions of ducts for convective heat transfer in laminar flow at constant wall temperature *Int. J. Heat Mass Transfer* **43** 767–75
[31] Chen Y P, Zhang C B, Shi M H and Wu J F 2009 Three-dimensional numerical simulation of heat and fluid flow in noncircular microchannel heat sinks *Int. Commun. Heat Mass Transfer* **36** 917–20
[32] Wang H T, Chen Z H and Gao J G 2016 Influence of geometric parameters on flow and heat transfer performance of micro-channel heat sinks *Appl. Therm. Eng.* **107** 870–9
[33] di Capua H M, Escobar R, Diaz A J and Guzmán A M 2018 Enhancement of the cooling capability of a high concentration photovoltaic system using microchannels with forward triangular ribs on sidewalls *Appl. Energy* **226** 160–80
[34] Xia G D, Ma D D, Zhai Y L, Li Y F, Liu R and Du M 2015 Experimental and numerical study of fluid flow and heat transfer characteristics in microchannel heat sink with complex structure *Energy Convers. Manage.* **105** 848–57
[35] Yi P, Khoshmanesh K, Chrimes A F, Campbell J L, Ghorbani K, Nahavandi S, Rosengarten G and Kalantar-zadeh K 2014 Dynamic nanofin heat sinks *Adv. Energy Mater.* **4** 1300537
[36] Zhai Y L, Xia G D, Liu X F and Wang J 2015 Characteristics of entropy generation and heat transfer in double-layered micro heat sinks with complex structure *Energy Convers. Manage.* **103** 477–86
[37] Yagodnitsyna A A, Kovalev A V and Bilsky A V 2017 Experimental study of ionic liquid-water flow in T-shaped microchannels with different aspect ratios *J. Phys.: Conf. Ser.* **899** 032026
[38] Shen H, Wang C-C and Xie G N 2018 A parametric study on thermal performance of microchannel heat sinks with internally vertical bifurcations in laminar liquid flow *Int. J. Heat Mass Transfer* **117** 487–97
[39] Mohammed H A, Gunnasegaran P and Shuaib N H 2011 Numerical simulation of heat transfer enhancement in wavy microchannel heat sink *Int. Commun. Heat Mass Transfer* **38** 63–68
[40] Xu J L, Gan Y H, Zhang D C and Li X H 2005 Microscale heat transfer enhancement using thermal boundary layer redeveloping concept *Int. J. Heat Mass Transfer* **48** 1662–74
[41] Dehghan M, Daneshipour M, Valipour M S, Rafee R and Saedodin S 2015 Enhancing heat transfer in microchannel heat sinks using converging flow passages *Energy Convers. Manage.* **92** 244–50
[42] Chai L, Xia G D, Zhou M Z and Li J 2011 Numerical simulation of fluid flow and heat transfer in a microchannel heat sink with offset fan-shaped reentrant cavities in sidewall *Int. Commun. Heat Mass Transfer* **38** 577–84
[43] Hua J Y, Li G, Zhao X B, Li Q H and Hu J 2016 Study on the flow resistance performance of fluid cross various shapes of micro-scale pin fin *Appl. Therm. Eng.* **107** 768–75
[44] Pandit J, Thompson M, Ekkad S V and Huxtable S T 2014 Effect of pin fin to channel height ratio and pin fin geometry on heat transfer performance for flow in rectangular channels *Int. J. Heat Mass Transfer* **77** 359–68
[45] Moores K A, Kim J and Joshi Y K 2009 Heat transfer and fluid flow in shrouded pin fin arrays with and without tip clearance *Int. J. Heat Mass Transfer* **52** 5978–89
[46] Mei D Q, Lou X Y, Qian M, Yao Z H, Liang L W and Chen Z C 2014 Effect of tip clearance on the heat transfer and pressure drop performance in the micro-reactor with micro-pin-fin arrays at low Reynolds number *Int. J. Heat Mass Transfer* **70** 709–18
[47] Ghani I A, Sidik N A C, Mamat R, Najafi G, Ken T L, Asako Y and Japar W M A A 2017 Heat transfer enhancement in microchannel heat sink using hybrid technique of ribs and secondary channels *Int. J. Heat Mass Transfer* **114** 640–55
[48] Pan M Q, Wang H Q, Zhong Y J, Hu M L, Zhou X Y, Dong G P and Huang P N 2019 Experimental investigation of the heat transfer performance of microchannel heat exchangers with fan-shaped cavities *Int. J. Heat Mass Transfer* **134** 1199–208
[49] Li P, Luo Y Y, Zhang D and Xie Y H 2018 Flow and heat transfer characteristics and optimization study on the water-cooled microchannel heat sinks with dimple and pin-fin *Int. J. Heat Mass Transfer* **119** 152–62
[50] Ridouane E H and Campo A 2008 Heat transfer enhancement of air flowing across grooved channels: joint effects of channel height and groove depth *J. Heat Transfer* **130** 021901
[51] Xu M H, Lu H, Gong L, Chai J C and Duan X Y 2016 Parametric numerical study of the flow and heat transfer in microchannel with dimples *Int. Commun. Heat Mass Transfer* **76** 348–57
[52] Liu H L, Li B T, Zhang L K and Li X 2020 Optimizing heat-absorption efficiency of phase change materials by mimicking leaf vein morphology *Appl. Energy* **269** 114982

[53] Chen K 2005 Second-law analysis and optimization of microchannel flows subjected to different thermal boundary conditions *Int. J. Energy Res.* **29** 249–63
[54] Polat M E and Cadirci S 2022 Artificial neural network model and multi-objective optimization of microchannel heat sinks with diamond-shaped pin fins *Int. J. Heat Mass Transfer* **194** 123015
[55] Wang Q F, Zhang S Q, Zhang Y, Fu J H and Liu Z T 2023 Enhancing performance of nanofluid mini-channel heat sinks through machine learning and multi-objective optimization of operating parameters *Int. J. Heat Mass Transfer* **210** 124204
[56] Zhou L W, Garg D, Qiu Y, Kim S-M, Mudawar I and Kharangate C R 2020 Machine learning algorithms to predict flow condensation heat transfer coefficient in mini/micro-channel utilizing universal data *Int. J. Heat Mass Transfer* **162** 120351
[57] Normah G-M, Oh J-T, Chien N B, Choi K-I and Robiah A 2015 Comparison of the optimized thermal performance of square and circular ammonia-cooled microchannel heat sink with genetic algorithm *Energy Convers. Manage.* **102** 59–65
[58] Wang X-D, An B and Xu J-L 2013 Optimal geometric structure for nanofluid-cooled microchannel heat sink under various constraint conditions *Energy Convers. Manage.* **65** 528–38
[59] Leng C, Wang X-D, Wang T-H and Yan W-M 2015 Optimization of thermal resistance and bottom wall temperature uniformity for double-layered microchannel heat sink *Energy Convers. Manage.* **93** 141–50
[60] Alperen Y and Sertac C 2020 Multi objective optimization of a micro-channel heat sink through genetic algorithm *Int. J. Heat Mass Transfer* **146** 118847
[61] Naqiuddin N H, Saw L H, Yew M C, Yusof F, Poon H M, Cai Z S and Thiam H S 2018 Numerical investigation for optimizing segmented micro-channel heat sink by Taguchi-Grey method *Appl. Energy* **222** 437–50
[62] Hung T-C, Yan W-M, Wang X-D and Huang Y-X 2012 Optimal design of geometric parameters of double-layered microchannel heat sinks *Int. J. Heat Mass Transfer* **55** 3262–72
[63] Arie M A, Shooshtari A H, Dessiatoun S V, Al-Hajri E and Ohadi M M 2015 Numerical modeling and thermal optimization of a single-phase flow manifold-microchannel plate heat exchanger *Int. J. Heat Mass Transfer* **81** 478–89
[64] Shi X J, Li S, Mu Y J and Yin B T 2019 Geometry parameters optimization for a microchannel heat sink with secondary flow channel *Int. Commun. Heat Mass Transfer* **104** 89–100
[65] Gaikwad V P, Ghogare S D and Mohite S S 2016. Numerical study on microchannel heat sink with asymmetric leaf pattern *Proc. Int. Conf. on Advanced Technologies for Societal Applications* (Springer) pp 495–507
[66] Tan H, Wu L W, Wang M Y, Yang Z H and Du P G 2019 Heat transfer improvement in microchannel heat sink by topology design and optimization for high heat flux chip cooling *Int. J. Heat Mass Transfer* **129** 681–9
[67] Xia Y, Chen L, Luo J W and Tao W Q 2023 Numerical investigation of microchannel heat sinks with different inlets and outlets based on topology optimization *Appl. Energy* **330** 120335
[68] Gilmore N, Timchenko V and Menictas C 2021 Manifold microchannel heat sink topology optimisation *Int. J. Heat Mass Transfer* **170** 121025
[69] Ho J Y, See Y S, Leong K C and Wong T N 2021 An experimental investigation of a PCM-based heat sink enhanced with a topology-optimized tree-like structure *Energy Convers. Manage.* **245** 114608
[70] Fawaz A, Hua Y C, Le Corre S, Fan Y L and Luo L G 2022 Topology optimization of heat exchangers: a review *Energy* **252** 124053
[71] Beebe D J, Moore J S, Bauer J M, Yu Q, Liu R H, Devadoss C and Jo B-H 2000 Functional hydrogel structures for autonomous flow control inside microfluidic channels *Nature* **404** 588–90
[72] Whitesides G M 2006 The origins and the future of microfluidics *Nature* **442** 368–73
[73] Yin H B, Gao X N, Ding J, Zhang Z G and Fang Y T 2010 Thermal management of electronic components with thermal adaptation composite material *Appl. Energy* **87** 3784–91
[74] Golestaneh S I, Karimi G, Babapoor A and Torabi F 2018 Thermal performance of co-electrospun fatty acid nanofiber composites in the presence of nanoparticles *Appl. Energy* **212** 552–64
[75] Mohammed Adham A, Mohd-Ghazali N and Ahmad R 2013 Thermal and hydrodynamic analysis of microchannel heat sinks: a review *Renew. Sustain. Energy Rev.* **21** 614–22
[76] Salman B H, Mohammed H A, Munisamy K M and Kherbeet A S 2013 Characteristics of heat transfer and fluid flow in microtube and microchannel using conventional fluids and nanofluids: a review *Renew. Sustain. Energy Rev.* **28** 848–80
[77] Ma D D, Xia G D, Wang J, Yang Y C, Jia Y T and Zong L X 2017 An experimental study on hydrothermal performance of microchannel heat sinks with 4-ports and offset zigzag channels *Energy Convers. Manage.* **152** 157–65
[78] Ali H M and Arshad W 2015 Thermal performance investigation of staggered and inline pin fin heat sinks using water based rutile and anatase TiO_2 nanofluids *Energy Convers. Manage.* **106** 793–803
[79] Ganvir R B, Walke P V and Kriplani V M 2017 Heat transfer characteristics in nanofluid—a review *Renew. Sustain. Energy Rev.* **75** 451–60
[80] Saidur R, Leong K Y and Mohammed H A 2011 A review on applications and challenges of nanofluids *Renew. Sustain. Energy Rev.* **15** 1646–68
[81] Huminic G and Huminic A 2012 Application of nanofluids in heat exchangers: a review *Renew. Sustain. Energy Rev.* **16** 5625–38
[82] Peyghambarzadeh S M, Hashemabadi S H, Chabi A R and Salimi M 2014 Performance of water based CuO and Al_2O_3 nanofluids in a Cu-Be alloy heat sink with rectangular microchannels *Energy Convers. Manage.* **86** 28–38
[83] Sarkar J 2011 A critical review on convective heat transfer correlations of nanofluids *Renew. Sustain. Energy Rev.* **15** 3271–7
[84] Mohammed H A, Bhaskaran G, Shuaib N H and Saidur R 2011 Heat transfer and fluid flow characteristics in microchannels heat exchanger using nanofluids: a review *Renew. Sustain. Energy Rev.* **15** 1502–12
[85] Babar H and Ali H M 2019 Airfoil shaped pin-fin heat sink: potential evaluation of ferric oxide and titania nanofluids *Energy Convers. Manage.* **202** 112194
[86] Wu J M, Zhao J Y, Lei J and Liu B 2016 Effectiveness of nanofluid on improving the performance of microchannel heat sink *Appl. Therm. Eng.* **101** 402–12
[87] Ghazvini M and Shokouhmand H 2009 Investigation of a nanofluid-cooled microchannel heat sink using fin and porous media approaches *Energy Convers. Manage.* **50** 2373–80
[88] Ahmed H E, Mohammed H A and Yusoff M Z 2012 An overview on heat transfer augmentation using vortex generators and nanofluids: approaches and applications *Renew. Sustain. Energy Rev.* **16** 5951–93

[89] Ting T W, Hung Y M and Guo N Q 2014 Effects of streamwise conduction on thermal performance of nanofluid flow in microchannel heat sinks *Energy Convers. Manage.* **78** 14–23
[90] Hatami M and Ganji D D 2014 Thermal and flow analysis of microchannel heat sink (MCHS) cooled by Cu-water nanofluid using porous media approach and least square method *Energy Convers. Manage.* **78** 347–58
[91] Hussien A A, Abdullah M Z and Al-Nimr M A 2016 Single-phase heat transfer enhancement in micro/minichannels using nanofluids: theory and applications *Appl. Energy* **164** 733–55
[92] Chein R and Chuang J 2007 Experimental microchannel heat sink performance studies using nanofluids *Int. J. Therm. Sci.* **46** 57–66
[93] Ho C J, Wei L C and Li Z W 2010 An experimental investigation of forced convective cooling performance of a microchannel heat sink with Al_2O_3/water nanofluid *Appl. Therm. Eng.* **30** 96–103
[94] Azizi Z, Alamdari A and Malayeri M R 2015 Convective heat transfer of Cu–water nanofluid in a cylindrical microchannel heat sink *Energy Convers. Manage.* **101** 515–24
[95] Zhu H Y, Wang S L, Zhang M H, Li T Y, Hu G H and Kong D S 2021 Fully solution processed liquid metal features as highly conductive and ultrastretchable conductors *npj Flex. Electron.* **5** 25
[96] Kim M, Cho C, Shin W, Park J J, Kim J, Won P, Majidi C and Ko S H 2022 Nanowire-assisted freestanding liquid metal thin-film patterns for highly stretchable electrodes on 3D surfaces *npj Flex. Electron.* **6** 99
[97] Smither R K, Forster G A, Kot C A and Kuzay T M 1988 Liquid gallium metal cooling for optical elements with high heat loads *Nucl. Instrum. Methods Phys. Res.* A **266** 517–24
[98] Zhang X-D, Yang X-H, Zhou Y-X, Rao W, Gao J-Y, Ding Y-J, Shu Q-Q and Liu J 2019 Experimental investigation of galinstan based minichannel cooling for high heat flux and large heat power thermal management *Energy Convers. Manage.* **185** 248–58
[99] Zhang X-D, Li X-P, Zhou Y-X, Yang J and Liu J 2019 Vascularized liquid metal cooling for thermal management of kW high power laser diode array *Appl. Therm. Eng.* **162** 114212
[100] Sureshkumar R, Mohideen S T and Nethaji N 2013 Heat transfer characteristics of nanofluids in heat pipes: a review *Renew. Sustain. Energy Rev.* **20** 397–410
[101] Saidur R, Kazi S N, Hossain M S, Rahman M M and Mohammed H A 2011 A review on the performance of nanoparticles suspended with refrigerants and lubricating oils in refrigeration systems *Renew. Sustain. Energy Rev.* **15** 310–23
[102] Asadi A 2018 A guideline towards easing the decision-making process in selecting an effective nanofluid as a heat transfer fluid *Energy Convers. Manage.* **175** 1–10
[103] Luo X B, Hu R, Liu S and Wang K 2016 Heat and fluid flow in high-power LED packaging and applications *Prog. Energy Combust. Sci.* **56** 1–32
[104] Li P, Zhang D, Xie Y H and Xie G N 2016 Flow structure and heat transfer of non-Newtonian fluids in microchannel heat sinks with dimples and protrusions *Appl. Therm. Eng.* **94** 50–58
[105] Ebrahimi A, Naranjani B, Milani S and Javan F D 2017 Laminar convective heat transfer of shear-thinning liquids in rectangular channels with longitudinal vortex generators *Chem. Eng. Sci.* **173** 264–74
[106] Liao S L, He Y L, Chu Y J, Liao H G and Wang Y P 2019 Solvent-resistant and fully recyclable perfluoropolyether-based elastomer for microfluidic chip fabrication *J. Mater. Chem.* A **7** 16249–56
[107] Whalley R D, Abed W M, Dennis D J C and Poole R J 2015 Enhancing heat transfer at the micro-scale using elastic turbulence *Theor. Appl. Mech. Lett.* **5** 103–6
[108] Tatsumi K, Nagasaka W, Kimura R, Shinotsuka N, Kuriyama R and Nakabe K 2019 Local flow and heat transfer characteristics of viscoelastic fluid in a serpentine channel *Int. J. Heat Mass Transfer* **138** 432–42
[109] Li M *et al* 2022 Crystallization induced realignment of carbon fibers in a phase change material to achieve exceptional thermal transportation properties *J. Mater. Chem.* A **10** 593–601
[110] Choi J, Dun C C, Forsythe C, Gordon M P and Urban J J 2021 Lightweight wearable thermoelectric cooler with rationally designed flexible heatsink consisting of phase-change material/graphite/silicone elastomer *J. Mater. Chem.* A **9** 15696–703
[111] Advincula P A, de Leon A C, Rodier B J, Kwon J, Advincula R C and Pentzer E B 2018 Accommodating volume change and imparting thermal conductivity by encapsulation of phase change materials in carbon nanoparticles *J. Mater. Chem.* A **6** 2461–7
[112] Liu Y S, Yang Y Z and Li S X 2016 Graphene oxide modified hydrate salt hydrogels: form-stable phase change materials for smart thermal management *J. Mater. Chem.* A **4** 18134–43
[113] Zhao B, Moore J S and Beebe D J 2001 Surface-directed liquid flow inside microchannels *Science* **291** 1023–6
[114] Prins M W J, Welters W J J and Weekamp J W 2001 Fluid control in multichannel structures by electrocapillary pressure *Science* **291** 277–80
[115] Wen R F, Ma X H, Lee Y C and Yang R G 2018 Liquid-vapor phase-change heat transfer on functionalized nanowired surfaces and beyond *Joule* **2** 2307–47
[116] Deng D X, Zeng L and Sun W 2021 A review on flow boiling enhancement and fabrication of enhanced microchannels of microchannel heat sinks *Int. J. Heat Mass Transf.* **175** 121332
[117] Qu W L and Mudawar I 2003 Flow boiling heat transfer in two-phase micro-channel heat sinks—-II. Annular two-phase flow model *Int. J. Heat Mass Transfer* **46** 2773–84
[118] Sur A and Liu D 2012 Adiabatic air–water two-phase flow in circular microchannels *Int. J. Therm. Sci.* **53** 18–34
[119] Wei L, Pan L-M, Zhao Y-M, Ren Q-Y and Zhang W-Z 2017 Numerical study of adiabatic two-phase flow patterns in vertical rectangular narrow channels *Appl. Therm. Eng.* **110** 1101–10
[120] Saisorn S and Wongwises S 2008 A review of two-phase gas-liquid adiabatic flow characteristics in micro-channels *Renew. Sustain. Energy Rev.* **12** 824–38
[121] Yang G *et al* 2021 A superhydrophilic metal-organic framework thin film for enhancing capillary-driven boiling heat transfer *J. Mater. Chem.* A **9** 25480–7
[122] Zhang Y X, Wang J T, Liu W and Liu Z C 2017 Heat transfer and pressure drop characteristics of R134a flow boiling in the parallel/tandem microchannel heat sinks *Energy Convers. Manage.* **148** 1082–95
[123] Radwan A, Ookawara S, Mori S and Ahmed M 2018 Uniform cooling for concentrator photovoltaic cells and electronic chips by forced convective boiling in 3D-printed monolithic double-layer microchannel heat sink *Energy Convers. Manage.* **166** 356–71
[124] Radwan A, Ookawara S and Ahmed M 2019 Thermal management of concentrator photovoltaic systems using two-phase flow boiling in double-layer microchannel heat sinks *Appl. Energy* **241** 404–19

[125] Li W, Zhou K, Li J Y, Feng Z Z and Zhu H 2018 Effects of heat flux, mass flux and two-phase inlet quality on flow boiling in a vertical superhydrophilic microchannel *Int. J. Heat Mass Transfer* **119** 601–13
[126] Kim S-M and Mudawar I 2017 Thermal design and operational limits of two-phase micro-channel heat sinks *Int. J. Heat Mass Transfer* **106** 861–76
[127] Park J E and Thome J R 2010 Critical heat flux in multi-microchannel copper elements with low pressure refrigerants *Int. J. Heat Mass Transfer* **53** 110–22
[128] Qu W L and Mudawar I 2004 Measurement and correlation of critical heat flux in two-phase micro-channel heat sinks *Int. J. Heat Mass Transfer* **47** 2045–59
[129] Abo-Zahhad E M, Ookawara S, Radwan A, Memon S, Yang Y, El-Kady M F and El-Shazly A H 2021 Flow boiling in a four-compartment heat sink for high-heat flux cooling: a parametric study *Energy Convers. Manage.* **230** 113778
[130] Jagirdar M and Lee P S 2017 A diagnostic tool for detection of flow-regimes in a microchannel using transient wall temperature signal *Appl. Energy* **185** 2232–44
[131] Zhang T J, Peles Y, Wen J T, Tong T, Chang J-Y, Prasher R and Jensen M K 2010 Analysis and active control of pressure-drop flow instabilities in boiling microchannel systems *Int. J. Heat Mass Transfer* **53** 2347–60
[132] Deng D X, Wan W, Shao H R, Tang Y, Feng J Y and Zeng J 2015 Effects of operation parameters on flow boiling characteristics of heat sink cooling systems with reentrant porous microchannels *Energy Convers. Manage.* **96** 340–51
[133] Baldassari C and Marengo M 2013 Flow boiling in microchannels and microgravity *Prog. Energy Combust. Sci.* **39** 1–36
[134] Ge H S, Li H Y, Mei S F and Liu J 2013 Low melting point liquid metal as a new class of phase change material: an emerging frontier in energy area *Renew. Sustain. Energy Rev.* **21** 331–46
[135] Lv L D, Wang Y Q, Ai H, Chen T R, Zhang X and Song S K 2022 3D graphene/silver nanowire aerogel encapsulated phase change material with significantly enhanced thermal conductivity and excellent solar-thermal energy conversion capacity *J. Mater. Chem.* A **10** 7773–84
[136] Wu S, Li T X, Wu M Q, Xu J X, Hu Y H, Chao J W, Yan T S and Wang R Z 2020 Highly thermally conductive and flexible phase change composites enabled by polymer/graphite nanoplatelet-based dual networks for efficient thermal management *J. Mater. Chem.* A **8** 20011–20
[137] Ji H X, Sellan D P, Pettes M T, Kong X H, Ji J Y, Shi L and Ruoff R S 2014 Enhanced thermal conductivity of phase change materials with ultrathin-graphite foams for thermal energy storage *Energy Environ. Sci.* **7** 1185–92
[138] Eisapour M, Eisapour A H, Hosseini M J and Talebizadehsardari P 2020 Exergy and energy analysis of wavy tubes photovoltaic-thermal systems using microencapsulated PCM nano-slurry coolant fluid *Appl. Energy* **266** 114849
[139] Wang T Y, Wang S F, Luo R L, Zhu C Y, Akiyama T and Zhang Z G 2016 Microencapsulation of phase change materials with binary cores and calcium carbonate shell for thermal energy storage *Appl. Energy* **171** 113–9
[140] Pu L, Xu L L, Zhang S Q and Li Y Z 2019 Optimization of ground heat exchanger using microencapsulated phase change material slurry based on tree-shaped structure *Appl. Energy* **240** 860–9
[141] Wu W, Bostanci H, Chow L C, Hong Y, Wang C M, Su M and Kizito J P 2013 Heat transfer enhancement of PAO in microchannel heat exchanger using nano-encapsulated phase change indium particles *Int. J. Heat Mass Transfer* **58** 348–55
[142] Zhang P and Ma Z W 2012 An overview of fundamental studies and applications of phase change material slurries to secondary loop refrigeration and air conditioning systems *Renew. Sustain. Energy Rev.* **16** 5021–58
[143] Ikutegbe C A, Al-Shannaq R and Farid M M 2022 Microencapsulation of low melting phase change materials for cold storage applications *Appl. Energy* **321** 119347
[144] Nomura T, Sheng N, Zhu C Y, Saito G, Hanzaki D, Hiraki T and Akiyama T 2017 Microencapsulated phase change materials with high heat capacity and high cyclic durability for high-temperature thermal energy storage and transportation *Appl. Energy* **188** 9–18
[145] Liu L, Zhang X Y, Liang H B, Niu J L and Wu J-Y 2022 Cooling storage performance of a novel phase change material nano-emulsion for room air-conditioning in a self-designed pilot thermal storage unit *Appl. Energy* **308** 118405
[146] Cao J H, He Y J, Feng J X, Lin S, Ling Z Y, Zhang Z G and Fang X M 2020 Mini-channel cold plate with nano phase change material emulsion for Li-ion battery under high-rate discharge *Appl. Energy* **279** 115808
[147] Liang H B, Liu L, Zhong Z W, Gan Y X, Wu J-Y and Niu J L 2022 Towards idealized thermal stratification in a novel phase change emulsion storage tank *Appl. Energy* **310** 118526
[148] Huang L, Noeres P, Petermann M and Doetsch C 2010 Experimental study on heat capacity of paraffin/water phase change emulsion *Energy Convers. Manage.* **51** 1264–9
[149] Roy S K and Avanic B L 1997 Laminar forced convection heat transfer with phase change material emulsions *Int. Commun. Heat Mass Transfer* **24** 653–62
[150] Lu Q, Wang X, Zhao H-W, Wang X-R, Zhao J-Q, Kong H-R, Wang T, Liang C, Li J-H and Xu W Q 2022 A hierarchically encapsulated phase-change film with multi-stage heat management properties and conformable self-interfacing contacts for enhanced interface heat dissipation *J. Mater. Chem.* A **10** 23617–29
[151] Fu W C, Yan X, Gurumukhi Y, Garimella V S, King W P and Miljkovic N 2022 High power and energy density dynamic phase change materials using pressure-enhanced close contact melting *Nat. Energy* **7** 270–80
[152] Song H F, Liu J M, Liu B L, Wu J Q, Cheng H-M and Kang F Y 2018 Two-dimensional materials for thermal management applications *Joule* **2** 442–63
[153] Li J and Peterson G P 2007 3-Dimensional numerical optimization of silicon-based high performance parallel microchannel heat sink with liquid flow *Int. J. Heat Mass Transfer* **50** 2895–904
[154] Wang B X and Peng X F 1994 Experimental investigation on liquid forced-convection heat transfer through microchannels *Int. J. Heat Mass Transfer* **37** 73–82
[155] Mudawar I and Bowers M B 1999 Ultra-high critical heat flux (CHF) for subcooled water flow boiling-I: CHF data and parametric effects for small diameter tubes *Int. J. Heat Mass Transfer* **42** 1405–28
[156] Zhang H Y, Pinjala D, Wong T N, Toh K C and Joshi Y K 2005 Single-phase liquid cooled microchannel heat sink for electronic packages *Appl. Therm. Eng.* **25** 1472–87
[157] Cacucciolo V, Shintake J, Kuwajima Y, Maeda S, Floreano D and Shea H 2019 Stretchable pumps for soft machines *Nature* **572** 516–9
[158] Sharma C S, Tiwari M K, Zimmermann S, Brunschwiler T, Schlottig G, Michel B and Poulikakos D 2015 Energy efficient hotspot-targeted embedded liquid cooling of electronics *Appl. Energy* **138** 414–22

[159] Wei T W 2020 A cool design for hot microchips *Nature* **585** 188–9
[160] Zhao Y Q, Zhang Y-L, Huang J-A, Zhang Z Y, Chen X F and Zhang W J 2015 Plasmonic nanopillar array embedded microfluidic chips: an *in situ* SERS monitoring platform *J. Mater. Chem.* A **3** 6408–13
[161] van Erp R, Soleimanzadeh R, Nela L, Kampitsis G and Matioli E 2020 Co-designing electronics with microfluidics for more sustainable cooling *Nature* **585** 211–6
[162] Ditri J, Pearson R R, Cadotte R, Hahn J W, Fetterolf D, McNulty M and Luppa D 2016 GaN unleashed: the benefits of microfluidic cooling *IEEE Trans. Semicond. Manuf.* **29** 376–83
[163] Palko J W *et al* 2017 Extreme two-phase cooling from laser-etched diamond and conformal, template-fabricated microporous copper *Adv. Funct. Mater.* **27** 1703265
[164] Gambin V, Poust B, Ferizovic D, Watanabe M, Mandrusiak G, Lin D and Dusseault T 2016. Impingement cooled embedded diamond multiphysics co-design *Proc. 2016 15th IEEE Intersociety Conf. on Thermal and Thermomechanical Phenomena in Electronic Systems* (IEEE) pp 1518–29
[165] Xia G H, Zhuang D W, Ding G L and Lu J C 2020 A quasi-three-dimensional distributed parameter model of micro-channel separated heat pipe applied for cooling telecommunication cabinets *Appl. Energy* **276** 115544
[166] Gamrat G, Favre-Marinet M and Le Person S 2009 Modelling of roughness effects on heat transfer in thermally fully-developed laminar flows through microchannels *Int. J. Therm. Sci.* **48** 2203–14
[167] Wang H L, Wang Y and Zhang J Z 2005 Influence of ribbon structure rough wall on the microscale Poiseuille flow *J. Fluids Eng.* **127** 1140–5
[168] Koo J and Kleinstreuer C 2005 Analysis of surface roughness effects on heat transfer in micro-conduits *Int. J. Heat Mass Transfer* **48** 2625–34
[169] Hetsroni G, Mosyak A, Pogrebnyak E and Yarin L P 2005 Fluid flow in micro-channels *Int. J. Heat Mass Transfer* **48** 1982–98
[170] Shen S, Xu J L, Zhou J J and Chen Y 2006 Flow and heat transfer in microchannels with rough wall surface *Energy Convers. Manage.* **47** 1311–25
[171] Steinke M E and Kandlikar S G 2006 Single-phase liquid friction factors in microchannels *Int. J. Therm. Sci.* **45** 1073–83
[172] Dahiya A, Sehgal S S and Singh H 2016 CFD and heat transfer analysis of microchannel heat sink with different inlet and outlet flow arrangements *Indian J. Sci. Technol.* **9** 1–5
[173] Kumaran R M, Kumaraguruparan G and Sornakumar T 2013 Experimental and numerical studies of header design and inlet/outlet configurations on flow mal-distribution in parallel micro-channels *Appl. Therm. Eng.* **58** 205–16
[174] Rahimi M, Asadi M, Karami N and Karimi E 2015 A comparative study on using single and multi header microchannels in a hybrid PV cell cooling *Energy Convers. Manage.* **101** 1–8
[175] Abou-Ziyan H, Ibrahim M and Abdel-Hameed H 2020 Characteristics enhancement of one-section and two-stepwise microchannels for cooling high-concentration multi-junction photovoltaic cells *Energy Convers. Manage.* **206** 112488
[176] Ma D D, Xia G D, Li Y F, Jia Y T and Wang J 2016 Design study of micro heat sink configurations with offset zigzag channel for specific chips geometrics *Energy Convers. Manage.* **127** 160–9
[177] Xia G D, Jiang J, Wang J, Zhai Y L and Ma D D 2015 Effects of different geometric structures on fluid flow and heat transfer performance in microchannel heat sinks *Int. J. Heat Mass Transfer* **80** 439–47
[178] Tang W, Sun L C, Liu H T, Xie G, Mo Z Y and Tang J G 2017 Improvement of flow distribution and heat transfer performance of a self-similarity heat sink with a modification to its structure *Appl. Therm. Eng.* **121** 163–71
[179] Maranzana G, Perry I and Maillet D 2004 Mini- and micro-channels: influence of axial conduction in the walls *Int. J. Heat Mass Transfer* **47** 3993–4004
[180] Tiselj I, Hetsroni G, Mavko B, Mosyak A, Pogrebnyak E and Segal Z 2004 Effect of axial conduction on the heat transfer in micro-channels *Int. J. Heat Mass Transfer* **47** 2551–65
[181] Sheikholeslami M, Gorji-Bandpy M and Ganji D D 2015 Review of heat transfer enhancement methods: focus on passive methods using swirl flow devices *Renew. Sustain. Energy Rev.* **49** 444–69
[182] Chen G, Jiang X C, Li Y J, Bai J J, Shah S W A, Gao Y, Tang Y, Zhang S W and Pan C N 2023 A highly efficient and sustainable heat sink via liquid film boiling in hybrid mesh with active liquid supply *Energy Convers. Manage.* **277** 116688
[183] Sirovich L and Karlsson S 1997 Turbulent drag reduction by passive mechanisms *Nature* **388** 753–5
[184] Zhang Y F, Lv Q, Wang H D, Zhao S Y, Xiong Q H, Lv R T and Zhang X 2022 Simultaneous electrical and thermal rectification in a monolayer lateral heterojunction *Science* **378** 169–75
[185] Machida Y, Matsumoto N, Isono T and Behnia K 2020 Phonon hydrodynamics and ultrahigh-room-temperature thermal conductivity in thin graphite *Science* **367** 309–12
[186] Guo Z Y 2001 Mechanism and control of convective heat transfer: coordination of velocity and heat flow fields *Chin. Sci. Bull.* **46** 596–9
[187] Alam T and Kim M-H 2018 A comprehensive review on single phase heat transfer enhancement techniques in heat exchanger applications *Renew. Sustain. Energy Rev.* **81** 813–39
[188] Abo-Zahhad E M, Ookawara S, Radwan A, El-Shazly A H and Elkady M F 2019 Numerical analyses of hybrid jet impingement/microchannel cooling device for thermal management of high concentrator triple-junction solar cell *Appl. Energy* **253** 113538
[189] Abou-Ziyan H, Ibrahim M and Abdel-Hameed H 2020 Performance modeling and analysis of high-concentration multi-junction photovoltaics using advanced hybrid cooling systems *Appl. Energy* **269** 115060
[190] Zhuang Y, Ma C F and Qin M 1997 Experimental study on local heat transfer with liquid impingement flow in two-dimensional micro-channels *Int. J. Heat Mass Transfer* **40** 4055–9
[191] Huang X M, Yang W, Ming T Z, Shen W Q and Yu X F 2017 Heat transfer enhancement on a microchannel heat sink with impinging jets and dimples *Int. J. Heat Mass Transfer* **112** 113–24
[192] Wan C Y, Rao Y and Chen P 2015 Numerical predictions of jet impingement heat transfer on square pin-fin roughened plates *Appl. Therm. Eng.* **80** 301–9
[193] Ghahremannezhad A and Vafai K 2018 Thermal and hydraulic performance enhancement of microchannel heat sinks utilizing porous substrates *Int. J. Heat Mass Transfer* **122** 1313–26
[194] Drummond K P, Back D, Sinanis M D, Janes D B, Peroulis D, Weibel J A and Garimella S V 2018 A hierarchical manifold microchannel heat sink array for high-heat-flux two-phase cooling of electronics *Int. J. Heat Mass Transfer* **117** 319–30
[195] Xu C, Xu S L and Eticha R D 2021 Experimental investigation of thermal performance for pulsating flow in

a microchannel heat sink filled with PCM (paraffin/CNT composite) *Energy Convers. Manage.* **236** 114071

[196] Nishimura T, Oka N, Yoshinaka Y and Kunitsugu K 2000 Influence of imposed oscillatory frequency on mass transfer enhancement of grooved channels for pulsatile flow *Int. J. Heat Mass Transfer* **43** 2365–74

[197] Nandi T K and Chattopadhyay H 2014 Numerical investigations of developing flow and heat transfer in raccoon type microchannels under inlet pulsation *Int. Commun. Heat Mass Transfer* **56** 37–41

[198] Lo C-W, Chu Y-C, Yen M-H and Lu M-C 2019 Enhancing condensation heat transfer on three-dimensional hybrid surfaces *Joule* **3** 2806–23

[199] Leng C, Wang X-D, Yan W-M and Wang T-H 2016 Heat transfer enhancement of microchannel heat sink using transcritical carbon dioxide as the coolant *Energy Convers. Manage.* **110** 154–64

[200] Qiu P X, Liu F L, Xu C M, Chen H, Jiang F, Li Y and Guo Z B 2019 Porous three-dimensional carbon foams with interconnected microchannels for high-efficiency solar-to-vapor conversion and desalination *J. Mater. Chem.* A **7** 13036–42

[201] Liu C, Hong K, Sun X, Natan A, Luan P C, Yang Y and Zhu H L 2020 An 'antifouling' porous loofah sponge with internal microchannels as solar absorbers and water pumpers for thermal desalination *J. Mater. Chem.* A **8** 12323–33

[202] Jia D D, Yu X, Tan H, Li X Q, Han F, Li L L and Liu H 2017 Hierarchical porous carbon with ordered straight micro-channels templated by continuous filament glass fiber arrays for high performance supercapacitors *J. Mater. Chem.* A **5** 1516–25

[203] Li J G, Chen C J, Gan W T, Li Z H, Xie H, Jiao M L, Xiao S L, Tang H and Hu L B 2021 A bio-inspired, hierarchically porous structure with a decoupled fluidic transportation and evaporative pathway toward high-performance evaporation *J. Mater. Chem.* A **9** 9745–52

[204] Hsieh W H, Wu J Y, Shih W H and Chiu W C 2004 Experimental investigation of heat-transfer characteristics of aluminum-foam heat sinks *Int. J. Heat Mass Transfer* **47** 5149–57

[205] Liu H G, Wu S Q, Tian N, Yan F X, You C Y and Yang Y 2020 Carbon foams: 3D porous carbon materials holding immense potential *J. Mater. Chem.* A **8** 23699–723

[206] Tzeng S-C, Jywe W-Y, Lin C-W and Wang Y-C 2005 Mixed convective heat-transfers in a porous channel with sintered copper beads *Appl. Energy* **81** 19–31

[207] Islam K, Riggs B, Ji Y P, Robertson J, Spitler C, Romanin V, Codd D and Escarra M D 2019 Transmissive microfluidic active cooling for concentrator photovoltaics *Appl. Energy* **236** 906–15

[208] Dong J, Zhuang X R, Xu X H, Miao Z H and Xu B 2018 Numerical analysis of a multi-channel active cooling system for densely packed concentrating photovoltaic cells *Energy Convers. Manage.* **161** 172–81

[209] Yang K J and Zuo C C 2015 A novel multi-layer manifold microchannel cooling system for concentrating photovoltaic cells *Energy Convers. Manage.* **89** 214–21

[210] Ki S *et al* 2022 An energy-efficient battery thermal management system incorporating a porous metal-based multiscale flow manifold *Energy Convers. Manage.* **269** 116147

[211] Arie M A, Shooshtari A H, Rao V V, Dessiatoun S V and Ohadi M M 2017 Air-side heat transfer enhancement utilizing design optimization and an additive manufacturing technique *J. Heat Transfer* **139** 031901

[212] Jung K W, Kharangate C R, Lee H, Palko J, Zhou F, Asheghi M, Dede E M and Goodson K E 2019 Embedded cooling with 3D manifold for vehicle power electronics application: single-phase thermal-fluid performance *Int. J. Heat Mass Transfer* **130** 1108–19

[213] Chu X Y, You H H, Tang X J, Zhou W, Li X Y, Yuan D and Zhou S P 2021 Smart microchannel heat exchanger based on the adaptive deformation effect of shape memory alloys *Energy Convers. Manage.* **250** 114910

[214] Narendran G and Gnanasekaran N 2022 Investigation on novel inertial minichannel to mitigate maldistribution induced high temperature zones *Energy Convers. Manage.* **271** 116300