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Overview of Single-phase Immersion Liquid Cooling Technology

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Abstract: With the rapid advancement of high-performance computing technologies such as artificial intelligence and cloud computing, data centers face dual pressures: surging chip thermal density and the imperative to reduce energy consumption and emissions. Traditional air cooling technologies, constrained by their physical limitations, struggle to meet increasingly stringent thermal management demands, making liquid cooling an inevitable choice. This paper focuses on outlining single-phase immersion liquid cooling technology. This approach achieves efficient heat dissipation by directly immersing heat-generating electronic components in an insulating coolant, leveraging the liquid's high thermal conductivity and specific heat capacity. Compared to phase-change immersion cooling and indirect liquid cooling, single-phase immersion eliminates interfacial thermal resistance, shortens heat transfer paths, and handles extremely high heat flux densities. It also offers comprehensive advantages including simplified system architecture, lower initial investment and operational costs, reduced noise, and high space utilization. Analysis indicates this technology significantly reduces data center energy consumption, bringing Power Usage Effectiveness (PUE) close to theoretical limits. It represents a critical technological pathway for enabling green, high-density, and sustainable data center development.

Keywords: Data Center; Liquid Cooling Technology; Single-phase Immersion Liquid Cooling.

1. Introduction

With the explosive growth of the digital economy, cutting-edge technologies such as artificial intelligence, cloud computing, and big data are advancing toward a phase of high-quality development. As the foundation for these technologies, data centers are facing unprecedented demands for computing power and energy consumption challenges. Traditional air-cooling technology has long been the mainstream solution for data center thermal management, but its physical limitations are becoming increasingly apparent. With the rapid increase in chip-level thermal density—particularly when training larger AI models—the thermal design power of chips in high-performance computing clusters and AI servers has surpassed the kilowatt range. Air's low thermal mass and poor thermal conductivity efficiency have now become the bottlenecks in air-cooling system performance. Particularly now, the carbon peaking and carbon neutrality goals have set clear requirements for data centers to pursue green and sustainable development. Reducing cooling system energy consumption and improving data center PUE have become core issues in next-generation data center construction. The limitations of air-cooling systems necessitate the industry's search for alternative technological solutions. Against this backdrop, liquid cooling technology, with its thermal conductivity and specific heat capacity far surpassing air, is regarded as the inevitable choice for next-generation data center thermal management.

2. Data Center Liquid Cooling System

The computational power of data centers permeates every aspect of social production and daily life. High computing power implies that server operations and cooling systems consume enormous amounts of energy. Currently, reducing costs, improving efficiency, and pursuing green, low-carbon development have become core requirements for data center advancement. PUE serves as the primary metric for evaluating a data center's energy utilization efficiency.

PUE is the ratio of all energy consumed by a data center to the energy used by its IT load[1]:

$$PUE = \frac{E_D}{E_I}$$

In the equation, E_D represents the total energy consumption of the data center;
E_I represents the total energy consumption of IT equipment.

China's Data Center White Paper indicates that multiple provinces and municipalities have implemented requirements for design PUE not exceeding 1.2[2]. The “East Data, West Computing” policy explicitly mandates that by 2025, data centers at eastern hub nodes must achieve PUE < 1.25, while those at western hub nodes must achieve PUE < 1.2. Currently, the optimal PUE for air-cooled system data centers has reached approximately PUE < 1.25.

Faced with current policy targets for PUE metrics, the energy efficiency of traditional air-cooling technology has approached its limits. To achieve these goals, liquid cooling technology has emerged as a new solution for reducing energy consumption in data centers.

Liquid cooling is categorized into direct and indirect cooling[3]. Indirect cooling includes cold plate and micro-channel cooling, while direct cooling employs immersion cooling. Immersion cooling submerges a server's heat-generating electronic components—such as CPUs, memory modules, and hard drives—directly into a cooling fluid. This fluid dissipates the heat generated by the components. Based on whether the cooling fluid undergoes a phase change, immersion cooling is further classified into single-phase immersion cooling and phase-change immersion cooling.

In phase-change immersion liquid cooling, electronic components are submerged in a sealed liquid-cooled cabinet containing a low-boiling-point coolant. As the components operate and heat up, the coolant absorbs thermal energy until it reaches its boiling point and undergoes a phase transition. The resulting vapor bubbles rise to the top of the cabinet and enter an external circulation loop. Within this loop, a condenser heat exchanger cools the vaporized coolant back into liquid form. This condensed coolant then drips back into the cabinet. Water or other cooling media circulating through the condenser transfer the absorbed heat away, completing the cycle. As shown in Figure 1, this is a flowchart of a phase-change immersion liquid cooling system.

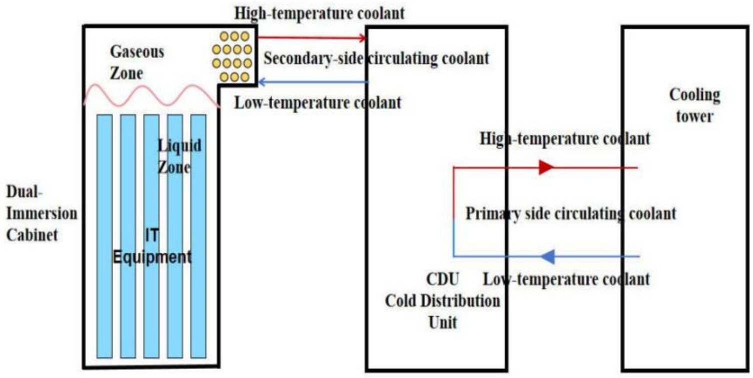

Fig 1. Schematic Diagram of Phase Change Immersion Liquid Cooling System

Single-phase immersion liquid cooling employs a high-boiling-point coolant that circulates via a pump. Heat generated by electronic components is transferred through a heat exchanger to external cooling equipment. Throughout the entire heat dissipation cycle, the coolant undergoes no phase change.As shown in Figure 2, this is a schematic diagram of a single-phase immersion liquid cooling system.

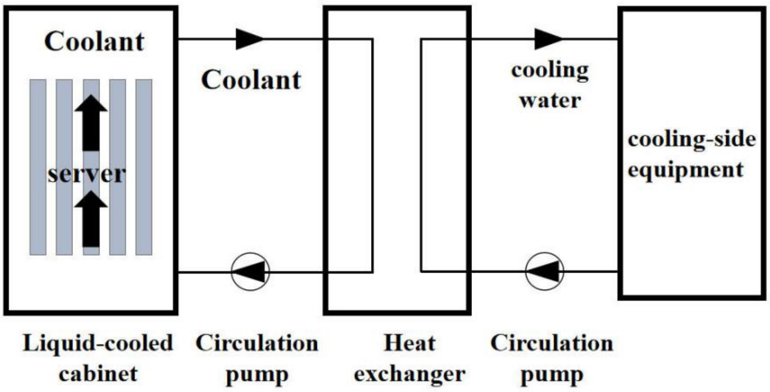

Fig 2. Single-Phase Immersion Liquid Cooling System Flowchart

Phase-change liquid cooling solutions offer outstanding thermal dissipation advantages and are well-suited for high-density computing scenarios. However, the specialized coolant requires customized enclosed cabinets, condensation systems, liquid distribution systems, and more. Compared to standard rack-mounted servers, this significantly increases manufacturing costs and complexity, resulting in high initial investment costs, relatively complex operation and maintenance, and more intricate technology. Therefore, within liquid cooling solutions, single-phase immersion cooling eliminates all interfacial thermal resistance and achieves the shortest possible heat dissipation path compared to indirect liquid cooling requiring complex piping and cold plates. This enables it to handle extremely high heat flux densities exceeding 1000 W/cm² while offering lower investment costs than phase-change immersion cooling systems [4]. In summary, single-phase immersion cooling demonstrates distinct advantages and is poised to become the future heat dissipation solution for data centers.

3. Single-phase Immersion Liquid Cooling

The core issues that need to be addressed in single-phase immersion liquid cooling technology are the coolant, heat sinks, and liquid cooling enclosure structure.

The selection of coolant is critical. Coolants with lower kinematic viscosity and higher thermal expansion coefficients exhibit superior performance. Their physical properties influence thermal performance as follows:

$$h \propto \beta^{0.25}\rho^{0.25}C_p^{0.25}\lambda^{0.75}\mu^{-0.25}$$

In the equation,his the heat transfer coefficient; β is the thermal expansion coefficient; Cp is the specific heat capacity; λ is the thermal conductivity; μ is the kinematic viscosity. Figure 3 shows the classification of coolants. The current development trends for commonly used coolants in China include hydrocarbon and silicone-based coolants, as well as fluorocarbon coolants.

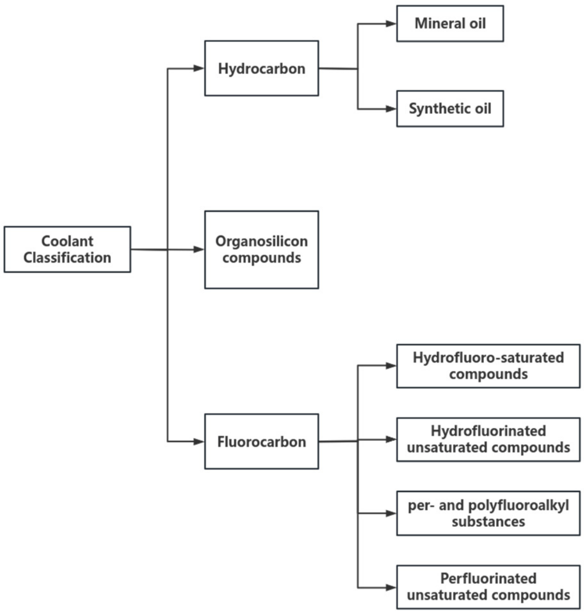

Fig 3. Coolant Classification Diagram

This classification not only clarifies the technical approach for coolants but also directly determines the core direction and key research topics for subsequent liquid cooling technology studies. Table 1 presents research progress on single-phase immersion liquid cooling technology under different coolants [5].

Immersion liquid cooling offers distinct advantages:

1. Direct contact between the coolant and electronic components reduces convective thermal resistance between the coolant and the heated surfaces of the electronic equipment, achieving a high heat transfer coefficient;
2. Completely resolve heat dissipation for all heating components in one go, eliminating the need for hybrid cooling solutions to cool the remaining low-heat server components;
3. High density of electronic equipment layout with minimal space requirements;
4. The coolant possesses high thermal conductivity and specific heat capacity, resulting in minimal variation in operating temperature;
5. Utilizing immersion liquid cooling eliminates the need for fans, thereby reducing noise, saving energy, and lowering consumption, with a PUE approaching 1;

Table 1. Research Progress in Immersion Liquid Cooling

Coolant	Flow state	Research Findings	Operating Parameters	Surface treatment methods	Power
Mineral oil	single-phase	Compared to air cooling, mineral oil cooling reduces temperatures by 8.74% and power consumption by 16.83%.	Inlet temperature:25~45℃	/	95
PAO-6, FC-40	single-phase	PAO-6 viscosity is more sensitive to temperature changes, chip power consumption increases, thermal resistance of FC-40 decreases by 10.4%, and thermal resistance of PAO-6 decreases by 25.8%.	Inlet temperature: 15~35℃ Inlet flow velocity:1~3L/min	/	200~600
fluoride solution	single-phase	The dynamic viscosity of coolant has the greatest impact on cooling performance.	Inlet temperature:20℃ Inlet flow velocity:5.1L/s	/	2*270

6. The coolant exhibits excellent insulation properties with a high dielectric strength. It is non-flammable, non-combustible, non-toxic, harmless, and non-corrosive. It possesses good chemical stability and material compatibility, making it environmentally friendly.

4. Summary

Single-phase immersion liquid cooling technology demonstrates significant application potential in thermal management for next-generation high-density data centers due to its notable advantages in efficient heat dissipation, simplified structure, energy conservation, and environmental friendliness. By enabling direct contact between the coolant and heat-generating electronic components, this technology effectively reduces thermal resistance, enhances heat transfer efficiency, and addresses heat dissipation for all heat-generating components while avoiding the complexity of hybrid cooling solutions. Furthermore, its high insulation properties, environmental friendliness, and low operational noise enhance its suitability for green data center construction. Against the backdrop of carbon peaking and carbon neutrality goals and stringent PUE requirements, single-phase immersion liquid cooling not only effectively addresses the thermal challenges of ultra-high-power chips but also significantly reduces overall data center energy consumption. This technology propels data centers toward greater efficiency, energy savings, and sustainable development, offering broad prospects and application value.

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