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Emerging Trends in Sustainable Thermal Management for Data Centers

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***Abstract*—The reduction of energy consumption and thermal management in cooling systems is one of the factors that have developed in an attempt to address the current trend of increasing data centers with high heat dissipation rates and the energy problematic environment, as the traditional air-based cooling systems are proving ineffective as they consume high amounts of energy and might not be sufficiently scalable. This paper addresses new trends in sustainable data center thermal management taking note of innovative cooling approaches that incorporate air, liquid, heat-pipe, immersion and free cooling. In addition, similarities between the study and the thermal management methods used in electric vehicles are also drawn, in which the necessity of materials with high developmental rates, intelligent control, and energy-efficient designs are stated. Recent research contributions are addressed in detail to establish significant progression, limitations, and gaps of research. The review suggests that there is a need to have integrated, adaptive and intelligent thermal management structures that balance performance and energy efficiency, cost and environmental sustainability. The findings are instructive to researchers and scholars who would like to come up with next generation, more energy-efficient thermal management systems in data centers and other high-power systems.**

Keywords*—Data Center, Cooling System, Thermal Management, Energy Consumption, Energy Efficiency, Heat-Pipe Cooling, High-Density Computing.

I. INTRODUCTION

The high rate of cloud computing, big data analytics, AI, and IoT applications has resulted in the proliferation of data centres around the world [1]. Data centres, which are the keystone of the modern digital infrastructure, have escalating energy demands due to the growing computational density. The thermal regulation is the most important of operational challenges, since too much heat produced by small electrical components poses a threat to reliability and lifespan of the system [2]. As workloads continue to grow, traditional air-based cooling systems based on the widespread use of energy-consuming chillers are approaching their efficiency limit, and require power equivalent to small power plants [3]. This high energy consumption also amplifies the environmental impact of data centres as well as the operating costs. At the same time, strict temperature controls should be maintained to prevent the excessive heating of electronic parts, which typically require functioning at temperatures that are far lower than the critical ones. The following series of increasing energy consumption and rigid thermal requirements has led to thorough research work on improving the cooling efficiency without compromising system reliability [4][5].

Due to these challenges, the past studies have largely focused on the best temperature range to cool server rooms through the maximisation of airflow arrangements and operating conditions under steady-state conditions. These approaches often overlook the dynamism in each data centre operation even though it has offered practical information on temperature dispersion and mitigation of hotspots [6]. As a matter of fact, the data centers are subjected to unending changes in thermal load owing to the varying data processing requirements, daily traffic patterns and long-term increase in computing power [7]. Further on, another problem that complicates thermal control and underscores the shortcomings of the fixed cooling strategies is the unexpected workload spikes and environmental shift. These are practical implications that have raised the importance of learning the temporary heat behaviour of data centres. To address this need, the modelling and numerical simulation, with the assistance of selective experimentation, have gradually been applied to address the airflow, temperature distributions, and heat transfer rates during the stable and non-regular conditions. This allows critical hotspots and inefficient airflow areas to be identified, and the resulting scientific foundation of the intended cooling improvements. Through the control of acting parameters like airflow, inlet temperatures and cooling distribution, which is typically controlled by chiller systems, thermal management strategies can be adjusted dynamically to suit different operating requirements.

Recently, sustainable and energy efficient thermal management systems, which integrate smart airflow, new cooling structures as well as other strategies of heat-removal to minimise the use of energy intensive systems have been under investigation, growing beyond the traditional cooling optimisation [8]. Smart control systems, predictive analytics, AI-driven optimisation, and the architecture of server, rack, and data centre designs are all receiving more attention, which allows for real-time response to dynamic thermal loads. Future data centres will be able to handle increasing computing needs with little ecological effect because to these advancements, which constitute a paradigm shift towards sustainable thermal management that combines dependability, energy efficiency, and environmental responsibility.

A. Paper Organizatioon

The following is how this paper is organised. Section II presents a full overview of energy- and thermal-aware resource management in cloud data centres. Section III extends the discussion to thermal management concepts and strategies in electric vehicles. Section IV presents a comprehensive review of recent literature, and research gaps. Finally, Section V summarises the paper's findings and suggests future research areas in energy-efficient and sustainable heat management systems.

II. ENERGY THERMAL-AWARE RESOURCE MANAGEMENT IN CLOUD DATA CENTRES

A data centre's cooling system, electricity distribution, and information technology and computing (including servers, networks, and storage) are only a few of the many subsystems that make up the facility [9]. However, cooling and computing systems use the most electricity. Figure 1 displays each device's proportion of energy use. Reducing the energy usage of the cooling system is more important in this situation. In addition, the cooling system must guarantee efficient heat transfer capacity in order for the data centre to achieve data centre thermal management, which is the safe dissipation of heat and maintenance of a uniform temperature distribution [10].

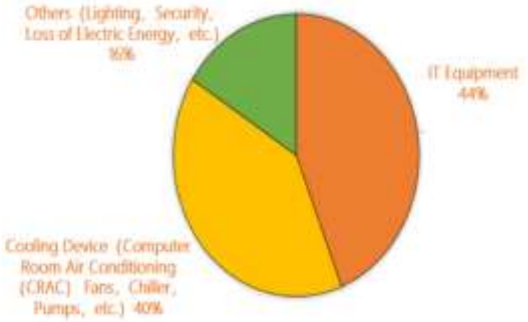

Fig. 1. Data Center Energy Distribution.

Air, liquid, and free cooling are the three main types of data centre cooling systems.

A. Air Cooling for Data Centers

Data centres have two distinct levels of air cooling: one for each individual room, and another for each every row. Figure 2 shows the mechanical layouts of the two cooling systems [11][12]. In contrast to room-based cooling systems, row-based cooling systems include air conditioners that are typically positioned above the cold aisles or in a row between rack servers. Instead of combining the air from beneath the floor with the original air throughout the data centre, the air is fed directly into the cold aisles between the racks.

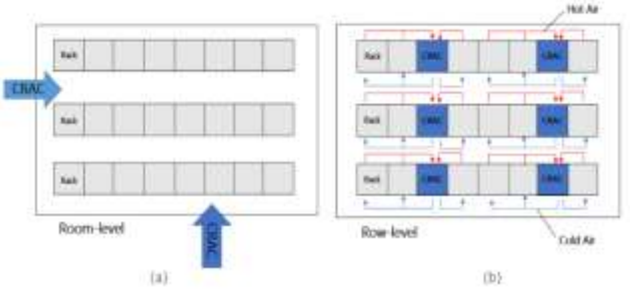

Fig. 2. Two Types of Room Cooling Systems: (a) Room-Based Cooling System; (b) Row-Based Cooling System [13]

B. liquid cooling systems

The colling process is carried out using a coolant, usually water or a water-based combination, that stays in the liquid phase [14]. The components release their heat into the coolants by conduction, which subsequently cools the coolant before recirculating it to a mechanical chiller or heat exchanger. Two-phase liquid cooling and heat-pipe cooling use phase-change mechanisms to achieve highly efficient heat transfer in data centers [15]. Two-phase systems dissipate high thermal loads with low energy input but face challenges such as flow instability, while heat-pipe cooling passively transfers heat using sealed working fluids, often enhanced by mechanical refrigeration. The two offer small and energy-saving solutions to cooling of high-density data centers. The Heat pipe cooling mechanism is demonstrated in Figure 3.

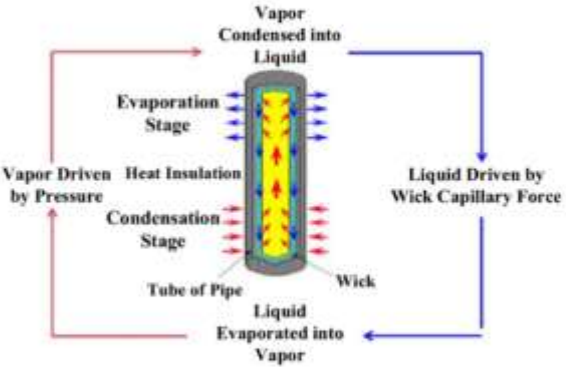

Fig. 3. Heat-Pipe Cooling Mechanism [16].

C. free cooling systems

Free cooling also saves on mechanical cooling by taking advantage of naturally available materials such as water or air to cool down data centres. It is very energy efficient and assists in minimizing operating expenses in favourable climates. Free cooling can significantly reduce the energy used by data centres because it uses naturally available cold sources.

III. THERMAL MANAGEMENT AND ELECTRIC VEHICLES

Electric vehicles are also designed with thermal management to ensure that different components of the car can work within safe and efficient temperature ranges [17]. With the transformation of vehicles, a more sophisticated process of thermal management is sought due to the replacement of traditional ICEs by hybrid and all-electric powertrains. The challenges associated with each of these configurations are different and each has to be handled with specific cooling and heating strategies to sustain performance, efficiency, and reliability. The importance of thermal management to BEV performance, efficiency, comfort, safety, and dependability is presented in Figure. 4. Here is a breakdown of its impact:

Fig. 4. Key Roles of Thermal Management [18]

- **Vehicle performance:** Maintaining optimal temperatures in the battery, power electronics, and motor ensures consistent power delivery, acceleration, and regenerative braking efficiency [19].
- **Energy consumption:** Efficient thermal management reduces energy losses from cooling/heating systems, improving overall vehicle efficiency and extending driving range [20].
- **Comfort:** Controlled cabin climate improves passenger comfort while optimizing energy consumption to prevent significant reductions in driving range.
- **Safety:** Thermal management mitigates the risk of thermal runaway in batteries, prevents overheating of power electronics, and supports consistent braking performance.
- **Reliability:** Reducing thermal stress and related degradation over time contributes to the extended operational lifetime of critical vehicle components.

A. *Thermal Management of Electric Vehicles*

The need for improved performance, safety, and battery longevity has recently prompted substantial improvements in electric vehicle (EV) thermal management (see Figure 5). The state-of-the-art now includes a variety of cutting-edge materials and technologies intended to increase thermal efficiency and address the particular difficulties posed by EVs.

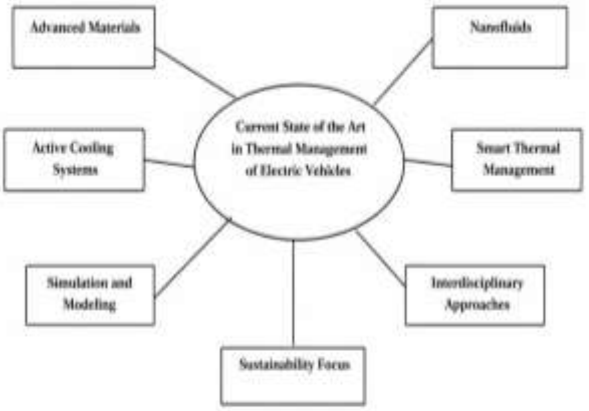

Fig. 5. The Current State-of-the-Art Technologies and Materials

- **Advanced Materials:** Phase change materials (PCMs) and materials with high heat conductivity are becoming more popular. When it comes to charging and discharging, PCMs are masters at absorbing and releasing heat, keeping temperatures steady.
- **Nanofluids:** The enhanced thermal characteristics of nanofluids, which are man-made nanoparticle suspensions in fluid bases, have led to their rise to prominence. Nanofluids are a promising alternative to conventional cooling fluids for advanced cooling applications in electric vehicles, according to studies.
- **Active Cooling Systems:** The electric cars currently are equipped with active thermal management systems which regulate temperatures through fans and pumps. These systems can be adjusted dynamically to changing temperature conditions in order to prevent overheating.
- **Smart Thermal Management:** Thermal management is being revolutionised with the utilisation intelligent technologies, including ML and predictive analytics [21]. To avoid overheating of the vehicle and take pre-emptive control of the cooling systems, the cooling systems use real-time data gathered by the sensors on the car and re-tune thermal strategies in real-time.
- **Simulation and Modelling:** Advanced computational fluid dynamics (CFD) and thermal modelling are models that are being used to design and optimise thermal management systems. These technologies can be used to predict thermal behaviour and optimize designs by engineers before they start developing physical prototypes to simulate various operating conditions.
- **Interdisciplinary Approaches:** The necessity of interdisciplinary collaboration toward the effective thermal management is gaining more and more acceptance. To present comprehensive solutions addressing the challenging issues in EV thermal management, a focused effort is underway to integrate the information of data analytics, mechanical engineering and materials science.
- **Sustainability Focus:** The application of environmentally friendly materials and energy-efficient thermal management will continue to gain prominence with the automobile industry shifting to sustainability. Research is focussing more on systems that maximise thermal performance while consuming the least amount of energy and on recyclable materials.

B. *Thermal Management Strategies*

Thermal management strategies play a vital role in the optimization of the success and safety of EV battery packs. These include active cooling, passive cooling, and thermal insulation. Rapid heat dissipation during charging and discharging cycles is possible with active cooling technologies such as liquid cooling. On the other hand, passive cooling methods like PCMs regulate temperature without further energy input. The operational temperature levels stay stable due to thermal insulation; hence, there is low exposure to overheating or TR [22]. With the above strategy combinations, EV battery packs will enhance their performances and safety aspects. Below are some of the most influential thermal management strategies:

1) *Uniform temperature distribution*

Uniform temperature profiles are needed in the pack to get good performance and life. In the case of uneven temperature profiles, locally formed hotspots can severely damage certain battery cells due to a lack of uniform aging of these cells, greatly lowering overall battery capacity. Effective conduction and spreading within the pack are rather critical in keeping cell temperatures below some limit.

2) *Cooling system efficiency*

One of the major problems in managing battery temperatures is the achievement of efficient cooling [23]. Most EVs rely on liquid cooling systems in controlling the temperatures in the battery. Advanced heat transfer material or PCM and so on must be designed and applied to increase dissipative heat and subsequently also increase cooling efficiency.

3) *Integration with vehicle design*

The whole vehicle architecture must be appropriately integrated with the TMS system. The system has to be compact and of minimum weight so that the overall performance and efficiency of the range are not heavily influenced. Therefore, the process of integration and finding a better fit has to be collaborated on at various stages by all manufacturers of batteries and the manufacturers of vehicles with TMS.

4) *Cost considerations*

Among the most critical factors involved in accepting EVs is cost. The TMS will be cost-effective, sacrificing neither performance nor safety. Cost-effective cooling solutions are to be developed through low-cost material usage and streamlined processes aimed at reducing the total TBS TMS cost.

5) *TR prevention*

TR is a very serious safety concept in LIBs. It is initiated when the temperature rises, and TR can lead to an uncontrollable, self-sustaining reaction in the battery pack with consequent overheating, venting, or explosion. Advanced thermal monitoring features along with safety features within the BMS, such as active cooling, thermal sensors, and protective layers, are required to provide for the effective detection and management of potential situations with TR.

6) *Environmental impact and energy efficiency*

The TMS must consider its environmental performance and efficiency in terms of energy use. Conventional air-cooling systems use huge mechanical systems, which are not the best and a significant average efficiency decreases on the vehicle [24]. The TMS can have a smaller footprint and can have better total energy efficiency by exploring alternative ways of cooling, such as passive cooling or utilizing waste heat.

7) *Thermal modeling (TM) and simulation*

The optimization of TMS involves one of the crucial aspects the performance of TM and simulation. The intricate heat transfer processes in the battery pack cannot however be easily captured. Cell heterogeneity, heat generation during high rate charging, and transient thermal behavior models can help optimize the approach to thermal management and system design optimization in order to achieve higher performance and safety.

IV. LITERATURE REVIEW

This study conducted a comprehensive literature review based on research articles found in IEEE and Scopus to say the least and other industry websites and publications. The recent publications have been on the thermal management technology advancements. Phase transition materials have been applied increasingly by people as a viable method of increasing heat dissipation. The second interesting aspect in this area is the emergence of smart thermal management technologies.

Asim et al. (2025) explores potential cooling solutions proposed by the scholarly community, such as advanced techniques such as immersion cooling, spray cooling, jet impingement, microchannel cooling, solid state cooling, phase change cooling, and nanofluids cooling. Beyond touching upon the current market and industrial trends, the review also delves into the new materials used to regulate heat in EV high-power electronics (HPE) system, and the environmental impact of thermal management, and the future of effective thermal management of EV HPE systems [25].

Togun et al. (2025) adopts a whole-brain strategy through integrating numerous cooling methods and highly emphasizing on environmental sustainability and cost-effectiveness. This effort is aimed at offering a helpful tool to researchers, engineers, and business experts to ensure improved effectiveness, reliability, and durability of BTMS in electric cars. It achieves it by describing the challenges of thermal management of electric cars and provides solutions [26].

Rasool et al. (2024) discuss the latest advancements in temperature management of batteries such as NEPCMs, air cooling, metallic fin intensification, and enhanced composite materials based on nanoparticles to greatly enhance their performance. The notion of PCMs developed by nanotechnology appears new and interesting to the scientific community. The li-battery life span increase of hybrid and ternary battery modules is already drawing attention, which will eventually enable their wider deployment across a variety of applications, from electric cars to portable devices and beyond [27].

Zhoghuo and Alex (2024) offers a description of the existing approaches toward thermal management which have lately been derived to address issues of heat regulation, temperature control, and heat dissipation in engineering. Electric vehicles, renewable energy systems, data centres, and electronic devices are just a few examples of the new technologies that need careful thermal management to avoid performance drops, component failure, and shorter operational lifespans caused by overheating. The significance of heat management in the engineering field and its role in improving performance and reliability are pointed out in the beginning of the abstract. It discusses the challenges that heat production is subjected to and how innovative approaches can be used to effectively deal with thermal issues [28].

Kalantarpour and Vafai (2024) explore long-term sustainability and performance of innovative thermal management schemes, e.g. radiative cooling, air cooling, liquid cooling and immersion cooling. The efficiency of the heat dissipation of each scheme is determined, and special attention is paid to microchannel liquid cooling systems, advanced heat pipes, and dielectric fluid immersion cooling. It also examine the radiative cooling as a passive method that can translate into operational efficiency and savings of energy. This detailed analysis will help to illuminate these technologies in terms of their comparative advantages and the ways to make data centre operations sustainable [29].

Zhao et al. (2023) analyses possible fixes, including reducing the cold airflow route and improving airflow dispersion via application, control, and design. The study also offers future insights and addresses the shortcomings of the current hotspot removal research. The purpose of this study is to provide useful information on local hotspot removal in data centres while taking integrated thermal and airflow distribution management techniques into account. Energy-efficient data centre design, operation, and retrofitting may be aided by the conclusion [30].

TABLE I. SUMMARY OF REVIEWED STUDIES ON THERMAL MANAGEMENT TECHNIQUES FOR DATA CENTERS

Ref.	Technology / Focus Area	Contributions	Challenges Identified	Recommendations
Asim et al., (2025)	Advanced cooling techniques for EV HPE systems – spray, jet impingement, microchannel, solid-state, phase change, immersion, and nanofluid cooling.	Comprehensive review of modern cooling strategies and novel materials; addressed environmental implications and industrial trends.	Lack of empirical validation and performance benchmarking of combined cooling techniques.	Conduct experimental studies on hybrid cooling systems and evaluate eco-friendly materials for sustainable EV thermal management.
Togun et al., (2025)	Integrated and sustainable cooling strategies for EV Battery Thermal Management Systems (BTMS).	Provided holistic integration of multiple cooling methods emphasizing energy efficiency and environmental sustainability.	Economic feasibility and scalability of multi-technology integration remain uncertain.	Develop cost-efficient models and real-world validation of BTMS optimization techniques.
Rasool et al., (2024)	Nano-Enhanced Phase Change Materials (NEPCMs), air cooling, and metallic fin-based heat regulation.	Introduced nano-enhancement in PCMs to boost battery lifespan and thermal performance.	Limited real-world application data; nanoparticle stability and material compatibility issues.	Further explore long-term performance of NEPCMs and hybrid PCM-air systems under real EV conditions.
Zhoghuo and Alex, (2024)	General overview of advanced thermal management in EVs, renewable systems, and electronic devices.	Highlighted significance of thermal regulation across industries; addressed issues of overheating and reliability.	Lacks detailed quantitative comparison among existing thermal management techniques.	Focus on quantitative evaluation frameworks for domain-specific cooling optimization.
Kalantarpour and Vafai, (2024)	Air, liquid, immersion, and radiative cooling systems for data centers.	Compared effectiveness and sustainability of multiple cooling technologies; identified energy-saving potential of radiative cooling.	Limited cross-domain generalization beyond data centers.	Extend comparative studies to other domains like EVs and high-performance computing systems.
Zhao et al., (2023)	Airflow optimization and hotspot elimination strategies in data centers.	Proposed airflow design improvements for energy-efficient thermal control.	Limited integration with liquid or hybrid cooling mechanisms.	Combine airflow optimization with intelligent control systems and hybrid cooling models.

Nanofluid cooling, immersion cooling, phase change materials, and airflow optimisation in electric cars and data centres are some of the thermal management technologies that have been studied in these research. However, a notable research gap exists in the integration and real-time optimization of hybrid cooling systems that balance efficiency, cost, and sustainability. Most existing works are either conceptual or limited to simulation-based analysis, lacking large-scale experimental validation and cross-domain applicability. Furthermore, the absence of intelligent control frameworks powered by AI or IoT for adaptive thermal regulation highlights an opportunity for future research to develop data-driven, scalable, and energy-efficient thermal management solutions. These key insights and comparisons are summarized in Table I.

V. CONCLUSION AND FUTURE WORK

Critical infrastructures like data centres rely heavily on energy resources, especially for cooling, to keep running. Constant global data centre growth results in massive increases in energy consumption, which has far-reaching economic and ecological consequences. Therefore, academics and practitioners must prioritise the energy efficiency of data centres. This review has shown how emerging cooling technologies and better thermal control methods can be used to provide reliable data center operation and conserve energy. The discussion demonstrates that the implementation of non-standard cooling design, enhanced airflow layout and system integration can considerably enhance thermal stability and performance capability especially in dense computing platforms. However, the implementation of sophisticated thermal management solutions has a number of obstacles, since most of the suggested solutions are evaluated in controlled environments and may not readily be applicable to real world data centres. The costs of implementation are high, retrofit is complex, maintenance is required, and there is little coordination of the IT workloads and cooling infrastructure with environmental factors all contributing to hindering large-scale deployment. Future research must concentrate on holistic thermal management systems that optimize computing, cooling and energy consumption concurrently. The keys to long-term and sustainable operation of the data center may be dynamic response to the changing workloads provided by intelligent monitoring, predictive control and adaptive optimization, and the long-term field studies, waste heat recovery, and low-carbon cooling technologies.

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