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Measurement of the Thermal Performance of a Custom-Build Single-Phase Immersion Cooled Server at Various High and Low Temperatures for Prolonged Time

The next radical change in the thermal management of data centers is to shift from conventional cooling methods like air-cooling to direct liquid cooling to enable high thermal mass and corresponding superior cooling. There has been in the past few years a limited adoption of direct liquid cooling in data centers because of its simplicity and high heat dissipation capacity. Single-phase engineered fluid immersion cooling has several other benefits like better server performance, even temperature profile, and higher rack densities and the ability to cool all components in a server without the need for electrical isolation. The reliability aspect of such cooling technology has not been well addressed in the open literature. This paper presents the performance of a fully single-phase dielectric fluid immersed server over wide temperature ranges in an environmental chamber. The server was placed in an environmental chamber and applied extreme temperatures ranging from −20 °C to 10 °C at 100% relative humidity and from 20 to 55 °C at constant 50% relative humidity for extended durations. This work is a first attempt of measuring the performance of a server and other components like pump including flow rate drop, starting trouble, and other potential issues under extreme climatic conditions for a completely liquid-submerged system. Pumping power consumption is directly proportional to the operating cost of a data center. The experiment was carried out until the core temperature reached the maximum junction temperature. This experiment helps to determine the threshold capacity and the robustness of the server for its applications in extreme climatic conditions. [DOI: 10.1115/1.4045156]

Introduction

Due to the ever-increasing need for data, there is a continually increasing demand for information technology (IT) applications and services, which in turn, has provided sustained growth and interest in data centers. Many large and medium enterprises access and store online content on the World Wide Web. Because of this ever-increasing demand, the data center cooling costs are constantly on the rise as they need large amounts of energy for the cooling purpose. Due to this vast energy consumption by data center facilities, operators have placed a significant emphasis on the energy efficiency of the building's overall operation. Cooling typically accounts for 40% of a data center's total energy bill [1]. Traditionally, data centers use air as the primary cooling medium where the rejected heat from IT hardware is absorbed by the air. This heat is rejected to the outside ambient, either mixed with incoming fresh air, or cooled through refrigeration processes. With an increase in heat densities of electronic components, removing heat constantly from the data centers is the biggest concern, as air is less capable of efficient cooling due to its low thermal conductance. Because of the above inadequacy of traditional air-cooling, many discussions are focused on new immersion cooling technology.

Submerging servers and IT equipment in a dielectric medium for cooling provides substantial energy savings as it accommodates heavy energy loads and density. Its heat capacity by volume is 1120–1400 times greater than air [1–10]. It also helps to keep the temperature constant irrespective of changes in server workload, which indicates that the server is in a good isothermal environment. Single-phase immersion cooled servers are simple, easy to manufacture, and inexpensive as it provides simplicity and ease in planning as only one medium is used for cooling purpose, which in turn keeps the server in proper hygiene. In traditional air-cooling with airside economization, some dust, and dirt particles enter the facility. These dirt and dust particles get accumulated inside the chassis and lead toward the mechanical failure. Immersion cooling also minimizes and/or eliminates many common operational issues like solder joint failures, oxidation, or corrosion of electrical contacts. Other advantages are elimination of fans, no sensitivity to humidity, or any temperature condition, etc. Operating expense of this equipment is exceptionally low too [2–13].

One of the major causes of electronic failures is due to thermally induced stresses and strains caused by excessive differences in coefficients of thermal expansion across the materials. This experiment is analogous to the thermal cycling and thermal aging

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process, which helps determine the performance and efficiency of servers in extreme environmental temperature ranges for a prolonged period in an environmental chamber. It analyzes the effects of extreme temperatures on a single-phase dielectric fluid submerged server, which provides a support to validate the ruggedness and robustness of the server. The performance of a server and other components like pump and connector sealing were observed at different temperature cycles between $-20\,^{\circ}\mathrm{C}$ and $10\,^{\circ}\mathrm{C}$ at 100% relative humidity and from 20 to $55\,^{\circ}\mathrm{C}$ at constant 50% relative humidity. Some additional relations and properties of different components examined in this study include power drawn versus chamber temperature and average core temperatures versus chamber temperatures. This research helps to determine the threshold limit of a server at extreme temperature and qualifies the robustness of the system for its reliability and performance. The experiment was performed in steady-state conditions. The utilization of central processing unit (CPU) was fixed at 100%, pump rotation was fixed at 100%, and the chamber temperature was fixed for each experiment.

Server Configuration

In this experiment, the server is fully immersed in a single-phase dielectric fluid. The system (with stand and heat exchanger) weighs approximately 24 lbs (10.9 kg).

Server Specifications

Server dimensions: 2.3 in. $(H) \times 8.1$ in. $(W) \times 15.3$ in. (L).
Server Specification: Windows i7 5th Gen with Quad core processor.
Storage: NVME SSD, $1 \times$ mSATA III SSD, SATA SSD

The server shown in Fig. 1 is equipped with a high-end Intel Core i7 CPU and 16 GB of memory making it a high-performance system. The total power of the system is around 100–110 W. The pump used in the experiment is a Laing DDC-3.2 pump in RT with specifications as given below.

Pump Specifications

Dimensions $(W \times D \times H)$: $90 \times 62 \times 38\,\mathrm{mm}^3$
Motor: Electronically COMMUTATED ball bearing motor
Nominal voltage: 12 V DC

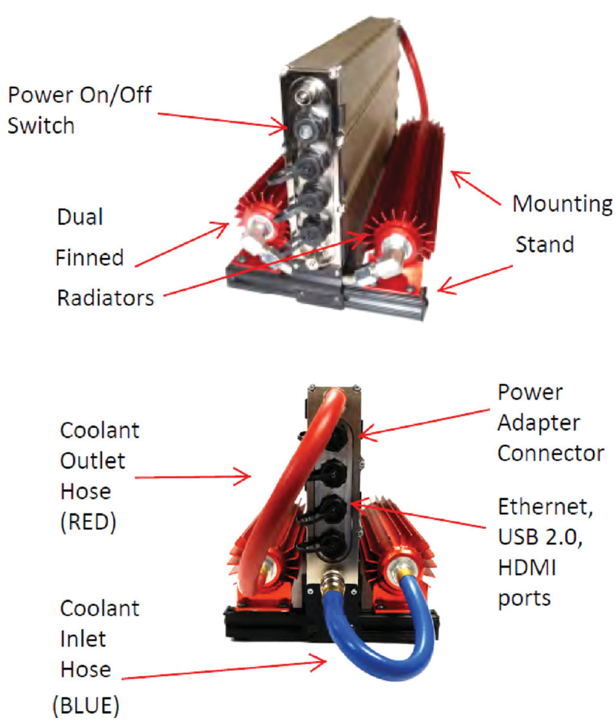


Fig. 1 System overview

Nominal power consumption: 18 W
Certified voltage: 6–13.2 V
Maximum flowrate: >900 l/h
Maximum system temperature: $60\,^{\circ}\mathrm{C}$
Materials in contact with the coolant: stainless steel 1.4571, PPS-GF40, EPDM O-rings, aluminum oxide, hard coal, viton
Fittings: $2 \times 3/8$ in. barbed fittings (for hoses with an outer diameter of 10 mm and 8 mm inner diameter).

The pump in the system is fixed at its maximum rpm, which is 6000 rpm. The pump's rpm does not change with the load of the server. This server has rugged seal enclosure and waterproof I/O connectors, which are IP67 Rated. The electronics inside are protected from air particulates, moisture contaminants, and other contaminants. Customized EKWPs vertical impingement heat sink allows fluid to flow in both directions.

As shown in Fig. 1, all primary components of the system have been integrated into a single unit for customers' convenience. The electronics enclosure comprises the computer system and an internal pump, which circulates coolant through the system. Two finned radiators transfer heat from the system to the surrounding environment. Rugged hoses conduct the cooling liquid between the enclosure and the radiators. The mounting stand conveniently packages the enclosure, radiators, and hoses together with provisions to remove the enclosure, if needed. Optional weatherproof power and I/O cables are equipped with screw-on caps to protect the connectors from moisture, dirt, dust, or other contaminants.

Software Used

PRIME95. PRIME95 is one of the most popular CPU stress-testing programs. It tests the computer for stability issues by stressing CPU to its maximum limit. PRIME95 runs Lucas Lehmer iteration indefinitely and only terminates a stress test when it encounters an error and informs the user that the system may be unstable. PRIME95's stress test feature can be configured to test various system components by changing the fast Fourier transform (FFT) size. There are three preset configurations available. The first is small FFTs, which primarily tests floating-point unit (FPU) and CPU caches. The second one is in-place FFTs, which gives maximum power consumption, tests FPU and CPU caches, and some part of random access memory. The last FFTs blends the tests by including everything, even random access memory. In this experiment, the small FFTs option is used since it allows FPU testing at maximum stress so the system can operate in a more stable condition [14].

CORE TEMP. CORE TEMP is a compact program to monitor CPU temperature. It displays real-time temperatures of each individual core (core temperature) in each processor when the load of the server varies. CORE TEMP is completely motherboard independent. The temperature readings are very accurate as the software collecting the data directly from a digital thermal sensor. The digital thermal sensor is located near the hottest part of each core. This sensor does not rely on an external circuit to report temperature. All core temperature values are stored in the processor. CORE TEMP software can access and provide real-time reading. This method eliminates any kind of inaccuracies [15].

Dielectric Fluid. The system is filled with OPTICOOL dielectric liquid, which is used to cool the electronics. OPTICOOL is electrically nonconductive, biodegradable, nontoxic, nonhazardous cooling oil with a consistency like light mineral oil. At room temperature $(25\,^{\circ}\mathrm{C})$; fluid thermal conductivity, specific heat, kinematic, and dynamic viscosity are 0.1366 W/m/K, 2.145 J/g/K, 7.65 cSt, and 0.0627 poise, respectively. The flash point of the dielectric fluid is $185\,^{\circ}\mathrm{C}$, and it provides high cooling efficiency, safety, and thermal stability at a low cost. It is designed to be used in circulating systems, which includes both heating and cooling systems of electrical applications.

Experimental Setup

Environmental Chamber. Thermatron SE-600-10-10 environmental chamber provides versatility in testing environments. This type of chamber enables the user to change its environment as per user fed values. The chamber consists of an onboard condenser, which is water-cooled, with an airflow rate of 1000 CFM. Temperatures and humidity in the chamber range from −70 °C to 180 °C (−94 °F to 356 °F) and 10–98%, respectively. In this experiment, the server is kept inside a Thermotron SE 600-10-10 Environmental chamber, and the thermocouples were attached at various locations on the server as shown in Fig. 2.

Thermocouple. In the experiment, T-Type thermocouples were used. The Type T thermocouples are very stable and are often used in extremely low temperature applications such as cryogenics or ultra-low freezers [5]. The Type T has excellent repeatability between –380 °F and 392 °F. The temperature range of type T thermocouples is from −454 °F to 700 °F (−270 °C to 370 °C) and standard accuracy is ±1.0 C or ±0.75% [16].

Data Acquisition and Multiplexer. In this experiment, Agilent 34972 A DAQ system was used to log the temperatures of the thermocouples. DAQ's capability of combining the precision measurement with various signal connections makes this instrument very versatile and reliable. DAQ has three module slots into the rear of the instrument to accept any combination of data acquisition component or multiplexer. All the data were recorded directly through its pre-installed Agilent 34901 A software in the system. This software gives more flexibility for logging data as the user desire.

Power Meter. The power meter used in this experiment was Watts Up Pro. It is one of the most efficient, precise, and accurate power measuring devices. This device logs data at any interval defined by the user. It measures total server power, voltage, current, cost, Watt-hour, power factors, duty, and power cycle, etc.

Methodology

Positions of Thermocouples. T-type thermocouples were attached on the server at eight different locations. Figures 3 and 4 show the precise locations of the thermocouples on the server. Nomenclatures are as follows:

- Ch-1: top of the server;
- Ch-2: left of the server;
- Ch-3: right of the server;
- Ch-4: inlet of the server;

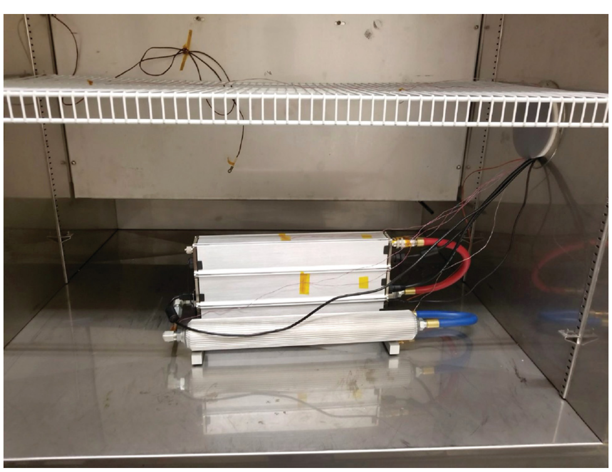


Fig. 2 Experimental setup in the environmental chamber

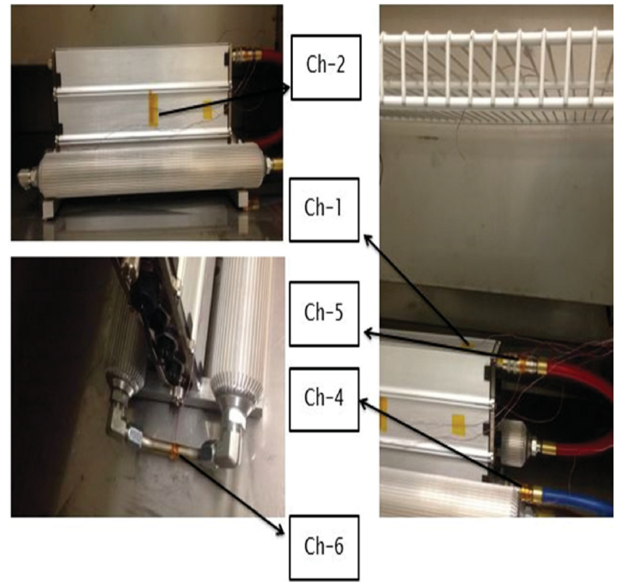


Fig. 3 Front side of the server

- Ch-5: outlet of the server;
- Ch-6: connector of two radiators;
- Ch-7: calibrator front (air);
- Ch-8: calibrator back (air).

Calibration of Thermocouples. Before attaching the thermocouples on the server, the thermocouples needed to be calibrated. For calibration, the thermocouple was attached to Agilent 34901 A 20 Channel Multiplexer Module and Agilent 34972 A DAQ system. The free end of the thermocouple was kept in the ice water beaker with a thermometer. Individually, the thermocouple value was checked from the DAQ system and compared with the thermometer value.

The calibrated thermocouples were attached on the server. The server was placed in the environmental chamber and before starting the actual experiments, the thermocouples were calibrated again. Calibration was done in the following order:

(1) Environmental chamber was programed to set at ambient temperature (25 °C).
(2) Once temperature was set, the thermocouples were checked through the DAQ systems. The variation between the thermocouple measured temperatures and the temperature in the environmental chamber was around ±0.3 °C.

Experimental Procedure. The server was started, and 100% load was given by PRIME95 software. The temperature of the chamber was set to 25 °C with 50% RH. The experiment was performed

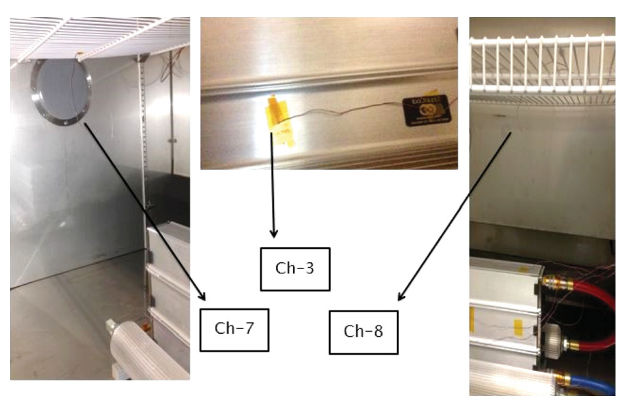


Fig. 4 Backside of the server

for 4 h. The voltage, current, power, and all four core temperatures were logged at the interval of 15 min by the power meter and software CORE TEMP. Temperatures of the thermocouples were logged by AGILENT software.

After 4 h, the chamber was stopped and opened; inspection was done on the server to check for any leakage from the connectors, abnormal noise, and condensation on the radiators. After inspection, the server was kept idle for 4 h allowing it to reach to its normal state and the next experiment was performed. For the second experiment, the temperature of the chamber was kept at 20 °C with 50% RH. The experiment was performed for 4 h and readings of core temperatures, power, voltage, and current were taken at 15-min intervals. Four hours later, the chamber was stopped to inspect the server for any leakage or any abnormal noise. This procedure was repeated and performed at 10 °C, 0 °C, −5 °C, −10 °C, −15 °C, and −20 °C temperatures with 100% RH for 4 h.

The same experimental procedure was used for higher temperatures. The server was tested at different chamber temperatures of 30 °C, 35 °C, and at 40 °C with 50% RH for 4 h with all the parameters recorded during that time. As the initial experiments were performed for 4 h successfully without any deterioration in performance, the remaining experiments were performed for 8 h and 144 h, respectively, at higher temperatures. For 45 °C, 50 °C, and 55 °C, the same experiment was performed but for a longer period, i.e., for 8 h with 50% RH. Temperatures of thermocouples and cores were recorded every 30 min by the systems.

After the above-mentioned experiments, the server was tested at 45 °C for 144 h. This experiment was performed for detailed analysis of server performance. Core temperatures were recorded at 2 h intervals. The inlet and outlet temperatures of the fluid and power were recorded every 4 h. Longer duration experiment was performed at higher temperatures to assess the reliability and performance issues of the server.

Results

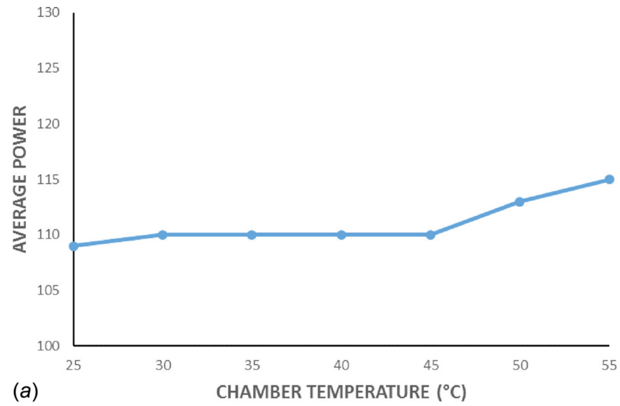
All the values of average powers (CPU + pumping power), core temperatures, and inlet/outlet temperatures of the fluids were averaged for each environmental chamber temperature. The relationship between the averaged value of each parameter and the respective temperatures have been presented in the form of graphs as shown below for higher and lower temperatures separately.

Figures 5(*a*) and 5(*b*) show the variation in average power with respect to environmental chamber temperatures. Figure 5(*a*) shows that at 25 °C, the power consumption of the server is 109.1 W, which steps up to 109.6 W at 30 °C and remains constant until 45 °C. After 45 °C, it rises to 112.8 W and 113.2 W for 50 °C and 55 °C, respectively. The power increase at the higher temperatures after 45 °C is due to a decrease in pump power and increase in leakage current in the system at higher temperatures. This is because of the decrease in viscosity of the fluid at the higher temperatures.

Figure 5(*b*) shows that the power consumption of the server is constant around 91.5 W at 20 °C and 10 °C and rose up to 110 W and 110.9 W at 0 °C and −20 °C, respectively. This rise in power consumption at extreme low temperatures is due to increasing viscosity of the fluid. The pump drove more power to maintain the flowrate of the fluid.

Figures 6(*a*) and 6(*b*) show the average core temperatures of a server with respect to the changing chamber temperatures. Figure 6(*a*) shows that at 25 °C, all core temperatures were below 65 °C. It is noticeable that the average core temperature is increasing drastically with the rising chamber temperature. This same pattern was observed for all other core temperatures.

At 55 °C, core 0 temperature almost reached the maximum junction temperature (T_j) of the system. The set junction temperature of the system is 92 °C. This experiment helped us to decide the threshold of the chamber temperatures. Once we reached the maximum junction temperature of the system at 55 °C, we did not perform an experiment above that temperature to avoid the overclocking of the CPU.



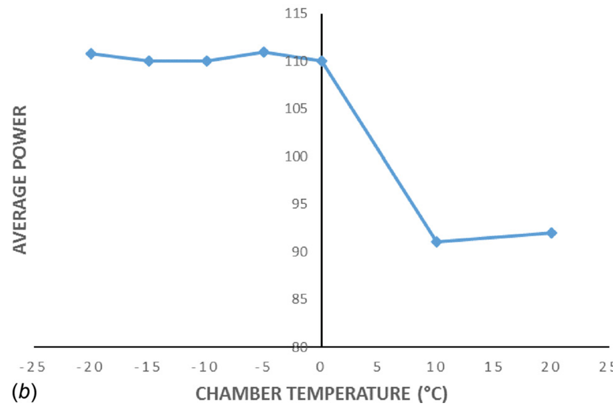


Fig. 5 (*a*) Average power (W) versus temperatures (°C) graph (high temperatures) and (*b*) average power (W) versus temperatures (°C) graph (low temperatures)

In Fig. 6(*b*), the temperatures of all cores dropped down with decreasing chamber temperature. At 20 °C and −20 °C, the temperature of the primary core (Core 0) is 59 °C, and 18 °C, respectively. Even at low surrounding temperature, the efficiency and performance of the server was the same. There was no abnormal noise or leakage from the server. The system was not frozen and did not have any starting issue.

For Figs. 6(*a*) and 6(*b*), the trends are roughly linear, which is predictable with Fourier's law. A resistance analysis should be conducted to see the system performance.

Figures 7(*a*) and 7(*b*) show average inlet/outlet temperatures of the server with respect to the environmental chamber temperature. It is evident that there is almost 1 °C difference between the inlet and outlet temperature of the server. Inlet and outlet temperatures are the temperatures of a coolant entering and exiting the server. The difference in temperature is almost the same from −20 °C to 55 °C.

Figures 8–10 are the results of the experiment, which was performed at 45 °C for 144 h. At 2 h intervals, the core temperature reading was recorded. Similarly, inlet and outlet temperatures of fluid and power were recorded every 4 h.

Figure 8 shows core temperatures of the server with respect to time. Server core temperatures were almost constant in the cycle. The maximum range of temperature for each core was around 2–3 °C. The average core temperatures of each core were almost the same.

Figure 9 shows inlet/outlet temperatures of the server with respect to time. The pre-installed AGILENT software did data logging at 4-h intervals. The difference between inlet and outlet temperatures was around 2–3 °C. Figure 10(*a*) shows the temperature difference of 1 °C for all the environment (ambient) temperatures (including 45 °C) of the server. That helped to determine that the system temperature increases if the system is run for a longer period at higher ambient temperature. This also gave an

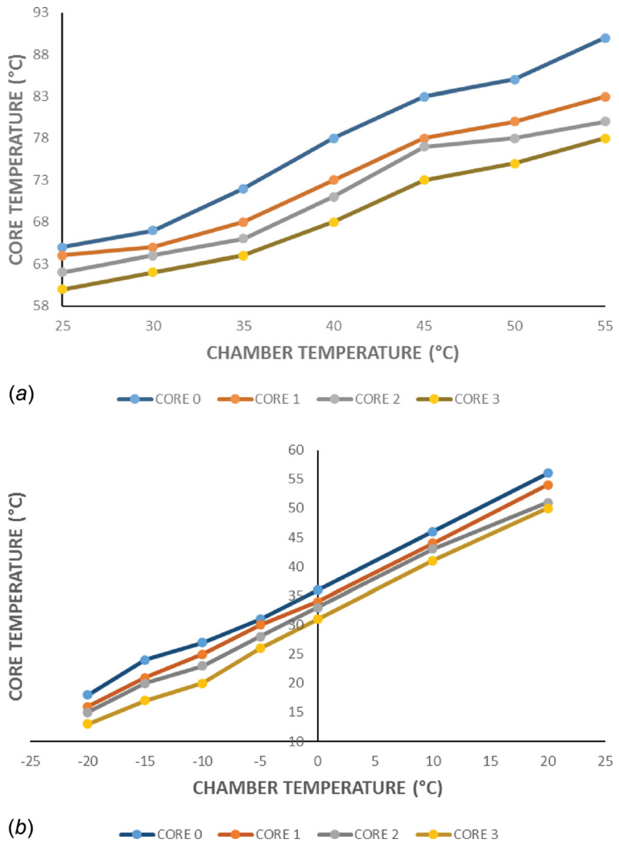


Fig. 6 (*a*) Average core temperatures (°C) versus chamber temperatures (°C) (high temperatures) and (*b*) average core temperatures (°C) versus chamber temperatures (°C) (low temperatures)

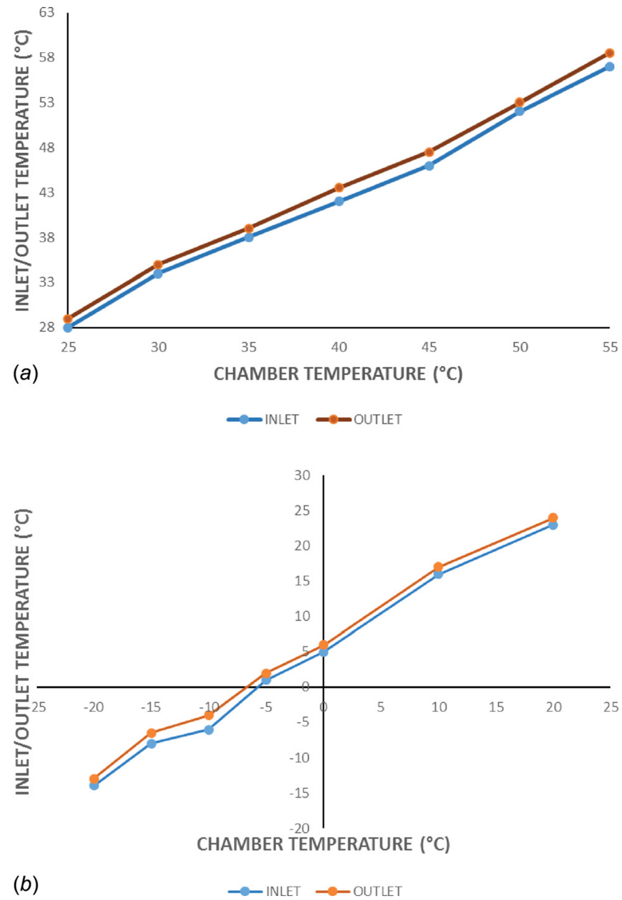


Fig. 7 (*a*) Average inlet and outlet temperatures (°C) versus chamber temperatures (°C) (high temperatures) and (*b*) average inlet and outlet temperatures (°C) versus chamber temperatures (°C) (low temperatures)

opportunity to the radiators to be acclimated with the environment to allow better performance.

Figure 10 shows server power with respect to time. The average power consumption of the server at 45 °C is around 109.5 W, which is the same as shown in Fig. 5(*a*). The power consumption of the server was almost constant for the whole cycle (144 h).

Conclusion and Future Work

From the experimental results, it can be inferred that the fully submerged server can be used in extreme weather conditions. At extreme temperatures, the server was performing efficiently

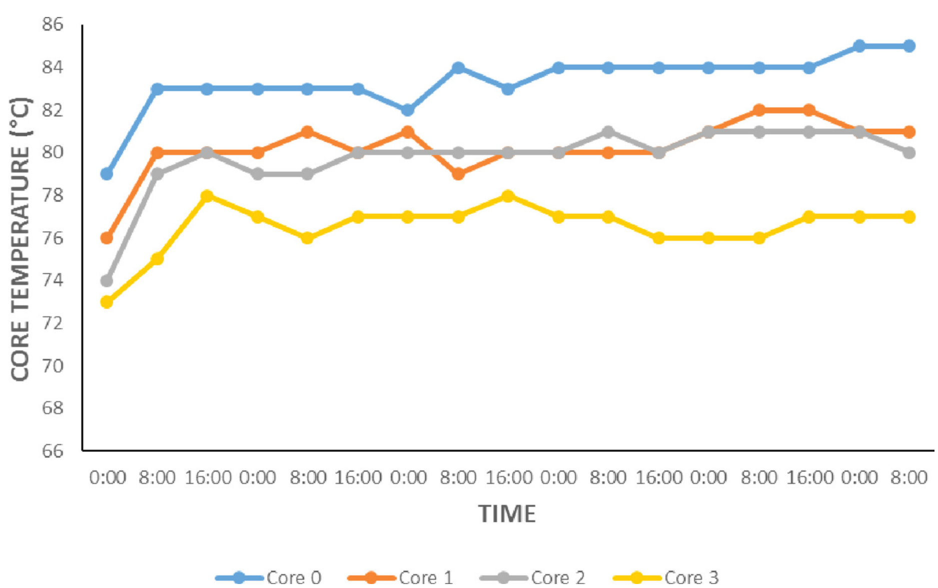


Fig. 8 Core temperature (°C) versus time (h)

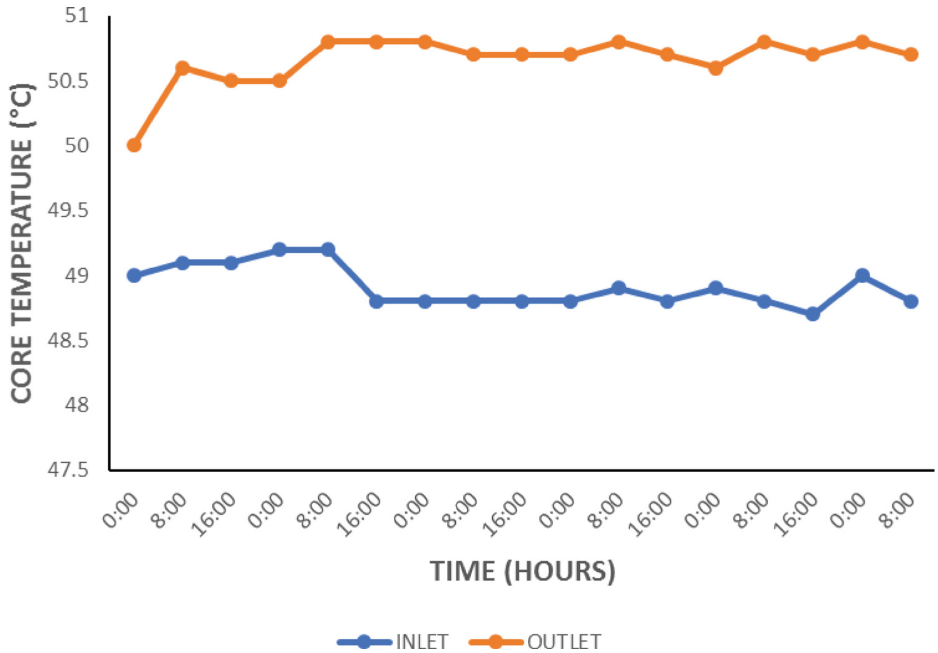


Fig. 9 Inlet/outlet temperature (°C) versus time (h)

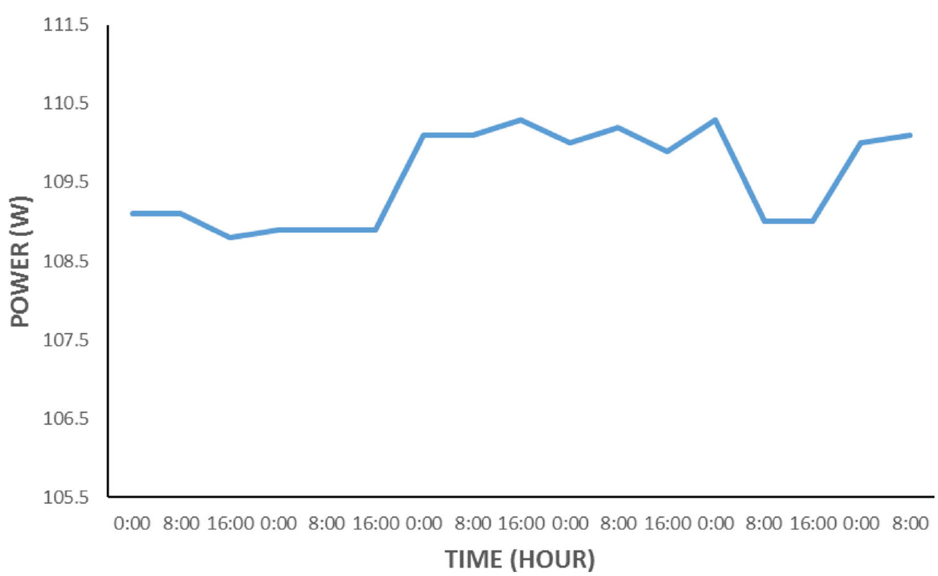


Fig. 10 Power (W) versus time (h)

without compromising its reliability or any mechanical issues such as start issues. From the results above, we can conclude that the server can perform efficiently between $-20\,^{\circ}$C and $55\,^{\circ}$C. There was no leakage through any connectors and no abnormal noise from the server. The server is robust and can withstand the harsh environment with the average power variation being only about 20 W. It is evident that the performance of passive heat exchanger was very efficient based on the number of hours spent on the experiment (144 h).

With the server being operated under full computing load during the test with high performance, this is noteworthy since other fanless computers are not capable of cooling such a high-performance configuration under the conditions of the above-mentioned test to the authors' knowledge. The server is completely submerged and hermitically sealed. This server can be adopted in military and industrial applications as its performance was very efficient and showed very promising results in high temperatures. Since the server is compact it can be transported anywhere, even to remote locations.

The experiment was performed in steady-state conditions. This same experiment will be performed for transient conditions for future research. For the transient experiment, the server-computing load and pump utilization will be varied for different environmental conditions with the server being opened to check the integrity of components and reliability. The change in the physical and chemical properties of the fluid would also be measured. This system is completely sealed, and we did not have an access of inside. For future research, we intend to place thermocouples to measure the temperature of the fluid inside the system. This system uses the synthetic hydrocarbon dielectric fluid which shows high variations in the viscosity with respect to temperature consuming the higher pumping power at low temperatures. The fluorochemical fluids which have more consistent thermophysical properties should be used instead.

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Funding Data

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Nomenclature

DAQ = data acquisition
FFT = fast Fourier transform
RH = relative humidity
T_j = junction temperature

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