

# **Review of High-Performance Computing Liquid Cooling Technologies**

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## **Abstract**

The escalating thermal demands of high-performance computing (HPC) have rendered traditional air-cooling methodologies inadequate, necessitating a paradigm shift toward liquid-based solutions. This review systematically examines the evolution of computer cooling systems, evaluating the limitations of air cooling (low thermal conductivity, 40% data centre power usage) and assessing three liquid cooling categories: direct-to-chip, immersion, and hybrid systems. Key advancements include microchannel heat sink optimisation, nanofluid integration, and phase-change mechanisms. Direct-to-chip cooling manages >400W TDP, while immersion cooling offers superior thermal efficiency. Hybrid configurations provide transitional pathways for existing facilities. A critical research gap is the absence of standardised comparative performance models. This review establishes the foundation for a comprehensive simulation model to optimise liquid cooling system design for next generation exascale computing environments.

## **Keywords**

High-performance computing, liquid cooling, thermal management, immersion cooling, direct-to-chip cooling, Rack.

## **1. Introduction**

In today's fast-paced world of high-performance computing (HPC), the need for cutting-edge cooling solutions is more urgent than ever. Traditional methods of cooling with air are no longer sufficient to cope with the intense heat generated by the latest hardware configurations, leading to various performance and reliability issues. Emerging cooling systems are an evolving field of innovation that promises to transform the way we manage thermal challenges in HPC environments. These systems not only provide superior cooling capabilities but also demonstrate impressive energy efficiency, making them a top choice for those seeking optimal performance and reliability (Anghel 2023).

This paper examines the evolution of cooling systems in data centers, with a particular focus on the transition from traditional air-based cooling methods to advanced liquid cooling technologies which are Direct to Chip, Immersion (Single Phase and Two Phase) and Hybrid liquid cooling. As artificial intelligence workloads continue to expand, conventional cooling systems are increasingly insufficient to manage the rising thermal demands of high-density computing environments. In response, this study explores current trends in liquid cooling solutions for high-performance computing. It also looks at how sound-based testing methods can be used to detect and reduce unwanted noise. By considering both heat and noise, the paper aims to fill gaps in current research on performance limits and system reliability.

## **2. High-Performance Computing (HPC) Liquid Cooling Systems**

### **2.1 Traditional methods of cooling**

Traditional cooling techniques, primarily air-based solutions, have long served as the foundation for thermal management in high-performance computing environments (Vallury et al. 2015). To disperse thermal energy into the surrounding environment, these methods typically involve using fans to circulate ambient air over heat-generating components and through server racks. Conventional air-cooling systems face significant challenges due to the continuous increase in heat dissipation caused by multi-core processors and dense computing clusters, despite their effectiveness at lower power densities (Gupta et al. 2021). Since air cooling is becoming less effective at reducing the significant heat produced by modern high-density processors, this increasing thermal output calls for a re-examination of current cooling paradigms (Azarifar et al. 2024).

The rising electric power usage and intensity of heat in high-performance computing (HPC) applications, because of technological advancements such as the Intel Xeon Phi co-processors, necessitate the formation of advanced and efficient approaches to thermal control in addition to air cooling (Sarangi et al. 2015). The growing thermal challenge consequently has promoted the value of modelling temperature and energy to characterise and predict large-scale computing system dynamics (Ellsworth and Iyengar 2009). Air has a low thermal conductivity (approximately 0.026 W/m·K) and a volumetric heat capacity roughly 3,300 times lower than water. These properties limit its heat removal capability, particularly as server racks transition from historical averages of 5–15 kW to modern demands often exceeding 40–100 kW per rack in AI-accelerated environments (Crosley, B.2026).

Moreover, the high initial cost of powering and cooling HPC centres, which is nearly equal to the cost of purchasing the systems, highlights the need for energy-efficient thermal solutions (Satyanarayanan 2011). Though popular, air cooling's inherent drawbacks, including its inherently lower thermal conductivity than liquid coolants as well as lower effectiveness at higher heat flux levels, are fast becoming evident (Azarifar et al. 2024).

This has driven the investigation into other cooling technologies that can provide superior heat extraction and energy effectiveness. As a result, the air-cooling demand usually translates to a higher physical footprint for data centres to allow for the necessary airflow and heat exchange technology, leading to additional costs and environmental footprint. The standard air-cooling system is fast reaching its cooling threshold, and the need for additional fans to provide relief for high heat generation results in additional power usage and spatial demands (Sarangi et al. 2015).

Due to the high amount of energy consumed by cooling, frequently up to 40% of the overall energy spent in a data centre, it becomes extremely important to tackle these inefficiencies for the sake of economic and environmental sustainability. This huge energy requirement for cooling, in addition to that for the IT equipment itself, forms a significant portion of the overall operational cost and carbon footprint of HPC infrastructures, thus making energy-efficient cooling one area of research and development where investment needs to increase (Ellsworth and Iyengar 2009). The world electricity demand from centralised data centres will reach over 857 TWh by 2028, cooling and power delivery systems contributing a substantial 30–40% to this consumption (Tamvada and Moghaddam 2022). Such estimates illustrate the unsustainable nature of future reliance on conventional air-cooling technology for coping with the thermal loads of the ever-increasing power densities in today's HPC systems, thereby necessitating the widespread adoption of more advanced and efficient cooling technologies (Tamvada and Moghaddam 2022).

However, the shift from traditional air-cooling strategies to innovative ones creates distinct challenges, such as higher up-front capital expenditure and increased complexity in the support structure, requiring judicious cost-benefit analysis. The advantages in the long run, in terms of reduced operation costs and enhanced thermal performance by liquid cooling strategies, usually justify the expenditure in the end and thus represent a viable option for the high-performance computing sectors. The necessity for superior temperature control has driven research into innovative cooling technologies, such as two-phase cooling, where the latent heat of vaporisation is used to achieve extremely efficient transfer of the unwanted heat, achieving performance well above the single-phase method (Tamvada and Moghaddam 2022).

The literature review shows that traditional air-based cooling remains widely adopted, it is no longer sufficient for modern HPC environments characterised by high thermal densities and energy demands. Its limitations in thermal efficiency, scalability, and sustainability necessitate a shift toward more advanced cooling technologies. Emerging liquid-based and hybrid cooling solutions provide higher heat transfer performance, reduced energy consumption, and improved environmental sustainability, making them increasingly vital for next-generation HPC systems.

### **2.2 Modern Cooling System for HPC**

Modern cooling technologies have emerged as the ultimate solution for managing the increase in thermal loads for the exponentially increasing growth and performance demands in the central processing units (CPUs) and

(GPUs) in computing systems. As HPC environments continue to evolve, the traditional air-cooling strategies are no longer sufficient to meet the demands in thermal control. Figure 1 illustrates the historical trend in CPU power consumption.

This section of the literature review provides a comprehensive discussion on modern cooling technologies specifically designed for HPC applications. It focuses on three main types of liquid cooling systems: direct-to-chip, immersion, and hybrid liquid cooling systems. The review also highlights the thermal efficiencies, operational benefits, and limitations of each approach, offering insights into their effectiveness in enhancing performance, reliability, and energy efficiency in HPC environments.

### 2.2.1 Direct to Chip Liquid Cooling

Direct Liquid Cooling (DLC) has become one of the most important methods for managing heat, especially in High-Performance Computing, where the ongoing quest for greater computing power has increased heat generation (Ali et al. 2022). DLC stands out by introducing a cooling fluid directly into close contact with heat-generating components, contrasting sharply with traditional air-cooling systems (Das 2006). Due to the close contact, more effective heat removal is achievable, making DLC a vital technology for maintaining optimal operating temperatures in densely packed, power-intensive HPC setups (Jehhef 2018). The adoption of DLC is driven by the rising thermal design power of CPUs and GPUs, which now routinely surpass the capabilities of conventional air cooling (Gong 2021).

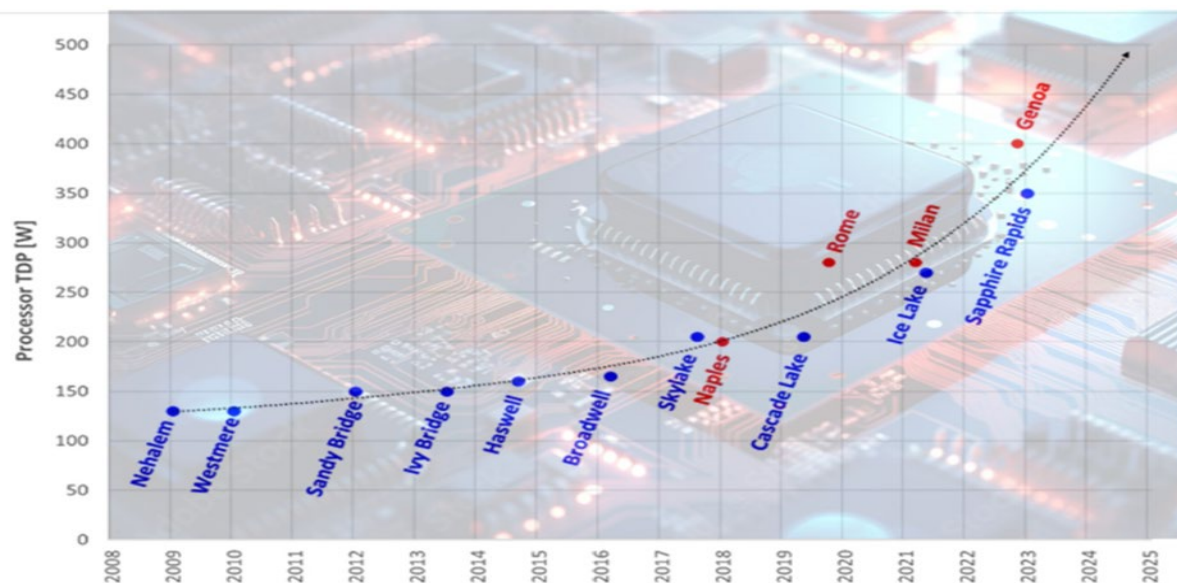


Figure 1. CPU power consumption history (Vigil and Vigil 2024).

The fundamental principle of DLC involves circulating a liquid coolant through a network of cold plates carefully attached to heat-generating components such as CPUs, GPUs, and memory modules. The heat produced by these devices is absorbed by the cold plate and transferred to the moving liquid coolant. The heated coolant is then directed to a heat exchanger or Coolant Distribution Unit, where the absorbed thermal energy is expelled to a separate cooling loop, usually connected to chillers or cooling towers, thus enabling the thermodynamic cycle.

The choice of fluid is a key design consideration, encompassing options such as water, glycol-water mixtures, and dielectric fluids, each offering distinct properties related to viscosity, thermal conductivity, and electrical compatibility. Figure 2 illustrates how the Direct Liquid Cooling (DLC) system operates.

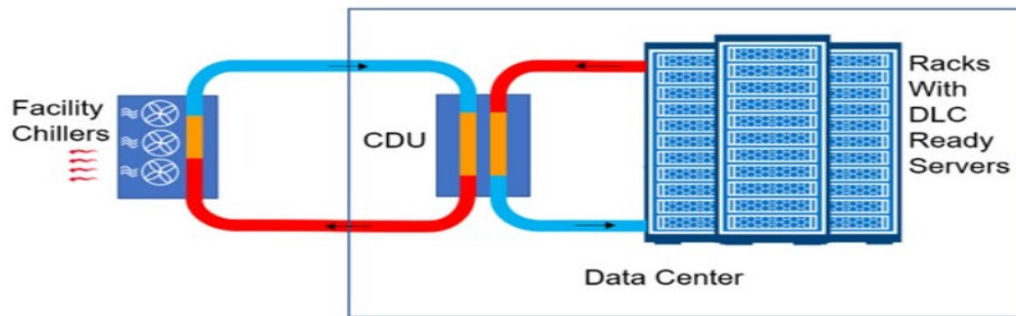


Figure 2. How the DLC works (Vigil and Vigil 2024).

An effective DLC system comprises several components, each playing a unique and vital role in the overall success of the cooling system. Cold plates usually made from thermally conductive materials such as copper or aluminium, are the primary elements responsible for extracting heat from electronic components (Shatskiy, Gulevsky, and Osipov 2021). Pumps, piping, and related components work together to circulate the coolant, ensuring a continuous, controlled flow rate and pressure for effective heat transfer. Heat exchangers, also known as Coolant Distribution Units, transfer heat from the coolant to another cooling system.

The entire setup is constructed with manifolds and quick disconnects to facilitate easy installation, maintenance, and replacement of parts. Monitoring and control units provide data on temperature, flow rates, and pressures, enabling the operator to make adjustments that optimise the cooling performance of the DLC system and maintain its reliability.

The options for DLC configurations encompass a broad range of approaches based on application requirements and performance objectives. Cold plate cooling is by far the most common method, where cold plates are directly attached to individual components to cool them locally. On-chip liquid cooling is a much more advanced technique, where microchannels are attached directly onto the chip surface, enabling heat to be removed at its source. Rear-door heat exchangers are sometimes combined with DLC systems to recover and vent the excess heat into the air surrounding the rack enclosure, providing supplementary cooling option.

There are many different types of DLC to meet various application needs and performance objectives. Cold plate cooling is the most common type of DLC. Cold plates are mounted directly on individual components for localised cooling. A more advanced concept is direct liquid cooling, where microchannels are etched directly onto the chip surface for highly efficient heat removal at the source. Rear-door heat exchangers can also be integrated into DLC systems to dissipate the remaining heat into the air, using the rack enclosure structure for additional cooling.

DLC offers significant advantages for High Performance Computing (HPC), particularly where enhanced thermal management is necessary. It delivers considerably higher heat removal efficiency than air cooling, supporting CPUs with thermal design power exceeding 400W (Kim, Lee, and Rhi 2025). This leads to lower Power Usage Effectiveness values, which are vital for data centre sustainability, and improves energy efficiency something only achievable with DLC.

Due to its superior cooling capabilities, DLC also allows for substantially higher rack densities than air cooling (greater than 50-80 kW/rack), providing an effective way to increase computational density within a smaller footprint (Jayarajan and Azimov 2023). Additionally, DLC systems operate much more quietly than air-cooled systems, reducing noise pollution in data centres (less noise = less pollution). Finally, DLC is more environmentally friendly as it decreases or even eliminates the need for energy-intensive air conditioning units (Li et al. 2020).

DLC has proven to be a crucial and distinctive thermal management solution for high-performance computing environments. By avoiding the issues linked to air cooling and easily coupling the liquid coolant directly to the heat-generating components, DLC can handle the very high heat fluxes produced by new high Thermal design processor (TDP), leading to higher computational densities, increased energy efficiency, and improved hardware longevity. The implementation of advanced microchannel heat sinks and the potential offered by nanofluids are key advancements in heat transfer technology that continue to enhance cooling effectiveness at the heat source. However, significant challenges remain regarding operational complexity, the long-term stability of nanofluids, and the economic viability of these advanced designs. Overall, DLC must continue to evolve through smarter control systems, new advanced materials, and innovative ideas to meet the increasing demand for higher

computational power, while maintaining and enhancing thermal management capabilities for next generation exascale and post-exascale computing systems.

### 2.2.2 Immersion Liquid Cooling

The increasing demand for high-performance computing has also risen, accompanied by heat generation that promotes the development of new efficient cooling solutions to prevent thermal throttling (Radebaugh 2009). Immersion cooling provides a viable alternative to air and direct liquid cooling methods in high-density computing environments such as data centres and supercomputers. It offers improved heat dissipation and energy efficiency by directly submerging electronic components, like CPUs and GPUs, into a thermally conductive, electrically non-conductive dielectric fluid, creating a close thermal interface that enhances heat extraction (Jehhef 2018). The typical power density of the immersion liquid cooling system ranges from 100 to 200 kW, and its heat transfer coefficient is 50 to 1,000 times higher than that of conventional air-cooling methods (Crosley, B.2026).

This contact reduces thermal resistance from heat sinks and thermal interface materials (TIM), enhancing cooling efficiency. Operating at lower temperatures directly boosts system reliability, extends component lifespan, and may allow for higher clock speeds and better computing performance (Moita, Moreira, and Pereira 2021). In this context, immersion cooling surpasses traditional air cooling and direct liquid cooling due to its superior heat transfer efficiency and energy savings. Air cooling remains the most common method but is limited because it lacks the thermal conductivity and heat capacity needed for the intense heat generated by high-performance components. While direct liquid cooling offers better thermal performance than air cooling, it is still influenced by the thermal interface and is prone to leaks or corrosion (Guan et al. 2022). The limitations of air and water cooling are amplified by the demands of miniaturisation, higher operational speeds and data transfer rates, and higher energy densities involving devices such as lasers and optical fibres (Ali et al. 2022). Improved efficiencies and designs in data centres within the IT sector are increasing interest in hot water-cooling strategies (Meijer 2010). There are two types of immersion cooling systems: single-phase and two-phase. Figure 3 illustrates single-phase and two-phase immersion cooling systems.

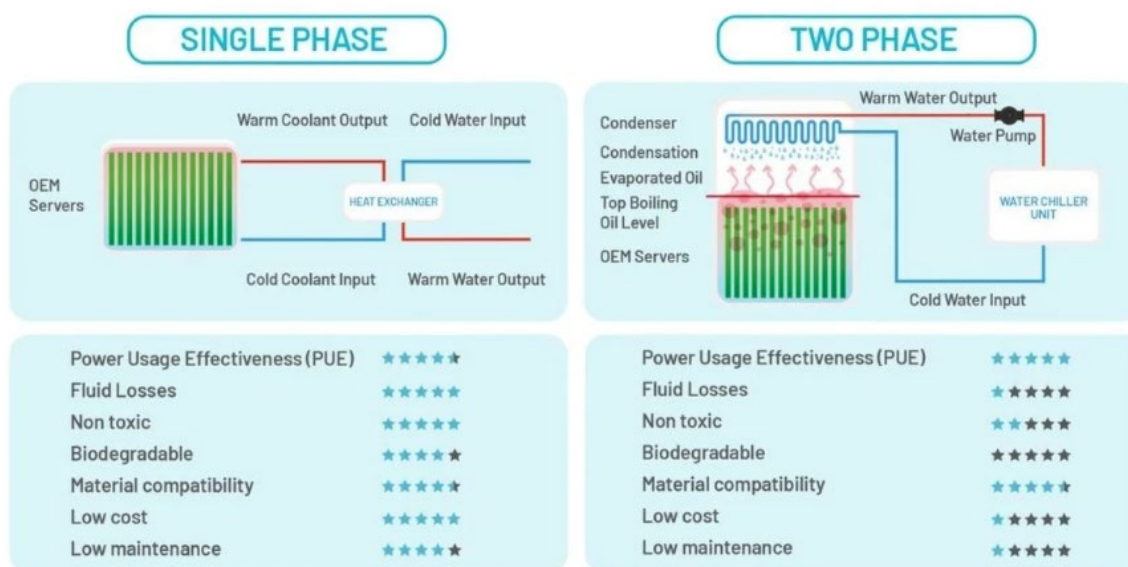


Figure 3. Single and two-phase immersion for HPC (Comms 2024).

Each operates on different principles and offers distinct advantages. In single-phase immersion cooling, the dielectric fluid circulates in liquid form throughout the entire system. The liquid dielectric absorbs heat as it moves through the circuit and is then discharged via a heat exchanger or an external cooling loop (Shatskiy, Gulevsky, and Osipov 2021). Once heated, the dielectric is pumped to a heat exchanger, where the heat is dissipated to a second cooling loop or the surrounding environment. In two-phase cooling, the dielectric exploits the latent heat of vaporisation to achieve much more efficient heat transfer. Here, the dielectric immediately boils upon contact with the heat generated by the electronic components, absorbing a significant amount of thermal energy as it transitions from liquid to vapour. The vapour rises and condenses on a heat exchanger (condenser) located physically above the liquid pool, rejecting the absorbed thermal energy. The liquid condensate then flows back to

the pool, and the cycle continues. Two-phase immersion cooling, based on flow boiling and jet impingement, provides an excellent solution for cooling electronics with high heat fluxes (Gómez et al. 2021).

To decide whether to use single-phase or two-phase immersion cooling, many factors must be considered, including heat load, power density, space limitations, and cost. Immersion cooling works by transferring heat efficiently from electrical components to the dielectric fluid, which then carries the heat away and dissipates it into the surrounding environment. This process involves convection, and in the case of two-phase cooling, evaporation of the coolant is used to cool hotspots on the chip (Wang et al. 2025). When choosing dielectric fluids, they need to possess certain thermophysical properties to ensure good performance and reliability for immersion cooling systems.

Dielectric fluids need a specific balance of thermophysical properties, including high thermal conductivity, high specific heat capacity (or heat of vaporization), low viscosity, and high dielectric strength. When choosing dielectric fluids, they must possess certain thermophysical characteristics to ensure optimal performance and reliability in immersion cooling systems.

Immersion cooling depends on effectively removing heat from electronic components through contact with a dielectric fluid. Its cooling capability relies on the dielectric fluid's thermal conductivity, heat capacity, and flow rate. The choice of dielectric fluid greatly influences the performance and reliability of immersion cooling systems. Ideal dielectric fluids should possess high thermal conductivity, low viscosity, high dielectric strength, and high chemical inertness to ensure efficient heat transfer, low pumping power, insulation, and compatibility with electronic components. Common dielectric fluids for immersion cooling include synthetic oils, fluorocarbons, and hydrofluoroethers. Direct contact liquid cooling, or immersion cooling, involves the dielectric coolant being in direct contact with the battery, eliminating thermal and contact resistance between the cooling system and the battery, thereby enhancing the efficiency of heat transfer and dissipation (Kim, Lee, and Rhi 2025). New technologies are emerging that combine multiple cooling systems for better performance. Hybrid cooling systems employ at least two different methods. The simplicity of manufacture and low cost of air-cooling systems are notable, and while air-cooling systems are less complex, liquid cooling methods can achieve a higher heat transfer coefficient (Tripathi and Marconnet 2024).

### **2.2.3 Hybrid Liquid Cooling**

The increase in power densities in high-performance computing environments demands enhanced thermal management strategies for efficient operation and reliable component longevity. These hybrid cooling systems can integrate various advanced technologies, including liquid cooling, phase change materials, and vapour chambers, to reduce hot spots and improve heat distribution across components. Besides power densities, heterogeneous computing units like GPUs and highly specialised accelerators pose additional thermal management challenges. Hybrid cooling systems effectively manage flux densities ranging from 100 W/cm<sup>2</sup> to 1000 W/cm<sup>2</sup> (Bamdezh and Molaeimanesh 2020). Consequently, there has been substantial research into microchannel heat sinks, which remove high heat loads from small spaces, and the integration of phase change materials with heat pipes for improved transient thermal management (Asim and Siddiqui 2022).

Such systems leverage a liquid's superior thermal conductivity compared to air, resulting in more efficient cooling. The adoption of a hybrid cooling system could greatly facilitate heat extraction from critical components and address the physical limitations typically associated with high-density computing racks. These hybridised cooling methods using liquid-based solutions are essential to enhance the performance and reliability of computing systems, such as exascale HPC and post-exascale HPC, which will perform more tasks per second than any HPC systems that have come before (Sharifi et al. 2025).

The following Figure 4 illustrates how the hybrid immersion cooling system works.

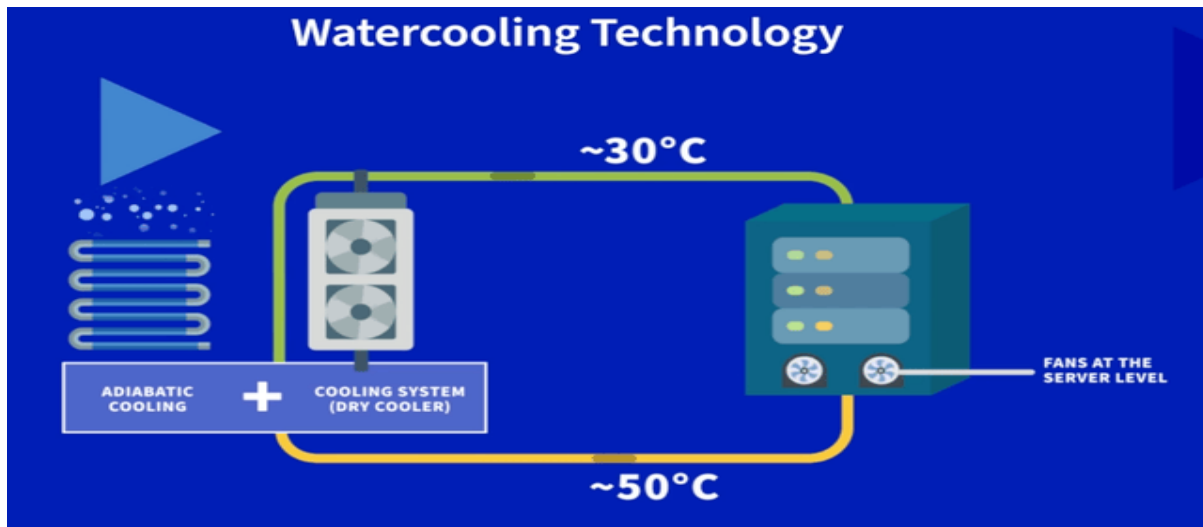


Figure 4. Hybrid Immersion liquid Cooling system Jay .(2023).

This necessitates a reflective review of hybrid cooling systems, including recent innovations in design and applications, performance analyses, types of cooling used, and external sustainability impacts within the HPC sector. In particular, the development of hybrid cooling technologies such as air-liquid hybrid systems, immersion cooling combined with hybrid methods, and other composite material-based approaches to manage extreme thermal loads in HPC clusters will be examined. These systems must not only address peak thermal loads but also enhance reliability and extend component lifespan by maintaining stable operating temperatures and reducing thermal cycling (Netti et al. 2022). Microchannel heat sinks utilise nanofluids, which can markedly improve heat transfer performance while also increasing pressure drops due to high concentrations of nanoparticles.

The balance between increasing thermal dissipation capacity (thermal effective power) and reducing extra energy consumption is a key factor in designing sustainable HPC cooling systems. New heat exchanger technology, including heat exchangers with hydrofoil-shaped ribs on the vertical sidewalls, which use a nano-encapsulated phase change material slurry for cooling, offers further opportunities to improve the thermal performance of a direct evaporative cooling system while effectively managing pressure penalties (Zhang et al. 2022).

Apart from these active cooling improvements, the revived technology of immersion cooling, first proposed in the 19th century for transformers, is an attractive means of transferring the heat directly from the electronic components and allows heat management at higher densities (Pambudi et al. 2022), which lends itself to heat-reuse strategies, thus saving a major proportion of energy usage, as because you can avoid not using the chiller systems, and deal with waste heat by introducing it into secondary fluid loop. This would improve power usage effectiveness in a significant way and enable captured waste heat to be used as an energy supply for district heating or other industrial use, this technology would support the emergence of a data centre circular economy. New heat exchanger designs are also important and advancing, including hydrofoil shaped sidewall ribs, and nano-encapsulated, phase change material slurries which all provide opportunities to improve thermal performance, but understand pressure (Rehman et al. 2020).

The selection of suitable cooling fluids, including advanced nanofluids and dielectric fluids, is also important as it affects not just heat transfer coefficients but also material compatibility and environmental impact. New ideas to improve heat exchange involve changing the type of heat transfer liquids, for example, using nanofluids with enhanced thermal properties and efficiency during convective exchange (Maghrabie et al. 2021). This also includes hybrid nanofluids that exhibit better thermal conductivities than conventional fluids and sometimes single component nanofluids, which boost heat transfer efficiencies in various heat exchanger applications. The use of nanofluids in heat exchangers, such as plate-fin designs and heat pipe configurations, shows significant potential to enhance thermal-hydraulic performance across laminar, transitional, and turbulent flow regimes. The key improved thermophysical properties of nanofluids particularly thermal conductivity and convective heat transfer coefficients enable advanced thermal management and open opportunities for miniaturisation and energy-efficient cooling systems in HPC. This enhancement results from nanoparticles dispersed in the base fluid, further increasing the fluid's thermal conductivity and disrupting thermal boundary layers around heated surfaces, thus rapidly removing heat from high-power-density components (Mebarek-Oudina et al. 2021).

Thermal transport fluids have become increasingly efficient and their proper usage with nanoparticles has provided an opportunity for a complete rethink in the process heat transport fluids literature and improving the

thermal management of future HPC systems. Even stable hybrid nanofluids, when hybrid between two types of nanoparticles with some level of synergy and performing better than the single-nanoparticle suspensions (Moita, Moreira, and Pereira 2021).

### 3. Discussion

The relentless increase in power and flux densities within high-performance computing systems has necessitated a paradigm shift from inadequate air-cooling to sophisticated hybrid thermal management solutions. This chapter establishes that the integration of liquid cooling, phase change materials, and advanced components like microchannel heat sinks is critical for managing extreme thermal loads, ensuring component reliability, and enabling the future of exascale and post-exascale computing. The emergence of advanced heat transfer fluids, particularly nanofluids and hybrid nanofluids, presents a significant opportunity to dramatically enhance heat transfer coefficients and support the trend towards miniaturisation. However, the successful implementation of these systems hinges on overcoming key challenges related to nanofluid stability, economic viability, and environmental impact. Ultimately, the path forward requires a balanced design philosophy that prioritises not only superior heat extraction but also energy efficiency and sustainability, thereby supporting the development of more powerful and reliable computing infrastructures. Among the various cooling methods, air cooling has become increasingly inadequate, remaining viable primarily for systems operating below approximately 15–25 kW per rack. Table 1 presents a comparative analysis of different cooling technologies and their performance characteristics.

Table 1. Comparative Analysis (Crosley, B.2026)

Cooling Method	Typical Rack Power Density	Heat Transfer Advantage	Advantage Key Limitations	Energy Savings Potential
Traditional Air Cooling	15–50 kW	Baseline	High fan power, hotspots, noise	Baseline
Direct-to-Chip Liquid	100–200+ kW	~50–1000× higher heat transfer coeff.	Higher upfront cost, fluid management	30–50% in high density
Immersion Cooling	150–500+ kW	Eliminates air flow entirely	Retrofitting complexity, fluid compatibility	Up to 40–94%

Among these methods, liquid cooling systems consistently demonstrate superior thermal performance and energy efficiency at high power densities. However, these advantages come with trade-offs, particularly in terms of higher capital costs and increased system complexity. In contrast, the limitations of air cooling are not merely incremental; they reflect a fundamental mismatch between the rapid growth in computing power and the physical constraints of convective heat transfer.

### 4. Conclusion

This review of the literature shows that the limited thermal efficiency and high energy consumption of traditional air-cooling technologies make them increasingly unsuitable for contemporary high-performance computing (HPC) environments. Liquid-cooling solutions have become a more efficient method of handling extreme thermal loads as computing components like CPUs and GPUs continue to increase in density and heat output. Immersion cooling offers the best thermal performance and energy-saving potential among these, but it comes at a higher cost and requires more infrastructure. Direct-to-chip liquid cooling is a practical and effective option for current systems. Although hybrid cooling systems can provide small benefits, their implementation complexity frequently limits their potential. In general, certain operational and financial factors influence the cooling strategy selection. To create and simulate optimized liquid-cooling models that can enhance thermal performance, energy efficiency, and long-term operational sustainability in HPC data centers, more research is required, as this review makes clear.

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## **Biographies**

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