

Review

A Review of Non-Uniform Load Distribution and Solutions in Data Centers: Micro-Scale Liquid Cooling and Large-Scale Air Cooling

Yifan Li ¹, Congzhe Zhu ¹, Xiuming Li ^{2,*} and Bin Yang ^{1,*}

¹ School of Energy and Safety Engineering, Tianjin Chengjian University, Tianjin 300384, China; yifan100zixuan@163.com (Y.L.); zhucongche1124@163.com (C.Z.)

² Liaoning Engineering Research Center of Process Industry Energy Saving and Low-Carbon Technologies, School of Metallurgy, Northeastern University, Shenyang 110819, China

* Correspondence: lixiuming@smm.neu.edu.cn (X.L.); binyang@tcu.edu.cn (B.Y.)

Abstract: Nowadays, the number of transistors on electronic components is increasing exponentially leading to an ultra-high heat flux ($10^6 \sim 10^7$ W/m²). The non-uniform load distribution on the chip and the local hot spots in the thermal environment are key issues in a data center (DC). Microchannel liquid cooling is an effective method to inhibit heat accumulation on the chip. Optimizing the air distribution is a crucial approach to realizing energy savings. This study summarizes the latest research on thermal management by microchannel liquid cooling and air distribution optimization in DCs. The existing issues concerning the structure universality of the microchannel heat sink (MCHS), the stability of flow boiling and the new coolant, the prediction of local hot spots, and the intelligent control of the cooling system are identified. Furthermore, a novel cooling strategy of multi-scale synergy is recommended, which is expected to suppress local hot spots and heighten temperature uniformity. This review provides valuable insights into multi-scale thermal management for DCs. It paves the way for applying innovative cooling technologies and artificial intelligence methods to promote the efficient operation and low-carbon retrofit of DCs.

Keywords: data center; microchannel liquid cooling; air distribution; multi-scale synergy; intelligent regulation



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1. Introduction

As information technology (IT) such as cloud computing and artificial intelligence evolves at express speed, the DC occupies a crucial position in promoting digital and intelligent reformation; it is also an important guarantee for ensuring high-quality economic/social development. The number, scale, and market proportion of DCs are increasing progressively [1,2], and their power consumption has also increased significantly [3,4]. The proportion of power consumption for the cooling system in DCs is about 38%, second only to that of IT equipment [5,6]. Improving the cooling efficiency is vital to the green evolution of DCs.

However, the transient heat production of electronic chips is being improved constantly, while the heating area is very small. If the core chips cannot be cooled in time, local overheating will reduce the processing speed of electronic components severely and damage the IT equipment ultimately [7,8]. Therefore, the thermal management of a DC has become a research focal point. The heat transfer of DCs spans multiple spaces

and timescales, and the thermal management of DCs is divided into room/system-based, rack/server-based, and chip-based cooling solutions [9,10]. Bringing the concentrated heat on the chip from the small-space to the large-space environment efficiently, and then transferring it to the atmosphere, is closely related to the overall efficiency of the DCs.

The heat is initially generated in electronic chips, which are core components in digital information. The exponential growth of data transmission and processing brings about high heat production in the chips. The traditional room air conditioner makes it difficult to accomplish the heat removal task and will greatly increase the power consumption of DCs [11,12]. Chip-level liquid cooling technology has gradually become a research emphasis [13,14]. According to whether the cooling medium contacts the electronic chips directly, the liquid cooling is divided into direct and indirect type. The direct type mainly includes immersion cooling [15] and spray cooling [16]. Nevertheless, dielectric fluid or mineral/synthetic oil are the major coolants of the direct-type cooling, but their heat transfer coefficient (HTC) is much lower than that of water. Inversely, the coolant in indirect liquid cooling does not contact with the electronic chips, so cooling mediums with a high heat capacity can be employed. For instance, adopting nanofluids in indirect liquid cooling is considered an effective method to heighten the cooling efficiency [17,18]. The security of the indirect liquid cooling system is better, and the maintenance cost is lower compared with that of the direct liquid cooling [19,20]. Nowadays, microchannel liquid cooling is gaining much attention as a promising indirect cooling solution, owing to the advantages of large area/volume ratio, high heat transfer intensity, small size, lightweight, easy integration, etc. The structure of the microchannel heat sink (MCHS), the flow distribution, the flow state, and the characteristics of the cooling mediums have a noteworthy influence on the cooling efficiency [21,22].

When heat is transferred from the electronic components to the indoor space, the airflow management controls the temperature field. A reasonable and uniform airflow distribution ensures that the DC is in a good thermal environment, thereby improving energy efficiency. The original unorganized air supply method leads to cold and hot fluid mixing, temperature maldistribution, and large power consumption with excessive cooling, which is unable to eliminate the local overtemperature. To heighten the cooling effectiveness, room-scale cooling has gradually evolved into row-scale and rack-scale cooling technologies. Some researchers have studied the impacts of air management modes, layouts of computer room air conditioning (CRAC) and server, and air supply parameters on the indoor environment. Results show that temperature maldistribution with hot air recirculation or cold air bypass is the crucial factor that worsens the thermal environment. Reasonable air distribution can significantly heighten the cooling effect and reduce power consumption [23–25].

According to the above literature, the existing reviews for the thermal management of DCs typically focus on liquid cooling and air cooling separately. However, the heat on the electronic chip will eventually dissipate into the large space affecting the thermal environment. There is a lack of systematic discussion on multi-scale thermal management. Therefore, the latest research on micro-scale liquid cooling and large-scale air cooling is outlined. The issues, solutions, prospects, and the synergy of cooling technologies at different levels are analyzed. The framework of this review is depicted in Figure 1. Firstly, the applications of microchannel liquid cooling in DCs are summarized, including the configurations of MCHSs, the phase change cooling characteristics, and the thermal performance of nanofluids. Secondly, the optimizations of large-space air management are analyzed, including the air distributions, the configurations of rack-based cooling, and the monitoring and prediction of the indoor environment by machine learning (ML). Finally, existing issues and further research points on chip-level cooling and multi-scale thermal

management are clarified. An innovative hybrid cooling system is introduced to eliminate the uneven load and local overheating in DCs.

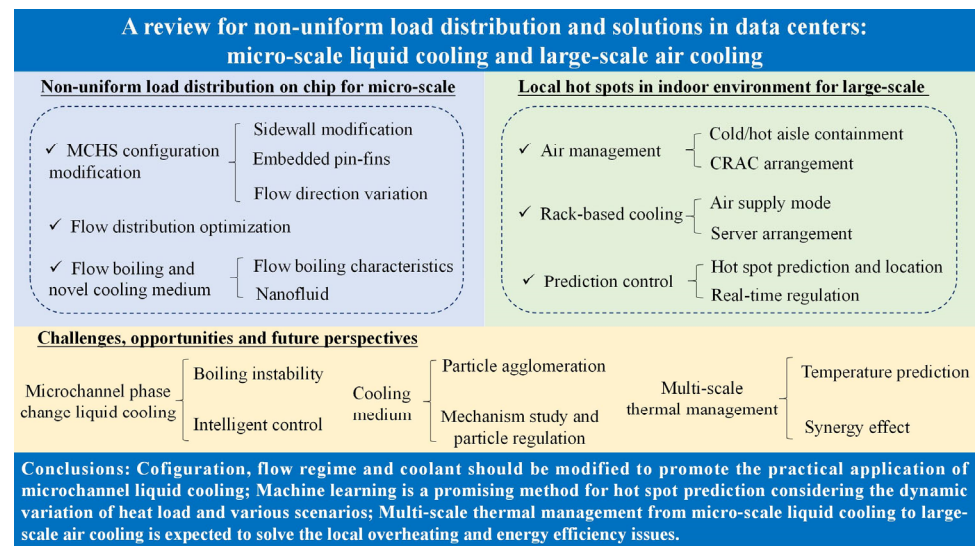


Figure 1. The framework of this review.

The novelty of this paper includes the following: (1) considering the overall path of heat transport, the current research and existing problems of cooling technologies at different levels are discussed systematically; (2) the development directions and solutions of chip-level liquid cooling are pointed out, including flow state and cooling medium; (3) an innovative hybrid cooling system with chip-level microchannel cooling and large-space air cooling is recommended to solve the local overheating of high-power DCs while improving the overall energy efficiency.

2. Non-Uniform Load Distribution on Chip for Micro-Scale

To cope with the challenge of an extremely high load of electronic components with weight and volume limitations, the MCHS was put forward by Tuckerman and Pease [26] and has been widely used to suppress local overheating in electronic devices [27,28]. The schematic of the assembly structure for microchannel liquid cooling is presented in Figure 2. The MCHS is closely fitted with the electronic chip by thermally conductive silicone grease. The cooling medium is driven by the pump to flow in the MCHS to absorb heat from the chip. Then, the cooling medium is cooled to a constant temperature by a condenser. The research on microchannel liquid cooling mainly includes MCHS configuration optimization, flow boiling performance, and novel coolants.

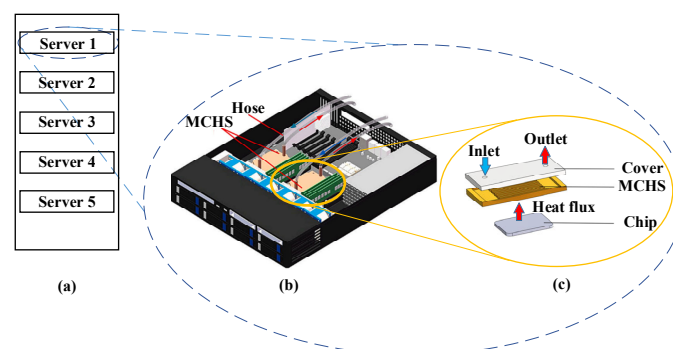


Figure 2. Schematic of the assembly structure for microchannel liquid cooling. (a) Rack; (b) Server [29]; (c) Microchannel heat sink.

2.1. MCHS Configuration Modification for Solving Non-Uniform Load

2.1.1. Sidewall Modification

The geometric structure of the MCHS has an apparent impact on its thermal characteristics. Configuration optimization is a popular method to strengthen heat transfer with high efficiency and no external power [30,31]. Some investigations have been performed on the modification of sidewall of the channel, which obtained good performances in thermal capacity, pressure drop, and temperature uniformity [32–38]. The main configurations in the open literature include the jetting and throttling structures (Figure 3a), micro-plates (Figure 3b), micro-ribs (Figure 3c), and combination of grooves and ribs on the sidewalls (Figure 3d). Results indicated that the periodic interruption of the boundary layers caused by the jetting/throttling structures or grooves was the essential factor for enhanced thermal capability [32–34]. The micro-plates and ribs on the sidewalls brought about flow acceleration. The cooling capability was closely related to structural parameters [35–37]. The combination of grooves and ribs gave rise to a stronger disturbance in the thermofluid near the sidewalls [38]. The alternation between fluid acceleration and deceleration heightens thermal transport efficiency.

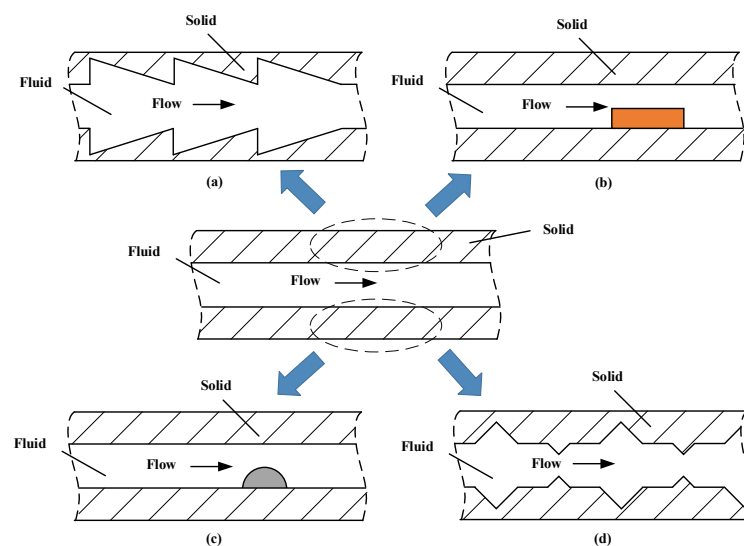


Figure 3. Schematic of the microchannel with various grooves or ribs on the sidewalls, (a) microchannel with jetting and throttling structures; (b) microchannel with micro-plate; (c) microchannel with rib; (d) microchannel with grooves and ribs.

2.1.2. Embedded Pin-Fins

The micro pin-fins embedded in the center of the flow passage can strengthen chaotic advection, and promote thermofluid redistribution, which has an obvious impact on heat transfer. Some researchers have introduced a variety of combinations of fins and microchannels, revealing the mechanism of the heightened cooling efficiency [39–50]. The main configurations of embedded pin-fins in the existing literature are described in Figure 4. The embedded pin-fins induce more severe turbulence on the mainstream and obtain better cooling performance. The hydrodynamic characteristics have a direct influence on the temperature performance of the MCHSs. Eneren et al. [40] examined the evolution features of the velocity field in heat sinks with offset strip fins or square pin-fins by micro-PIV. The consistent monotonic decay of flow perturbations with a single exponential mode was proved. The pressure drop and flow friction caused by fin structures were also analyzed, which helped to explain the essence of heat transport enhancement.

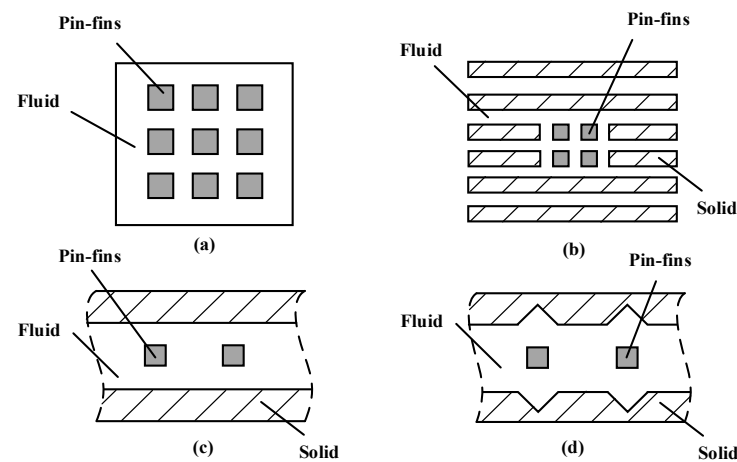


Figure 4. Configurations of embedded pin-fins, (a) pin-fins in entire flow region; (b) pin-fins in local region; (c) pin-fins in the center of a channel; (d) coupling of grooves and embedded pin-fins.

The layout, volume fraction, and shape of the pin-fins also have an important impact on the thermofluid features [41–45]. The non-closed droplet pin-fin introduced more violent disturbance and a more uniform temperature field. For the asymmetric fins, the flow direction had a considerable effect on the heat dissipation [43]. The staggered arrangement and small volume fraction were beneficial to heighten the cooling capability [45]. Moreover, the synergy effect of grooves and fins was explored, the combined configurations obtained a superior cooling effect under a relatively small pump power because of the flow passage enlargement [48–50]. To reduce pump power and heighten the comprehensive capability of this kind of configuration, further structural optimization is needed.

2.1.3. Flow Direction Variation

Some scholars find that the flow direction variation is conducive to interrupting the boundary layer and enhancing the impinge impact on the sidewalls, thereby taking away the heat rapidly [51–57]. Breaking the sidewalls to form secondary passages or adopting curved microchannels are typical methods as shown in Figure 5. The results revealed that the secondary channels destroyed the boundary layer and promoted thermofluid mixing. The wavy microchannels with or without microstructures heightened the thermal capability and optimized the thermofluid distribution by the periodic variation in the flow field. The MCHSs with up–down wavy structures had a better cooling effect than their left–right wavy counterparts, because the Dean vortices near the sidewalls induced a more efficient mixing of cold and hot fluids [55]. In addition, the synergy effect of secondary/wavy channels and embedded pin-fins triggered the backflow and tended to achieve a better overall performance due to the uniform flow distribution and adequate mixing [56,57].

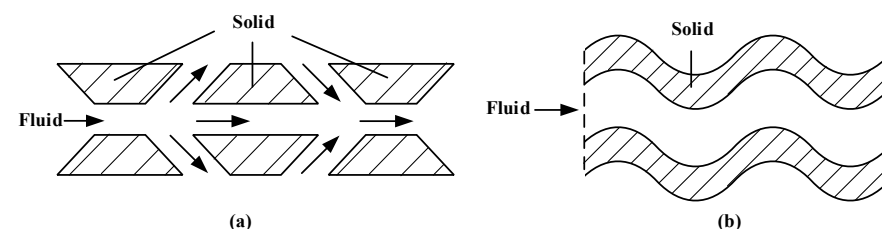


Figure 5. Microchannel configuration for varying flow direction: (a) secondary channels; (b) wavy microchannel.

2.2. Flow Distribution Optimization for Solving Non-Uniform Load

The flow route and distribution in the MCHSs have an obvious influence on the cooling capacity and pump power, which is a notable element impacting the system's capability [21,58–63]. The flow divergence/confluence caused by various inlet/outlet layouts directly modifies the flow state and heat transfer characteristics [64–71]. Figure 6 summarizes the main arrangements in the open literature. Xia et al. [68] introduced three types of entrance/exit positions and configurations for heightening the temperature homogeneity (Figure 6a). The I-shaped layout and the rectangular configuration provided the most uniform velocity distribution because of the interaction between the fluid branching and the header wall. Savino et al. [69] designed double-layer cooling plates, and the optimizations of the flow configuration and the header design were performed (Figure 6b). The cross-flow mitigated the fluid maldistribution, enhanced the thermal capacity, and reduced the thermal resistance by 11.8%. Rajalingam et al. [70] found that the temperature difference on the cooling plate could be effectively reduced by adding another entrance. Modifying the angle between the two entrances could heighten the temperature uniformity (Figure 6c). Cao et al. [71] compared different manifold structures (Figure 6d); the pump power of manifold MCHSs was lower than that of the parallel microchannels. The effectiveness of shortening the flow path for reducing power consumption was verified again.

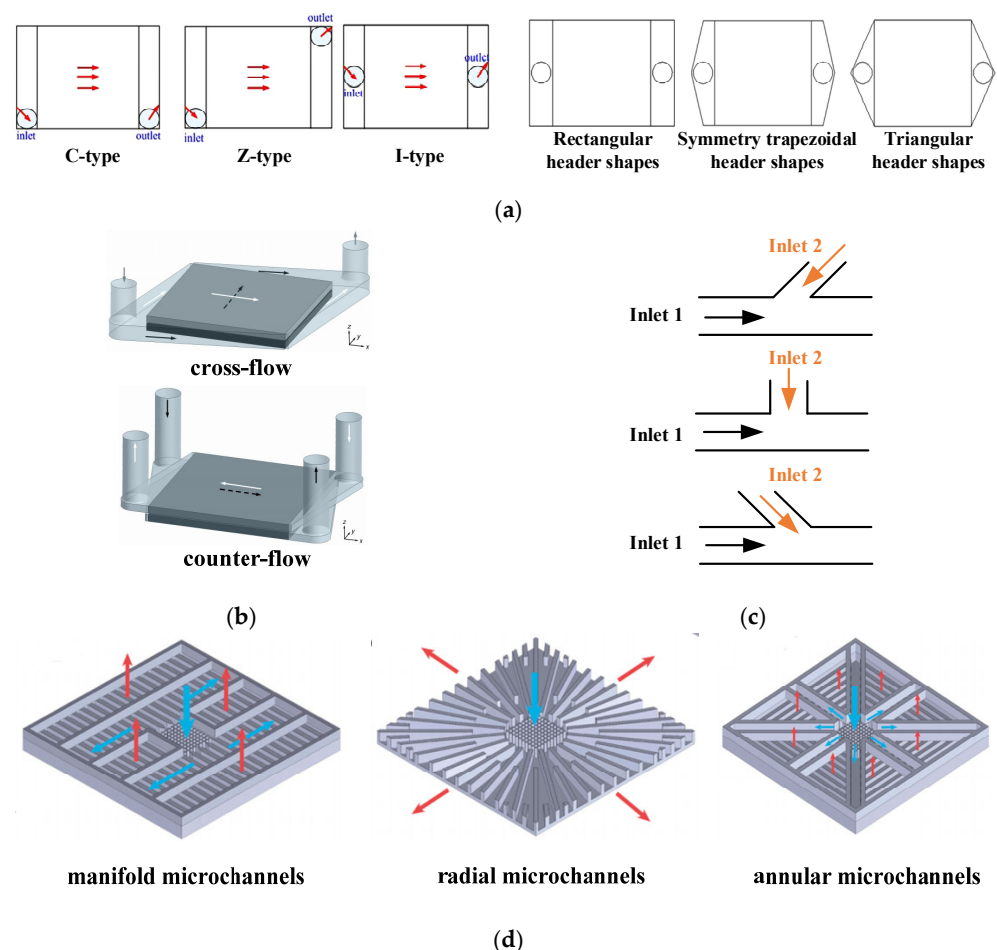


Figure 6. Investigation of flow path and distribution. (a) Various flow divergence/confluence configurations [68]; (b) double-layer cooling plates with different flow configurations [69]; (c) various arrangements of secondary inlet; (d) different manifold structures [71].

In addition, the MCHSs with fractal network configurations can optimize the flow distribution and improve the temperature homogeneity better than the traditional parallel

channels. The fractal level and local structure are the key factors affecting the heat dissipation capability [72–74]. Topology optimization has attracted more and more attention in recent years. It provides a feasible method to heighten the comprehensive efficiency of MCHSs [75–79]. The multiple targets of enhanced HTC and reduced pump power are expected to be achieved by this approach.

2.3. Flow Boiling and Novel Cooling Medium for Solving Non-Uniform Load

2.3.1. Flow Boiling Characteristics

Many studies have shown that latent heat can obtain higher cooling efficiency and eliminate overheating accompanied by lower power consumption better than single-phase liquid cooling. However, the micro-scale boiling instability easily leads to a boiling crisis, which seriously hinders the application of microchannel flow boiling [80–82]. Some researchers tried to optimize the two-phase distribution and heighten boiling stability by changing the configuration [83–95]. The gas–liquid distribution could be adjusted by changing the aspect ratio of the microchannel, thus mitigating the bubble confinement [95,96]. Moreover, some scholars noted that the capillary effect on the contact surface had a considerable impact on the phase change cooling of the microchannels [96–101]. The mixed wettability surface was expected to realize lower ONB, larger HTC, and higher CHF simultaneously [99]. Table 1 provides the typical cooling mediums, configurations, and main findings in the open literature. The results revealed that the microstructures had a non-negligible impact on bubble behavior and two-phase evolution, which could regulate the thermofluid features.

Table 1. Typical configurations and phenomena of the flow boiling in microchannels.

Author	Coolant	Configuration	Finding
Drummond et al. [87]	HFE-7100	Manifold channel	Shortening flow length achieved maximum HTC with acceptable pressure drop
Deng et al. [88]	DI water	Microchannel with pin-fins	HTC increased with reduced pressure drop and more stable boiling
Li et al. [89]	Pure acetone (CH ₃ COCH ₃)	Microchannel with grooves and fins	Periodic impact promoted nucleation and steam removal
Tiwari et al. [90]	Water	Wavy microchannel	Curved structure delayed the evolution from bubble to slug
Zhao et al. [91]	DI water	Leaf-vein-type structure	Bubbles mainly moved along the vein structures
Xia et al. [83] and Zong et al. [92]	Pure acetone (CH ₃ COCH ₃)	Microchannel with flow direction variation	Lower ONB and delayed CHF with a more stable boiling
Luo et al. [85] and Fallahtafi et al. [93]	HFE-7100	Microchannel with jet effect	Decreased thermal resistance with pressure drop augmentation
Cheng et al. [94]	Water	Microchannels with different widths	Narrow microchannels impeded the bubble evolution
Zhang et al. [96] and Zhao et al. [97]	Water	Different surfaces with various wettability	Hydrophobicity surface obtained lower ONB; superhydrophilic surface heightened HTC and reduced pump power
Vontas et al. [100]	Ethanol	Six different wettability cases	Liquid film evaporation was better than contact line evaporation

2.3.2. Nanofluid

Nanofluid is a novel coolant that has stable and high thermal conductivity by adding metal or non-metal nanoparticles uniformly to the traditional coolant, as proposed by Choi et al. [102]. Nowadays, the research on nanofluids with a single type of particle mainly includes the following: (1) preparation and stability; (2) energy transport parameters; (3) surface characteristics; and (4) convective heat transfer characteristics. Based on the existing literature, the high temperature, large volume fraction, high PH level, and surface modification can effectively increase the thermal conductivity [103–106]. Some researchers believe that compared with pure water, the HTC for the nanofluids is heightened, especially for high concentrations. However, some researchers discovered that nanofluids did not observably enhance heat transport. Eneren et al. [107] found that the interplay of abrasion, erosion, and corrosion caused by the particle agglomeration was the main reason. Some scholars attributed this phenomenon to different evaluation indicators and excessively large concentrations [108,109].

A hybrid nanofluid is composed of two or more nanoparticles mixed with the base liquid, which is expected to meet the multiple requirements of good stability, high thermal conductivity, and good rheology [110–118]. Compared with mono-nanofluids, some investigators concluded that the synergy effect of multi-particles with high thermal conductivity markedly improved the thermal transport capability [115,116]. However, other researchers argued that some combinations of particles reduced the thermal transport in comparison with the corresponding mono-nanofluids [117,118]. Some efforts have been made in studying the thermohydraulic capability of the nanofluid medium in MCHSs, as listed in Table 2.

Table 2. Summary of nanofluids for microchannel liquid cooling.

Author	Coolant	Configuration	Finding
Esmailzadeh et al. [106]	DI water and 1-pyrene carboxylic-acid-functionalized graphene nanofluid	Heat pipe	Thermal performance increased by 49.4%
Eneren et al. [107]	Al ₂ O ₃ /water and TiO ₂ /water	Straight channels	Channel material abrasion due to particle agglomeration
Souby et al. [108]	rGO–Co ₃ O ₄ and MWCNT–Fe ₃ O ₄ hybrid nanofluids	Straight channels	Reduced maximum temperature of the CPU for high concentration
Chu et al. [111]	AlN–Ti ₂ O ₃ /water hybrid nanofluid	Circular channels	Improved HTC for high concentration
Bahiraei et al. [112]	Graphene–silver nanoparticles	L-shaped and C-shaped heat sink	Lower irreversibility than pure water
Jamshidmofid et al. [113]	Graphene oxide–cobalt oxide/water hybrid nanofluids	MCHS with sinusoidal cavities and rectangular ribs	Nanofluid increased the HTC more than the pressure drop
Aguirre et al. [114]	Al ₂ O ₃ -MWCNT/water/ethylene glycol	Micro pin-fin heat sink	Nanoparticles did not ensure a higher thermal efficiency
Chen et al. [116]	MWNTs and Fe ₂ O ₃	/	Heat conductive networks were formed by MWNTs and Fe ₂ O ₃ particles
Jana et al. [117]	Cu/water and CNT–Cu/water	/	Mono-nanofluid showed the greatest thermal conductivity

In conclusion, the development of phase change cooling and new cooling mediums is important to heighten the efficiency of microchannel liquid cooling. However, these approaches have not been applied to the thermal management of actual DCs due to the instability of the boiling process and the agglomeration of nanofluids. The particle motion and scale effects at the micro-level directly affect the stability and energy transport characteristics of nanofluids. In addition, the nanoparticles increase the dynamic viscosity, which leads to a large pump power. The overall energy efficiency should be considered for applying nanofluids [119,120].

3. Local Hot Spots in Indoor Environment for Large-Scale

Based on the overall heat removal route, after the heat is carried out from a small space to the room space, reasonable air distribution is indispensable for transferring the heat to the atmosphere efficiently [121]. The main issues of air distribution in DCs cover the uneven flow distribution, the mismatch between the air supply and demand, and the airflow loss. It is urgent to develop more efficient control methods to ensure that the indoor environment of the DCs is maintained within the safe thresholds [23]. The hot air recirculation and cold air bypass remain a matter of concern leading to thermal inefficiencies. Shortening the route of cold air and employing row-scale and rack-scale cooling technologies with cold/hot aisle containment are identified as effective ways to heighten energy efficiency, as displayed in Figure 7 [122]. Moreover, artificial intelligence technology for thermal performance prediction and optimization has made important progress in recent years.

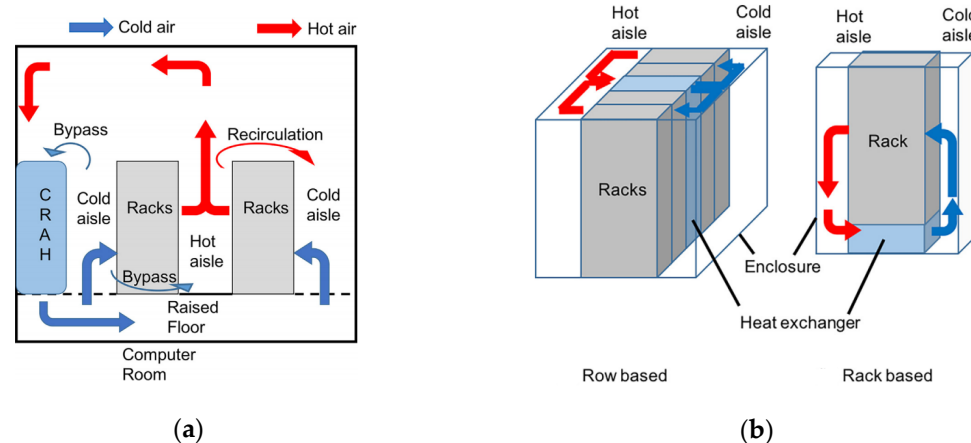


Figure 7. Different air management methods [122]. (a) Conventional air distribution with hot air recirculation and cold air bypass; (b) row-scale and rack-scale cooling with cold/hot aisle containment.

3.1. Air Management for Solving Local Hot Spots

To avoid the instability and non-uniformity in the air velocity and temperature fields caused by unreasonable air conditioning systems and suppress the local hot spots caused by hot air recirculation, some researchers have carried out optimization studies on the air management [123–129].

Cold/hot aisle containment can markedly improve airflow distribution, reduce the mixing of cold and hot air, and heighten energy efficiency [130–135]. Lee et al. [130] proposed an airflow management method of overhead downward flow with cold aisle containment, which effectively avoided the interlacing of hot/cold air. The impacts of supply air temperature and velocity on the cooling capability were studied, and a relatively low power consumption was achieved. Jao et al. [131] performed experiments to test the impact of inhomogeneous heat load, configurations, and airflow rate on the air distribution

for aisle semi-containment, full containment, and non-containment. The high flow rate and the fully enclosed cold aisles were proved to enhance the air distribution uniformity.

The arrangement of the CRAC has a significant impact on the temperature distribution, airflow circulation, and bypass [136–141]. Locating the CRAC perpendicular to the racks presented a superior effect for enhancing flow uniformity, reducing hot air recirculation, and cold air bypass compared with the inline arrangement [138]. Abbas et al. [139] evaluated the thermal features for different configurations of symmetrical/unsymmetrical cooling units and contained/non-contained top aisles by numerical simulation, as described in Figure 8. They found that the aligned arrangement and top aisle containment were beneficial to modifying the temperature distribution, indoor environment, and energy saving. Considering the variation in the outdoor environment, Fang et al. [140] compared the effect of different arrangements of the CRAC on the velocity and temperature fields in the DC; the temperature distribution at the entrance of the racks was estimated by a uniformity index. For row-based cooling, the reasonable layouts of the CRAC and aisle containment could guarantee the balance between the air supply and demand. The layout of the cold/hot/cold aisle promoted the heat balance and heightened the energy efficiency [141].

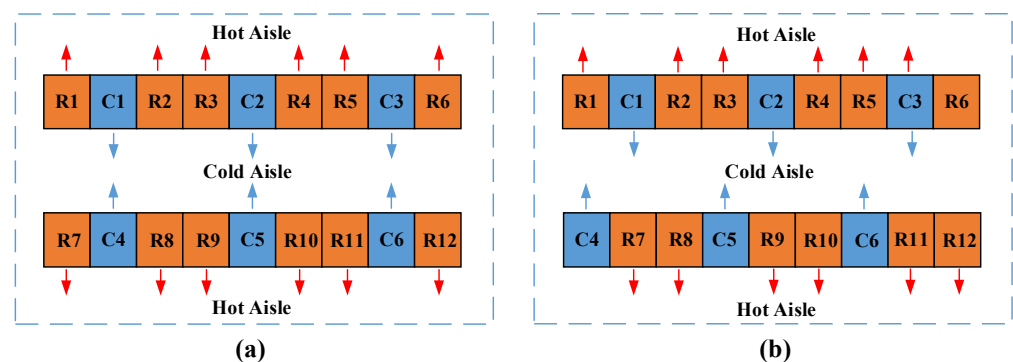


Figure 8. Different cooling unit arrangements, (a) aligned and (b) staggered layouts.

3.2. Rack-Based Cooling for Solving Local Hot Spots

The rack-based cooling technology is a feasible method to accurately control the temperature distribution in the cabinet. Some efforts have been made to illustrate the air supply mode and the arrangement of servers in the local thermal environment of the racks [142–144]. The direct-supply air types mainly include (1) an overhead air supply or (2) an air supply through a raised floor with perforated tiles. For overhead air supply, the cooling effect is influenced by the airflow rate and airtight treatment. The airflow distribution could be improved by employing a deflector and a diffuser [145,146]. For air supply through a raised floor with perforated tiles, the geometry of the underfloor plenum had a considerable impact on the velocity and pressure distributions. Modifying the structure of the underfloor plenum and ventilation tiles played an active role in eliminating the vortices and optimizing the flow distribution [147–149].

The proper layout of servers can heighten the cooling efficiency and avoid hot spots [150–153]. The installation of air deflectors, baffles, and top exits effectively mitigates the overheating. Wu et al. [154] improved air management by installing baffles at the cabinet entrance. The optimal arrangement and structure parameters for the baffles were obtained, which could effectually mitigate the hot spots in the cabinet for a fan-wall DC. Wang et al. [155] analyzed the layouts of the server and the response features of the thermal environment within the cabinet to the dynamic heat load experimentally and numerically. They concluded that the near-heat source impact, thermal buoyancy, and top heat accumulation were the main factors affecting the thermal environment. Feng et al. [156] discussed the impact of blind plates on the air environment parameters in the

racks. They found that the blind plates benefited a heightened thermal capability and realized energy saving. The high-power IT equipment was recommended to be set at the rack's center.

3.3. Prediction Control for Solving Local Hot Spots

In recent years, some researchers have begun to explore the application of intelligent technologies such as machine learning (ML) for hot spot prediction, shutter control, and global optimization to retain the indoor environment of DCs.

Some initial attempts at indoor environment prediction in DCs by ML have been conducted [157,158]. Wang et al. [122] proposed two frameworks both model driven and data driven severally to establish the transient thermal model of DCs; both methods could predict the real-time temperature. Sasakura et al. [159] constructed a gradient-boosting decision tree model to predict the temperature at the cabinet entrance after the CRAC was shut down. The ML model showed good robustness. Khan et al. [160] adopted five supervised ML classification models to illustrate the indoor environment of the DC; the random forest classification model presented the optimal precision. Wang et al. [161] adopted a deep learning model to forecast the thermal features for air cooling. The datasets were established by various thermal environments for different air parameters. The convolutional neural network (CNN) model predicted the peak temperature in the CPU accurately through Bayesian optimization.

The preliminary explorations show that ML intelligent algorithms can achieve the accurate prediction of thermal environment parameters. However, the various temperature prediction models are only applicable to specific scenarios and do not consider the ambient temperature and chip temperature comprehensively.

Matching the supply and demand of cooling in DCs by efficient and intelligent control methods is a challenge [142]. The accurate prediction of local hot spots provides opportunities for intelligent regulation [162–166]. Grishina et al. [167] introduced an unsupervised ML model to identify hot spots and then adjusted the cluster load schedule. Saiyad et al. [168] established an artificial neural network (ANN) to predict thermal parameters, which achieved fast temperature prediction and could be used for real-time energy-efficient control. Fulpagare et al. [169] proposed a deep reinforcement learning (DRL) algorithm to detect and regulate the thermal environment parameters for individual zones. The power consumption of the fan was reduced by 12% to 50%.

At present, there is still a lack of multi-scale models for the overall heat transport path. Considering the dynamic variation in the heat load, it is necessary to further heighten the accuracy and timeliness of hot spot location and thermal environment classification by ML. The intelligence algorithm provides the possibility for the synergic operation and regulation of different cooling methods according to real-time parameters.

4. Discussion and Outlook

As the electronic chips tend to miniaturize with high frequency and low delay, the heat production on the chips increases dramatically with local overheating, which seriously threatens the stable operation of DCs. The development direction and hot spots of DC cooling technology mainly include three aspects: (1) Chip-level liquid cooling is an effective method to eliminate high heat flux in a small space. Microchannel liquid cooling has the advantages of high cooling efficiency and easy integration, which has a good application potential in DC thermal management [21,22]. By optimizing the configuration, changing the flow regime, and modifying the cooling medium, higher energy transport efficiency can be achieved under a smaller flow rate, thus improving the water utilization efficiency and reducing the power usage efficiency. (2) ML provides a feasible solution for parameter

classification and hot spot prediction [142,158]. The real-time monitoring of temperature parameters and the intelligent control of operating parameters are inevitable requirements for the development of DCs. Employing AI technologies to supervise and regulate the operating conditions in real-time is vital for realizing energy savings. (3) The thermal management systems at different levels are closely linked and synergic [10,161]. It is of much concern to establish hybrid thermal management from the chip-scale cooling to the large-space environment considering the overall heat transport path and the dynamic variation in the heat load. The synergy of multi-scale cooling technologies is expected to cope with the heat dissipation and energy efficiency issues of high-power DCs. To solve the existing issues and promote the practical application of advanced cooling technologies, further studies are recommended to be carried out.

4.1. Issues and Solutions for Microchannel Phase Change Liquid Cooling

The main concern of the current investigation is the heat and mass transport mechanisms in the micro-scale boiling process; there have been few practical studies in actual DCs. The main reasons include three aspects: (1) For the micro-scale, the ONB is relatively high, which leads to the explosive growth of nucleate bubbles. The rapid bubble expansion in the micro-space easily causes millisecond-level fluctuations in the wall temperature, resulting in uneven distribution of the two-phase fluid and serious boiling instability. The unstable flow boiling increases flow resistance and induces premature dryout and a liquid cooling system crisis [80–82]. (2) In the micro-space, the bubble behavior and two-phase flow evolve rapidly, showing complex nonlinear and chaotic characteristics. Especially, the complex microstructures increase the motion randomness of bubbles, which has a significant impact on bubble behavior and flow evolution [84,89]. (3) It is difficult to measure the transient multi-physical fields and predict the HTC, pressure drop, CHF, and other parameters during flow boiling.

Solving the above issues is a prerequisite for controlling the flow boiling process and applying it to the chip-level cooling in DCs. Computer vision and deep learning provide new ways for bubble parameter extraction, transient velocity field measurement, and flow pattern recognition [170–172]. It is essential to introduce computer vision, machine learning, and control technologies for ensuring the stability of the phase change cooling system.

4.2. Issues and Solutions for Novel Cooling Medium

The thermal characteristics of various nanofluids are very different due to the particle type, size, concentration, dispersant, etc. Some researchers concluded that nanofluids did not observably enhance heat transport [107–109]. Moreover, there are conflicting conclusions about the effect of hybrid nanofluids on energy transport efficiency in comparison with single-component nanofluids [115–118]. In general, the main challenges for the practical application of nanofluids include: (1) nanoparticle agglomeration leading to poor stability and material abrasion [107] and (2) flow friction heightened by nanoparticles, which causes an increase in pump power consumption [119,120].

To find out the key parameters affecting the thermal properties of nanofluids, the particle type, size, concentration, preparation method, operating parameter, etc., need to be comprehensively analyzed. ML is a promising method for the prediction of thermal transport parameters. Moreover, the motion and morphology of nanoparticles, i.e., Brownian motion, thermophoresis, infiltration, etc., directly impact the stability, thermal properties, and cooling performance of nanofluids. These should be further studied by molecular dynamics simulations and experiments to reveal the essence of particle deposition and to find effective control methods for high-efficiency energy transport.

4.3. Issues and Solutions for Multi-Scale Thermal Management

The optimization studies of air distribution mainly depend on numerical simulation and similarity experiments, which need to be examined based on the actual DCs. The temperature prediction models for DCs are only applicable to specific scenarios [173]. The transient distribution of air temperature needs to be supervised to obtain the thermal stagnation zone within a large space [142]. Moreover, the temperature difference between the air outlet of the server and the return air inlet of the cooling unit can reflect the issues of cold air bypass. The temperature difference between the air inlet of the server and the supply air outlet of the cooling unit can reflect hot air recirculation. However, the above two temperature differences have not been fully monitored. Reducing the two temperature differences helps to achieve a balance between efficiency and cost. In addition to the temperature of the indoor environment, the chip and device temperatures also need to be monitored to locate and predict the non-uniform load [174].

A single air cooling technology makes it difficult to take away the heat accumulated on chips within a small space and realize the multiple goals of local hot spot elimination and efficiency improvement. Considering the dynamic variation in the heat load and the overall heat transfer path, an innovative cooling strategy with multi-scale synergy is recommended as depicted in Figure 9. Microchannel liquid cooling is used to eliminate uneven load distribution on the chip, and air management is adopted to control the indoor environment of DCs. A total energy efficiency prediction model under different cooling modes should be constructed. When the power consumption of single air cooling exceeds that of the hybrid system, the corresponding chip temperature is defined as the threshold. If the chip temperature is lower than the threshold, the air cooling system operates separately. If the temperature is greater than the threshold, the microchannel liquid cooling is started, and the hybrid cooling system works cooperatively.

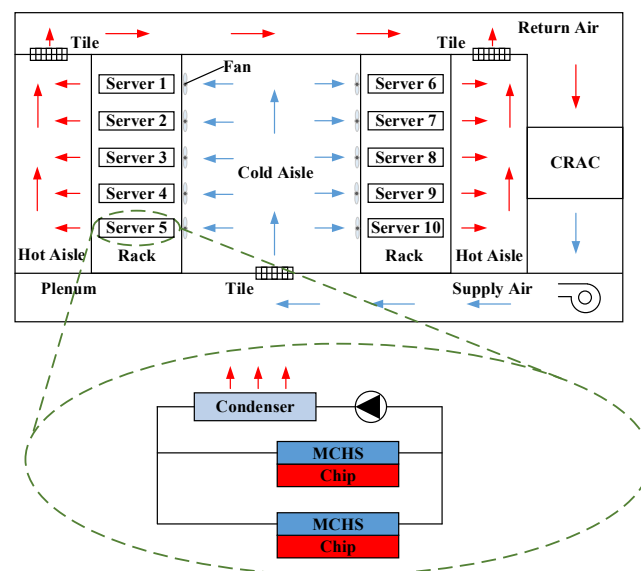


Figure 9. Schematic of the hybrid cooling system.

To achieve synergy cooling, the roadmap of the multi-scale system is described in Figure 10. The multi-scale model will be established, and the parameter sensitivity analysis will be carried out. The hot spots of the large space and the local overheating on the chip will be located and predicted by the ML based on the databases of influencing factors. For the hot spots of the large space, the airflow distribution optimization will be conducted. For the local overheating on the chip, microchannel liquid cooling will be performed. By real-time monitoring of thermal environment parameters and chip temperature, the

cooling mode and operating parameters are intelligently controlled to minimize the total power consumption.

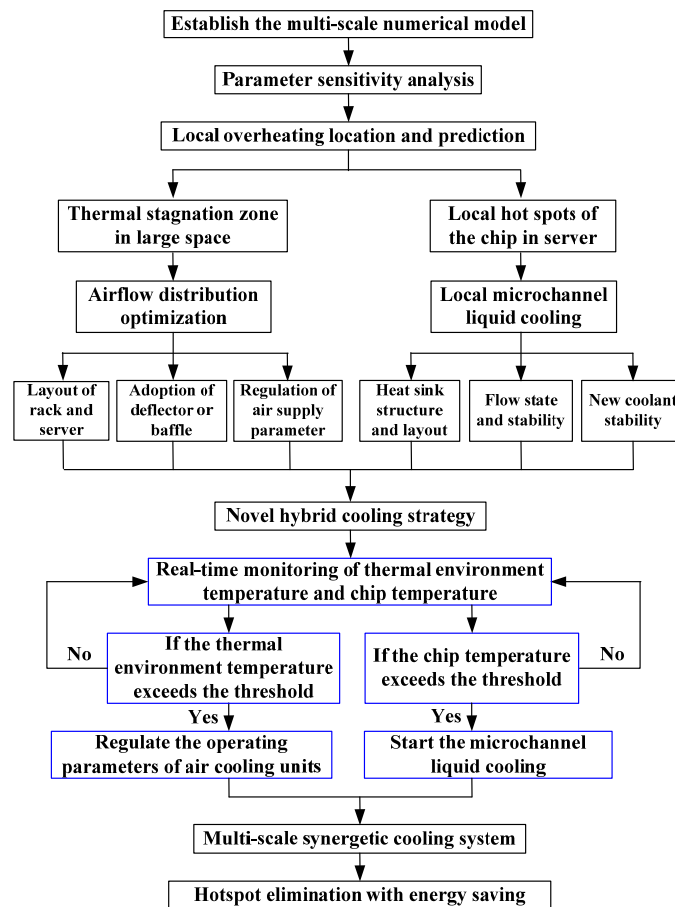


Figure 10. Roadmap of the multi-scale synergy cooling.

5. Conclusions

Advanced cooling methods with high efficiency and energy saving are important guarantees for the green, low-carbon, and sustainable development of DCs. In this paper, the latest research on micro-scale microchannel liquid cooling and large-scale air cooling is introduced. Microchannel liquid cooling can remove the heat concentrated on the electronic chips precisely. Air management can ensure a favorable indoor environment. The multi-scale synergy cooling is expected to address the local overheating and energy saving challenges in DCs.

- Optimizing the structure and arrangement of MCHSs can effectively heighten the cooling efficiency, but the complex structures usually result in a large pump power of liquid cooling systems. The optimized configurations are only suitable for specific conditions; their applicability and transferability are insufficient. The stability of flow boiling and nanofluids should be heightened to promote their practical application in DCs.
- Modifying air distribution and adopting rack-based cooling are effective means to eliminate the local hot spots in the large space and improve the thermal distribution within the racks. Machine learning provides valuable insights for hot spot prediction and control. The accuracy and timeliness of the prediction models need to be further heightened considering the dynamic variation in the heat load and various scenarios.

- The innovative hybrid cooling with micro-scale liquid cooling and large-scale air cooling is expected to solve the local overheating and energy efficiency issues. A multi-scale synergy model should be established to realize fast prediction and dynamic control by real-time monitoring of the environment and chip temperatures.

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Nomenclature

ANN	Artificial neural network
CHF	Critical heat flux
CNN	Convolutional neural network
CPU	Central processing unit
CRAC	Computer room air conditioning
DC	Data center
DRL	Deep reinforcement learning
HTC	Heat transfer coefficient
IT	Information technology
MCHS	Microchannel heat sink
ML	Machine learning
ONB	Onset of nucleate boiling
PIV	Particle image velocimetry

References

1. Cho, J.; Lim, S.B. Balanced comparative assessment of thermal performance and energy efficiency for three cooling solutions in data centers. *Energy* **2023**, *285*, 129370. [[CrossRef](#)]
2. Du, Y.H.; Zhou, Z.H.; Yang, X.C.; Yang, X.Q.; Wang, C.; Liu, J.W.; Yuan, J.J. Dynamic thermal environment management technologies for data center: A review. *Renew. Sustain. Energy Rev.* **2023**, *187*, 113761. [[CrossRef](#)]
3. Liu, Y.N.; Wei, X.X.; Xiao, J.Y.; Liu, Z.J.; Xu, Y.; Tian, Y. Energy consumption and emission mitigation prediction based on data center traffic and PUE for global data centers. *Glob. Energy Interconnect.* **2020**, *3*, 272–282. [[CrossRef](#)]
4. Wang, F.J.; Lv, C.W.; Xu, J.P. Carbon awareness oriented data center location and configuration: An integrated optimization method. *Energy* **2023**, *278*, 127744. [[CrossRef](#)]
5. Pambudi, N.A.; Sarifudin, A.; Firdaus, R.A.; Ulfa, D.K.; Gandidi, I.M.; Romadhon, R. The immersion cooling technology: Current and future development in energy saving. *Alex. Eng. J.* **2022**, *21*, 9509–9527. [[CrossRef](#)]
6. Vasques, T.L.; Moura, P.; Almeida, A. A review on energy efficiency and demand response with focus on small and medium data centers. *Energ. Effic.* **2019**, *12*, 1399–1428. [[CrossRef](#)]
7. Isazadeh, A.; Ziviani, D.; Claridge, D.E. Thermal management in legacy air-cooled data centers: An overview and perspectives. *Renew. Sustain. Energy Rev.* **2023**, *187*, 113707. [[CrossRef](#)]
8. Chethana, G.D.; Gowda, B.S. Thermal management of air and liquid cooled data centres: A review. *Mater. Today Proc.* **2021**, *45*, 145–149. [[CrossRef](#)]
9. Smoyer, J.L.; Norris, P.M. Brief Historical Perspective in Thermal Management and the Shift Toward Management at the Nanoscale. *Heat Transf. Eng.* **2019**, *40*, 269–282. [[CrossRef](#)]
10. Dai, Y.J.; Zhao, J.; Shi, J.W.; Wang, W.; Tao, W.Q. A Multi-Scale Thermal Analysis Method for Data Centers with Application in a Ship Data Center. *J. Therm. Sci.* **2021**, *30*, 1973–1985. [[CrossRef](#)]
11. Khattak, Z.; Ali, H.M. Air cooled heat sink geometries subjected to forced flow: A critical review. *Int. J. Heat Mass Transf.* **2019**, *130*, 141–161. [[CrossRef](#)]
12. Alam, M.W.; Bhattacharyya, S.; Souayeh, B.; Dey, K.; Hammami, F.; Rahimi-Gorji, M.; Biswas, R. CPU heat sink cooling by triangular shape micro-pin-fin: Numerical study. *Int. Commun. Heat Mass Transf.* **2020**, *112*, 104455. [[CrossRef](#)]

13. Li, Y.F.; Wang, T.Y.; Wang, Z.P.; Zhu, C.Z.; Yang, J.L.; Yang, B. Thermal–Hydraulic Performance Analysis of Combined Heat Sink with Open Microchannels and Embedded Pin Fins. *Energies* **2024**, *17*, 5301. [\[CrossRef\]](#)
14. Nada, S.A.; El-Zoheiry, R.M.; Elsharnoby, M.; Osman, O.S. Experimental investigation of hydrothermal characteristics of data center servers' liquid cooling system for different flow configurations and geometric conditions. *Case Stud. Therm. Eng.* **2021**, *27*, 101276. [\[CrossRef\]](#)
15. Kuncoro, I.W.; Pambudi, N.A.; Biddinika, M.K.; Widiastuti, I.; Hijriawan, M.; Wibowo, K.M. Immersion cooling as the next technology for data center cooling: A review. *J. Phys. Conf. Ser.* **2019**, *1402*, 44057. [\[CrossRef\]](#)
16. Xu, R.; Wang, G.Y.; Jiang, P. Spray Cooling on Enhanced Surfaces: A Review of the Progress and Mechanisms. *J. Electron. Packag.* **2022**, *144*, 010802. [\[CrossRef\]](#)
17. Aksoy, Y.T.; Zhu, Y.S.; Eneren, P.; Koos, E.; Vetrano, M.R. The Impact of Nanofluids on Droplet/Spray Cooling of a Heated Surface: A Critical Review. *Energies* **2021**, *14*, 80. [\[CrossRef\]](#)
18. Bhattad, A.; Atgur, V.; Rao, B.N.; Banapurmath, N.R.; Khan, T.M.Y.; Vadlamudi, C.; Krishnappa, S.; Sajjan, A.M.; Shankara, R.P.; Ayachit, N.H. Review on Mono and Hybrid Nanofluids: Preparation, Properties, Investigation, and Applications in IC Engines and Heat Transfer. *Energies* **2023**, *16*, 3189. [\[CrossRef\]](#)
19. Guo, C.; Wang, T.; Guo, C.; Jiang, Y.Y.; Tan, S.C.; Li, Z.G. Effects of filling ratio, geometry parameters and coolant temperature on the heat transfer performance of a wraparound heat pipe. *Appl. Therm. Eng.* **2022**, *200*, 117724. [\[CrossRef\]](#)
20. Li, J.N.; Yang, L. Recent Development of Heat Sink and Related Design Methods. *Energies* **2023**, *16*, 7133. [\[CrossRef\]](#)
21. Alihosseini, Y.; Targhi, M.Z.; Heyhat, M.M.; Ghorbani, N. Effect of a micro heat sink geometric design on thermo-hydraulic performance: A review. *Appl. Therm. Eng.* **2020**, *170*, 114974. [\[CrossRef\]](#)
22. Vallejo, J.P.; Prado, J.I.; Lugo, L. Hybrid or mono nanofluids for convective heat transfer applications. A critical review of experimental research. *Appl. Therm. Eng.* **2022**, *203*, 117926. [\[CrossRef\]](#)
23. Lu, H.J.; Zhang, Z.B.; Yang, L. A review on airflow distribution and management in data center. *Energy Build.* **2018**, *179*, 264–277. [\[CrossRef\]](#)
24. Chu, W.X.; Wang, C.C. A review on airflow management in data centers. *Appl. Energy* **2019**, *240*, 84–119. [\[CrossRef\]](#)
25. Cao, K.Y.; Li, Z.Y.; Luo, H.L.; Jiang, Y.G.; Liu, H.C.; Xu, L.; Gao, P.; Liu, H. Comprehensive review and future prospects of multi-level fan control strategies in data centers for joint optimization of thermal management systems. *J. Build. Eng.* **2024**, *94*, 110021. [\[CrossRef\]](#)
26. Tuckerman, D.B.; Pease, R.F.W. High-performance heat sinking for VLSI. *IEEE Electron Device Lett.* **1981**, *2*, 126–129. [\[CrossRef\]](#)
27. He, Z.Q.; Yan, Y.F.; Zhang, Z.E. Thermal management and temperature uniformity enhancement of electronic devices by micro heat sinks: A review. *Energy* **2021**, *216*, 119223. [\[CrossRef\]](#)
28. Li, Z.Y.; Luo, H.L.; Jiang, Y.G.; Liu, H.C.; Xu, L.; Cao, K.Y.; Wu, H.J.; Gao, P.; Liu, H. Comprehensive review and future prospects on chip-scale thermal management: Core of data center's thermal management. *Appl. Therm. Eng.* **2024**, *251*, 123612. [\[CrossRef\]](#)
29. Miao, J.; Li, C.; Pan, M.Q. Experimental and numerical analysis of variable cross-section channel liquid cooling plate for server chips thermal management. *Therm. Sci. Eng. Prog.* **2024**, *49*, 102470. [\[CrossRef\]](#)
30. Du, L.; Hu, W.B. An overview of heat transfer enhancement methods in microchannel heat sinks. *Chem. Eng. Sci.* **2023**, *280*, 119081. [\[CrossRef\]](#)
31. Sadique, H.; Murtaza, Q.; Samsher. Heat transfer augmentation in microchannel heat sink using secondary flows: A review. *Int. J. Heat Mass Transf.* **2022**, *194*, 123063. [\[CrossRef\]](#)
32. Ma, D.D.; Xia, G.D.; Wang, W.; Jia, Y.T.; Yang, Y.C. Study on thermal performance of microchannel heat sinks with periodic jetting and throttling structures in sidewalls. *Appl. Therm. Eng.* **2019**, *158*, 113764. [\[CrossRef\]](#)
33. Zhu, Q.F.; Xia, H.X.; Chen, J.J.; Zhang, X.M.; Chang, K.P.; Zhang, H.W.; Wang, H.; Wan, J.F.; Jin, Y.Y. Fluid flow and heat transfer characteristics of microchannel heat sinks with different groove shapes. *Int. J. Therm. Sci.* **2021**, *161*, 106721. [\[CrossRef\]](#)
34. Kumar, P. Numerical investigation of fluid flow and heat transfer in trapezoidal microchannel with groove structure. *Int. J. Therm. Sci.* **2019**, *136*, 33–43. [\[CrossRef\]](#)
35. Manoj, A.; Goddummarri, U.V.; Rajalingam, A.; Chakraborty, S. Heat transfer and fluid flow characteristics of a microchannel heat sink with microplates—A critical computational study. *Appl. Therm. Eng.* **2023**, *226*, 120309. [\[CrossRef\]](#)
36. Akhtar, K.; Ali, H.; Din, I.U.; Abbas, A.; Zahir, M.Z.; Ahmad, F.; Alam, F.; Shah, N.; Aamir, M. Heat Transfer Augmentation and Entropy Generation Analysis of Microchannel Heat Sink (MCHS) with Symmetrical Ogive-Shaped Ribs. *Energies* **2023**, *16*, 2783. [\[CrossRef\]](#)
37. Rajalingam, A.; Chakraborty, S. Microchannel heat sink with microstructured wall—A critical study on fluid flow and heat transfer characteristics. *Therm. Sci. Eng. Prog.* **2023**, *38*, 101613.
38. Zhai, Y.L.; Li, Z.H.; Wang, H.; Xu, J.X. Thermodynamic analysis of the effect of channel geometry on heat transfer in double-layered microchannel heat sinks. *Energy Convers. Manag.* **2017**, *143*, 431–439. [\[CrossRef\]](#)
39. Zhao, J.; Huang, S.B.; Gong, L.; Huang, Z.Q. Numerical study and optimizing on micro square pin-fin heat sink for electronic cooling. *Appl. Therm. Eng.* **2016**, *93*, 1347–1359. [\[CrossRef\]](#)

40. Eneren, P.; Vangheffelen, A.; Aksoy, Y.T.; Vetrano, M.R. Flow periodicity in microchannels with fin arrays: Experimental validation. *Exp. Therm. Fluid Sci.* **2024**, *158*, 111261. [\[CrossRef\]](#)
41. Ali, N.; Srivastava, S.; Haque, I.; Yadav, J.; Alam, T.; Siddiqui, T.U.; Siddiqui, M.I.H.; Cuce, E. Heat dissipation and fluid flow in micro-channel heat sink equipped with semi-elliptical pin-fin structures: A numerical study. *Int. Commun. Heat Mass* **2024**, *155*, 107492. [\[CrossRef\]](#)
42. Wu, Y.Y.; Guo, Z.P.; Huang, Y.P.; Lu, Y.M.; Gao, C.; Guo, W.T.; Lv, H.C.; Liu, Y.; Niu, F.L. Optimize the design analysis of hybrid fin structure microchannel heat exchanger. *Prog. Nucl. Energy* **2024**, *175*, 105333.
43. Liu, H.Y.; Hua, J.Y.; Sang, K.Y.; Lan, H.; Niu, B.L.; Wu, W. Simulation of the effect of the structure and location of non-closed droplet microchannel on flow/thermal performance. *Int. Commun. Heat Mass* **2024**, *158*, 107840. [\[CrossRef\]](#)
44. Rajalingam, A.; Chakraborty, S. Effect of shape and arrangement of micro-structures in a microchannel heat sink on the thermo-hydraulic performance. *Appl. Therm. Eng.* **2021**, *190*, 116755.
45. Hekmatara, M.; Koopae, M.K. Numerical study of the influence of pin fin arrangement and volume fraction on the heat transfer and fluid flow phenomena within open microchannels. *Int. Commun. Heat Mass* **2024**, *155*, 107595. [\[CrossRef\]](#)
46. Soleymani, Z.; Rahimi, M.; Gorzin, M.; Pahamli, Y. Performance analysis of hotspot using geometrical and operational parameters of a microchannel pin-fin hybrid heat sink. *Int. J. Heat Mass Transf.* **2020**, *159*, 120141. [\[CrossRef\]](#)
47. Wei, J.W.; Chen, N.; Li, L.; Liu, J.W.; Zhao, J.Y.; Wang, C.R.; He, N. Effect of spoiler columns on heat transfer performance of aluminum nitride-based microchannel heat sink. *Ceram. Int.* **2022**, *48*, 36226–36237. [\[CrossRef\]](#)
48. Li, Y.F.; Yang, B.; Wang, Z.P.; Guo, Q. Investigation on the thermal and hydraulic characteristics of the micro heat sinks with grooves and pin fins by Taguchi-based sensitivity analysis. *Appl. Therm. Eng.* **2024**, *249*, 123454. [\[CrossRef\]](#)
49. Ye, M.Z.; Du, J.Q.; Wang, J.; Chen, L.; Varbanov, P.S.; Klemeš, J.J. Investigation on thermal performance of nanofluids in a microchannel with fan-shaped cavities and oval pin fins. *Energy* **2022**, *260*, 125000. [\[CrossRef\]](#)
50. Li, B.; Cui, Y.Q.; Li, G.D.; Jiang, H.Z. Numerical analysis on thermal-hydraulic performance of optimized microchannel heat sink with slant ribs and quatrefoil rib-elliptical groove complex structures. *Appl. Therm. Eng.* **2024**, *240*, 122165. [\[CrossRef\]](#)
51. Al-Neama, A.F.; Khatir, Z.; Kapur, N.; Summers, J.; Thompson, H.M. An experimental and numerical investigation of chevron fin structures in serpentine minichannel heat sinks. *Int. J. Heat Mass Transf.* **2018**, *120*, 1212–1228. [\[CrossRef\]](#)
52. Yang, M.; Cao, B.Y. Numerical study on flow and heat transfer of a hybrid microchannel cooling scheme using manifold arrangement and secondary channels. *Appl. Therm. Eng.* **2019**, *159*, 113896. [\[CrossRef\]](#)
53. Jahanbakhshi, A.; Nadooshan, A.A.; Bayareh, M. Multi-objective optimization of microchannel heatsink with wavy microtube by combining response surface method and genetic algorithm. *Eng. Anal. Bound. Elem.* **2022**, *140*, 12–31. [\[CrossRef\]](#)
54. Liu, X.F.; Zhang, H.; Wang, F.; Zhu, C.X.; Li, Z.Q.; Zhao, D.D.; Jiang, H.; Liu, Y.H.; Zhang, Z.R. Thermal and hydraulic performances of the wavy microchannel heat sink with fan-shaped ribs on the sidewall. *Int. J. Therm. Sci.* **2022**, *179*, 107688. [\[CrossRef\]](#)
55. Zhu, J.F.; Li, X.Y.; Wang, S.L.; Yang, Y.R.; Wang, X.D. Performance comparison of wavy microchannel heat sinks with wavy bottom rib and side rib designs. *Int. J. Therm. Sci.* **2019**, *146*, 106068. [\[CrossRef\]](#)
56. Liang, Z.X.; Wen, H.P.; Lv, Q.M.; Su, W.; Wang, C.H. Comparative performance analysis of microchannel heat sink with different geometric structures. *Int. J. Therm. Sci.* **2025**, *208*, 109495. [\[CrossRef\]](#)
57. Chamanroy, Z.; Morteza, K.A. Analysis of straight and wavy miniature heat sinks equipped with straight and wavy pin-fins. *Int. J. Therm. Sci.* **2019**, *146*, 106071. [\[CrossRef\]](#)
58. Anbumeenakshi, C.; Thansekhar, M.R. Experimental investigation of header shape and inlet configuration on flow maldistribution in microchannel. *Exp. Therm. Fluid Sci.* **2016**, *75*, 156–161. [\[CrossRef\]](#)
59. Hadad, Y.; Rangarajan, S.; Nemati, K.; Ramakrishnan, B.; Pejman, R.; Chiarot, P.R.; Sammakia, B. Performance analysis and shape optimization of a water-cooled impingement micro-channel heat sink including manifolds. *Int. J. Therm. Sci.* **2020**, *148*, 106145. [\[CrossRef\]](#)
60. Lad, A.A.; James, K.A.; King, W.P.; Miljkovic, N. Reduced Order Design Optimization of Liquid Cooled Heat Sinks. *J. Electron. Packag.* **2021**, *143*, 041105. [\[CrossRef\]](#)
61. Tang, K.; Lin, G.P.; Guo, Y.D.; Huang, J.Y.; Zhang, H.X.; Miao, J.Y. Simulation and optimization of thermal performance in diverging/converging manifold microchannel heat sink. *Int. J. Heat Mass Transf.* **2023**, *200*, 123495. [\[CrossRef\]](#)
62. Pu, X.J.; Zhao, Z.C.; Sun, M.K.; Huang, Y.Q. Numerical study on temperature distribution uniformity and cooling performance of manifold microchannel heat sink. *Appl. Therm. Eng.* **2024**, *237*, 121779. [\[CrossRef\]](#)
63. He, W.; Zhang, J.F.; Guo, R.; Pei, C.C.; Li, H.L.; Liu, S.C.; Wei, J.; Wang, Y.L. Performance analysis and structural optimization of a finned liquid-cooling radiator for chip heat dissipation. *Appl. Energy* **2022**, *327*, 120048. [\[CrossRef\]](#)
64. Wang, Y.B.; Zhu, K.; Cui, Z.; Wei, J. Effects of the location of the inlet and outlet on heat transfer performance in pin fin CPU heat sink. *Appl. Therm. Eng.* **2019**, *151*, 506–513. [\[CrossRef\]](#)
65. Qiu, J.C.; Zhou, J.H.; Zhao, Q.; Qin, H.S.; Chen, X.M. Numerical investigation of flow boiling characteristics in cobweb-shaped microchannel heat sink. *Case Stud. Therm. Eng.* **2021**, *28*, 101677. [\[CrossRef\]](#)

66. Sun, L.; Li, J.; Xu, H.; Ma, J.; Peng, H. Numerical study on heat transfer and flow characteristics of novel microchannel heat sinks. *Case Stud. Therm. Eng.* **2022**, *176*, 107535. [\[CrossRef\]](#)
67. Sreehari, D.; Sharma, A.K. On thermal performance of serpentine silicon microchannels. *Int. J. Therm. Sci.* **2019**, *146*, 106067. [\[CrossRef\]](#)
68. Xia, G.D.; Jiang, J.; Wang, J.; Zhai, Y.L.; Ma, D.D. Effects of different geometric structures on fluid flow and heat transfer performance in microchannel heat sinks. *Int. J. Heat Mass Transf.* **2015**, *80*, 439–447. [\[CrossRef\]](#)
69. Savino, S.; Nonino, C. Thermal Performance Improvement of Cross-Flow Double-Layered Microchannel Heat Sinks through Proper Header Design. *Energies* **2024**, *17*, 3790. [\[CrossRef\]](#)
70. Rajalingam, A.; Chakraborty, S. Improvement of uniformity in temperature distribution of a microchannel heat sink with secondary inlet. *Int. Commun. Heat Mass* **2024**, *159*, 108123.
71. Cao, B.Q.; Wu, Z. Microchannel heat sinks for hotspot thermal management: Achieving minimal pressure drop and maximal thermal performance. *Int. J. Heat Mass Transf.* **2025**, *236*, 126411. [\[CrossRef\]](#)
72. Yan, Y.F.; Yan, H.Y.; Feng, S.; Li, L.X. Thermal-hydraulic performances and synergy effect between heat and flow distribution in a truncated doubled-layered heat sink with Y-shaped fractal network. *Int. J. Heat Mass Transf.* **2019**, *142*, 118337. [\[CrossRef\]](#)
73. Huang, P.N.; Dong, G.P.; Zhong, X.E.; Pan, M.Q. Numerical investigation of the fluid flow and heat transfer characteristics of tree-shaped microchannel heat sink with variable cross-section. *Chem. Eng. Process.* **2020**, *147*, 107769. [\[CrossRef\]](#)
74. Lu, Z.H.; Zhang, K.; Liu, J.X.; Li, F. Effect of branching level on the performance of constructal theory based Y-shaped liquid cooling heat sink. *Appl. Therm. Eng.* **2020**, *168*, 114824. [\[CrossRef\]](#)
75. Li, X.H.; Zhang, L.K.; Li, B.T. Heat transfer augmentation in microchannel heat sink based on isogeometric topology optimization framework. *Appl. Math. Model.* **2022**, *104*, 163–187. [\[CrossRef\]](#)
76. Oztug, S.; Pan, L.; Weibel, J.A. Topology optimization of microchannel heat sinks using a homogenization approach. *Int. J. Heat Mass Transf.* **2021**, *169*, 120896. [\[CrossRef\]](#)
77. Xia, Y.; Chen, L.; Luo, J.W.; Tao, W.Q. Numerical investigation of microchannel heat sinks with different inlets and outlets based on topology optimization. *Appl. Energy* **2023**, *330*, 120335. [\[CrossRef\]](#)
78. Hu, J.H.; Chen, C.W.; Wang, X.Y.; Xin, G.M.; Wang, M. Improvement of flow and heat transfer performance of microchannels with different ribs using topology optimization. *Appl. Therm. Eng.* **2024**, *244*, 122672. [\[CrossRef\]](#)
79. Liu, S.L.; Xu, H.; Chen, M.; Xiang, Z.Y.; Zhao, M.L. Multi-objective topology optimization of a liquid-cooled microchannel for high power positive thermal coefficient heater with irregular design domain. *Int. J. Heat Mass Transf.* **2025**, *238*, 126422. [\[CrossRef\]](#)
80. Abdellatif, H.H.; Ambrosini, W.; Arcilesi, D.; Bhowmik, P.K.; Sabharwall, P. Flow Instabilities in boiling channels and their suppression methodologies—A review. *Nucl. Eng. Des.* **2024**, *421*, 113114. [\[CrossRef\]](#)
81. Camarasa, J.; Crespo, A.; Vilarrubí, M.; Ibáñez, M.; Barrau, J. A review of experimental studies on flow boiling instabilities mitigation through geometrical modifications. *Int. J. Heat Mass Transf.* **2024**, *235*, 126014. [\[CrossRef\]](#)
82. Sun, Y.H.; Huang, A.; Lu, J.L.; Jiang, Y.Y. Flow boiling characteristics of ethanol in a microchannel with low mass flux. *Int. J. Heat Mass Transf.* **2024**, *219*, 124845. [\[CrossRef\]](#)
83. Xia, G.D.; Tang, Y.X.; Zong, L.X.; Ma, D.D.; Jia, Y.T.; Rong, R.Z. Experimental investigation of flow boiling characteristics in microchannels with the sinusoidal wavy sidewall. *Int. Commun. Heat Mass* **2019**, *101*, 89–102. [\[CrossRef\]](#)
84. Li, Y.F.; Xia, G.D.; Jia, Y.T.; Cheng, Y.; Wang, J. Experimental investigation of flow boiling performance in microchannels with and without triangular cavities—A comparative study. *Int. J. Heat Mass Transf.* **2017**, *108*, 1511–1526. [\[CrossRef\]](#)
85. Luo, Y.; Li, W.; Zhang, J.Z.; Minkowycz, W.J. Analysis of thermal performance and pressure loss of subcooled flow boiling in manifold microchannel heat sink. *Int. J. Heat Mass Transf.* **2022**, *138*, 120362. [\[CrossRef\]](#)
86. Qian, J.Y.; Wang, R.; Wei, T.; Tang, H.; Hu, D.H. Numerical Analysis of Flow Boiling Characteristics of a Single Channel Heat Sink Subjected to Multiple Heat Sources. *Energies* **2023**, *16*, 3060. [\[CrossRef\]](#)
87. Drummond, K.P.; Back, D.; Sinanis, M.D.; Janes, D.B.; Peroulis, D.; Weibel, J.A.; Garimella, S.V. A hierarchical manifold microchannel heat sink array for high-heat-flux two-phase cooling of electronics. *Int. J. Heat Mass Transf.* **2018**, *117*, 319–330. [\[CrossRef\]](#)
88. Deng, D.X.; Zeng, L.; Sun, W.; Pi, G.; Yang, Y. Experimental study of flow boiling performance of open-ring pin fin microchannels. *Int. J. Heat Mass Transf.* **2021**, *167*, 120829. [\[CrossRef\]](#)
89. Li, Y.F.; Xia, G.D.; Ma, D.D.; Yang, J.L.; Li, W. Experimental investigation of flow boiling characteristics in microchannel with triangular cavities and rectangular fins. *Int. J. Heat Mass Transf.* **2020**, *148*, 119036. [\[CrossRef\]](#)
90. Tiwari, N.; Moharana, M.K. Conjugate effect on flow boiling instability in wavy microchannel. *Int. J. Heat Mass Transf.* **2021**, *166*, 120791. [\[CrossRef\]](#)
91. Zhao, Q.; Zhou, J.H.; Lu, M.X.; Liu, C.; Zhang, D.; Li, Q.; Chen, X.M. Irregular-shaped nucleated bubbles induced enhancement of subcooled flow boiling heat transfer in leaf vein inspired three-tiered open microchannels (LTOMCs). *Int. J. Heat Mass Transf.* **2023**, *221*, 124281. [\[CrossRef\]](#)

92. Zong, L.X.; Xia, G.D.; Jia, Y.T.; Liu, L.; Ma, D.D.; Wang, J. Flow boiling instability characteristics in microchannels with porous-wall. *Int. J. Heat Mass Transf.* **2020**, *146*, 118863. [\[CrossRef\]](#)
93. Fallahtafti, N.; Hosseini, F.; Hadad, Y.; Rangarajan, S.; Hoang, C.H.; Sammakia, B. Experimental characterization and geometrical optimization of a commercial two-phase designed cold plate. *Int. Commun. Heat Mass* **2024**, *155*, 107457. [\[CrossRef\]](#)
94. Cheng, X.; Wu, J.J. Geometry-metrics-dependent flow boiling characteristics in rectangular microchannels. *Int. J. Heat Mass Transf.* **2024**, *218*, 124733. [\[CrossRef\]](#)
95. Tang, X.Y.; Xu, Q.; Li, J.F.; Yu, H.Y.; Pei, C.Y.; Guo, L.J. Experimental study on flow boiling heat transfer in open copper microchannel heat sinks with different aspect ratios. *Int. J. Heat Mass Transf.* **2024**, *231*, 125879. [\[CrossRef\]](#)
96. Zhang, W.; Chai, Y.Z.; Xu, J.L.; Liu, G.L.; Sun, Y.Z. 3D heterogeneous wetting microchannel surfaces for boiling heat transfer enhancement. *Appl. Surf. Sci.* **2018**, *457*, 891–901. [\[CrossRef\]](#)
97. Zhao, Q.; Qiu, J.C.; Zhou, J.H.; Lu, M.X.; Li, Q.; Chen, X.M. Visualization study of flow boiling characteristics in open microchannels with different wettability. *Int. J. Heat Mass Transf.* **2021**, *180*, 121808. [\[CrossRef\]](#)
98. Žalec, D.; Može, M.; Zupančič, M.; Golobič, I. Elucidating the effects of surface wettability on boiling heat transfer using hydrophilic and hydrophobic surfaces with laseretched microchannels. *Case Stud. Therm. Eng.* **2024**, *57*, 104357. [\[CrossRef\]](#)
99. Ahmadi, V.E.; Guler, T.; Celik, S.; Ronshin, F.; Serdyukov, V.; Surtaev, A.; Sadaghiani, A.K.; Koşar, A. Effect of mixed wettability surfaces on flow boiling heat transfer at subatmospheric pressures. *Appl. Therm. Eng.* **2024**, *236*, 121476. [\[CrossRef\]](#)
100. Vontas, K.; Andredaki, M.; Georgoulas, A.; Miché, N.; Marengo, M. The effect of surface wettability on flow boiling characteristics within microchannels. *Int. J. Heat Mass Transf.* **2021**, *172*, 121133. [\[CrossRef\]](#)
101. Bai, J.J.; Sun, Y.L.; Huang, H.Z.; Chen, G.; Tang, Y.; Yuan, W.; Zhang, S.W. An open superhydrophilic microchannel heat sink for thin film boiling with a high coefficient of performance. *Renew. Sustain. Energy Rev.* **2023**, *186*, 113684. [\[CrossRef\]](#)
102. Choi, S.U.S.; Eastman, J.A. Enhancing thermal conductivity of fluids with nanoparticles. *ASME J. Heat Transf.* **1995**, *66*, 99–105.
103. Li, Y.J.; Zhou, J.E.; Tung, S.; Schneider, E.; Xi, S.Q. A review on development of nanofluid preparation and characterization. *Powder technol.* **2009**, *196*, 89–101. [\[CrossRef\]](#)
104. Ghadimi, A.; Saidur, R.; Metselaar, H.S.C. A review of nanofluid stability properties and characterization in stationary conditions. *Int. J. Heat Mass Transf.* **2011**, *54*, 4051–4068. [\[CrossRef\]](#)
105. Azizian, R.; Doroodchi, E.; Moghtaderi, B. Influence of Controlled Aggregation on Thermal Conductivity of Nanofluids. *J. Heat Transfer* **2016**, *138*, 1943–1955. [\[CrossRef\]](#)
106. Esmaeilzadeh, A.; Silakhori, M.; Ghazali, N.N.N.; Metselaar, H.S.C.; Mamat, A.B.; Sanjani, M.S.N.; Iranmanesh, S. Thermal Performance and Numerical Simulation of the 1-Pyrene Carboxylic-Acid Functionalized Graphene Nanofluids in a Sintered Wick Heat Pipe. *Energies* **2020**, *13*, 6542. [\[CrossRef\]](#)
107. Eneren, P.; Aksoy, Y.T.; Vetrano, M.R. Practical Challenges in Nanofluid Convective Heat Transfer Inside Silicon Microchannels. *Energies* **2023**, *16*, 7885. [\[CrossRef\]](#)
108. Souby, M.M.; Salman, M.; Prabakaran, R.; Kim, S.C. Hydrothermal characteristics and irreversibility behavior of microchannel heat sink operated with hybrid nanofluids: A critical assessment. *Case Stud. Therm. Eng.* **2023**, *49*, 103387. [\[CrossRef\]](#)
109. Lee, Y.K. The Use of Nanofluids in Domestic Water Heat Exchanger. *Adv. Appl. Mech.* **2014**, *3*, 9–24.
110. Kumara, S.; Kumara, A.; Kothiyal, A.D.; Bisht, M.S. A review of flow and heat transfer behaviour of nanofluids in micro channel heat sinks. *Therm. Sci. Eng. Prog.* **2018**, *8*, 477–493. [\[CrossRef\]](#)
111. Chu, Y.M.; Farooq, U.; Mishra, N.K.; Ahmad, Z.; Zulfikar, F.; Yasmin, S.; Khan, S.A. CFD analysis of hybrid nanofluid-based microchannel heat sink for electronic chips cooling: Applications in nano-energy thermal devices. *Case Stud. Therm. Eng.* **2023**, *44*, 102818. [\[CrossRef\]](#)
112. Bahiraei, M.; Heshmatian, S. Thermal performance and second law characteristics of two new microchannel heat sinks operated with hybrid nanofluid containing graphene–silver nanoparticles. *Energy Convers. Manag.* **2018**, *168*, 357–370. [\[CrossRef\]](#)
113. Jamshidmofid, M.; Bahiraei, M. Thermohydraulic assessment of a novel hybrid nanofluid containing cobalt oxide-decorated reduced graphene oxide nanocomposite in a microchannel heat sink with sinusoidal cavities and rectangular ribs. *Int. Commun. Heat Mass* **2022**, *131*, 105769. [\[CrossRef\]](#)
114. Aguirre, I.; González, A.; Castillo, E. Numerical study on the use of shear-thinning nanofluids in a micro pin-fin heat sink including vortex generators and changes in pin shapes. *J. Taiwan Inst. Chem. Eng.* **2022**, *136*, 104400. [\[CrossRef\]](#)
115. Aravind, S.S.J.; Ramaprabhu, S. Surfactant-free dispersion of silver nanoparticles into MWCNT-nanofluids for improved heat dissipation. *RSC Adv.* **2013**, *3*, 4199–4206. [\[CrossRef\]](#)
116. Chen, L.F.; Cheng, M.; Yang, D.J.; Yang, L. Enhanced Thermal Conductivity of Nanofluid by Synergistic Effect of Multi-Walled Carbon Nanotubes and Fe₂O₃ Nanoparticles. *Appl. Mech. Mater.* **2014**, *548–549*, 118–123.
117. Jana, S.; Khojin, A.S.; Zhong, W.H. Enhancement of fluid thermal conductivity by the addition of single and hybrid nano-additives. *Thermochim. Acta* **2007**, *462*, 45–55. [\[CrossRef\]](#)

118. Baghbanzadeh, M.; Rashidi, A.; Rashtchian, D.; Lotfi, R.; Amrollahi, A. Synthesis of spherical silica/multiwall carbon nanotubes hybrid nanostructures and investigation of thermal conductivity of related nanofluids. *Thermochim. Acta* **2012**, *549*, 87–94. [\[CrossRef\]](#)
119. Wen, D.S.; Ding, Y.L. Natural convective heat transfer of suspensions of titanium dioxide nanoparticles(nanofluids). *IEEE Trans. Nanotechnol.* **2006**, *5*, 220–227.
120. Alnaqi, A.A.; Alsarraf, J.; Al-Rashed, A.A.A.A.; Afrand, M. Thermal-hydraulic analysis and irreversibility of the MWCNTs-SiO₂/EG-H₂O non-Newtonian hybrid nanofluids inside a zigzag micro-channels heat sink. *Int. Commun. Heat Mass* **2021**, *122*, 105158. [\[CrossRef\]](#)
121. Zhou, J.; Kanbur, B.B.; Le, D.V.; Tan, R.; Duan, F. Multi-criteria assessments of increasing supply air temperature in tropical data center. *Energy* **2023**, *271*, 127043. [\[CrossRef\]](#)
122. Wang, Y.W.; Yiru Zhang, Y.R.; Nörtershäuser, D.; Le Masson, S.; Menaud, J.M. Model and data driven transient thermal system modelings for contained data centers. *Energy Build.* **2022**, *258*, 111790. [\[CrossRef\]](#)
123. Xiong, X.; Fulpagare, Y.; Lee, P.S. A numerical investigation of fan wall cooling system for modular air-cooled data center. *Build. Environ.* **2021**, *205*, 108287. [\[CrossRef\]](#)
124. Xiong, X.; Lee, P.S. Vortex-enhanced thermal environment for air-cooled data center: An experimental and numerical study. *Energy Build.* **2021**, *250*, 111287. [\[CrossRef\]](#)
125. Song, P.; Zhang, Z.B.; Zhu, Y. Numerical and experimental investigation of thermal performance in data center with different deflectors for cold aisle containment. *Build. Environ.* **2021**, *200*, 107961. [\[CrossRef\]](#)
126. Lee, Y.C.; Chen, K.Y.; Yan, W.M.; Shih, Y.C.; Chao, C.Y. Evaporative cooling method to improve energy management of overhead downward flow-type data center. *Case Stud. Therm. Eng.* **2023**, *45*, 102998. [\[CrossRef\]](#)
127. Fulpagare, Y.; Hsu, P.H.; Wang, C.C. Experimental analysis of airflow uniformity and energy consumption in data centers. *Appl. Therm. Eng.* **2022**, *209*, 118302. [\[CrossRef\]](#)
128. Zhang, J.; Mao, R.Y.; Li, C.; Lan, J.; Yi, X.Y.; Zhang, Z.J. Optimization air-conditioning system and thermal management of data center via fan-wall free cooling technology. *Appl. Therm. Eng.* **2023**, *234*, 121245. [\[CrossRef\]](#)
129. Wang, Y.T.; Bai, X.L.; Fu, Y.S.; Tang, Y.; Jin, C.Q.; Li, Z.Y. Field experiment and numerical simulation for airflow evaluation in a data center with row-based cooling. *Energy Build.* **2023**, *294*, 113231. [\[CrossRef\]](#)
130. Lee, Y.T.; Wen, C.Y.; Shih, Y.C.; Li, Z.T.; Yang, A.S. Numerical and experimental investigations on thermal management for data center with cold aisle containment configuration. *Appl. Energy* **2022**, *307*, 118213. [\[CrossRef\]](#)
131. Jao, Y.C.; Zhang, Z.W.; Wang, C.C. Effect of uneven heat load on the airflow uniformity and thermal performance in a small-scale data center. *Appl. Therm. Eng.* **2024**, *242*, 122525. [\[CrossRef\]](#)
132. Ni, J.; Jin, B.W.; Ning, S.L.; Wang, X.W. The Numerical Simulation of the Airflow Distribution and Energy Efficiency in Data Centers with Three Types of Aisle Layout. *Sustainability* **2019**, *11*, 4937. [\[CrossRef\]](#)
133. Cho, J.; Woo, J.; Park, B.; Lim, T. A Comparative CFD Study of Two Air Distribution Systems with Hot Aisle Containment in High-Density Data Centers. *Energies* **2020**, *13*, 6147. [\[CrossRef\]](#)
134. Kinoshita, T.; Kimura, T.; Muroya, K.; Tanaka, H.; Youro, M.; Urata, J. Optimization of Operational Conditions for Air Conditioning Systems with Aisle Capping Method. In Proceedings of the 8th Asia-Pacific Symposium on Information and Telecommunication Technologies, Kuching, Malaysia, 15–18 June 2010; IEEE: Piscataway, NJ, USA, 2010; pp. 1–6.
135. Wang, I.N.; Tsui, Y.Y.; Wang, C.C. Improvements of Airflow Distribution in a Container Data Center. *Energy Procedia* **2015**, *75*, 1819–1824. [\[CrossRef\]](#)
136. Nada, S.A.; Said, M.A.; Rady, M.A. CFD investigations of data centers' thermal performance for different configurations of CRACs units and aisles separation. *Alex. Eng. J.* **2016**, *55*, 959–971. [\[CrossRef\]](#)
137. Nada, S.A.; Said, M.A.; Rady, M.A. Numerical investigation and parametric study for thermal and energy management enhancements in data centers' buildings. *Appl. Therm. Eng.* **2016**, *98*, 110–128. [\[CrossRef\]](#)
138. Nada, S.A.; Said, M.A. Effect of CRAC units layout on thermal management of data center. *Appl. Therm. Eng.* **2017**, *118*, 339–344. [\[CrossRef\]](#)
139. Abbas, A.M.; Huzayyin, A.S.; Mouneer, T.A.; Nada, S.A. Thermal management and performance enhancement of data centers architectures using aligned/staggered in-row cooling arrangements. *Case Stud. Therm. Eng.* **2021**, *24*, 100884. [\[CrossRef\]](#)
140. Fang, L.L.; Xu, Q.S.; Yin, T.; Fang, J.C.; Shi, Y.S. Numerical analysis of layout of air conditioning in data center considering seasonal factors. *Energy Rep.* **2022**, *8*, 1365–1371. [\[CrossRef\]](#)
141. Cho, J.; Kim, Y. Development of modular air containment system: Thermal performance optimization of row-based cooling for high-density data centers. *Energy* **2021**, *231*, 120838. [\[CrossRef\]](#)
142. Li, X.M.; Li, M.Y.; Zhang, Y.B.; Han, Z.W.; Wang, S.W. Rack-level cooling technologies for data centers—A comprehensive review. *J. Build. Eng.* **2024**, *90*, 109535. [\[CrossRef\]](#)
143. Yuan, X.L.; Zhou, X.T.; Liu, J.X.; Wang, Y.; Kosonen, R.; Xu, X.J. Experimental and numerical investigation of an airflow management system in data center with lower-side terminal baffles for servers. *Build. Environ.* **2019**, *155*, 308–319. [\[CrossRef\]](#)

144. Nada, S.A.; Abbas, A.M. Solutions of thermal management problems for terminal racks of in-row cooling architectures in data centers. *Build. Environ.* **2021**, *201*, 107991. [\[CrossRef\]](#)
145. Chu, W.X.; Wang, R.; Hsu, P.H.; Wang, C.C. Assessment on rack intake flowrate uniformity of data center with cold aisle containment configuration. *J. Build. Eng.* **2020**, *30*, 101331. [\[CrossRef\]](#)
146. Zhan, B.F.; Shao, S.Q.; Lin, M.; Zhang, H.N.; Tian, C.Q.; Zhou, Y. Experimental investigation on ducted hot aisle containment system for racks cooling of data center. *Int. J. Refrig.* **2021**, *127*, 137–147. [\[CrossRef\]](#)
147. Phan, L.; Hu, B.C.; Lin, C.X. An evaluation of turbulence and tile models at server rack level for data centers. *Build. Environ.* **2019**, *155*, 421–435. [\[CrossRef\]](#)
148. Wan, J.X.; Zhou, J.; Gui, X. Intelligent Rack-Level Cooling Management in Data Centers With Active Ventilation Tiles: A Deep Reinforcement Learning Approach. *IEEE Intell. Syst.* **2021**, *36*, 42–52. [\[CrossRef\]](#)
149. Tradat, M.I.; Manaserh, Y.M.A.; Sammakia, B.G.; Hoang, C.H.; Alissa, H.A. An experimental and numerical investigation of novel solution for energy management enhancement in data centers using underfloor plenum porous obstructions. *Appl. Energy* **2021**, *289*, 116663. [\[CrossRef\]](#)
150. Jin, C.Q.; Bai, X.L. The study of servers' arrangement and air distribution strategy under partial load in data centers. *Sustain. Cities Soc.* **2019**, *49*, 101617. [\[CrossRef\]](#)
151. Zou, S.K.; Zhang, Q.; Yue, C.; Du, S. Effect of servers' arrangement on the performance of a loop thermosyphon system used in data center. *Appl. Therm. Eng.* **2021**, *192*, 116955. [\[CrossRef\]](#)
152. Yuan, X.L.; Xua, X.J.; Wang, Y.; Liu, J.X.; Kosonena, R.; Cai, H. Design and validation of an airflow management system in data center with tilted server placement. *Appl. Therm. Eng.* **2020**, *164*, 114444. [\[CrossRef\]](#)
153. Chu, W.X.; Wang, C.C. CFD Investigation of Airflow Management in a Small Container Data Center. *IEEE Trans. Compon. Packag. Manuf. Technol.* **2019**, *9*, 2177–2188. [\[CrossRef\]](#)
154. Wu, L.; Mao, R.Y.; Wu, H.W.; Zhang, J.; Li, C.; Yi, X.Y.; Huang, G.Q.; Zhang, Z.J. Optimization of airflow organization in fan-wall data center via baffles. *Appl. Therm. Eng.* **2024**, *244*, 122745. [\[CrossRef\]](#)
155. Wang, L.G.; Tang, Y.; Bai, X.L.; Mi, R.R.; Wang, Y.T. Experimental and optimization research of the rack thermal environment based on the dynamic server power. *J. Build. Eng.* **2024**, *96*, 110591. [\[CrossRef\]](#)
156. Feng, X.M.; Zhang, Z.B.; Zhang, Y.; Zhang, Y.X.; Yao, Y.; Wang, X.L. Investigating thermal performance and energy efficiency in under-floor air distribution data centers: A case study. *Therm. Sci. Eng. Prog.* **2024**, *54*, 102823. [\[CrossRef\]](#)
157. Tong, X.X.; Jiaqiang Wang, J.Q.; Liu, W.W.; Samah, H.A.; Zhang, Q.; Zhang, L.F. A time-varying state-space model for real-time temperature predictions in rack-based cooling data centers. *Appl. Therm. Eng.* **2023**, *230*, 120737. [\[CrossRef\]](#)
158. Zhang, Q.G.; Zeng, W.; Lin, Q.J.; Chng, C.B.; Chui, C.K.; Lee, P.S. Deep reinforcement learning towards real-world dynamic thermal management of data centers. *Appl. Energy* **2023**, *333*, 120561. [\[CrossRef\]](#)
159. Sasakura, K.; Aoki, T.; Komatsu, M.; Watanabe, T. Rack Temperature Prediction Model Using Machine Learning after Stopping Computer Room Air Conditioner in Server Room. *Energies* **2020**, *13*, 4300. [\[CrossRef\]](#)
160. Khan, W.; Chiara, D.D.; Kor, A.L.; Chinnici, M. Advanced data analytics modeling for evidence-based data center energy management. *Physica A* **2023**, *624*, 128966. [\[CrossRef\]](#)
161. Wang, N.B.; Guo, Y.H.; Huang, C.Q.; Tian, B.; Shao, S.Q. Multi-scale collaborative modeling and deep learning-based thermal prediction for air-cooled data centers: An innovative insight for thermal management. *Appl. Energy* **2025**, *377*, 124568. [\[CrossRef\]](#)
162. Akbar, S.; Li, R.X.; Waqas, M.; Jan, A. Server temperature prediction using deep neural networks to assist thermal-aware scheduling. *Sustain. Comput. Inform. Syst.* **2022**, *36*, 100809. [\[CrossRef\]](#)
163. Huang, N.; Li, X.; Xu, Q.M.; Chen, R.H.; Chen, H.D.; Chen, A. Artificial Intelligence-Based Temperature Twinning and Pre-Control for Data Center Airflow Organization. *Energies* **2023**, *16*, 6063. [\[CrossRef\]](#)
164. MirhoseiniNejad, S.M.; Badawy, G.; Down, D.G. Holistic thermal-aware workload management and infrastructure control for heterogeneous data centers using machine learning. *Future Gener. Comput. Syst.* **2021**, *118*, 208–218. [\[CrossRef\]](#)
165. Mohsenian, G.; Khalili, S.; Tradat, M.; Manaserh, Y.; Rangarajan, S.; Desu, A.; Thakur, D.; Nemati, K.; Ghose, K.; Sammakia, B. A novel integrated fuzzy control system toward automated local airflow management in data centers. *Control Eng. Pract.* **2021**, *112*, 104833. [\[CrossRef\]](#)
166. Deng, W.Q.; Wang, J.Q.; Yue, C.; Guo, Y.; Zhang, Q. Model-based control strategy with linear parameter-varying state-space model for rack-based cooling data centers. *Energy Build.* **2024**, *319*, 114528. [\[CrossRef\]](#)
167. Grishina, A.; Chinnici, M.; Kor, A.L.; Rondeau, E.; Georges, J.P. A Machine Learning Solution for Data Center Thermal Characteristics Analysis. *Energies* **2020**, *13*, 4378. [\[CrossRef\]](#)
168. Saiyad, A.; Patel, A.; Fulpagare, Y.; Bhargav, A. Predictive modeling of thermal parameters inside the raised floor plenum data center using Artificial Neural Networks. *J. Build. Eng.* **2021**, *42*, 102397. [\[CrossRef\]](#)
169. Fulpagare, Y.; Huang, K.R.; Liao, Y.H.; Wang, C.C. Optimal energy management for air cooled server fans using Deep Reinforcement Learning control method. *Energy Build.* **2022**, *277*, 112542. [\[CrossRef\]](#)

170. Wang, K.; Hong, Z.H.; Liang, H.; Junya, I.; Cheng, S.B.; Okamoto, K. Experimental investigation on the characteristics of bubble growth and slide on a downward-facing heater surface in flow boiling. *Int. J. Therm. Sci.* **2023**, *184*, 108008. [[CrossRef](#)]
171. Shibata, N.; Miwa, S.; Sawa, K.; Takahashi, M.; Murayama, T.; Tenma, N. Identification of high-pressure two-phase flow regime transition using image processing and deep learning. *J. Nat. Gas Sci. Eng.* **2022**, *102*, 104560. [[CrossRef](#)]
172. Soibam, J.; Scheiff, V.; Aslanidou, J.; Kyprianidis, K.; Fdhila, R.B. Application of deep learning for segmentation of bubble dynamics in subcooled boiling. *Int. J. Multiph. Flow* **2023**, *169*, 104589. [[CrossRef](#)]
173. Wang, S.; Kang, Y.F.; Xu, Y.X.; Ma, C.M.; Wang, H.T.; Wu, W.G. Data center temperature prediction and management based on a Two-stage self-healing model. *Simul. Modell. Pract. Theory* **2024**, *132*, 102883.
174. Zhao, R.L.; Du, Y.H.; Yang, X.C.; Zhou, Z.H.; Wang, W.F.; Yang, X.Q. A critical review on the thermal management of data center for local hotspot elimination. *Energy Build.* **2023**, *297*, 113486. [[CrossRef](#)]

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