EXPERIMENTAL ANALYSIS OF A SINGLE-PHASE DIRECT LIQUID COOLED SERVER PERFORMANCE AT EXTREMELY LOW TEMPERATURES FOR EXTENDED TIME PERIODS

by

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Abstract

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A data center is a centralized facility that we use for housing the computer systems and its related components such as high-end servers, redundant data connection and security controls. 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 (DLC) to deal with high thermal mass. The past few years have consistently seen wider adoption of direct liquid cooling because of its simplicity and high heat dissipation capacity. Passive single phase engineered fluid immersion cooling has several other benefits like better server performance, even temperature profile and higher rack densities.

This report provides an overview of the considerations of using single-phase dielectric fluid to cool a server based on experiments conducted at extreme conditions in an environmental chamber. The server was placed in the environmental chamber ranging from extremely low temperatures at -20°C to 20°C and varying humidity for extended durations. Thermal overstress experiment was

performed on a fully immersed server and its cooling system components. This work explores the effects of low temperature on the performance of a server and other components like pump including flow rate drop and starting trouble under extreme climatic conditions. The possibility of connector seals observing reduced performance upon accelerated temperature cycling is addressed. Throttling limit for the CPU along with power draw over a range of different temperatures was recorded. Similar observations were recorded for pump. Dependence of pump performance on operating temperature determines the flow rate and operating temperature relationship. Pumping power consumption is directly related to the operating cost of a data center.

This research can be expanded by performing similar experiments at elevated temperatures to establish an operating temperature envelope in order to get the optimum performance of a direct liquid cooled high-density server.

Table of Contents

List of Illustrations

List of Tables

Chapter 1

Introduction

A data center is a facility used to house computer systems and associated components, such as telecommunications and storage systems. It generally includes redundant or backup power supplies, redundant data communications connections, environmental controls (e.g. air conditioning, fire suppression) and various security devices. IT operations are a crucial aspect of most organizational operations around the world. One of the main concerns is business continuity; companies rely on their information systems to run their operations. If a system becomes unavailable, company operations may be impaired or stopped completely. It is necessary to provide a reliable infrastructure for IT operations, in order to minimize any chance of disruption. Information security is also a concern, and for this reason a data center has to offer a secure environment which minimizes the chances of a security breach. A data center must therefore keep high standards for assuring the integrity and functionality of its hosted computer environment. This is accomplished through redundancy of mechanical cooling and power systems. [18].

The sole purpose of data center cooling technology is to maintain environmental conditions suitable for information technology equipment (ITE) operation. Achieving this goal requires removing the heat produced by the ITE and transferring that heat to some heat sink. [19]. Almost all industries like health care, finance, government, entertainment, enterprise businesses rely on data center. Data center facilities size ranges from a few hundred square feet to over one million square feet. These data center have different environment which differs from other facilities which are built for human comfort or industrial use. Power consumption per square foot of floor space of data center facility can be as much as an order of magnitude higher as compared to typical office buildings, schools, and commercial buildings. These high power densities have several challenges like cooling infrastructure which includes different types of cooling methods and its cost. Fig 1-1 shows the rows of racks filled with IT equipment (ITE) in data center [1], [2]. Because of this ever-increasing demand, the data center cooling costs are constantly on the rise. Cooling typically accounts for 40% of a data center's total energy bill. [1], [3], [9].

Removing heat constantly from the data centers is the one of the biggest concerns as with increase in heat densities of electronic components and densities at the rack level; air becomes less capable of efficient cooling. Due to this inadequacy of traditional air-cooling, many discussions are focused on the new immersion technology. Submerging servers and IT equipment in a dielectric medium for cooling provides substantial energy savings as it accommodates heavy energy loads and density [1], [2], [10], [14].

There are many benefits of the immersion cooling: it helps keep the temperature constant irrespective of changes in server workload. This is because its heat capacity by volume is 1120-1400 times greater than air [1], [2], [3]. The server is in a good isothermal environment. Another advantage is server hygiene. In traditional air-cooling, some dust and dirt particles enter the facility. These dirt and dust particles get accumulated inside the chassis with the computers and lead towards the mechanical failure.

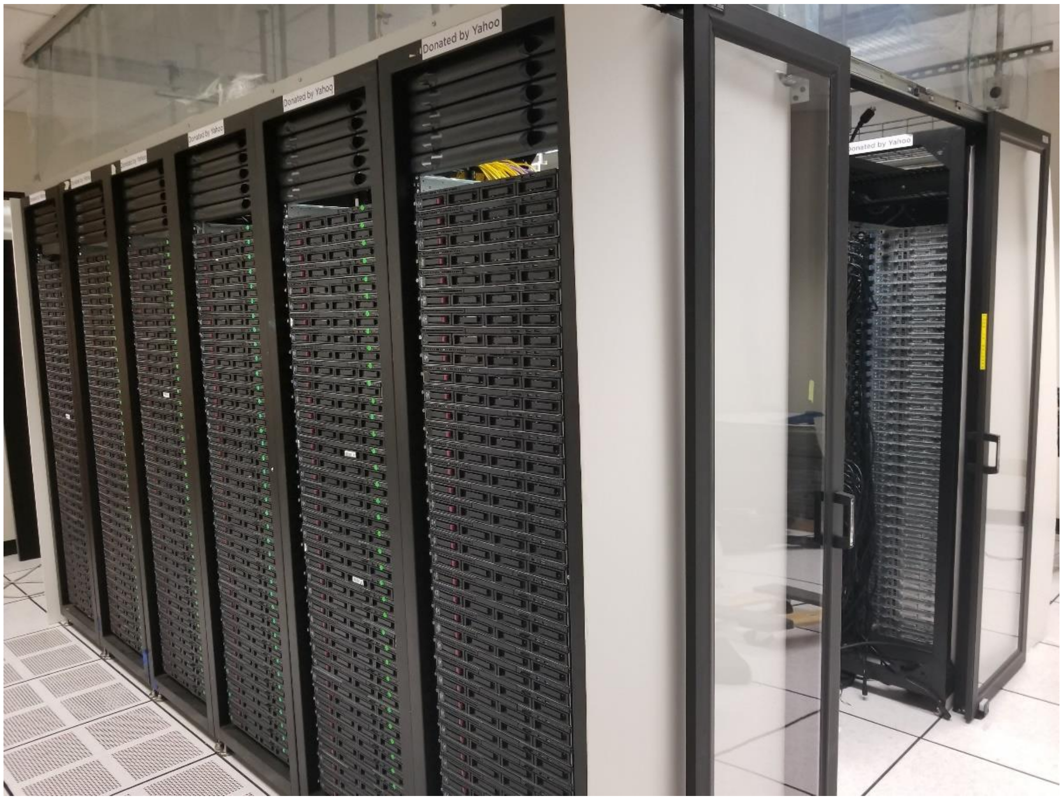

Figure 1-1: Data Center

Immersion cooling also minimizes common operational issues and eliminates the causes of failure like solder joint failures. It provides benefits like even operating temperature for PCB components, prevention of oxidation or corrosion of electrical contacts, no moving parts like fans, no sensitivity to humidity or any temperature condition. Operating expense of this equipment is exceptionally low [2], [11]. Single-phase immersion cooled servers are simple, easy to manufacture and inexpensive.

Figure 1-2, shows the flow path of immersion cooling system. The low temperature dielectric fluid is pumped into the server system. The dielectric fluid absorbs the heat from the system and exits at higher temperature. The fluid is cooled in a heat exchanger and pumped into the system.

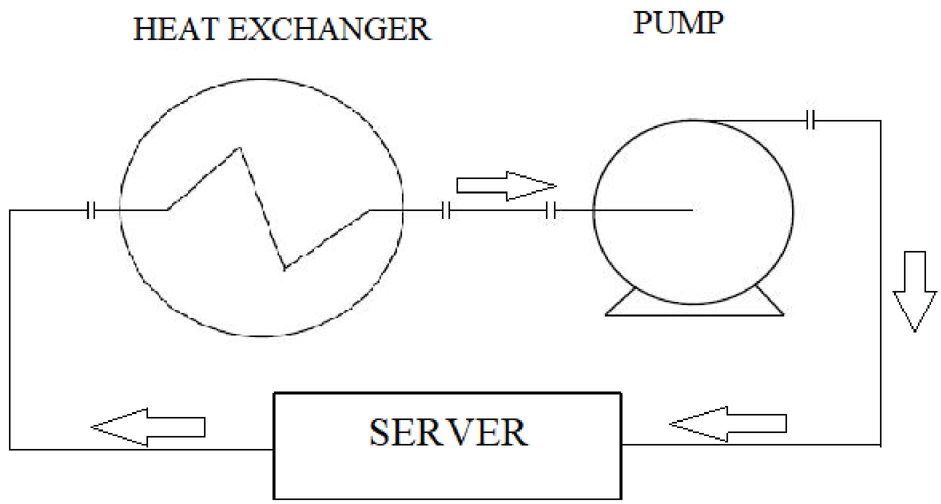

Figure 1-2: Schematic diagram of immersion cooling system

Most of electronic failures happen due to thermally induced stresses and strains caused by excessive differences in coefficients of thermal expansion (CTE) across materials. This experiment is based on thermal cycling and thermal aging process which determine the performance of servers in different environmental temperature ranges for prolonged periods in an environmental chamber. It reviews the effects of low temperatures on the single-phase dielectric fluid submerged server, which provides a helping hand to validate the ruggedness and robustness of the server. The performance of a server and other components like pump and connectors sealing were observed at different temperature cycles typically between -20°C to 20°C (lower temperatures than the operating temperatures typically found in air cooling based on ASHRAE Thermal Guidelines) at 50% Relative Humidity. Some additional relations and properties of different components, examined like power draw vs temperature. This research helps to determine the threshold limit of a server with the lower temperature and qualifies the robustness of the system for its reliability and performance.

Chapter 2

System Configuration

In this experiment, a server, which is fully immersed in a single-phase dielectric fluid is used to check its performance at different temperature ranges. The server comprises of a computer system and an internal pump, which circulates cooling medium i.e. dielectric fluid through the system. Two passive heat exchangers transfer heat from the system to the surrounding environment. Rugged hoses conduct the cooling liquid between the enclosure and the heat exchanger. Specifications of the server and the fluid are as follows:

Server dimensions: 2.3” (H) x 8.1” (W) x 15.3” (L).

Server Specification: Intel Core i7 5th Gen with Quad core processor.

Storage: NVME SSD, 1 x mSATA III SSD, SATA SSD

Pump Specification:

- Dimensions (WxDxH) of the pump is 90x62x38mm.
- Motor has electronically commuted ball bearing. • Nominal voltage and power consumption: 12V DC and 18W.
- Maximum flow rate and system temperature: >900l/h and 60°C.
- Materials in contact with the coolant: Stainless steel 1.4571, PPS-GF40, EPDM O-Rings, Aluminum oxide.

Pump in the server is maintained at 6000 rpm which is its maximum limit and does not change with the load of the server. Server have rugged seal enclosure and waterproof I/O connectors, which is IP67 Rated. Electronics are protected from air particulates, moisture contaminants and other contaminants [12]. Customized heat sink is used in the server. It is EKWPs vertical impingement heat sink where fluid can flow in both directions.

Chapter 3

Software used

3.1 Prime 95:

Prime95 is one of the most popular CPU stress-testing software. 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 pre-set configurations available. First, Small FFTs primarily tests FPU and CPU caches. Second, In-Place FFTs which gives maximum power consumption and tests FPU and CPU caches, some part of RAM and the last, Blend which tests everything including RAM. In this experiment small FFTs option has been used since it tests FPU at maximum stress and system operates in more stable condition. [4].

3.2 Core temp:

Core Temp is a compact program to monitor CPU temperature. It shows the real time core temperature of each individual core in each processor. Core Temp is completely motherboard independent. The core temperature readings are accurate as the software collects the data directly from a Digital Thermal Sensor (or DTS). DTS is located near the hottest part of each core. This sensor does not rely on any external circuit located to report temperature. All core temperature values are logged in the system can be accessed any time. This helps in eliminating any kind of inaccuracy or human error. [5].

3.3 Dielectric fluid:

The server is fully submerged in a single phase dielectric fluid. The properties of the dielectric fluid (Opticool 872552) are given in the Table (1). Flash point of the dielectric fluid is 185°C. It is a synthetic fluid that provides great cooling efficiency, safety and thermal stability at a low cost. It is designed to use in circulating systems, which includes both heating and cooling systems of electrical applications [6].

Table 1-1: Property Table

Temp °C	Kinematic Viscosity (cSt)	Dynamic Viscosity (poise)	Specific Heat (kw-s/kg-K) (J/g/K)	Thermal Conductivity (W/m/K)
0	18.8	0.1519	2.054	0.1381
10	12.5	0.1002	2.092	0.1375
20	8.82	0.0701	2.129	0.1369
30	6.52	0.0514	2.167	0.1364
40	5.00	0.0397	2.204	0.1358
50	3.96	0.0307	2.242	0.1352
60	3.22	0.0247	2.280	0.1346
70	2.69	0.0205	2.2317	0.1341
80	2.27	0.0171	2.355	0.1335
90	1.95	0.0146	2.392	0.1329
100	1.70	0.0126	2.430	0.1323

Chapter 4

Experimental setup

4.1 Environmental chamber:

Thermatron SE-600-10-10 environmental chamber provides versatility in testing environments. It helps the user in allocating the desired environmental conditions as per user fed values by using different parameters such as relative humidity and temperature as per requirement for a given duration of time. In this experiment, the server is kept inside a Thermotron SE 600 Environmental chamber, and the thermocouples were attached at various locations on the server. Working condition of the environmental chamber for Temperature ranges from -70°C to 180°C (-94°F to 356°F) and humidity ranges from 10% to 98%. [7]

Figure 4-1: Thermatron SE-600-10-10 Environmental Chamber

4.2 Thermocouple:

In the experiment T-Type thermocouples were used. Type-T thermocouple is a very stable and is often used in extremely low temperature applications such as cryogenics or ultra-low freezers [5]. The type T has excellent repeatability between –380°F to 392°F. Temperature Range of Type T is from -454°F to 700°F (-270°C to 370°C) and Standard Accuracy is +/- 1.0C or +/- 0.75%. [8].

4.3 DAQ and Multiplexer:

In this experiment, Agilent 34972A 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. It also has three module slots into the rear of the instrument to accept any combination of data acquisition component or multiplexer (MUX). All the data were recorded directly in the through its pre-installed Agilent 34901A software in the system. This software gives more flexibility for logging data as user desire.

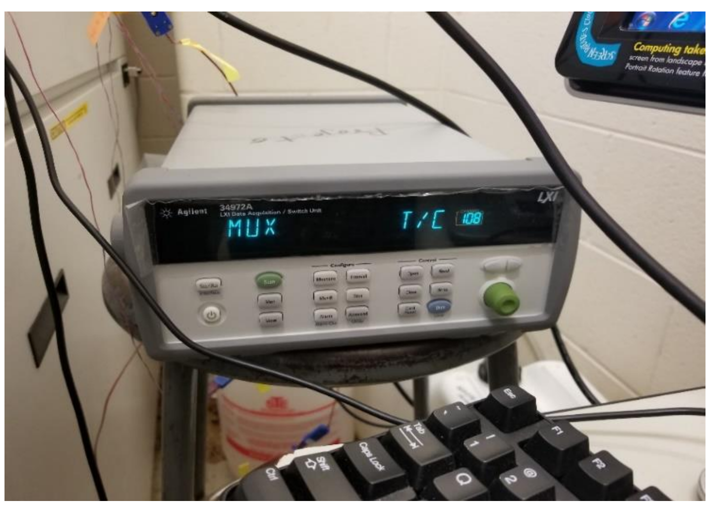

Figure 4-2: Multiplexer

4.4 Power meter:

The Power meter used in this experiment was Watts Up Pro (Figure 3). It is one of the efficient, precise and accurate power measuring devices. This device logs data at any interval defined by the user. It measures power, voltage, current, cost, watt-hour, power factors, duty and power cycle etc.

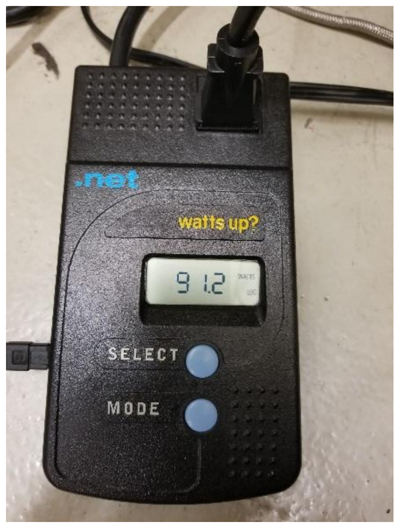

Figure 4-3: Power meter

Chapter 5

Methodology

5.1 Positions of thermocouples:

T-type thermocouples were attached on the server at eight different locations. Figures (5-1 and 5-2) showcases the 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
- Ch-5: Outlet of the server
- Ch-6: Connector of two radiators
- Ch-7: Calibrator Front (Air)
- Ch-8: Calibrator Back (Air)

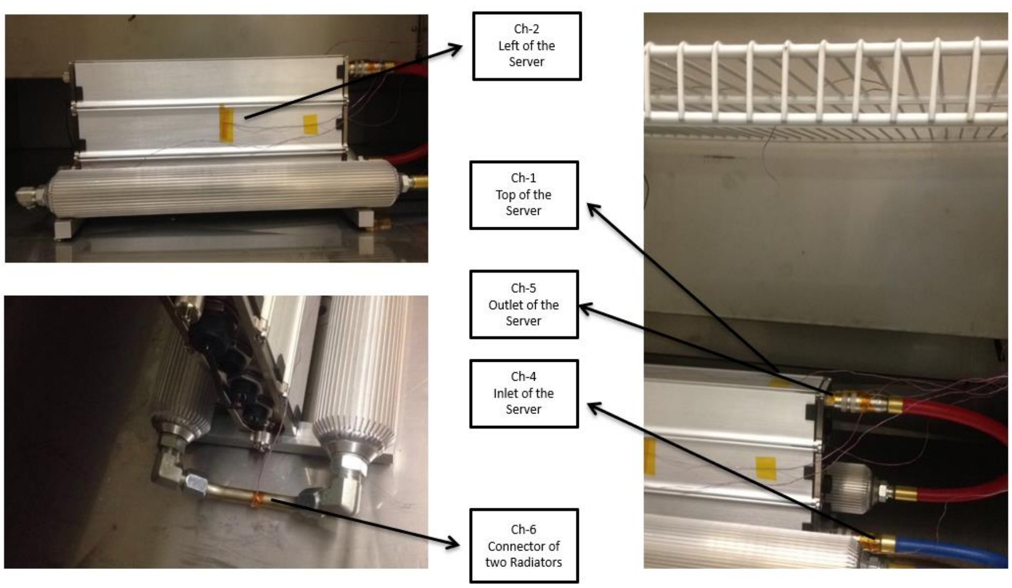

Figure 5-1 Front side of the server

Figure 5-2 Back side of the server

5.2 Calibration of thermocouples:

After connecting all the thermocouples, the server was placed in the environmental chamber. Before starting the actual experiment, the thermocouples were calibrated. Calibration was done in the following order:

1. After attaching one end of all the thermocouple on server, the other end was installed in the Agilent 34901A 20 Channel Multiplexer Module.
2. The server was placed in the middle of the environmental chamber as shown in Fig 5-3. Multiplexer module was then inserted in the Agilent 34972A DAQ system. Connectivity of the thermocouples were checked when the Agilent system was switched on.
3. Environmental chamber was started and allowed to set at temperature (25°C).
4. Once temperature was reached, the thermocouples were checked through the DAQ systems. The variation between the thermocouple measured temperatures and the temperature in the environmental chamber was only -/+ 1 °C.

After calibration of the thermocouples, the server was started and 100% load was given by Prime 95 software. The temperature of the chamber was set to 20°C with 50% RH. The experiment was performed for 4 hours. The voltage, current, power and all four core temperatures were logged at the interval of 15 minutes by the power meter and software Core Temp respectively. Temperatures of the thermocouples were logged manually from DAQ display.

After 4 hours, when the chamber 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 hours allowing it to reach to its normal state and the next experiment was performed. This procedure was repeated for the different chamber temperatures of 10°C, 0°C, -10°C, and -20°C with 50% RH and all the parameters were recorded.

Figure 5-3 Experimental setup in the Environmental Chamber

Chapter 6

Results

Experiments are performed for the temperatures 20°C, 10°C, 0°C, -10°C and -20°C for the duration of 4 hours and parameters were recorded at every 15 minutes of interval. Results are recorded for IT load (Power) of the server. Core temperature of all the cores which includes Core 0, Core 1, Core 2 and Core 3 are measured. Along with this, temperature of all the eight thermocouples is measured.

At 20°C temperature

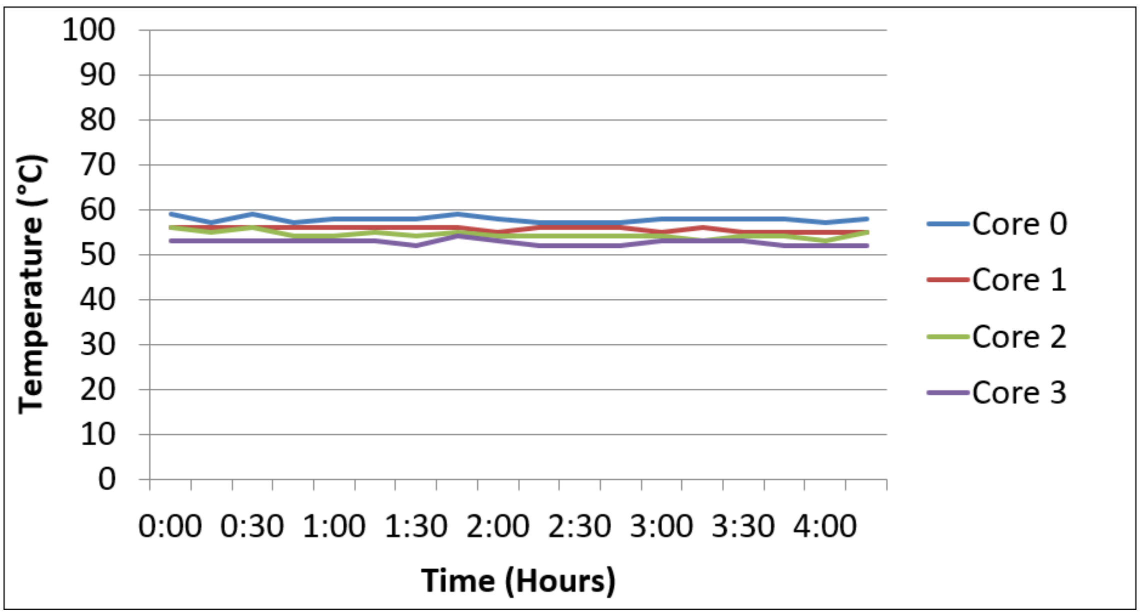

Figure 6-1(A): Core Temperature vs Time

From Figures 6-1 (A) it can be inferred that all core temperature of the server at 20°C are well within the limits (75°C). The core temperatures were almost constant between the range of 50 and 60°C. Average temperature of core 0, core 1, core 2, and core 3 is around 57.5°C, 56°C, 54°C and 53°C respectively. For the safety of the server the maximum junction is set at 92°C.

Figure 6-1(B) shows the temperatures of all eight thermocouples with respect to time. The temperatures were almost constant throughout the experiments. All temperatures are well under the limits. Figure 6-1(C) shows the power of the server with respect to time. The average power consumed by the server is around 92 W.

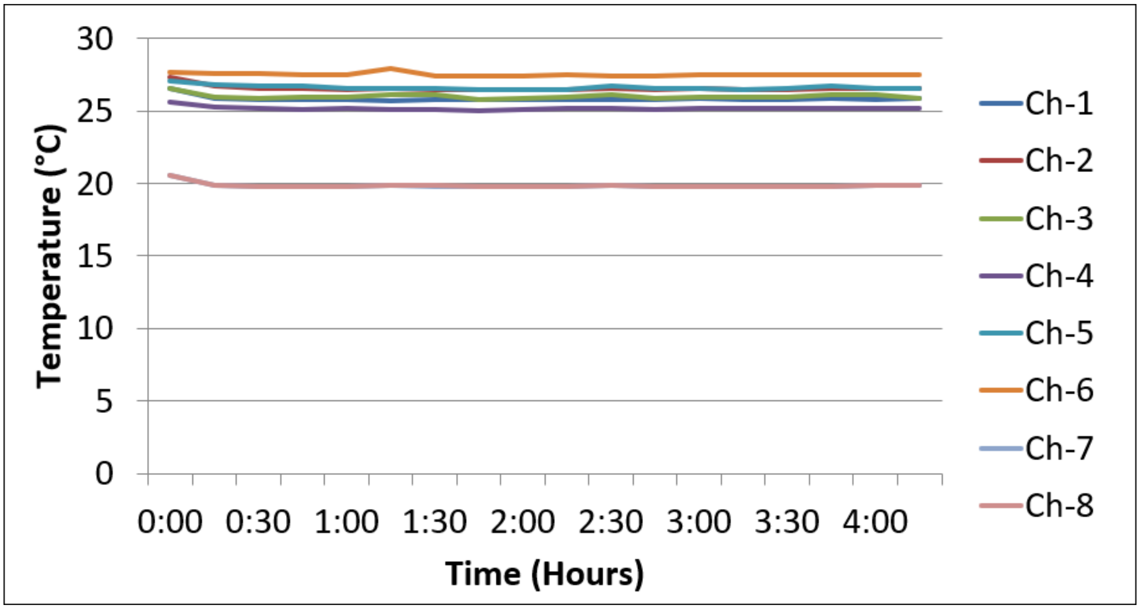

Figure 6-1 (B): Thermocouple temperature vs Time

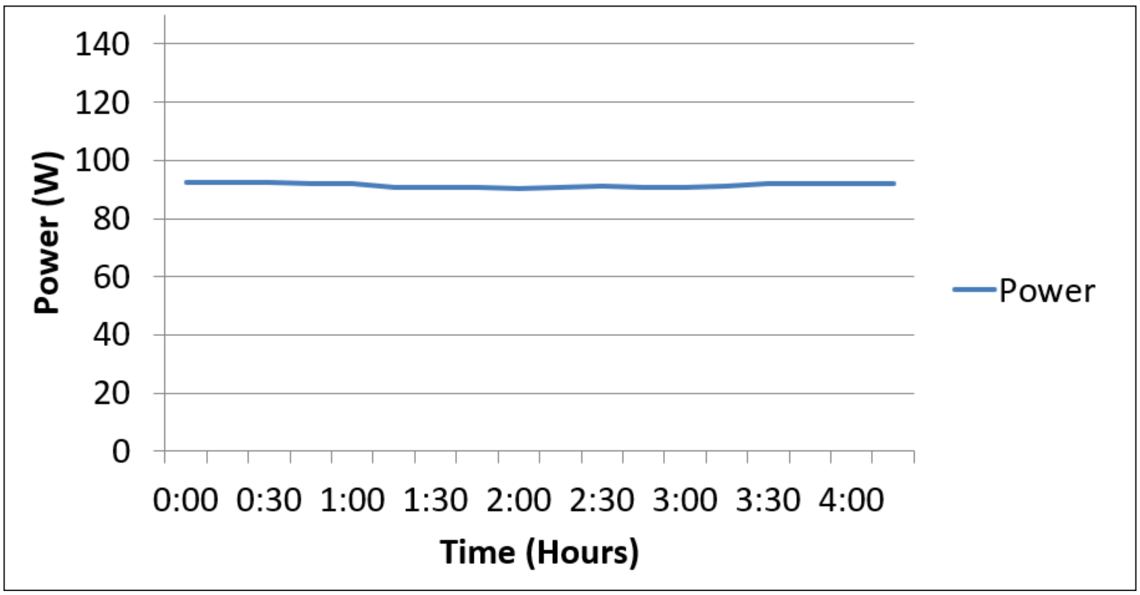

Figure 6-1(C): Power vs Time

At 10°C temperature

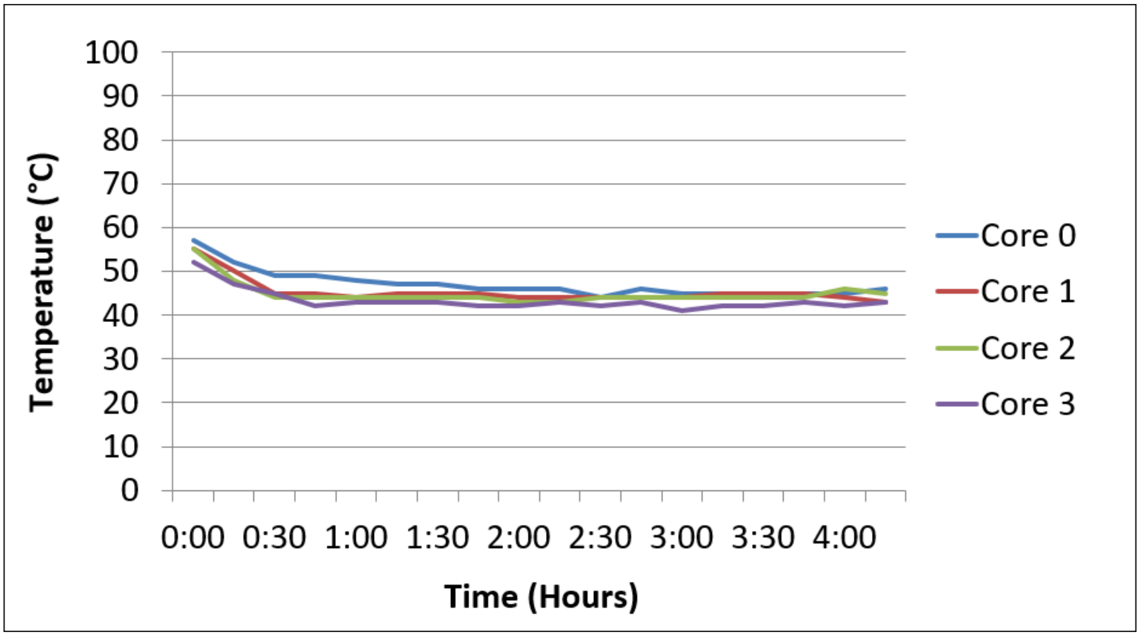

Figure 6-2(A): Core Temperature vs Time

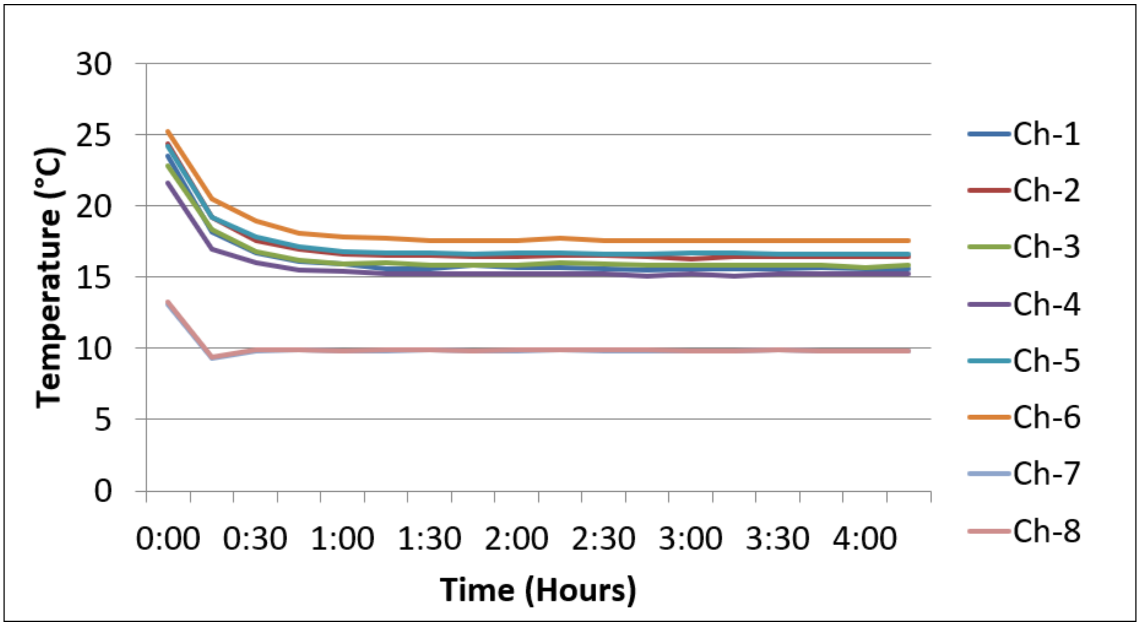

Figure 6-2(B): Thermocouple temperature vs Time

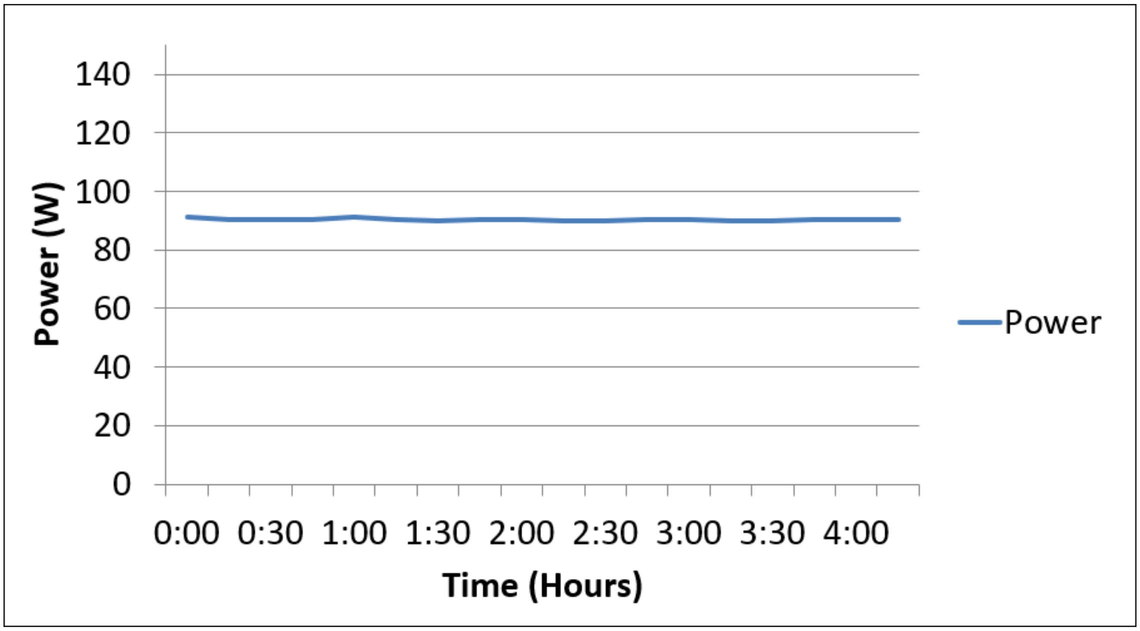

Figure 6-2(C): Power vs Time

From Figures 6-2 (A) it can be understood that all core temperature of the server at 10°C are well within the limits. The core temperatures were near to constant after 45 minutes. Figure 6-2(B) shows the temperatures of all eight thermocouples with respect to time. After 30 minutes the temperatures were constant throughout the experiments. All temperatures are well under the limits. Figure 6-2(C) shows the power of the server with respect to time. The average power consumed by the server is around 92 W.

At 0°C temperature

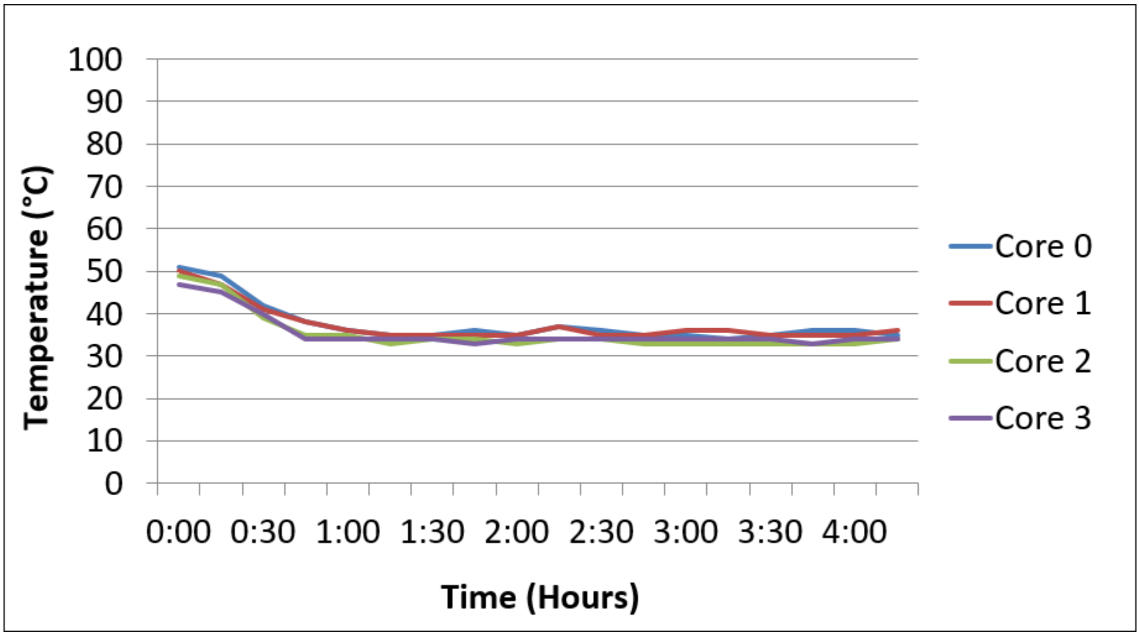

Figure 6-3(A): Core Temperature vs Time

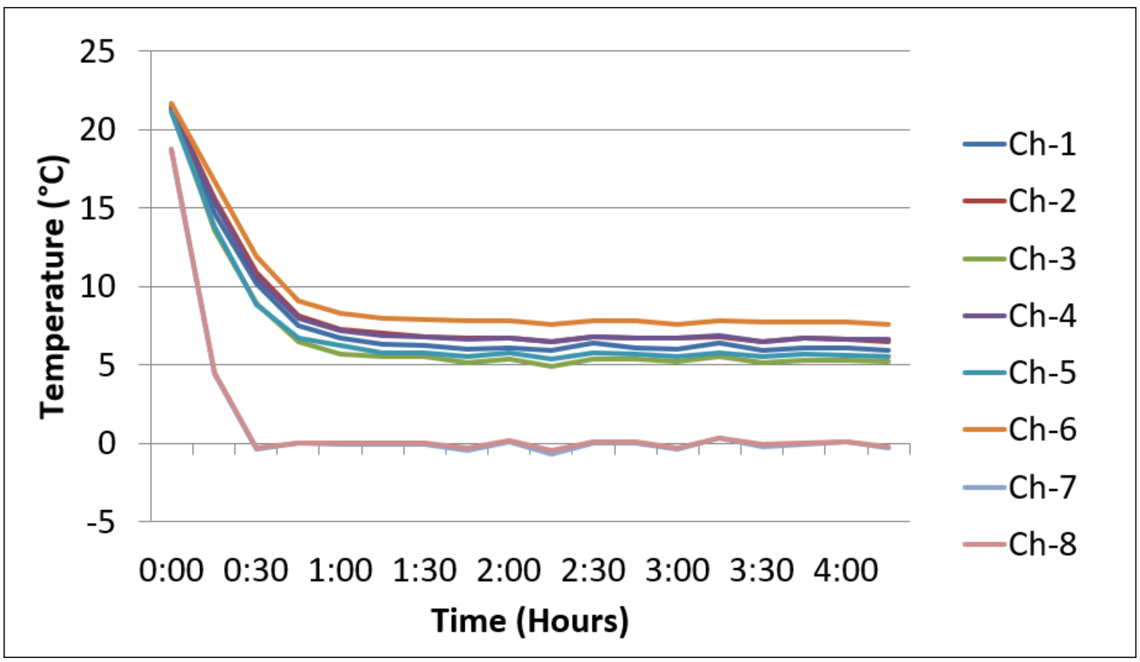

Figure 6-3(B): Thermocouple temperature vs Time

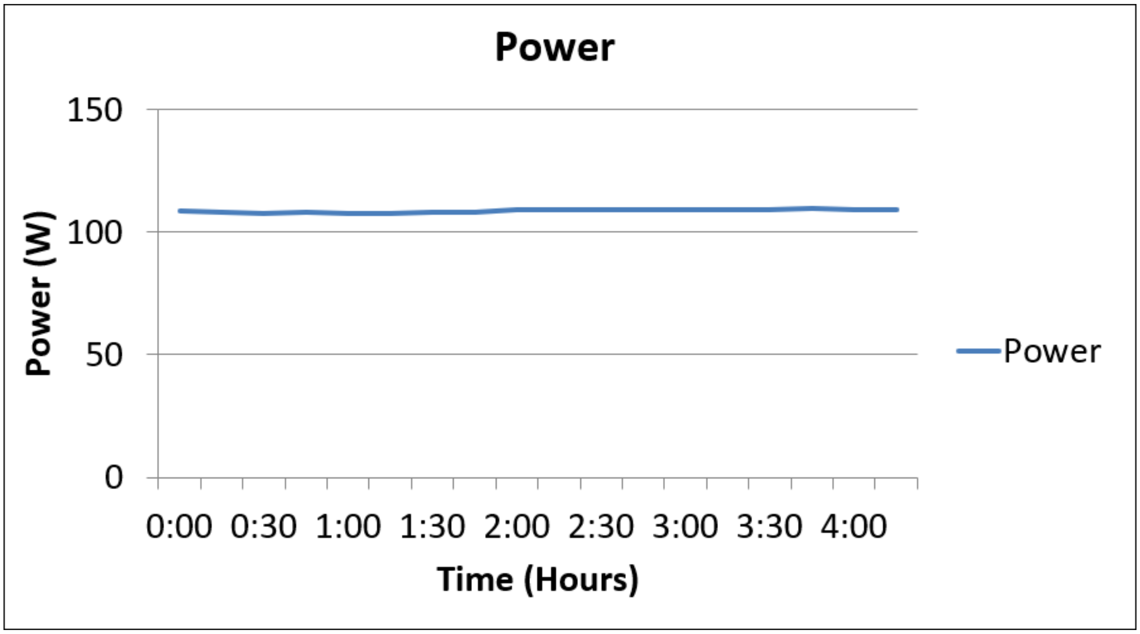

Figure 5-3(C): Power vs Time

From Figures 6-3 (A) it can be understood that all core temperature of the server at 0°C are well within the limits. The core temperatures were constant after 45 minutes. Average junction temperature of core 0, core 1, core 2, and core 3 was between 33°C and 37°C. Figure 6-3(B) shows the temperatures of all eight thermocouples with respect to time. After 45 minutes the temperatures were constant throughout the experiments. Temperature for Ch 7 and Ch8 are very low because they reflect the ambient temperature. Figure 6-3(C) shows the power of the server with respect to time. The average power consumed by the server is around 109 W.

At -10°C temperature

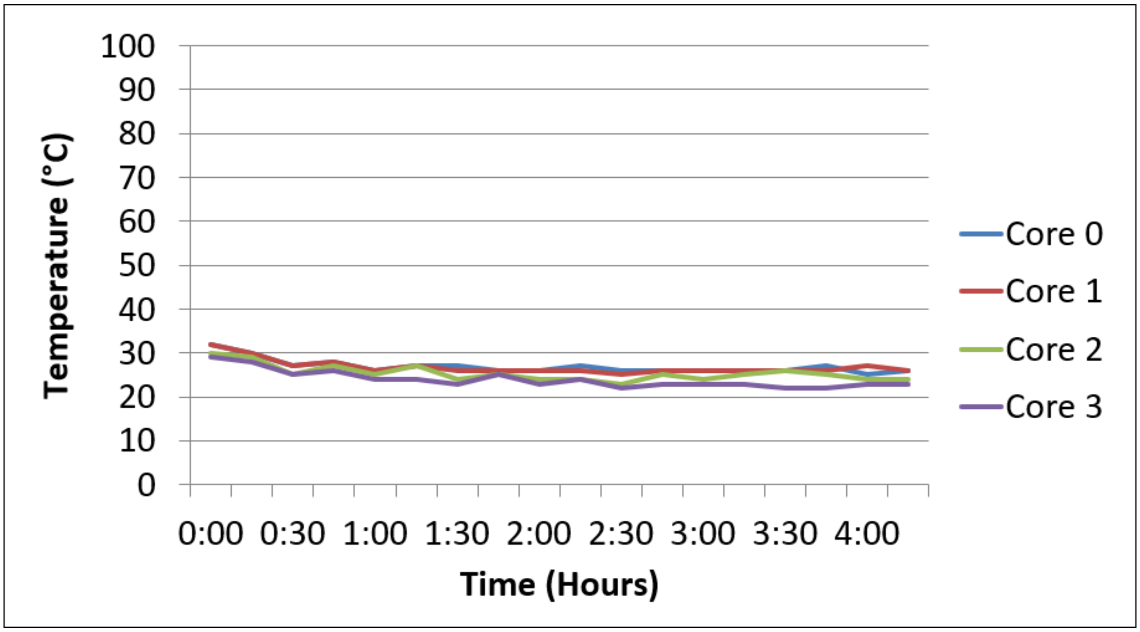

Figure 6-4(A): Core Temperature vs Time

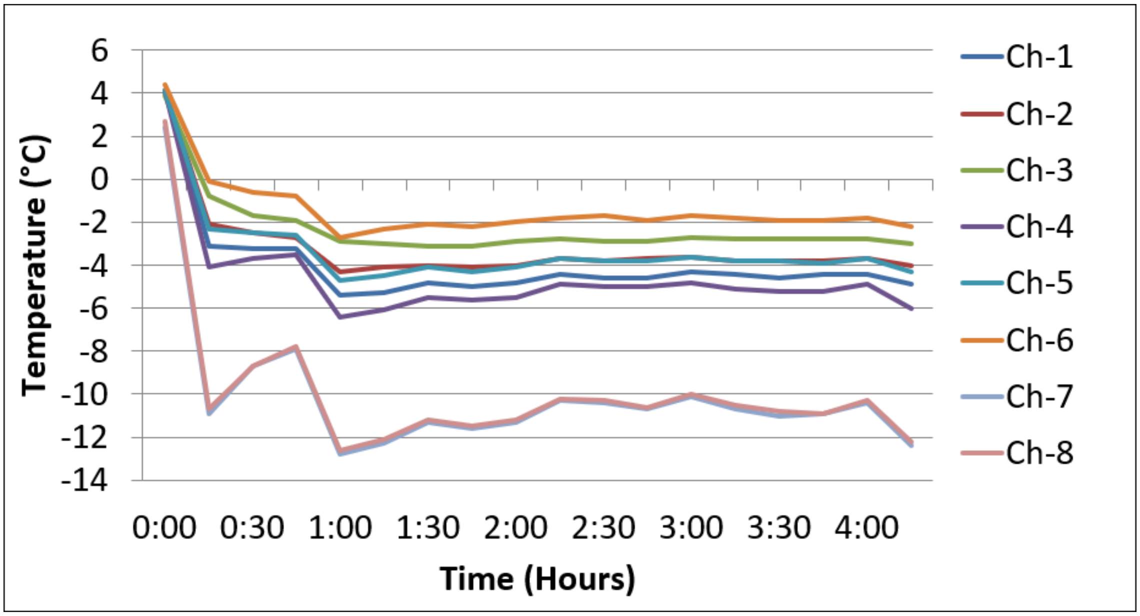

Figure 6-4(B): Thermocouple temperature vs Time

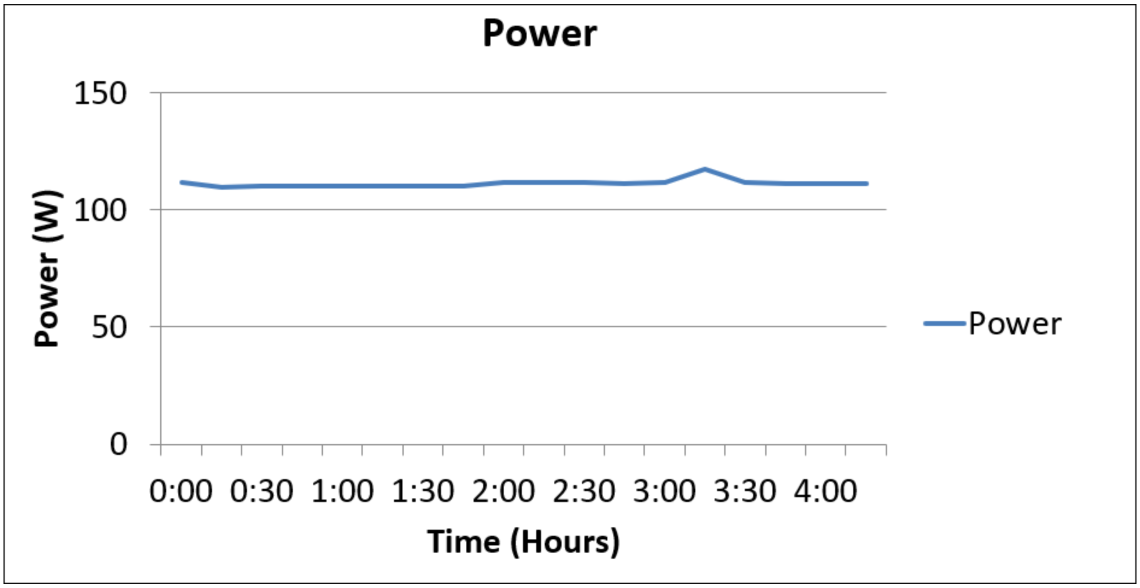

Figure 6-4(C): Power vs Time

At -10°C the parameters registered in every 15 minutes. Figures 6-4 (A) it can be inferred that average temperatures of core 0, core 1, core 2, and core 3 is around 27°C, 26°C, 25°C and 23°C respectively. Figure 6-4(B) shows the temperatures of thermocouples with respect to time. The temperature difference between inlet and outlet of the heat exchanger temperate is around2°C which remain constant after 45 minutes constant throughout the experiments. At -10°C, temperature of all the thermocouples was below 0°C. Figure 6-4(C) shows the power of the server with respect to time. The average power consumed by the server is around 109.8 W approximately.

At -20°C temperature

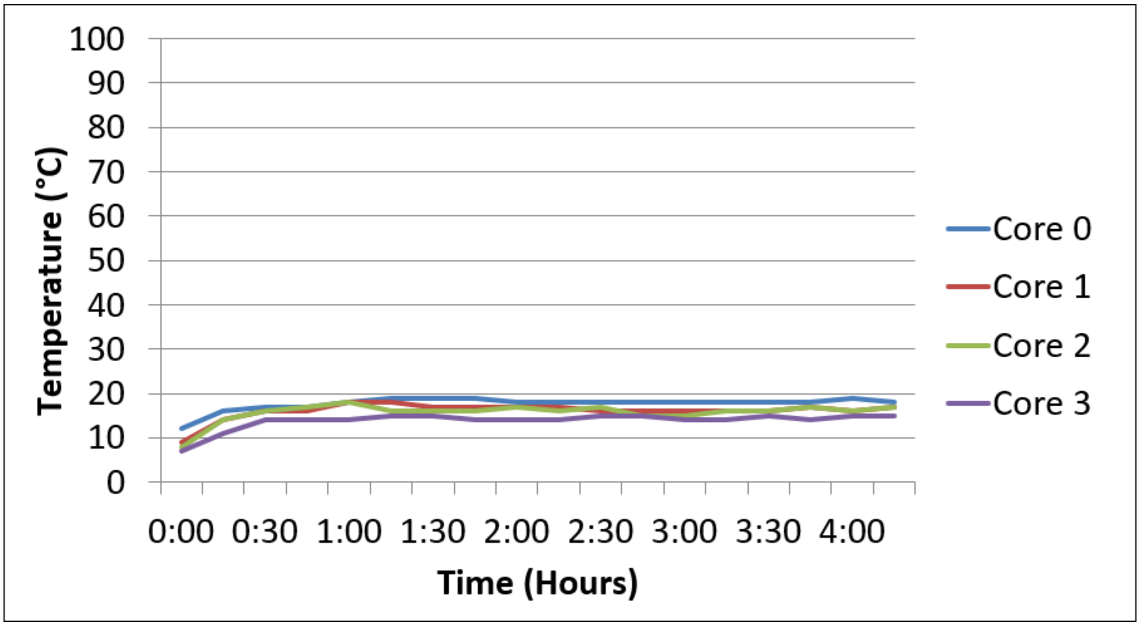

Figure 6-5(A): Core Temperature vs Time

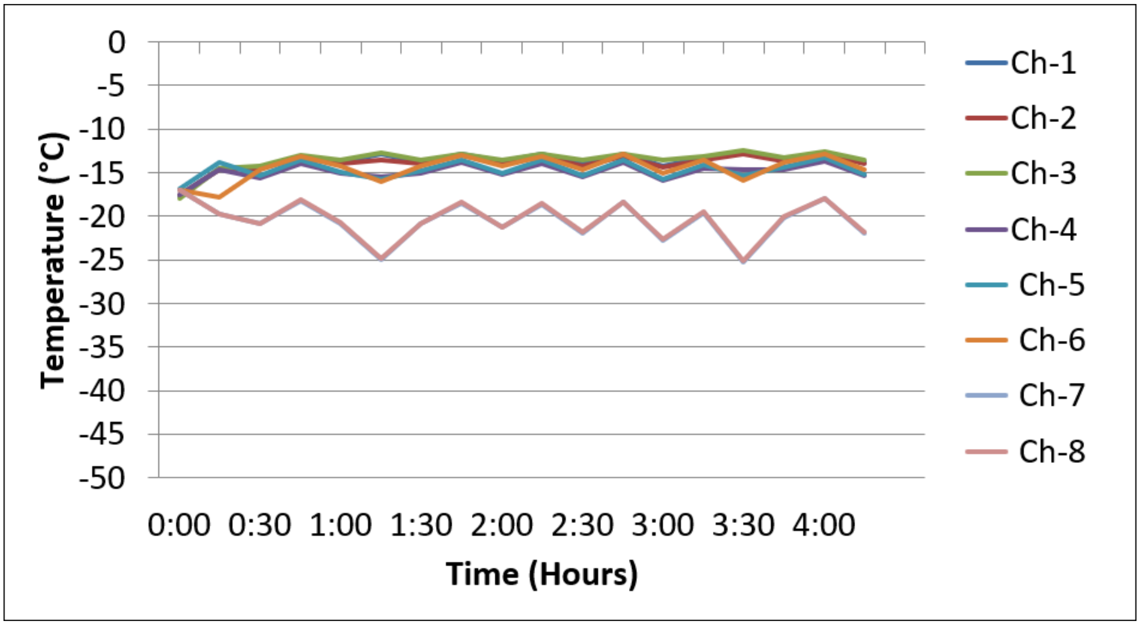

Figure 6-5(B): Thermocouple temperature vs Time

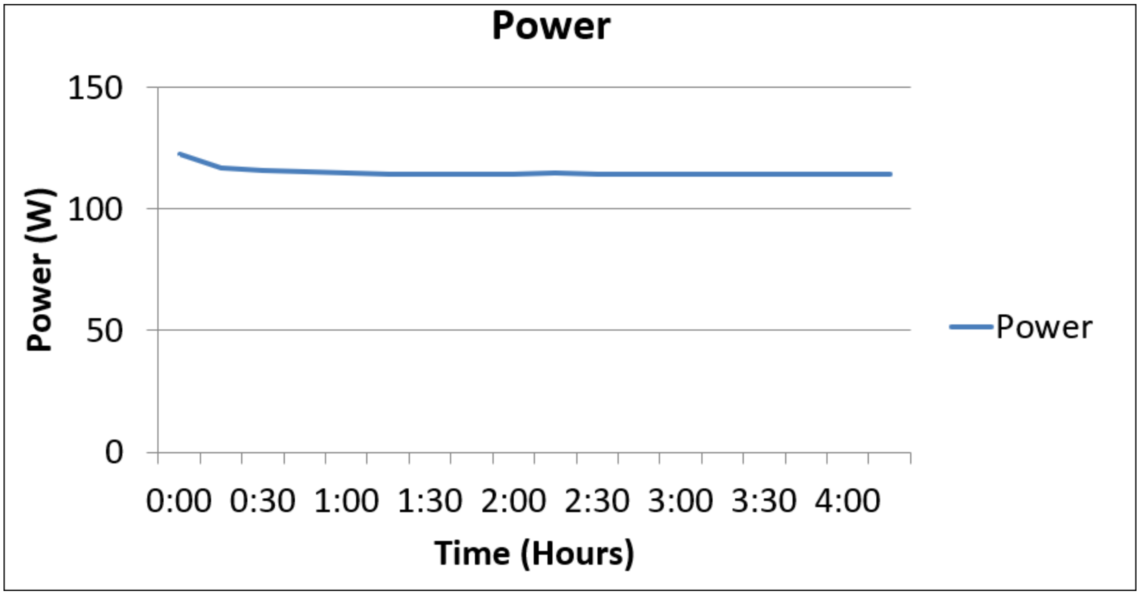

Figure 6-5(C): Power vs Time

From Figures 6-5 (A) it can be inferred that all core temperature of the server at -20°C are below 20°C which is way below the junction temperature. Average temperature of core 0, core 1, core 2, and core 3 is around 19°C, 17°C, 17°C and 16°C respectively. Figure 6-5(B) shows the temperature thermocouples with respect to time. The temperature difference between inlet and outlet of the heat exchanger temperate is less than 1°C. Figure 6-5(C) shows the power of the server with respect to time. The average power consumed by the server is around 114 W and is almost constant throughout the experiment after 30 minutes.

Chapter 7

Conclusion

From the experiment results, it can be inferred that the fully submerged server can be used in extreme weather conditions. As there is no direct contact with the surrounding environment the reliability of the server increased. At lower temperatures, the server was performing efficiently without compromising its reliability. From above results, hereby we can conclude that the server can withstand and can perform efficiently in extreme low temperature conditions. There was no leakage through any connectors and no abnormal noise from the server. The server is robust and can withstand the harsh environment as well. From all the experiments, it is evident that the performance of passive heat exchanger was very efficient. This server can be adapted in military and industrial applications as its performance was very efficient and showed very promising results in high temperatures. The waste heat from the server can be reclaimed thus the thermal efficiency can be increased further. Since the server is compact the size of racks can be reduce which will further reduce the initial capital cost. Also, it is a fan less server capable of cooling such a high configuration under such harsh conditions.

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