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Research Progress on Manifold Microchannel Technologies for Thermal Management of Microelectronic Chips

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Abstract. As high-performance computing, artificial intelligence, and power-electronic devices continue to evolve toward higher integration and power density, localized chip hotspots impose increasingly severe thermal constraints. Conventional air cooling and heat-spreading-only solutions are becoming insufficient to simultaneously remove high heat fluxes and maintain temperature uniformity. Microchannel liquid cooling offers a large surface-area-to-volume ratio, short heat-transfer paths, and high volumetric heat-transfer capability. In particular, manifold microchannels shorten the effective flow length and reshape coolant distribution, providing a promising route for cooling chips under high and spatially non-uniform heat loads. Based on a thorough revision of the original manuscript, this review discusses the development of microchannel heat sinks, geometric parameters and flow-distribution mechanisms of manifold structures, hotspot-oriented cooling strategies, field-synergy and secondary-flow mechanisms, thermal response under dynamic boundary conditions, multiphysics simulation, and advanced manufacturing. Current studies indicate that manifold structures can reduce streamwise pressure losses while improving local heat transfer; however, their performance strongly depends on the coupled manifold-microchannel geometry, flow uniformity, and operating boundary conditions, and no universal optimum geometric parameter exists independently of the specific application. Future work should focus on adaptive flow control for dynamic hotspots, chip-cooler co-design, two-phase and advanced coolants, data-driven optimization, and integrated additive manufacturing to move manifold microchannel cooling from high-performance prototypes toward reliable and scalable engineering systems.

Keywords: chip thermal management, manifold microchannel, hotspot cooling, flow distribution, heat-transfer enhancement

1. Introduction

With continued increases in transistor density, operating frequency, and packaging integration, electronic thermal design has shifted from controlling average temperature to simultaneously removing high heat fluxes and suppressing localized hotspots. Studies on high-performance computing, data centers, power electronics, and radio-frequency devices have shown that chip heat loads are not only increasing in magnitude but are also strongly non-uniform in space and time [1].

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Local overheating can intensify thermomechanical stress in interconnects and interfaces, accelerate electromigration, and induce electrical-parameter drift, ultimately affecting device performance and long-term reliability. Phase-change packaging, thermal spreading substrates, and highly conductive composite packages can mitigate certain transient or localized thermal loads [2], but efficient liquid cooling remains one of the most promising approaches for sustained high-heat-flux operation.

In 1981, Tuckerman and Pease fabricated rectangular microchannels in silicon and demonstrated heat dissipation on the order of 790 W/cm², establishing the foundation for microchannel liquid cooling of electronic chips. Subsequent research has progressed from simply reducing channel dimensions to the coupled optimization of channel geometry, surface structures, flow organization, coolant properties, and system integration [3]. As shown in Figure 1, In conventional parallel straight microchannels, long flow paths can cause substantial pressure drop and streamwise coolant heating. Under non-uniform heat loads, they can also produce the undesirable combination of overcooling in low-load regions and insufficient cooling at hotspots.

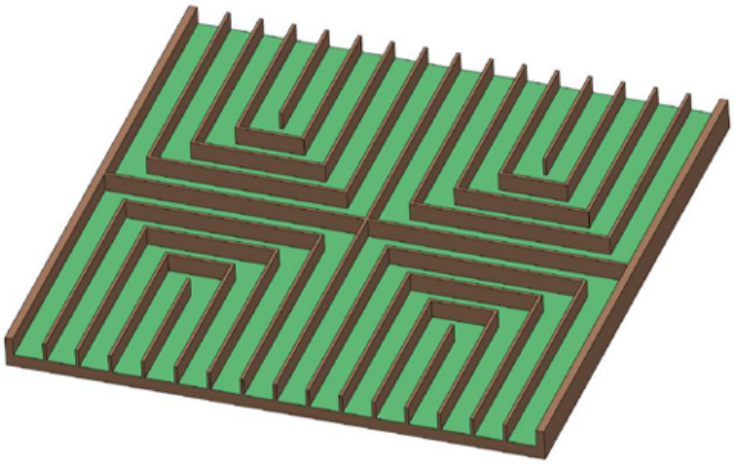


Figure 1. Schematic of a four-quadrant microchannel heat sink [3]

A manifold microchannel (MMC) system places supply and return manifolds above or adjacent to the microchannels and distributes coolant through multiple shorter local flow paths. Compared with a conventional long-channel arrangement with a single inlet, this configuration reduces the effective flow length, limits continuous thermal-boundary-layer growth, and provides additional design freedom to shape the flow distribution among channels [4]. MMC architectures are therefore particularly attractive for high-heat-flux chips, restricted pumping-power budgets, and devices containing multiple hotspots.

Some numerical values in the original manuscript, including specific "optimal inlet widths," "optimal gaps," and corresponding temperature-reduction percentages, were not linked to verifiable references. The revised manuscript therefore avoids presenting any single value as universally optimal. Instead, it emphasizes that optimal manifold dimensions must be determined jointly from the heat-source distribution, microchannel dimensions, Reynolds number, allowable pressure drop, and manufacturing constraints. The following sections review the topic from the perspectives of structure, hotspot management, heat-transfer mechanisms, and engineering implementation.

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2. Research progress on manifold microchannel structures

2.1. Development of microchannel heat sinks and the transition to manifold architectures

Conventional microchannel heat sinks typically consist of an inlet plenum, a bank of parallel microchannels, and an outlet plenum. Their large heat-transfer area per unit volume and compact footprint are advantageous, but pressure drop, streamwise coolant heating, and flow maldistribution become increasingly important as the chip area and channel length increase [5]. To overcome these limitations, researchers have developed wavy channels, branched channels, pin-fin and disturbance structures, and multilayer flow networks. The essential concept of the manifold architecture is not merely to increase local disturbance, but to modify the flow topology by dividing a large cooling area into multiple short-flow-path units supplied in parallel through a manifold.

Sarangi et al. developed a three-dimensional model to optimize parameters including microchannel width and depth, manifold depth, and manifold inlet/outlet lengths. Their study showed that the MMC concept can lower pressure drop through shortened flow paths while enhancing heat transfer by limiting thermal-boundary-layer growth [6]. Hierarchical manifolds were subsequently introduced to improve flow uniformity over larger cooling areas. Zhou et al. demonstrated numerically and experimentally that a hierarchical MMC can provide a more uniform channel flow distribution and high-heat-flux dissipation at relatively low pressure drop . These studies highlight the principal value of MMCs: coordinated control of flow distribution and local heat transfer.

2.2. Geometric parameters and flow-distribution optimization

Manifold geometry directly determines the pressure distribution at the entrances of parallel microchannels and is therefore a primary factor governing flow uniformity. Common design variables include manifold cross-sectional dimensions, manifold depth, inlet and outlet locations and lengths, the transition gap between the manifold and microchannels, and local contractions, expansions, or tapered sections. In general, a larger manifold flow area can reduce velocity variation and local pressure gradients, improving channel-to-channel flow uniformity, but it also increases package volume, coolant inventory, and structural thermal mass. Conversely, an excessively small manifold may generate strong jetting and impingement but can also induce separation, recirculation, and large local losses.

Consequently, parameters such as inlet width, manifold height, and the manifold-to-microchannel gap should be evaluated in terms of both heat-transfer benefit and hydraulic penalty. The original manuscript directly associated smaller inlet dimensions with improved hotspot cooling, which neglects the possible increase in pressure drop and flow maldistribution caused by excessive contraction. A more general interpretation is that moderate area variation, inlet repositioning, or deliberately non-uniform supply can redirect more coolant toward high-load regions, but the appropriate degree of redistribution depends on the resistance network and hotspot location [7].

Flow maldistribution generally arises from streamwise variations in manifold static pressure, inertia-induced separation and recirculation, and unequal branch resistances. As shown in Figure 2, Strong pressure recovery or local vortices in a manifold may cause some channels to receive excessive flow while others are starved. Hierarchical or tapered manifolds can mitigate this problem through staged distribution, shortened branches, or local resistance compensation [8]. Therefore, a comprehensive assessment of a manifold should report not only maximum temperature and thermal resistance, but also flow-rate dispersion, pressure drop, pumping power, and temperature uniformity.

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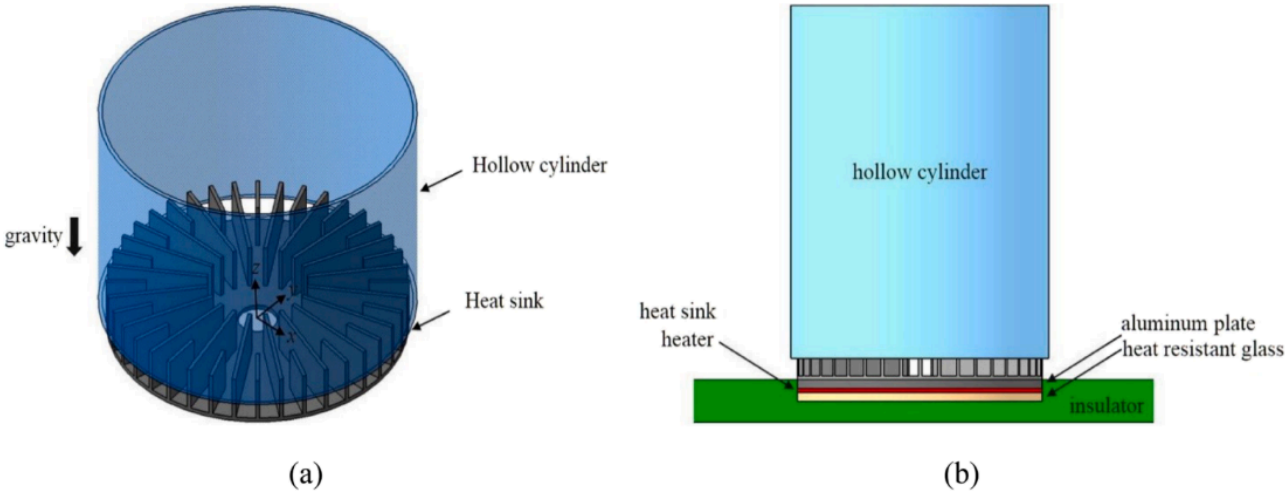


Figure 2. (a) Radiator geometry; (b) Experimental setup [8]

2.3. Representative optimization studies and advanced manufacturing

Recent MMC research has evolved from one-factor-at-a-time parameter sweeps toward multivariable and multi-objective optimization. In addition to thermal resistance and maximum temperature, pumping power, temperature uniformity, package volume, manufacturing tolerances, and reliability are increasingly included as design objectives. Wang et al. combined numerical simulations with a genetic-algorithm/back-propagation neural-network surrogate model to optimize flow and temperature maldistribution in a microchannel heat sink, demonstrating the value of data-driven surrogates for reducing the computational cost of high-dimensional searches . Such methods are well suited to rapid screening of complex manifold geometries, although their predictive capability remains dependent on the coverage and fidelity of the training data.

For fabrication, silicon devices can use lithography, deep reactive-ion etching (DRIE), and wafer bonding to realize high-aspect-ratio channels and intrachip cooling structures [9]. Metallic heat sinks can be fabricated by micromilling, laser processing, and additive manufacturing. Kong et al. used laser powder-bed fusion to monolithically fabricate an aluminum-alloy manifold-microchannel heat sink, demonstrating the ability of additive manufacturing to integrate complex three-dimensional fluid-routing networks [10]. Compared with multilayer fabrication and bonding, monolithic manufacturing can reduce interfaces and leakage risk, although surface roughness, internal defects, and dimensional consistency still require stringent control.

3. Microchannel research for chip hotspot thermal management

3.1. Formation of hotspots and thermal-management requirements

Chip hotspots arise from spatial and temporal variations in the power consumption of different functional units. Computing cores, cache blocks, power-device junctions, and RF units can generate local heat fluxes substantially higher than their surroundings. Compared with a uniformly heated chip, hotspot thermal management places greater emphasis on peak temperature, spatial temperature gradients, and thermal-cycling amplitude because these quantities are closely related to thermomechanical stress, performance drift, and service life. A cooling system designed only from

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average chip power can therefore provide insufficient cooling at hotspots while wasting flow rate and pumping power in low-load regions.

Near-junction and intrachip cooling are important approaches for shortening the heat-transfer path. Nela et al. investigated the electrothermal impact of embedded liquid cooling in GaN-on-Si devices, illustrating the need to co-design the cooling architecture with device electrical behavior. Drummond et al. experimentally studied a hierarchical manifold microchannel array under simultaneous background and localized hotspot heating in two-phase operation, demonstrating the potential of hierarchical direct cooling for extremely high local heat fluxes [11]. These studies suggest that hotspot-oriented cooling should move from spatially uniform cooling toward targeted cooling that follows the heat-source distribution.

3.2. Microchannel cooling strategies for hotspots

Existing hotspot-oriented microchannel concepts can be grouped into four categories. The first is non-uniform channel design, As shown in Figure 3, in which the local heat-transfer area is increased or the local thermal resistance is reduced in hotspot regions by using denser channels, pin fins, or disturbance structures. This approach is relatively straightforward, but abrupt geometry changes can increase pressure drop and manufacturing complexity [12].

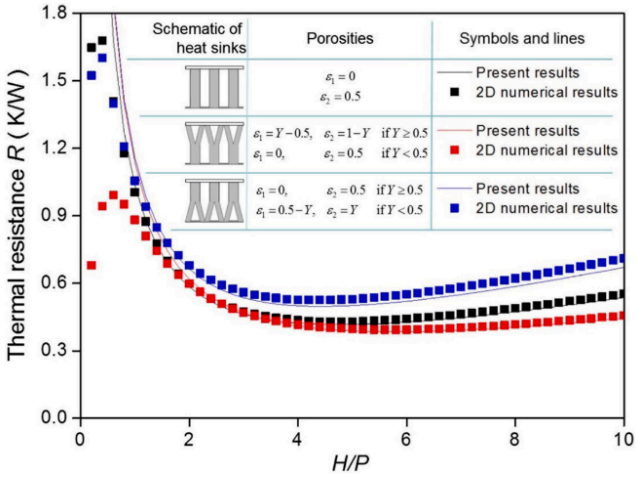


Figure 3. Schematic illustrating the effect of height variation on thermal resistance under different shapes [12]

The second strategy is flow-distribution optimization, in which manifolds, local throttling elements, or multiple inlets direct more coolant toward high-heat-load regions. MMCs are a representative implementation of this concept. Their advantage is that passive geometric design can redistribute flow without placing a separate actuator in every microchannel. Their limitation is that a fixed geometry may become less effective when hotspot locations change dynamically [13].

The third strategy is two-phase flow cooling. Flow boiling utilizes latent heat and can provide very high heat-transfer rates; because local high-temperature regions have stronger nucleation and evaporation driving forces, the process can exhibit a degree of self-adaptive enhancement. However, microchannel boiling is also susceptible to dryout, pressure-drop oscillations, flow redistribution, and critical-heat-flux limitations. These instabilities are especially important under non-uniform heating, where parallel branches are strongly coupled.

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The fourth strategy is near-junction or embedded cooling, in which microfluidic passages are positioned as close as possible to the heat-generating junction to reduce parasitic thermal resistance from packaging layers, thermal-interface materials, and spreading layers. This approach can significantly improve local thermal response, but it also imposes stricter requirements on mechanical integrity, electrical insulation, sealing, and manufacturing yield.

3.3. Advantages of manifold microchannels for hotspot cooling

The fundamental reason MMCs are well suited to hotspot cooling is their high degree of freedom in flow distribution. By adjusting manifold inlet locations, local cross sections, and branch resistances, the pressure and velocity fields can be shaped before the coolant enters the microchannels so that they better match the heat-source distribution. For multicore or multi-hotspot chips, multilevel manifolds or zoned coolant delivery can allocate the system flow among several local thermal regions while reducing competition among branches through resistance matching.

Experiments by Drummond et al. showed that hierarchical manifold arrays can maintain high heat-transfer capability over short flow paths when background heating and localized hotspots occur simultaneously. Zhou et al. further demonstrated that hierarchical flow-path design and uniform coolant delivery are also critical for reducing pressure drop and improving large-area heat-sink performance [14]. Thus, hotspot-oriented MMC design should not maximize hotspot flow alone; it should balance the minimum required cooling in low-load regions, overall temperature uniformity, and pumping-power constraints.

3.4. Nanofluids and emerging coolants

In addition to geometric enhancement, improving the effective thermophysical properties of the coolant is a common strategy. Nanofluids containing Al_2O_3, CuO, or carbon-based nanoparticles dispersed in water or glycol can increase effective thermal conductivity and modify boundary-layer heat transfer. The review by Japar et al. indicates that low nanoparticle volume fractions can improve heat-transfer performance under some microchannel conditions, but viscosity increases, sedimentation, clogging, corrosion, and long-term stability can offset part of the benefit [15]. Nanofluid evaluation should therefore focus on integrated thermo-hydraulic performance and reliability rather than thermal conductivity alone.

Low-melting-point liquid metals possess high thermal conductivity and a broad operating-temperature range and have been proposed as advanced coolants for high-heat-flux systems. Deng et al. reviewed convective heat transfer, pumping methods, and microchannel enhancement strategies for gallium- and bismuth-based liquid metals. Compared with water, liquid metals offer advantages in high-temperature and high-heat-flux environments, but wetting behavior, oxidation, corrosion, electrical conductivity, and material compatibility substantially increase system complexity. In the near term, they are more likely to be validated in specialized high-power devices or closed dedicated cooling loops.

3.5. Comparison of research emphases

International research moved relatively early from conventional external heat sinks toward near-junction, intrachip, and hierarchical manifold cooling, creating a continuous research chain from single-phase to two-phase operation and from device-level to system-level studies [16]. More recently, the emphasis has shifted toward high-heat-flux experimental validation, flow uniformity,

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three-dimensional integration, and manufacturability. Research in China has also progressed rapidly in microchannel structural enhancement, numerical optimization, thermo-hydraulic coupling, and advanced coolants, with strong links to high-power electronics and data-center liquid cooling.

From an engineering perspective, the main bottlenecks are no longer limited to the maximum heat-transfer coefficient of an individual structure. Long-term reliability, contamination control, pump and piping integration, sealing, online monitoring, and control under dynamic operating conditions are equally important. Future work should strengthen co-design across the device, package, and cooler and use consistent metrics for thermal resistance, pressure drop, pumping power, temperature uniformity, and reliability when comparing different concepts.

4. Heat-transfer enhancement mechanisms and variable boundary conditions

4.1. Application of the field-synergy principle

The field-synergy principle interprets convective heat-transfer enhancement in terms of the coordination between the velocity field and the temperature-gradient field. Guo, Tao, and Shah showed that, under otherwise comparable conditions, improving the synergy between the velocity vector and temperature gradient can strengthen convective heat transfer, and that the overall degree of synergy can be evaluated using a field-synergy number [17]. This principle provides a unified physical framework for understanding disturbance structures, jet impingement, and secondary-flow enhancement in microchannels.

In an MMC, the manifold not only distributes coolant but also reshapes the velocity direction and local shear at microchannel entrances. When the resulting flow transports cold fluid more effectively through near-wall high-temperature regions, shortens the thermal-boundary-layer development length, or strengthens transverse mixing, the synergy between the velocity and temperature fields is improved. Compared with simply pursuing a higher Reynolds number, a field-synergy-based design aims to concentrate momentum exchange where heat-transfer enhancement is truly needed while keeping pumping power acceptable.

4.2. Vortices and secondary-flow enhancement

Under many single-phase microchannel operating conditions, the flow remains laminar or transitional, and the developing thermal boundary layer limits further heat transfer. Turns, contractions, and jets at manifold entrances, together with pin fins, fins, or other disturbance elements inside channels, can generate transverse velocity components and secondary flows. These structures transport cooler core fluid toward the heated wall and move warmer near-wall fluid back into the main stream.

Secondary flow can disrupt or periodically renew the boundary layer, but stronger vortices are not always beneficial. Excessive separation and large recirculation zones can create low-velocity dead zones and additional local losses, causing the pumping-power penalty to outweigh the heat-transfer gain. Vortex design should therefore consider location, scale, and persistence so that the flow structures align with hotspot regions and primary heat-transfer surfaces.

At the manifold scale, flow uniformity and local enhancement can compete with one another. Uniform distribution often requires limiting excessive inertia and recirculation in the manifold, whereas hotspot enhancement may require higher local jet momentum. Hierarchical manifolds, tapered cross sections, and local resistance matching are valuable because they allow these objectives to be adjusted more independently.

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4.3. Thermal performance under dynamic and non-uniform boundary conditions

Real chip thermal loads are strongly transient. Workload changes modify hotspot intensity, position, and number, so a structure optimized under steady uniform heat flux may not remain optimal during dynamic operation. For a fixed-geometry MMC, the thermal response is jointly governed by fluid thermal inertia, heat spreading in the solid, flow redistribution, and the time scale of the control loop.

A fundamental design principle for spatially non-uniform heat sources is to match cooling capacity to local thermal load. Hotspot regions can receive higher flow rates, lower inlet temperatures, or shorter effective flow paths, while low-load regions receive only the minimum cooling required to maintain safe temperatures. This concept can be implemented passively using non-uniform manifolds or actively using multiple inlets, valves, pump-speed control, and temperature feedback. Hotspot experiments and flow-optimization studies both indicate that temperature uniformity cannot be achieved simply by increasing total flow; spatial distribution must also be improved [18].

For two-phase systems, dynamic boundary conditions additionally cause rapid shifts in the boiling onset location, vapor fraction, and branch pressure drop, which can amplify flow oscillation and dryout risk. More high-time-resolution experiments and transient multiphysics models are required to quantify the relationships among heat-source changes, flow response, and temperature recovery.

4.4. Multiphysics simulation and data-driven optimization

MMC design commonly involves three-dimensional flow, conjugate heat transfer, solid heat spreading, and thermomechanical stress. Finite-volume and finite-element methods are widely used; depending on the scale and operating conditions, axial conduction, entrance effects, temperature-dependent properties, or slip boundaries may also need to be considered. Two-phase cooling further requires treatment of interface evolution, nucleation, liquid-film evaporation, and critical heat flux.

Although high-fidelity CFD provides detailed velocity and temperature fields, its direct use in multi-objective optimization can be computationally expensive. Response surfaces, Kriging models, and neural-network surrogates are increasingly combined with genetic algorithms, particle-swarm methods, or Bayesian optimization to search the design space more efficiently. Wang et al. showed that surrogate models can introduce optimization metrics specifically targeting flow and temperature maldistribution and thereby accelerate structural optimization [19].

The reliability of data-driven optimization nevertheless depends on the quality of the training data, coverage of the parameter space, and the use of appropriate physical constraints. Future approaches should embed conservation laws, dimensionless relations, and manufacturing constraints into machine-learning models and calibrate them with experimental data to improve extrapolation and interpretability.

4.5. Fabrication and system integration

Silicon MMCs commonly rely on lithography, DRIE, thin-film processes, and wafer bonding to realize highly integrated intrachip or near-junction cooling structures. Metallic heat sinks are more compatible with micromilling, laser processing, electrochemical machining, and additive manufacturing. As fluid networks become increasingly three-dimensional, the process complexity and sealing risk of planar fabrication and multilayer bonding increase. Monolithic additive

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manufacturing has therefore received growing attention because it can directly create complex manifold and microchannel networks [20].

Engineering deployment must also address surface roughness and pressure loss, particle contamination, corrosion, thermal-cycling fatigue, connector sealing, pump reliability, and coolant maintenance. In data centers and high-power modules, cooler performance should ultimately be evaluated within the framework of total system energy, maintainability, and lifecycle cost rather than chip-level thermal resistance alone .

5. Conclusions and outlook

By shortening the effective flow length, regulating the pressure distribution among parallel branches, and enhancing local jetting and secondary flow, manifold microchannels provide an important approach for balancing heat transfer and pressure drop in high-heat-flux and hotspot-dominated chip cooling. Existing studies have demonstrated the effectiveness of MMCs in single-phase and two-phase operation, intrachip cooling, and hierarchical flow distribution [14-16]. At the same time, the original manuscript's treatment of a particular set of geometric dimensions as universally optimal was not sufficiently rigorous. The revised version makes clear that manifold structures must be optimized for the specific chip area, heat-source distribution, coolant, flow rate, and allowable pumping power.

Future research should prioritize: adaptive flow redistribution and closed-loop cooling for dynamic multi-hotspot conditions; co-design of the chip, package, manifold, and pumping network to reduce intermediate thermal resistance and system redundancy; stable and controllable two-phase cooling, nanofluids, and liquid-metal coolants together with long-term compatibility and contamination-control strategies; integration of high-fidelity simulation, experimental databases, and physics-constrained machine learning for efficient multi-objective optimization; and wafer-scale processing or additive manufacturing for integrated three-dimensional manifold-microchannel networks.

Overall, the development of manifold microchannel technology is shifting from the pursuit of extreme heat-transfer performance toward integrated optimization of thermal performance, hydraulic performance, dynamic response, manufacturability, reliability, and system energy efficiency. Reproducible experimental evaluation and design methods based on realistic chip operating conditions will be essential for advancing the technology from laboratory prototypes to reliable engineering applications.

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