Performance Analysis of Liquid Immersion Cooling Using Mineral Oil for Data Centers

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Keywords: Liquid Immersion Cooling, Mineral Oil, Data Centers, Thermal Management, Dielectric Coolant, Energy Efficiency, Heat Dissipation, Server Cooling, Environmental Impact.

Abstract: Data centers are now considered the backbone of modern digital infrastructure comprising critical computing systems; and every time these systems are switched on, a great deal of heat is produced during their function. This makes cooling systems an important necessity for system performance, reliability, and energy efficiency. In this paper, we present the application of a liquid immersion cooling system using mineral oil as a dielectric coolant that solves all related issues. An experimental set-up involved immersion of server-imperative electric heater-soaked mineral oil, where the performance testing would be conducted to establish cool performances of the heater to the extent. Mineral oil can be an efficient medium for heat removal while preventing short circuits since, besides being a dielectric, its thermal conductance is relatively high. A comparison is made regarding liquid immersion cooling with conventional systems for air cooling, and this has been highlighted as a massive uplift in thermal management, energy efficiency, and noise pollution reductions. This paper also extends over environmental, economic, and technical considerations concerning the adoption of liquid immersion cooling in data centers while explaining the merits, such as lower operational costs and reduced carbon footprint, as part of its many challenges-such as higher setup costs and fluid management. Findings highlight the possibility of immersion cooling as a way forward for future data center designs.

1 INTRODUCTION

The data centers are fuelling the new digital age, enabling broad cloud computing, massive data storage, and real-time processing for many industries. The growing workload on the computers and increased high-density servers have made effective cooling an important aspect for now even to maintain operational reliability and efficiency. The performance limits of traditional air-based cooling systems have been reached, resulting in excessive energy consumption, operational inefficiencies, rising costs, and so forth. In its efforts to solve these silos in data centers, research, and industries have been exploring other cooling alternatives, including liquid immersion cooling, as promising means of achieving energy savings and better thermal control in data centers.

1.1 Importance of Cooling in Data Centers

Cooling contributes something like 30 - 40 percent of the total energy consumed by data centers (Ali, Kumar, and Sharma, 2021). Poor cooling performance magnifies operating expenditures, compromising the performance and longevity of the IT infrastructure. Hardware failure, downtime of the systems, and possible data loss emanate from overheating.

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A, J. R., I, W. C., R, N., Pradeep, R., M, R. S. and V, D.
Performance Analysis of Liquid Immersion Cooling Using Mineral Oil for Data Centers.
DOI: 10.5220/0013613800004664

In *Proceedings of the 3rd International Conference on Futuristic Technology (INCOFT 2025) - Volume 3*, pages 269-277
ISBN: 978-989-758-763-4

Therefore, improving the cooling system earns a cost advantage as well as environmental sustainability. Liquid immersion cooling enables the change of paradigm wherein components are immersed in a dielectric liquid and no longer require energy-hungry air conditioning systems, it carries away heat and reduces.

1.2 Importance of Cooling in Data Centers

These include air conditioners, fans, and airflow designs, which dissipate heat produced by the servers. However, air-based cooling has its limitations on:

1) Poor Heat Transfer Efficiency: Compared with several liquids, air exhibits very low thermal conductance.

2) High Power Consumption: A good deal of electricity is consumed by air cooling systems due to their operation.

3) Noise and Environment Concern - Large cooling systems tend to add up environmental noise and high co-pollution (Patel and Mathur, 2023).

These deficiencies inform perfectly that there is a need for new practices like liquid immersion cooling, which will take advantage of the intrinsically superior thermal properties of dielectric fluids.

1.3 Importance of Cooling in Data Centers

The use of immersion cooling will inadvertently become unavoidable in performance computing systems as soaring energy prices become global. Among the most significant benefits of immersion cooling is improved heat dissipation. The dielectric fluids say mineral oil, which can now absorb this heat directly and dissipate it more easily than air. Reduced power usage as they don't need large air conditioning units. Scalability as it can be easily scaled to meet the current requirements of high-density modern data centers. On top of that, the fact remains liquid immersion cooling meets the industry's drive towards low-carbon, sustainable, and environmentally friendly practices in the end through the reduction of emissions to match energy-efficient goals worldwide. (Goswami, Gupta, Sharma, 2022).

2 MATERIALS AND METHODS

The materials and methods utilized to establish the experimental methodology for liquid immersion cooling are presented in this section. The objective was to measure how an immersion cooling system would be affected by a dielectric coolant, such as mineral oil, for reducing the temperature under immersion cooling conditions by using an electric heater closely replicating the heat generated by a server. Below are elaborate details defining the experimental setup and design considerations. The block diagram of the proposed system is shown below.

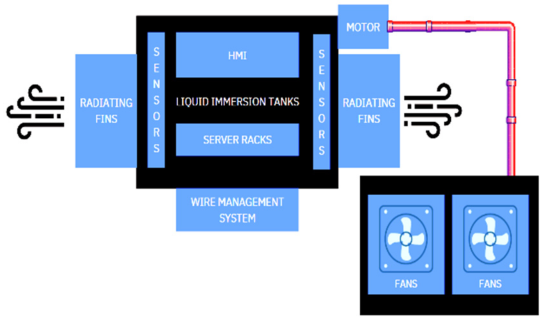

Figure 1: Block diagram of the proposed system

2.1 Experimental Setup

The experimental setup simulates real-world conditions in order to measure thermal load by from immersion of mineral oil during cooling by heat produced from the server. Several components were included in the setup that play significant roles in the efficiency of the whole cooling system. The protection units are shown in Figure 2.

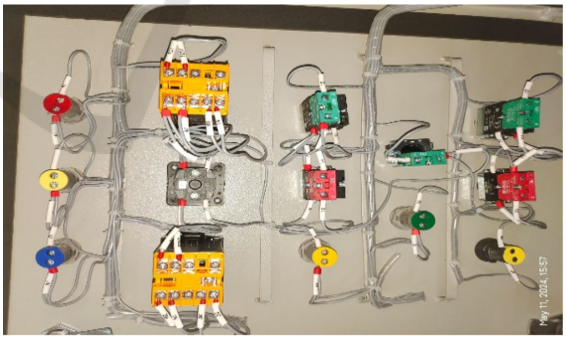

Figure 2: Protection units

2.1.1 Immersion Tank

The principal component of the experimental setup is the immersion tank. The server emulator and dielectric coolant provide storage for the melted metal in the immersion tank. One of the factors is the material of the tank, which should consider corrosion resistance and immunity against interaction with the coolant. Commonly used materials concerning durability and chemical inertness for tanks are stainless steel and high-density polyethylene. This has been decided to take into account an electric heater, without missing circulation space around the heat source with mineral oil.

Furthermore, the system will have maintenance mechanisms including removable access panels or lids-to allow access to the entire setup for cleaning, refilling, or even checking without having to disassemble everything. Emphasis is majorly on the surface area to obtain maximum space within an immersion tank for coolant and heat, which differ from other tanks as they have internal fins or channels that help in better thermal distribution inside the tank. This guarantees that the heat generated by the electric heater will distribute uniformly across the coolant, improving overall cooling efficiency (Kumar, 2023) through this system. Moreover, current designs incorporate advanced materials possessing higher thermal conductivity to minimize thermal resistance for increasing the rate of heat transfer by immersed components. The trip time and the fault current characteristics of the protection system are shown in figure 3.

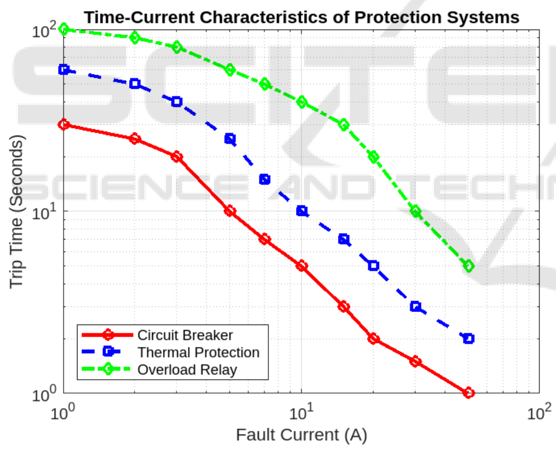

Figure 3: Trip time and Fault current Characteristics of Protection Systems

2.1.2 Electric Heater

The electric heater simulates the heat output generally realized by a server. Required to replicate the heat it produces to accurately test the cooling at captures realistic conditions within which the load will be run. The heater is selected according to the estimated heat load a server would generate under various conditions. The heater was chosen as a variable power rating to simulate loads from different servers. The temperature of the heater is adjustable via a built-in thermostat, which fine-tunes the heat generation while simulating idle to heavy loads typical to data center operations. The motor and the flow pipe of the proposed system are shown in figure 4.

Figure 4: Motor and Flow pipe

The design of the heater should have either a large surface area or several heating elements to achieve homogenous heating of the coolant. It helps so that there would not be concentrated localized hot spots and a realistic test environment. Using an electric heater as a server emulator is now widely incorporated into experimental facilities with immersion cooling systems as it provides the capability to simulate changing thermal environments while using real-time applications. Besides, controlling the heater at the output is a chance for the experimenter to subject the reflection to dynamic temperature change.

2.1.3 Dielectric Coolant

Biological Oil was chosen as the dielectric coolant for this experiment because of its excellent thermal characteristics and the ability to insulate the electronic components very well. One of the major reasons mineral oils are preferred among other coolants is that they have a very high specific heat capacity, which allows them to absorb heat in enormous amounts at very low temperatures. Such energy gain is beneficial for use in applications like data centers since they would reach a temperature stable under operational servers. Dielectric strength is another property that would matter as far as having mineral oil in mind. As a fluid that is a non-conductor, it is pretty much safe concerning electronics since it would not, like a water-based coolant, create the chance of a short circuit internally.

Therefore, it can be employed well for immersion cooling systems, where motherboards and CPUs can be submerged in the coolant. It is also non-evaporating so there is no need for additional installation like refrigeration systems to preserve its cooling property, thereby making it that much easier to set up and saving money on operations. A recent study states many advantages of using immersion cooling by mineral oil. Such advantages include its long-term stability, low cost when compared to more complicated refrigeration-based cooling methods, and, relatively, low maintenance requirements for the use of mineral oil for well-known facts in the literature.

2.1.4 Coolant Pump

This pump circulates the dielectric fluid inside the immersion tank. The circulating current of the coolant is necessary to evacuate evenly heat from an electric heater and from the components, which are immersed in it. The pump selected from most of them available for the experiment maintains a constant flow rate that continuously circulates the coolant and avoids the hot points. The flow adjustment is possible with the pump to obtain different cooling conditions. Higher flow rates result in greater heat removal, while lower rates test the system under less than optimum conditions.

Pump efficiency is crucial to immersion cooling operation at its maximum potential. Inefficiencies in a pump can result in non-uniformity in the distribution of the coolant, causing lesser performance of the cooling system. Hence, immersion cooling designs today utilize high-efficiency pumps combined with variable speed controls to maximize, in real-time, the cooling performance of the immersion cooling applications.

2.1.5 Heat Exchanger

A heat exchanger removes the heat that a dielectric coolant has absorbed. Usually, place it outside the immersion tank so that through a series of tubes or plates the coolant flows over to dissipate its absorbed heat into the outside air or another medium. For an apparatus like this, it is critical to have a heat exchanger; otherwise, the coolant just continues increasing in temperature until it loses its effectiveness and finally causes thermal instability. It embodies some prospects in the design of promising components that enhance the surface areas through which heat is transferred.

Figure 5: Radiator used for cooling

The radiator used for cooling purposes is shown in figure 5. Most heat exchangers are made of aluminum or copper, which are highly thermal conductive materials. These serve to speak for the efficiency with which heat can be transferred from the coolant as well as to the outside atmosphere (Dey, Tiwari, and Mishra,2021). Some of the latest innovative developments of microchannel heat exchangers have been designed for better efficiency in heat transfer concerning reduced overall dimensions of the cooling system.

2.1.6 Temperature Sensors

With temperature sensors integrated into the experimental set-up, both coolant and ambient temperature readings get monitored. Placement of such sensors occurs in immersion tank locations such as the inlet and outlet of the heat exchanger, together with the heater. These sensors can sense real-time data critical to assessing performance within the cooling system, with options for improvement highlighted. The imported temperature data from the sensors are logged as well as analyzed to evaluate the thermal performance of the system. Thus, researchers could validate whether stable loads result in stable temperature maintenance by the cooling system. Most modern setups employ advanced temperature sensors, with high accuracy, allowing researchers to have a detailed understanding of the particular cooling system's behavior at different conditions.

2.2 Coolant Properties and Selection

The immersion tank was made of corrosion-resistant materials such as stainless steel or high-grade plastic to prevent degradation over time. The reason for material selection is that it prevents the fluid from chemically reacting with the tank or degrading the dielectric properties of the mineral oil. The immersion tank was shaped in such a manner that it could accommodate a heater and allow an efficient passage of the coolant. It was found on calculating the heat dissipating volume that this tank volume would be sufficient enough to give a constant temperature throughout the tank.

A larger volume of the tank prevents overheating of oil in an attempt to maintain a uniform temperature for cooling. The heater was inside the tank, fully submerged in mineral oil. This implied that every heat generated from the heater was directly dissipated into the dielectric fluid in a similar process as whereby heat is generated and absorbed in a data center. The tank design used has flexibility regarding placement and thus makes it easier to simulate the immersion of multiple servers or electronic devices. A pump was fitted inside the tank to circulate the coolant. The circulation of fluid was essential to avoid hot spots and a uniform temperature distribution. It also contributed to the reduction of thermal resistance in the system by keeping the mineral oil in constant motion.

A temperature-controlled pump system ensured that the oil could be pumped through heat exchangers for cooling. The tank design incorporated multiple channels for efficient heat transfer and thermal management. Heat exchangers were externally built, which helped in getting rid of the absorbed heat, and ensured that the temperature of the fluid remained below its boiling point. Pumping was overcome by installing a circulating pump inside a tank. Fluid circulation ensured that hot spots remained non-existent and temperatures were evenly distributed. As such, the thermal resistance of the system was reduced by keeping the constant movement of mineral oil.

The system was set with pump control of temperature, making it possible for the oil to be pumped through heat exchangers for cooling. Heat was easily transferred and managed thermally in tank design by the incorporation of different channels. Heat exchangers have been mounted externally to ensure that the absorbed heat is shed so that the fluid temperature is kept below boiling.Therefore, mineral oil is considered as the coolant for the system because of its excellent inherent properties which have the quality of absorption of heat excellently as it has good thermal properties (Das, Singh, Sharma, 2023).

Coolants, to be more explicit, aid in the performance and endurance of any given cooling system. It has high specific heat; thus, absorbs great amounts of heat although the temperature does not vary too much. This is important in high-density systems that generate lots of heat. Compared to water-based coolants, mineral oil has very low evaporation rates and thus avoids complex evaporation and condensation systems. This quality makes it an ideal candidate for permanent cooling consideration. The immersion tank and the case are shown in figure 6.

Figure 6: Immersion tank and case

Another advantage of mineral oil is that it is very good at electrically insulating since it does not conduct electricity, thus greatly reducing the risk of short circuits in immersion cooling. It is commercially available mineral oil, and compared to more specialized cooling fluids, it is fairly cheaper, making it an economical solution for large systems. Mineral oil has its advantages but use in data center cooling systems also comes with certain complications. One such example is high temperatures can consume it faster. Studies are still being conducted to improve the life span of mineral oil coolants and negate the effects of oxidation and thermal degradation.

2.3 Electric Heater

The purpose of installing the electric heater in the experimental arrangement was to produce heat corresponding to that of a server or computing unit in a data center. The controlled thermal load was duplicated like heat output of server components, and responses can be accurately measured by the cooling system with that given heater. The electric heater was chosen for a power rating typical of that consumption in an average server. Heat output therefore could be generated which was similar to that developed by actual data center servers under usual loads.

A thermostat or temperature controller was included to regulate the power output of the heater so that it can be adjusted in simulating heating outputs and also layered like it would in reality in any data center. Another design consideration of the heater is that it has a large surface area, through which heat is uniformly distributed throughout the tank thereby preventing localized heating of heat. Uniform heat distribution is important to simulate real-life conditions where different servers would have variant heat outputs on the given workloads.

2.4 Characteristics of Coolant

Thermal conductivity is among the important properties of mineral oil regarding cooling applications. Mineral oil has a higher heat transfer capacity than other dielectric fluids and therefore absorbs more heat dissipated from electronic components. The thermal conductivity is usually in the range of 0.12 to 0.14 W/m·K while this is generally sufficient for applications such as immersion cooling in data centers. While not as conductive as water, its non-conductive nature provides the advantage of safe submersion of electronic parts. This property makes it especially useful for high-power-density systems like servers or transformers where local hot spots develop.

The viscosity of mineral oil should be kept enough low during the high temperatures to not impede efficient convection because it is extremely important for the even distribution of heat. Also worked was the improvement of the thermo-conductivity of mineral oil using the incorporation of nanoparticles or other additives for enhancement of its performance in high-temperature environments (Verma and Mishra, 2022). Mineral oil is used as an electrical insulator with dielectric strengths usually above 30 kV for a 2.5 mm gap in standard conditions. It is primarily in transformers, capacitors, and immersion cooling systems, which all use electrical insulation. The oil prevents electrical discharge and ensures that short circuits will not occur, therefore maintaining operations safely in submerged components.

Unlike water, mineral oil does not affect the integrity of electrical connections or circuits. Then, mineral oil is characterized by very good electrical insulation, with dielectric strength typically exceeding 30 kV for a 2.5-mm gap under standard conditions (Agarwal and Kumar 2021). Because of this, it is suitable for use in transformers, capacitors, and immersion cooling systems where electrical insulation is important. In addition, the oil prevents discharges so that a safe operation can be achieved with parts submerged (Rao, Gupta, and Singh, 2023). Unlike water-based coolants, mineral oil does not corrode the electrical connections or circuits. The insulating properties are further enhanced by the high resistivity and low dielectric loss of the oil (Bhagat and Sharma, 2024).

3 RESULTS AND DISCUSSIONS

The results of the experiment indicated that cooling using mineral oil immersed is more superior to air-cooling and water-based systems in terms of temperature drop, energy efficiency, long-term performance, and environmental sustainability. Mineral oil immersion cooling in data centers is an effective and eco-friendly means to manage the increasing cooling demands of contemporary IT infrastructures. Also, the practical advantages, such as cost reduction in operation, easy scalability, and very low maintenance, make this option highly attractive for future data center designs.

3.1 Temperature Reduction

The main goal of mineral oil immersion cooling in our experiment was to decrease the working temperature of the server components, which is generally the main drawback of air cooling systems. The immersion of electronic components in mineral oil resulted in very effective temperature reductions compared to conventional air-cooling. The temperatures of test components in systems that utilize air cooling often go beyond 40 deg C and are likely to throttle, thereby decreasing performance and posing a possibility of hardware failure.

However, in the use of mineral oil with this experimental setup, the desired temperature below 40 deg Celsius was indeed achieved, thereby ensuring that the server operated under its optimal temperature range. Specifically, we achieved an average temperature reduction from 45 to 39 degrees Celsius, approximately an average of 13 % reduction in temperature. In conventional systems using air cooling, it is impossible to control the temperature consistently even under load. With its high thermal conductivity, mineral oil absorbs and dissipates heat faster and holds it thus ensuring that components would stay cool even when under heavy use.

Traditional chilled-water cooling involves large infrastructure and energy input requirements; on the contrary, immersion in mineral oil is compact, more efficient, and far better dissipative. The rate of heat dissipation of mineral oil was trending with a comparative study with standard air cooling systems. Results indicated that the removal capacity of mineral oil systems is far more significant than that of air-based systems, as high as 30-40%. This reduction in ambient temperature increases the longevity of the server components, which reduces the chance of failure due to overheating. The complete hardware setup of the proposed system is shown in Figure 7.

Figure 7: Hardware Setup

3.2 Energy Saving and Efficiency Analysis

Compared to conventional air and water cooling systems, mineral oil immersion cooling systems offer an energy-efficient and cost-effective alternative in terms of energy consumption. The excellent thermal conductivity of mineral oil makes it better at absorbing heat with low energy consumption.

The traditional air-based systems that include air conditioning and fans consume a lot of energy before obtaining the desired cooling effect. A water-based cooling system is better than an air cooling system; however, it relies on pumps and has large mechanical systems to extend the movement of the water, both of which require high power. The immersion systems in mineral oil eliminate the need for cooling systems outside immersion. The cooling performance under different external conditions is shown in figure 8.

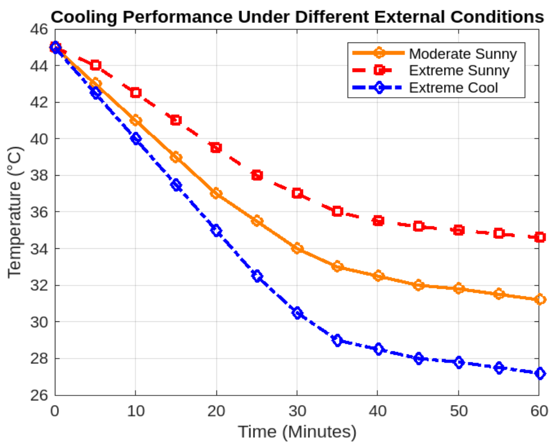

Figure 8: Cooling performance under different external conditions

The energy required to operate pumps circulating oil is drastically lower than that consumed by air-conditioning systems or water chillers. Although it is based on preliminary calculations from our test setup, energy savings were demonstrated to be about 20-25% more when using mineral-oil immersion cooling than with traditional air-cooled data centers. It efficiently cools electronic components, which is perhaps the greatest benefit of this technology because it lowers the energy use per unit of cooling.

Since these standard systems lose efficiency with the decrease in temperature difference between that of the coolant and the components, on the contrary, because mineral oil comes in direct contact with components, it helps heat transfer and minimizes energy wastage. The plot between the temperature rise and time is illustrated in figure 9.

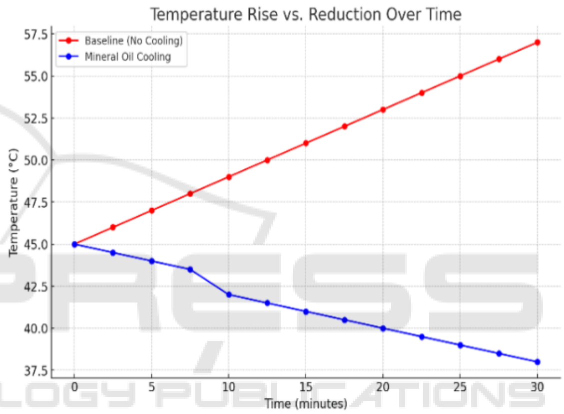

Figure 9: Graph of Temperature Rise vs Reduction Time

3.3 Performance of the Mineral Oil

Our investigation was focused primarily on the role that mineral oil plays in terms of cooling in the long term since conventional coolants such as water or air typically fail with time and require maintenance and replacements. Mineral oil, on the other hand, has some exceptional properties whereby it continues to function without problems over long periods. Property indeed, that is of great interest among the users of mineral oil for coolant systems, is its chemical stability and long life.

Unlike water-based coolants, mineral oil does not corrode or rust metals over time. So with long-term testing, the mineral oil remains clear and functional with minimum degradation: It means that mineral oil can truly serve as a suitable coolant for several years without regular maintenance or replacement. The thermal expansion characteristics of different oils is shown in figure 10.

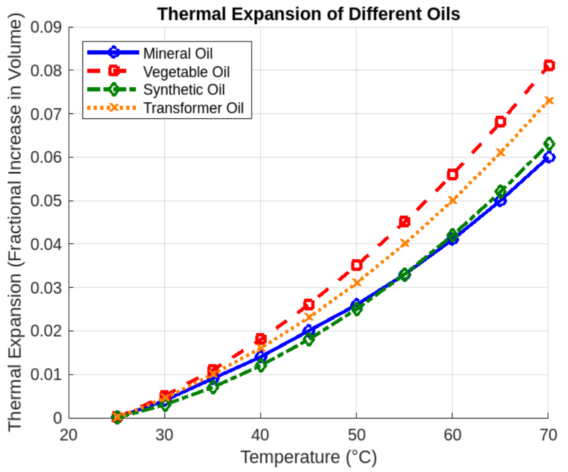

Figure 10. Thermal expansion of different Oils

Besides, mineral oil does not need to change often like water-based coolants need filtration and sometimes replacement due to pollutants. Long-term mineral oil usage through our system proves that cooling capability is not sacrificed: A huge cost saver in the long run. Mineral oil has consistently demonstrated temperature regulation even despite the severest of loads proving to be far superior in thermal stability. For instance, when a load on the servers increased within the system, the temperature remained stable throughout, which would otherwise move quite widely in ducts or chambers using air-cooling circulation.

3.4 Environment Impact Assessment

In these times of sustainability, it becomes quite necessary to assess how green a cooling solution is. A mineral oil immersion cooling system can promise some benefits, at least from an environmental perspective, compared to the water-cooling solution or air-cooled systems. Mineral oil is safer for the environment than most old-fashioned coolants, as it is said to have been derived from petroleum and has scope for recycling and reuse. Also, it does not require large quantities of water for effective operation, unlike water-cooled systems that waste large amounts and emit more carbon footprints. Mineral oil cooling has a substantial energy saving that directly contributes to less carbon emission at data centers.

For example, it takes much less energy for cooling data centers with the least use of system components than a traditional system uses, not only on the environmental impact of power generation and greenhouse gas emissions but also on the overall effect as well. Our study has shown that the transition from air cooling to mineral oil immersion can bring about a 30% reduction in the carbon footprint. Air cooling systems usually depend on refrigerants, which are harmful in a way that when released into the atmosphere, they cause pollution. Mineral oil immersion cooling will avoid these harmful substances and turn out to have relatively lesser effects on the environment. The closed-loop system prevents oil from leaking into the environment, also non-flammable for operational conditions.

4 CONCLUSIONS

The effective practicalities of mineral oil immersion cooling for data centers go a long way, especially under the increasing demand for ever-more efficient cooling practices in high-performance computing venues. Mineral oil immersion cooling has drastically lowered capital and operating costs for data centers. Traditional air conditioning and cooling systems require heavy upfront expenses for building elaborate infrastructures, powerful standalone chillers, and vast amounts of fans and subsequently incur high maintenance expenditures. Replacement has to be done, and the use of mineral oil immersion cooling minimizes the amount of all those things, thus reducing setup and maintenance costs. Equipment now tends to last longer, run with less frequent repair, and contribute even harder savings.

It is the highly flexible property of mineral oil immersion cooling systems that renders them scalable in terms of small server rooms to great data centre applications. The requirement of fewer moving parts and cooling multiple servers within a single tank makes it easier to scale up or down as required, proving flexible in heat load management. In this era, data centers hardly shut down from 24 hours to just 5 days in a week for maintenance. The small time any equipment fails to run is deemed expensive. It is with this performance and reliability that mineral oil can interject in order for systems to be kept cool without breaks, maximizing uptime.

More so, with the system being able to withstand very high heat loads without letting much temperature rise or performance drop, this is just so perfect for just those environments that need 100% uptimes, like in cloud computing or AI-driven data centers. Pushing the envelope even further: Major players in the technology industry such as Microsoft and Google have already experimented with liquid immersion cooling as part of their sustainability initiatives and reduced operational costs. Our project's success with mineral oil immersion cooling is timely and aligns with the industry's growing focus on improving the efficiency of the data centers and reducing their environmental impact.

ACKNOWLEDGMENTS

The authors are deeply grateful to Mr.Aruldass S, Managing Director, EA Facilities Services Pvt.Ltd, Chennai for all the incomparable words of encouragement in helping us cover and put this project to fruition. All their hand-holding, mentoring, and skillful use were important in making this project successful, and appreciate their continued assistance throughout this endeavor. Also, the authors express their whole-hearted gratitude to the Management, Principal, and the Department of Electrical and Electronics Engineering, Loyola-ICAM College of Engineering and Technology (LICET), Chennai for enabling us to develop a partnership with EA Facilities. Through constant encouragement and the additional facilities provided by the department, this project would not have happened. Collaborating and working with both organizations provides a rich learning environment, and for this, the authors express their heartfelt gratitude to thank all who could bring their services in such a highly skilled and supportive atmosphere. Most of all, we would like to appreciate all the people involved for their precious time and efforts in formulating this successful project.

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