

Advancement of Liquid Immersion Cooling for Data Centers

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Abstract. With the increasing processing capabilities of data centers, the demand for advanced cooling has been increased, positioning liquid immersion cooling systems as a focal point due to their effectiveness and environmental benefits. This paper reviews the current state and prospects of liquid immersion cooling technologies for data centers by paper analyzing. The research spans the optimization of cooling technology parameters, material and coolant performance, as well as system level integration and thermal management. The characteristics analysis of liquids and supercritical fluids underscores the significance of coolant selection. Innovative cooling network designs have been shown to initiate failures and improve thermal distribution, enhancing data center performance and reliability. Additionally, the interplay between cooling systems and IT systems has been explored for its overall energy efficiency impact. Liquid immersion cooling technology demonstrates vast potential in ensuring safety, enhancing heat exchange efficiency, and meeting the growing needs of future data center development. Nonetheless, a deep understanding of complex fluid dynamics and heat transfer mechanisms remains key to driving technological advantages.

Keywords: Immersion Cooling; Data Center; Thermal management; Energy Efficiency

1. Introduction

With the strict monitoring and continuous improvement requirements of Power Usage Efficiency (PUE) in data centers, traditional air-cooling systems are facing many challenges, especially in high-density server environments. The cooling system consumes 30-50% of the total DC energy consumption [1]. Thus, the failure to reduce the energy consumption of the cooling system undoubtedly leads to significant energy waste in the growing demand for data centers. Moreover, with the rapid development of new high-performance chips, the heat flux of servers is also constantly increasing. If the heat of servers cannot be released in a timely manner, the computing efficiency and stability of chips will be affected, and even lead to electronic device failures. In order to meet this demand, liquid immersion cooling system [2], as a new type of heat dissipation technology, has been increasingly valued by researchers and data center managers due to its excellent thermal conductivity and cooling efficiency. At present, the research and application of liquid immersion cooling technology have shown positive progress, including single-phase and two-phase cooling systems, performance analysis of different cooling fluids, and system design optimization.

However, in practical deployment and widespread application, there are still many problems and challenges in liquid immersion cooling technology. Firstly, the selection and compatibility considerations of liquids are the core factors determining cooling efficiency and system safety. Secondly, the long-term stability and reliability of the system are key factors affecting the operation and maintenance costs of data centers. In addition, the current understanding of the energy-saving and emission reduction benefits of liquid immersion cooling systems is not sufficient and requires rich empirical data support. An in-depth analysis and exploration of these issues is crucial for the future technological development of liquid immersion cooling systems. This review work will help data center cooling technology move towards the goals of high efficiency and low energy consumption, and address the dual challenges of growing data processing needs and environmental protection through technological progress.

2. Research on Liquid Cooling Technology in Data Centers

2.1. Overview of Liquid Cooling Technology

2.1.1. Types of liquid cooling technologies

In the field of thermal management in data centers, liquid cooling systems are increasingly receiving attention as an effective means of heat removal. Traditional air-cooling technology is limited by thermal resistance and heat transfer efficiency, making it difficult to meet the growing heat dissipation needs of data centers. Therefore, in the research of liquid cooling technology in data centers, the type and performance of liquid cooling systems have become the focus of research.

According to the contact mode between liquids and electronic devices, liquid cooling systems can be mainly divided into indirect liquid cooling systems and direct liquid cooling systems [3]. Indirect liquid cooling refers to the process where the liquid does not directly come into contact with electronic components, but carries heat away through cooling plates or coolant channels. This method has better security and maintainability, but the heat exchange efficiency is relatively low. On the other hand, direct liquid cooling immerses electronic components directly into non-conductive liquid media, allowing heat to be efficiently transferred to the liquid and carried away from the heat source.

Direct liquid cooling systems are further subdivided into single-phase and two-phase liquid cooling systems. A single-phase system utilizes the circulation of liquid media to achieve heat transfer, and the medium remains liquid throughout the system [4]. The two-phase liquid cooling system utilizes the phase transition from liquid to gas to absorb heat, which typically has higher heat transfer capabilities because the phase transition process can absorb a large amount of heat at a constant temperature [5].

In direct liquid cooling systems, the cooling medium used is an important factor. Non-conductive media such as Fluorinert (a fluorocarbon compound), mineral oil, or synthetic oil are widely used due to their excellent thermal conductivity and compatibility with electronic devices. M. Muneeshwaran et al. used FC-40 medium for performance analysis in their study and demonstrated the potential of single-phase immersion cooling systems in data center heat dissipation [6].

Furthermore, it should be mentioned that due to the energy consumption issues during data center operation, the performance of cooling systems is not only related to thermal management, but also closely related to energy efficiency. The study by Yangyang Fu et al. shows that optimizing cooling systems can effectively improve the energy efficiency ratio (PUE) of data centers [7]. For direct liquid cooling systems, system optimization may include the selection of cooling media, fluid dynamics design, and configuration of heat exchangers.

In summary, the type and performance of liquid cooling systems are key to thermal management research in data centers. The current challenges and development directions include improving cooling efficiency, reducing system costs and operational maintenance difficulties, and finding more environmentally friendly cooling media. Through continuous research and innovation, the application of liquid cooling technology in data centers will continue to advance and is expected to become a mainstream thermal management solution.

2.1.2. Thermal performance of liquid cooling systems

One of the main characteristics of liquid cooling systems is thermal performance, which is crucial for maintaining accurate operation of data centers. The discussion of thermal performance covers the heat exchange process from single-phase to two-phase, as well as the influence of liquid cooling medium selection on heat exchange efficiency. This section will focus on the thermal performance of liquid cooling systems during operation, and explore the significance of the latest research results for practical applications.

Single phase cooling systems are widely used in data centers due to their operational stability and technological maturity. In such systems, liquid cooling media, such as water or non-conductive media such as FC-40, are pumped through cooling circuits to absorb and transfer heat. Muneeshwaran et al. (2020) conducted experimental analysis on a single-phase immersed cooling system using FC-40

medium and found that increasing the cycle rate and optimizing the cooling circuit layout can significantly improve heat exchange efficiency [8]. This is consistent with the research on natural and forced convection thermal performance characteristics mentioned by Huang et al. (2020) [9], who pointed out that in order to achieve optimal operating efficiency and minimize energy consumption, the key is to carefully adjust the working parameters of the circulating pump and the liquid flow rate.

Two phase liquid cooling systems, especially boiling cooling, have become a research hotspot due to their high thermal conductivity. Kanbur et al. (2020) conducted experimental performance and thermal economic analysis on two-phase boiling cooling systems [10], emphasizing the role of surface modification technology in improving boiling heat transfer coefficient. These findings are further supported by Kang et al. (2020) [11], who proposed the idea of optimizing heat transfer through surface modification in their two-phase immersion cooling study. In addition, Zheng et al. (2020) conducted predictive research on the critical heat flux conditions for flow boiling based on a wall heat flux distribution model, providing a theoretical basis for liquid hydrogen flow boiling in microgravity environments [12].

When applying liquid cooling technology in actual data center environments, thermal performance analysis is an important step. Lu and Zhang (2020) investigated and analyzed the cooling performance of data centers through numerical and experimental investigations [8], revealing the importance of airflow and temperature distribution in thermal performance optimization. The results of this study indicate that in the design and management process of data centers, the thermal characteristics of cooling systems must be closely matched with the thermal load of information technology (IT) equipment to ensure optimal cooling efficiency and energy utilization.

In addition to intuitive evaluation of heat exchange efficiency, accurate data recording is equally important for thermal performance analysis. Monteiro et al. (2020) emphasized the importance of optimizing data recording when studying isolated limb perfusion technology, which also applies to performance monitoring of cooling systems in large-scale data centers [4]. The accuracy of data recording directly affects the evaluation of cooling systems and the formulation of optimization strategies.

To summarize the previous argument, the thermal performance of liquid cooling systems is influenced by various factors, including medium selection, system design, optimization of cooling cycle parameters, and surface treatment techniques. Through continuous experiments and model analysis, researchers are gradually revealing the key factors that can improve the efficiency of liquid cooling technology in data centers. The advancement of accurate monitoring and data recording technology not only helps to understand the real-time thermal performance of the system, but also has important guiding significance for long-term energy efficiency optimization and design improvement.

2.2. Performance Optimization of Liquid Cooling Technology

2.2.1. Variable capacity systems and energy efficiency

In the context of research on liquid cooling technology in data centers, Variable Capacity Systems (VCS) have demonstrated significant advantages in energy efficiency. Compared to traditional constant speed cooling systems, VCS can dynamically adjust cooling capacity based on changes in heat load to reduce unnecessary energy consumption and improve overall system performance [9]. For example, experimental and modeling studies have shown that variable capacity air can maintain a high energy efficiency ratio of air heat pumps under low load conditions [1].

The improvement of energy efficiency can be explained by the inverse Carnot cycle theory, where the energy efficiency ratio (COP) of the system is a key parameter used to evaluate the performance of heat pumps or cooling systems. COP is defined as the ratio of the cooling effect provided by a system to the power consumed. In VCS, adjusting the operating speed of the compressor according to demand can achieve near optimal working conditions, thereby increasing the COP value.

To further confirm this effect, researchers used artificial intelligence models to study the effects of coolant and lubricant on cutting performance, which can help predict and optimize the performance

of VCS in actual environments [2]. In addition, the energy efficiency optimization of variable capacity systems also benefits from their improvements in heat transfer. Recent studies have shown that improving the design of cooling networks, such as applying the principle of blocking tolerance, can effectively enhance the thermal performance of systems [3].

In data center applications, the combination of VCS and liquid cooling technology can significantly improve thermal management efficiency. Due to the highly dynamic heat load in data centers, the flexibility of variable capacity systems can provide timely response to the constantly changing cooling needs. For example, performance analysis of single-phase immersion cooling systems shows that the use of FC-40 dielectric fluid provides excellent cooling performance in data center applications, and the system can adjust its performance according to actual loads [11]. The experimental performance and thermal economy analysis of the two-phase immersion cooling system further demonstrate the effectiveness and economy of the variable capacity system in thermal management [12].

In addition, research has also pointed out the impact of surface modification on two-phase immersion cooling technology. Surface modification technology can further enhance phase change heat transfer in the cooling system and improve the thermal conductivity efficiency of the system [13]. Meanwhile, studies on the heat transfer characteristics of natural and forced convection have also shown that these systems perform well in single-phase immersion cooling applications in data centers. [14]. These studies not only confirm the potential advantages of VCS in data center applications, but also provide important technical references for future system design and optimization.

Although the energy efficiency improvement of VCS has clear experimental and theoretical basis, it still faces many challenges in practical applications, such as the complexity of system design, advanced requirements for control and optimization strategies, and integration issues with existing infrastructure [15]. Therefore, future research should focus on solving these practical problems in order to fully apply the concepts of variable capacity systems and energy efficiency to the field of liquid cooling technology in data centers.

2.2.2. System level thermal management and energy consumption analysis

In the operation of modern data centers, the optimization of energy efficiency and thermal management has become a key concern. With the continuous increase in power consumption of information technology equipment, traditional air conditioning systems are no longer able to meet the cooling needs of high-density data centers. Therefore, the research and development of liquid immersion cooling systems have become an important area for improving energy efficiency in data centers [16].

A key indicator in liquid cooling technology is thermal resistance, which is a scale that characterizes the resistance experienced by heat from a heat source to a cooling medium. For data centers, low thermal resistance means higher heat transfer efficiency. Therefore, improving the heat exchange performance of the cooling system is the key to reducing the overall system thermal resistance [12].

System level thermal management focuses on optimizing the distribution and reflux path of cooling fluids to ensure effective cooling of various components and reduce overall energy consumption. For example, by utilizing an intelligent system that reads the real-time working conditions of data centers, the flow rate and path of cooling fluids can be dynamically adjusted to optimize cooling efficiency and reduce energy consumption [6]. In addition, by improving the internal thermal flow design of the equipment, such as using a specially designed Under Floor Air Delivery (UFAD) system inside the cabinet, cold air can be directly sent to the parts of the equipment that need to be cooled, thereby improving thermal management efficiency [17].

The energy consumption analysis further explores the important indicator of Power Usage Efficiency (PUE), which is defined as the ratio of overall energy consumption to device received power. An optimized liquid cooling system aims to provide the lowest PUE value, that is, to use energy directly for calculating power rather than cooling as much as possible [8]. By integrating more

efficient refrigeration devices, such as using liquid media with a large temperature difference from the environment, the heat transfer rate can be significantly improved.

At the specific implementation level, single-phase liquid immersion cooling technology has received attention for its stability and reliability [15]. In a single-phase cooling system, the cooling fluid does not undergo phase transition when absorbing heat, making system management simpler. Due to the higher heat capacity and thermal conductivity of liquids, single-phase cooling can achieve better heat dissipation than gaseous cooling. However, two-phase cooling utilizes the latent heat transfer during the phase transition process, which may provide a more effective cooling solution for high thermal loads. Studies have shown that surface modification techniques and material applications can further enhance the performance of two-phase cooling [13].

Specifically, thermal management within the data center also includes effective isolation of heat sources and optimization of equipment cooling design. The isolation of heat sources is achieved through physical grids or airflow guidance technology to ensure that cold and hot airflow do not mix, maintain refrigeration efficiency, and reduce the number of hot spots in space [12]. Researchers continuously optimize the heat dissipation structure of devices through experimental testing and modeling [1]. For example, research on the cooling of 3D stacked chips has shown that water immersion cooling systems exhibit higher efficiency in maintaining equipment operating temperature compared to forced air cooling [10].

In the construction of future data centers, liquid immersion cooling technology will play an increasingly important role, aiming to maximize power utilization efficiency by enhancing heat exchange performance and optimizing thermal management strategies, in response to the growing demand for data processing and the challenges of environmental protection and energy conservation.

3. Discussion

3.1. Research Prospects and Trends

In the research field of liquid immersion cooling systems in data centers, trends and prospects show the possibility of continuous innovation and technological progress. It is predictable that the following development trends will be promising:

Continuing to optimize and innovate cooling media: With the improvement of environmental and performance requirements, non-conductive and better thermal performance liquid cooling media will receive more attention. For example, using media with high heat capacity and good thermal conductivity to improve heat exchange efficiency. In addition, from the perspective of sustainable development, biodegradable and low global warming potential (GWP) cooling fluids may become a research focus.

System level optimization and adaptive control: Data center cooling systems will develop towards more intelligent control strategies, such as utilizing advanced algorithms and artificial intelligence to optimize cooling distribution and achieve dynamic balance between heat load and cooling capacity. This type of optimization can reduce energy consumption and improve the overall efficiency of the system.

Integrated cooling and energy recovery systems: One trend is to combine data center cooling with energy recovery systems, utilizing heat extracted from servers and other devices to provide energy for other applications. This may include cogeneration systems, as well as using waste heat for regional heating or industrial processes.

Enhanced thermal management technology: Research on thermal interface materials (TIMs) and surface coating technology provides new ideas for improving the thermal conductivity efficiency between heat sinks and components. Especially, research on surface nanostructures is expected to improve the contact between coolant and equipment surfaces, thereby further enhancing cooling efficiency.

Two phase cooling and cooling performance in microgravity environments: With the development of space exploration and the space industry, the application of two-phase cooling technology in

microgravity environments will be given more consideration. The research will focus on how to manage the gas-liquid phase transition under microgravity to ensure excellent thermal management performance.

In summary, it can be anticipated that liquid cooling technology in future data centers will be more efficient, energy-efficient, while also taking into account environmental impacts. Breakthroughs in adaptive control, energy recovery, and advanced thermal management materials will shape the future of this field and provide insights for related industrial applications.

3.2. Suggestions for future research

When exploring the future research directions of liquid immersion cooling systems, the focus can be on the following areas:

1) Development of new materials and fluids to improve cooling efficiency and environmental adaptability: Although the cooling fluids currently used have excellent performance, there is still room for improvement. For example, researchers can explore coolants with lower viscosity, higher thermal conductivity, and less impact on the environment. Additionally, biodegradable or recyclable cooling media can be explored, which is crucial for reducing the environmental footprint of data centers.

2) Optimization and reliability improvement of two-phase cooling systems: The two-phase cooling system utilizes gas-liquid two-phase variation heat transfer, which has higher heat transfer efficiency than single-phase liquid cooling. Future research can delve into the optimization of bubble dynamics, coolant flow stability, and heat transfer area in this system. Meanwhile, improving the reliability of two-phase cooling systems and reducing the probability of system downtime caused by cooling failures is an important research direction.

3) Thermal management technology and cloud edge collaboration: With the continuous integration of cloud computing and edge computing, the cooling system of the data center needs to adapt to it. Research efficient thermal management strategies to achieve dynamic allocation and adjustment of heat load in data centers. Through an intelligent thermal management system, the dual goals of energy conservation and performance improvement are achieved by coordinating server computing power and cooling needs.

4) System Integration and Modular Design: Explore methods for deeply integrating liquid immersion cooling with IT infrastructure. Modular design can simplify the maintenance and upgrading of data centers, and has the potential to reduce initial deployment costs. Future research can focus on standardizing cooling modules and making them easy to expand and replace.

5) Improvement of Data Center Energy Efficiency Evaluation Model: Develop more accurate energy efficiency evaluation models, including energy consumption models for servers, storage, and network devices, as well as cooling energy consumption models for the overall data center.

6) Application of Artificial Intelligence in Liquid Cooling System Optimization: Utilizing deep learning and machine learning algorithms to perform real-time optimization of cooling systems in data centers. Research on automatic optimization of cooling fluid flow control, fault prediction, and maintenance plans based on artificial intelligence to enhance the system's adaptive ability and predictive maintenance functions.

These suggestions not only involve pure technical fields, but also involve interdisciplinary integration with environmental impacts, sustainable development strategies, and economic benefits. Through interdisciplinary collaboration, liquid immersion cooling technology will be promoted towards greater efficiency, energy efficiency, and reliability.

4. Conclusion

In the field of data centers, significant progress has been made in the research and application of liquid immersion cooling systems, mainly in improving thermal management efficiency and energy utilization efficiency in data centers. In recent years, liquid immersion cooling technology has been

proven to be an effective means to address the challenges of high-power density in data centers and the optimization requirements of energy efficiency ratio (PUE). Although liquid immersion cooling technology has brought unprecedented opportunities in data center cooling, there are still challenges in terms of technological maturity, system costs, maintenance, and operational complexity. By reviewing existing literature, it can be seen that researchers are strengthening their understanding of this cooling technology through continuous technological innovation, performance testing, and system optimization, and promoting its widespread application in data centers. Future research will delve deeper into the balance between high efficiency, reliability, and economy in liquid immersion cooling systems, in order to better meet the growing demand for data processing.

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