Academic Journal of Science and Technology
ISSN: 2771-3032 | Vol. 17, No. 2, 2025

Overview of Liquid Cooling Technology Development in Data Centers

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Abstract: This paper conducts a systematic study on the development of liquid cooling technology in data centers. It analyzes the energy consumption challenges faced by data centers amid the explosive growth of AI and computing power demands, as well as the limitations of air cooling technology in high-heat-density scenarios. The article highlights that liquid cooling technology, with its advantages of high thermal conductivity, low energy consumption, and high-density deployment, has become a key technological pathway for achieving green and low-carbon development in data centers. The paper elaborates on the principles, characteristics, and current applications of three liquid cooling technologies: cold plate, immersion, and spray cooling. Through practical case studies and comparative data, it demonstrates that liquid cooling can significantly reduce PUE to below 1.2, achieving 1.1 or lower in certain scenarios, while offering outstanding energy efficiency and heat recovery potential. Although challenges remain in cost, operational maintenance, and material compatibility, liquid cooling technology plays an irreplaceable role in advancing the efficient, green, and sustainable development of data centers.

Keywords: Data Center; Liquid Cooling Technology; Air Cooling Technology.

1. Introduction

Currently, the global AI industry is experiencing rapid expansion, while domestic computing power capacity is surging exponentially. In this era of accelerated deep computing development, data centers have become the core infrastructure underpinning the global digital transformation process. According to the International Energy Agency's World Energy Outlook 2024 report: From 2014 to 2023, global electricity consumption growth significantly outpaced overall energy demand. The rapid development of the digital economy has driven electricity demand for data centers, artificial intelligence, and related sectors from approximately 460 TWh in 2022 to potentially exceeding 1,000 TWh by 2026[1]. Research indicates that data center energy consumption will rise from 0.9% of global energy use in 2015 to 8% by 2030[2]. However, the rapid growth of data centers today is accompanied by challenges. Issues such as energy consumption, carbon emissions, resource efficiency, and security are becoming increasingly prominent. Particularly since the introduction of the “dual carbon” goals, relevant policies have set higher requirements for data center PUE. To support China's “dual carbon” objectives, achieve intelligent and green development in data centers, and advance the industry, researching more efficient cooling systems has become a shared goal across the entire sector.

Air cooling technology remains the most widely adopted thermal management solution in global data centers[3], yet its drawbacks are increasingly apparent. First, the cooling efficiency of air-cooled systems is significantly impacted by ambient temperature and airflow[4]. In high-temperature or high-density computing environments, relying solely on air convection struggles to rapidly dissipate heat generated by equipment. This often leads to localized cooling challenges, compromising server performance and potentially triggering hardware failures. Second, air-cooled systems rely on numerous fans for air circulation, resulting in high energy consumption and persistent noise that disrupts both the data center environment and operations personnel[5]. Furthermore, air as a heat transfer medium has low thermal mass and thermal conductivity, limiting further improvements in cooling capacity and making it difficult to meet future data center demands for high computing power and low PUE. Finally, air-cooled architectures typically require substantial data center floor space and complex supply/return ducting designs, consuming valuable building area. They also present challenges for future expansion or retrofitting, lacking flexibility. These drawbacks are driving the industry toward more efficient cooling technologies like liquid cooling.

2. Analysis of Liquid Cooling Technology Advantages in Data Center Applications

A data center is a centralized facility designed to house computer systems and related components. Virtually all digital services in our daily lives—such as sending emails, using mobile apps, and shopping online—are powered by servers within data centers that provide computing and support. Data centers underpin the advancement of all cutting-edge technologies, including cloud computing, big data, and artificial intelligence. With the proliferation of AI servers and GPU clusters, the power consumption per cabinet has surged dramatically, placing higher demands on electricity and cooling systems. Consequently, servers generate substantial heat during operation, necessitating its removal through refrigeration systems. This maintains the ambient temperature within a stable, optimal range, preventing equipment overheating and system crashes.

PUE is an internationally recognized metric for measuring data center power usage effectiveness. A value closer to 1 indicates a higher level of data center sustainability. The majority of data center energy consumption stems from IT equipment and cooling systems[6].

The energy consumption breakdown for data centers at different PUE levels is shown in Table 1. As the table demonstrates, reducing the energy consumption share of the cooling system is a highly effective approach to lowering a data center's PUE value.

Table 1. System Energy Consumption Distribution at Different PUE

PUE	Refrigeration System Energy Consumption Share (%)	IT Energy Consumption Share (%)
1.92	30	52
1.5	21	67
1.2	9.2	83

In typical air-cooled data center cooling systems, the equipment with the highest energy consumption is primarily the chillers and terminal air distribution units. Data center rooms feature a plenum chamber beneath the raised floor, with room air conditioners installed on one side of the room. The pressure differential between the plenum chamber and the room drives the cooling capacity. However, traditional air-cooled data centers suffer from localized overheating and cold air leakage. Attempting to cool overheated areas by reducing the temperature of the entire room leads to redundant cooling capacity, reduced cooling efficiency, and limitations imposed by air's thermophysics properties. The heat dissipation limit for air cooling is 34W/cm²[7], while the heat flux density of current mainstream chips can reach up to 100W/cm². The average PUE for air-cooled data centers currently hovers around 1.5. The Action Plan for Green and Low-Carbon Development in the Information and Communications Industry (2022-2025) requires that by 2025, the PUE of newly built large and extra-large data centers nationwide shall be reduced to below 1.3.

Air cooling can no longer meet the PUE requirements of modern data centers. Compared to air-cooled data centers, liquid cooling technology offers significant advantages for data centre applications. For example, it can satisfy the thermal dissipation demands of high-power cabinets. The selected liquid medium has a thermal conductivity that far exceeds that of air, which substantially enhances thermal performance and improves data centre cooling efficiency. Liquid cooling systems also require less floor space than air-cooled systems, making them easier to deploy in a variety of scenarios and greatly improving the utilization of building space. They also simplify heat exchange processes, as using high-specific-heat-capacity liquid working fluids reduces energy consumption during the cooling cycle. When using liquid cooling for heat dissipation, temperatures are higher than in conventional air-cooled systems, resulting in superior heat recovery performance. Table 2 presents information on selected data centers.

Table 2. Information Summary for Selected Data Centers

Data Center	Project Scale/kW	Cooling method	Research Methods	PUE
A Data Center in the United States[8]	900	Liquid cooling + Air cooling	Actual measurement	1.04
A Data Center in Tianjin[9]	200	Air cooling	Theoretical calculation	1.5~1.57
A Data Center in Xian[10]	18000	Air cooling	Theoretical calculation	1.3
A Data Center in Shanghai[11]	1000	Air cooling	Theoretical calculation	<1.2
A Date Center in Beijing[12]	2400	Liquid cooling + Air cooling	Theoretical calculation	1.085
A Data Center in North China[13]	650	Air cooling	Actual measurement	1.25

As shown in Table 2, in actual data center applications, the PUE of liquid-cooled data centers is significantly lower than that of air-cooled data centers. In summary, data center liquid cooling technology has become a key driver propelling data centers toward greener, more efficient, and sustainable evolution, thanks to its core advantages of highly efficient heat dissipation, low energy consumption, high-density deployment, green and low-carbon operation, and long-term economic viability.

3. Liquid Cooling Technology

Data center liquid cooling technology utilizes liquid as a cooling medium to dissipate heat from thermal components such as server chips. Compared to air, liquids possess higher specific heat capacity and superior thermal conductivity (water conducts heat 25 times more efficiently than air), enabling faster and more effective removal of heat from thermal components to achieve enhanced cooling performance. Liquid cooling technologies can be categorized into cold plate, immersion, and spray cooling. Cold plate liquid cooling further divides into single-phase and phase-change cold plates. Cold plate systems operate non-contact, while immersion and spray cooling employ contact methods.

3.1. Non-contact

Non-contact liquid cooling involves placing server heat-generating components close to a cold plate, with liquid flowing within the plate to dissipate heat from these components. The liquid does not directly contact the heat source, primarily utilizing a cold plate solution. Cold plate liquid cooling addresses heat dissipation for high-heat-generating components within servers, while other lower-heat components still rely on air cooling. The overall PUE advantage is limited. Furthermore, the close contact between the coolant and the load imposes strict requirements for leak prevention and flow control. Coolants typically use special fluids such as ethylene glycol and deionized water. Non-contact cold plate liquid cooling exhibits higher thermal resistance. Compared to traditional air cooling designs, it achieves 60%–90% energy savings. Consequently, a small number of fans are typically still required for partial heat exchange. Cold plate data centers can achieve a PUE below 1.2 while maintaining traditional cabinet deployment methods, enabling higher deployment density. Current data center infrastructure and server retrofitting present minimal difficulty and cost, but liquid leakage risks must be considered.

Cold plate liquid cooling technology can be categorized into single-phase and phase-change cold plates. Compared to air cooling, the closed-loop system of cold plate liquid cooling enables more precise cold distribution and supply. The specific heat capacity of liquid coolants is significantly higher than that of air, allowing cooling water temperatures to be raised to 40-55°C. This contrasts with the 18-27°C supply temperatures of air cooling, resulting in substantial reductions in refrigeration energy consumption.

Compared to conventional cold plate liquid cooling, phase-change coupled liquid cooling reduces system pressure drop, lowers the risk of fluid leakage, and enhances system reliability. Research on cold plate liquid cooling technology primarily focuses on optimizing cold plate channel structures. This can be achieved through manifold micro-channels, corrugated micro-channels, fin-column array micro-channel, microbial channel, Z-shaped manifold micro-channel, conical manifold micro-channel, layered manifold micro-channel, and parallel manifold micro-channel. These approaches generally improve flow characteristics by optimizing channel structures, enhance heat transfer capacity by increasing heat exchange surface area, and reduce data center energy consumption by minimizing pressure drops.

3.2. Contact

Contact liquid cooling involves direct contact between the liquid and the heat source.

(1) Immersion liquid cooling: Its core principle involves fully submerging computing equipment in a highly thermally conductive insulating coolant (such as fluoridated liquids, mineral oils, or synthetic fluids). The liquid directly contacts the equipment surfaces to absorb and rapidly dissipate heat. All electronic components are directly submerged in the cooling medium liquid. Heat transfers from the electronic components to the liquid. A circulation pump then transports the heated coolant to an external primary-side water system for liquid-to-liquid heat exchange. The cooled coolant returns to the reservoir, repeating the cycle continuously.

The cooling system consists of a cooling tank, coolant, heat ex-changer, and circulation pump. The cooling tank features a sealed structure to prevent coolant evaporation and contamination; the coolant possesses high thermal conductivity and electrical insulation properties, ensuring safety and efficient heat dissipation; the heat ex-changer facilitates heat exchange between the liquid and external cooling systems (such as chillers or dry coolers), while the circulation pump maintains coolant flow within the system. Heat generated by the equipment is efficiently conducted through the liquid. The liquid circulation system transports this heat to the heat ex-changer, where it is dissipated via the external cooling system before returning to the equipment enclosure. Key advantages of immersion liquid cooling technology include high heat dissipation efficiency, low energy consumption (significantly reduced PUE values), high equipment density, low noise levels, and simplified maintenance.

Immersion liquid cooling is categorized into single-phase immersion cooling and two-phase immersion cooling. The primary distinction between single-phase and two-phase immersion systems lies in whether the coolant undergoes a phase change during heat absorption. After absorbing heat, the coolant reaches its boiling point temperature and evaporates, utilizing latent heat of vaporization to carry away the heat. It then contacts the external circulation cooling system where the gas condenses back into liquid. Throughout this process, the coolant undergoes two distinct states—commonly known as phase change. While phase change offers extremely high efficiency, it demands a more complex system with stringent requirements for cabinet sealing integrity and operational maintenance. Single-phase immersion liquid remains in a consistent state, resulting in a relatively simpler and more controllable structure.

(2) Spray-type liquid cooling: In spray-type liquid cooling, the coolant drips down from spray modules at the top of the server chassis. It cools heat-generating components through convective heat exchange via direct contact between the coolant and these components. The heat is then dissipated through channels within the server that collect the coolant and direct it to heat ex-changers. The coolant typically consists of non-conductive, non-corrosive liquids such as mineral oil or fluoridated fluids. Spray-type liquid cooling can completely eliminate cooling fans, offers strong heat exchange capabilities, and saves coolant compared to immersion cooling, reducing data center PUE to around 1.1. However, it requires modifications to cabinets and server chassis, presenting greater operational and maintenance challenges.

4. Summary

This paper presents a systematic investigation into liquid cooling technology for data centers. Research indicates that despite practical challenges in large-scale deployment—including high initial investment costs, coolant material compatibility issues, and the need for fundamental operational system reforms—this technology demonstrates irreplaceable advantages in overcoming the limitations of air cooling and significantly reducing data center PUE energy consumption metrics. Its widespread adoption holds profound significance for advancing the green and low-carbon transformation of the data center industry. Particularly noteworthy is that the medium-to-high temperature cooling medium generated by liquid cooling systems creates favorable conditions for waste heat recovery. This enables integrated energy utilization applications such as district heating and agricultural greenhouse heating, substantially enhancing the energy recycling efficiency and environmental benefits of data centers. This paves the way toward truly efficient, green, and sustainable next-generation data centers.

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