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A Review on the Cooling Techniques Implemented in Data Center Cooling

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ABSTRACT :

Data center cooling is the process of removing heat generated by the servers. Its primary purpose is to maintain a cool temperature so that the equipment functions efficiently without overheating. Servers consume electricity and generate a large amount of heat during operation; without proper cooling, excessive heat can affect the performance, hardware, and lifespan of the equipment. Computational fluid dynamics (CFD) is a computer-based simulation method used to study heat transfer inside a data center. CFD can predict how different cooling techniques perform under various conditions, analyze airflow distribution, improve energy efficiency, and reduce design time and cost. Recent data center cooling techniques include direct-to-chip liquid cooling, in which cold plates are attached directly to the chips and coolant circulates through the plates; immersion cooling, in which servers are immersed in a non-conducting dielectric liquid that absorbs heat directly from the components; rear door heat exchangers, in which a water-cooled unit mounted on the server rack removes heat before it enters the data center room; and AI-based smart cooling, in which artificial intelligence continuously measures temperature and airflow and automatically adjusts the cooling while maintaining safe temperatures. In this review, an exhaustive discussion of the various recent cooling techniques available in the literature is presented in detail.

Keywords: Data Center Cooling, Computational Fluid Dynamics (CFD), Heat Transfer, Airflow Distribution, Direct-to-Chip Liquid Cooling, Immersion Cooling, Rear Door Heat Exchanger (RDHx), AI-Based Smart Cooling, Energy Efficiency, Thermal Management.

1. INTRODUCTION

Data centers have become an important part of our daily lives because they store and process the information we use through the internet and digital services. However, servers and other IT equipment produce a large amount of heat while operating continuously. If this heat is not removed properly, it can affect equipment performance and reliability. Therefore, an effective cooling system is necessary to maintain suitable temperatures. At the same time, cooling systems consume a significant amount of energy, making it important to find methods that provide better cooling while reducing energy consumption.

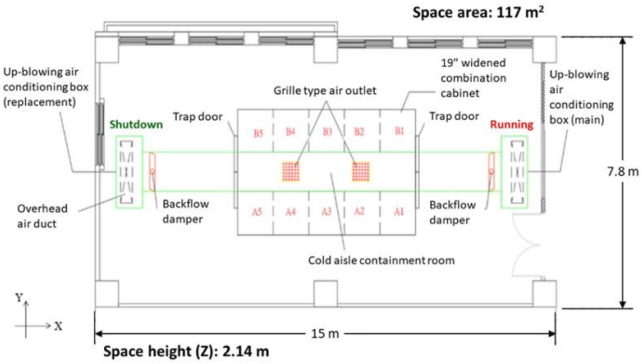


Fig. 1. Schematic of the research site.

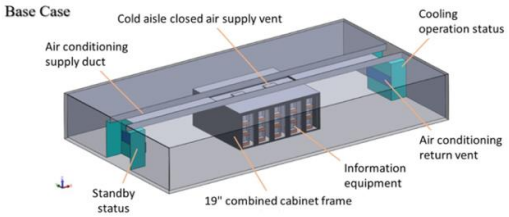


Fig. 1. Model of the research site [1].

Many researchers have studied different ways to improve cooling performance in data centers. Nada et al. [2] examined how raised-floor tile openings, rack power density, and cooling-unit placement affect cooling conditions. Yang et al. [3] investigated airflow and heat transfer around server racks and highlighted the importance of suitable floor depth and airflow rates. Abbas et al. [4] compared aligned and staggered in-row cooling arrangements, and Jao et al. [5] studied different aisle configurations under uneven heat loads. These studies show that the way cold air is supplied and hot air is removed can make a significant difference in maintaining suitable temperatures inside a data center.

Researchers have also explored ways to improve existing cooling systems and manage airflow more effectively. Singh et al. [6] studied changes to an existing cooling arrangement, Nada et al. [7] investigated methods to reduce hot-air recirculation, and Wang et al. [1] compared different aisle arrangements to understand their effects on airflow and the formation of hotspots. Cho [10] examined a Rear Door Heat Exchanger (RDHx), which removes heat from the air leaving server racks. Based on these studies, this review discusses ten research papers on data center cooling techniques, focusing on their working methods, cooling performance, and energy efficiency. The main aim is to understand the benefits and limitations of different approaches and identify ways to make data center cooling more effective and energy-efficient.

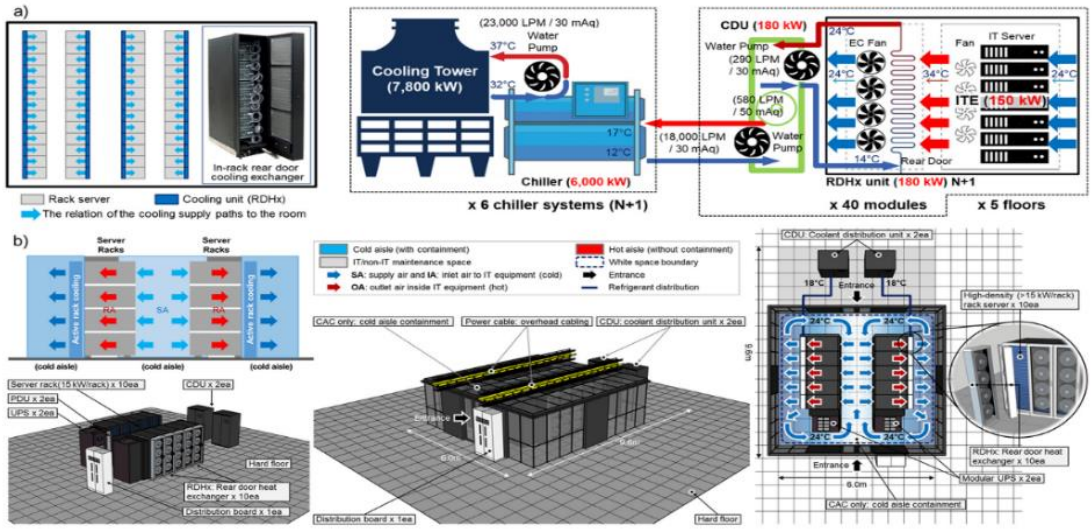


Fig. 2. A rack-based cooling solution: (a) RDHx, rear door heat exchanger, and (b) an IT module cooling system for an IT power density of 15 kW/rack [10].

2. METHODOLOGY

This review is based on different cooling techniques used in data centers. Each paper was studied to understand the common cooling problems, the methods used to address them, and the improvements achieved. The main focus was on room-based, row-based, and rack-based cooling systems, along with airflow management, aisle arrangements, raised-floor design, and improvements to existing cooling systems. The selected studies used different approaches, including Computational Fluid Dynamics (CFD) simulations, experimental testing, and comparisons of cooling arrangements [1–8].

The researchers examined factors such as airflow rate, heat generated by servers, cooling-unit placement, aisle containment, and hot-air recirculation [6]. Some studies also investigated retrofitting existing cooling systems [7], while another examined the use of a Rear Door Heat Exchanger (RDHx) to improve heat removal [10].

Finally, the findings from the papers were compared to understand how each technique affects temperature distribution, airflow, cooling performance, and energy efficiency. The advantages and limitations of the different methods were considered to identify suitable approaches for reducing hotspots, maintaining proper temperatures around server racks, and improving the overall energy efficiency of data centers.

3. TYPES OF COOLING TECHNIQUES IMPLEMENTED IN DATA CENTERS

3.1 Aisle Containment and Overhead Enclosure

Aisle containment uses panels or enclosures to separate hot exhaust air from the cold air supplied to the servers. An overhead enclosure helps guide hot air towards the return path instead of allowing it to spread throughout the room. The overall improvement depends on the enclosure design and how air moves around the racks [1].

3.2 Room-Based Cooling System

Room-based cooling uses Computer Room Air Conditioning (CRAC) units to cool the entire server room. Cold air is supplied to the room and distributed towards the server racks, often through a raised floor. Proper airflow and cooling-unit placement are important to ensure that all servers receive enough cold air and do not overheat [2].

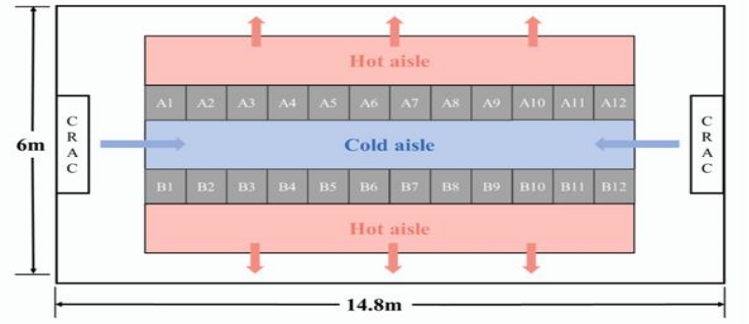


Fig. 3. Layout of room-based cooling system [2].

3.3 Row-Based Cooling System

In row-based cooling, cooling units are placed close to the server racks, usually between the rows. This helps cold air reach the servers more directly and reduces unnecessary airflow movement. The arrangement of the cooling units also affects how effectively heat is removed from the racks [2].

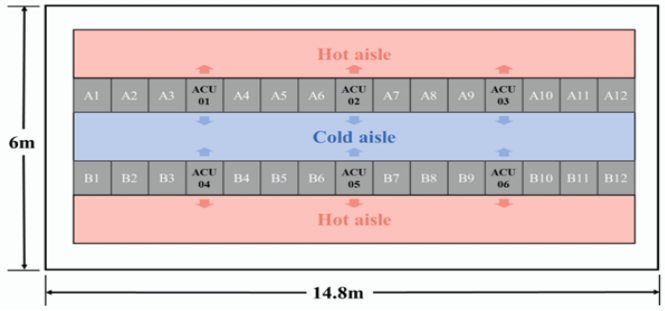


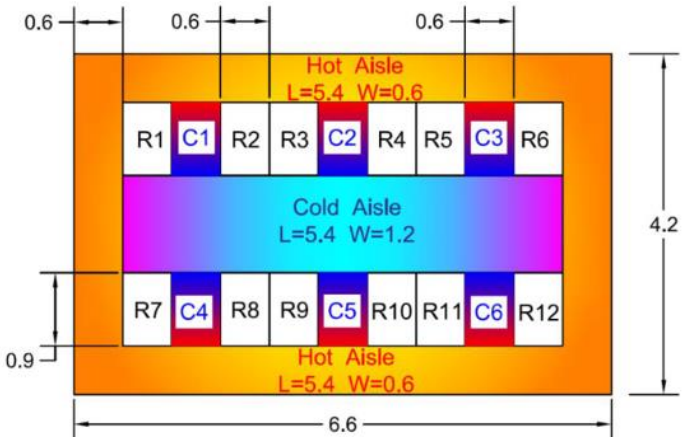
Fig. 4. Layout of row-based cooling system [2].

3.4 Raised-Floor Airflow Management

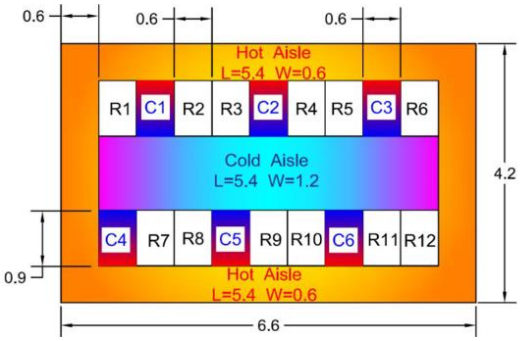
Raised-floor cooling uses the space beneath the floor to carry cold air into the server room. Perforated tiles allow the air to move upward towards the server racks. The floor depth, tile openings, and airflow rate influence the uniformity of cold-air distribution and the effectiveness of server cooling [3].

3.5 Aligned and Staggered In-Row Cooling

This technique compares two ways of arranging cooling units near server racks: aligned and staggered. The arrangement affects airflow distribution and the removal of heat from the racks. Abbas *et al.* [4] studied these configurations and found that the aligned arrangement performed better under the conditions investigated in their study.



(a) Aligned configuration A.1 (H = 3 m) and B.1 (H = 2 m)

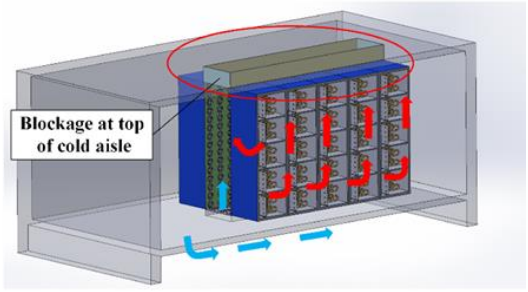


(b) Staggered configuration A.2 (H = 3 m) and B.2 (H = 2 m)

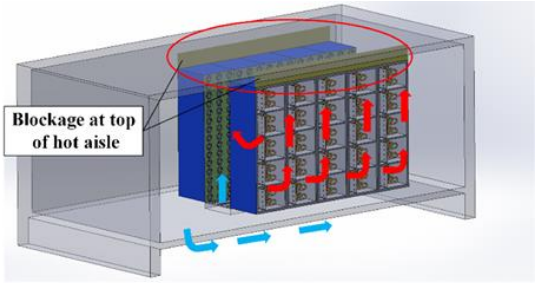
Fig. 5. Plan views for DC room dimensions equipped with in-row cooling units for (a) aligned arrangement and (b) staggered IRU arrangement [4].

3.6 Semi-Enclosed Aisle Cooling

Semi-enclosed aisle cooling uses partial barriers around server aisles to control the movement of hot and cold air. This arrangement helps prevent hot exhaust air from mixing with the cold air supplied to the servers. Its performance depends on the aisle design and the amount of heat produced by the racks [5].



(a) Semi-enclosed cold aisle



(b) Semi-enclosed hot aisle

Fig. 6. Experimental configuration [5].

3.7 Retrofitting Existing Cooling Systems

Retrofitting means making improvements to an existing cooling system rather than replacing the entire setup. These changes can help cold air reach the servers more effectively and reduce the mixing of hot and cold air. It is a useful approach for improving the cooling performance of existing data centers [6].

3.8 Airflow Management Using Baffles

Baffles are used to guide air in the desired direction and reduce unwanted mixing between hot and cold air. Kuzay *et al.* [8] studied the use of a baffle behind server racks to create a more controlled path for hot exhaust air. This modification improved airflow management and reduced the problems caused by hot-air recirculation [7].

3.9 Cooling Performance and Energy Efficiency Analysis

Cooling performance analysis helps determine whether a cooling system removes heat effectively without using unnecessary energy. Researchers examine factors such as temperature distribution, airflow patterns, and energy consumption to understand how well the system performs. These findings help identify possible improvements and select suitable cooling arrangements for data centers [8].

3.10 Rear Door Heat Exchanger (RDHx) Cooling

A Rear Door Heat Exchanger is fitted to the back of a server rack to remove heat from the hot air leaving the servers. This helps prevent excess heat from spreading into the data center room and supports cooling in high-density server environments. Cho [10] studied this technique to understand its cooling performance and energy efficiency.

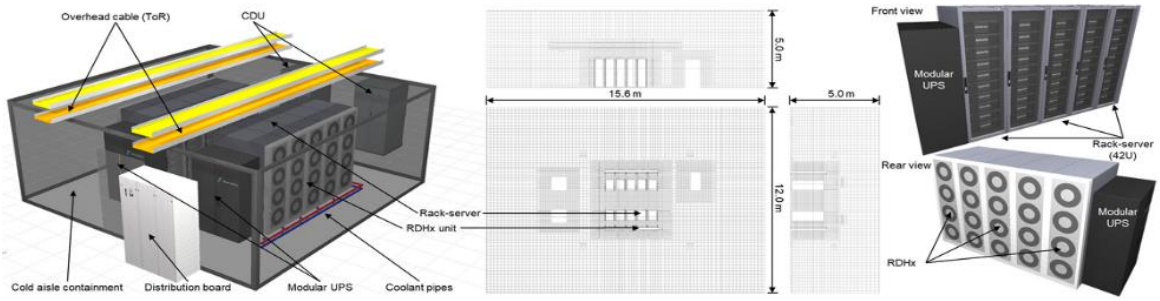


Fig. 7. A CFD analysis model of RDHx system; physical model structure and solution domain [10].

4. RESULTS AND DISCUSSION

4.1 Cooling System Design

The reviewed papers discuss different cooling methods used in data centers, such as room-based, row-based, in-row, and rack-based cooling. Each method has its own advantages depending on the heat produced by the servers and the arrangement of the data center. Choosing the right cooling system helps maintain suitable temperatures and improves overall cooling performance.

4.2 Airflow Management

Proper airflow is essential to keep servers cool. The studies show that raised floors, perforated tiles, baffles, and aisle containment help direct cold air toward the servers and prevent hot air from mixing with it. When airflow is managed properly, hotspots can be reduced and cooling becomes more effective.

4.3 Cooling Performance

The results show that room-based cooling can work well at lower rack power densities, while row-based cooling can be more effective when the heat load increases. The study on in-row cooling also found that aligned cooling units performed better than staggered units in the configurations tested. This shows that the cooling arrangement should be selected according to the heat load and layout of the data center.

4.4 Retrofitting and Optimization

Some researchers studied ways to improve existing data centers without completely replacing their cooling systems. Adding baffles, changing cooling arrangements, and improving aisle containment helped control airflow and reduce hot-air recirculation. Other studies used optimization and exergy analysis to understand how cooling systems could operate more efficiently.

4.5 Rack-Based Cooling and RDHx

The Rear Door Heat Exchanger (RDHx) removes heat from the air leaving the server rack. The rack inlet temperatures remained close to 24 °C, and the average cooling PUE was approximately 1.27 in the energy model. These findings show that RDHx can be a promising option for data centers with high server heat loads.

4.6 Testing and Performance Analysis

The researchers used computer simulations, experimental testing, and temperature measurements to study how different cooling systems perform. These methods helped them understand airflow movement, temperature differences, hot-air recirculation, and energy use. Testing and simulation together provide a better understanding of how cooling systems behave under different conditions.

4.7 Applications

The cooling techniques discussed in these papers can be used in data centers with different sizes and server loads. Room-based and row-based systems support general cooling needs, while aisle containment, baffles, and RDHx can help manage heat more effectively in demanding environments. The choice depends on the available space, server heat load, and cooling requirements.

4.8 Recent Developments in Data Center Cooling

Recent research focuses on improving airflow, bringing cooling closer to server racks, and reducing unnecessary energy consumption. Techniques such as in-row cooling, aisle containment, baffle-based retrofitting, and RDHx are being studied to improve temperature control and reduce the mixing of hot and cold air.

4.9 Future Scope

Future research should focus on developing cooling systems that use less energy while maintaining safe operating temperatures for servers. Combining better airflow arrangements with improved monitoring and control may help reduce hotspots and cooling costs. Further testing in real data centers is also needed to confirm how well these methods perform in practical conditions.

5. CONCLUSION

Data center cooling is essential for keeping servers at safe temperatures and ensuring they work efficiently. This review shows that proper airflow management, aisle containment, baffles, and suitable cooling systems can help reduce heat buildup and improve cooling performance. Methods such as row-based cooling and Rear Door Heat Exchangers (RDHx) can be useful for managing the heat produced by servers. However, the best cooling method depends on the server load and the layout of the data center. Future studies should focus on developing simpler, more energy-efficient cooling solutions that reduce power consumption while maintaining reliable server performance.

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