EXPERIMENTAL ANALYSIS FOR OPTIMIZATION OF THERMAL PERFORMANCE OF A SERVER IN SINGLE PHASE IMMERSION COOLING

By

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THESIS

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ABSTRACT

EXPERIMENTAL ANALYSIS FOR OPTIMIZATION OF THERMAL PERFORMANCE OF A SERVER IN SINGLE PHASE IMMERSION COOLING

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Liquid immersion cooling of servers in synthetic dielectric fluids is an emerging technology which offers significant cooling energy saving and increased power densities for data centers. A noteworthy advantage of using immersion cooling is high heat dissipation capacity which is roughly 1200 times greater than air. Other advantages of dielectric fluid immersion cooling include high rack density, better server performance, even temperature profile, reduction in noise. The enhanced thermal properties of oil lead to the considerable saving of both upfront and operating cost over traditional methods. In this study, a server is completely submerged in a synthetic dielectric fluid. Experiments were conducted to observe the effects of varying the volumetric flow rate and oil inlet temperature on thermal performance and power consumption of the server. Various parameters like total server power consumption, the temperature of all heat generating components like Central Processing Unit (CPU), Dual in Line Memory Module (DIMM), input/output hub (IOH) chip, Platform Controller Hub (PCH), Network Interface Controller (NIC) will be measured at steady state. Since this is an air-cooled server, the results obtained from the experiments will help in proposing better heat removal strategies like heat sink optimization, better ducting and server architecture. Assessment will also be made on the effect of thermal shadowing caused by the two CPUs on the nearby components like DIMMs and PCH.

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Chapter 1

1.1 Introduction

A data center is a facility composed of networked computers and storage that businesses or other organizations use to organize, process, store and disseminate large amounts of data. A business typically relies heavily upon the applications, services and data contained within a data center, making it a focal point and critical asset for everyday operations [1]. Due to rapid increase in business and industries, there is increase in demands of processing and storage of data. Increasing demands of processing and storage of data, causes corresponding increase in power density of servers. 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.

1.2 Data Center Power Consumption

In United States, data centers consumed about 70 billion kilowatt-hours of electricity in 2014, representing 2 percent of the country’s total energy consumption. This is a 4 percent increase in total data center energy consumption from 2010 to 2014, and a huge change from the preceding five years, during which total US data center energy consumption grew by 24 percent, and an even bigger change from the first half of last decade, when their energy consumption grew nearly 90 percent.

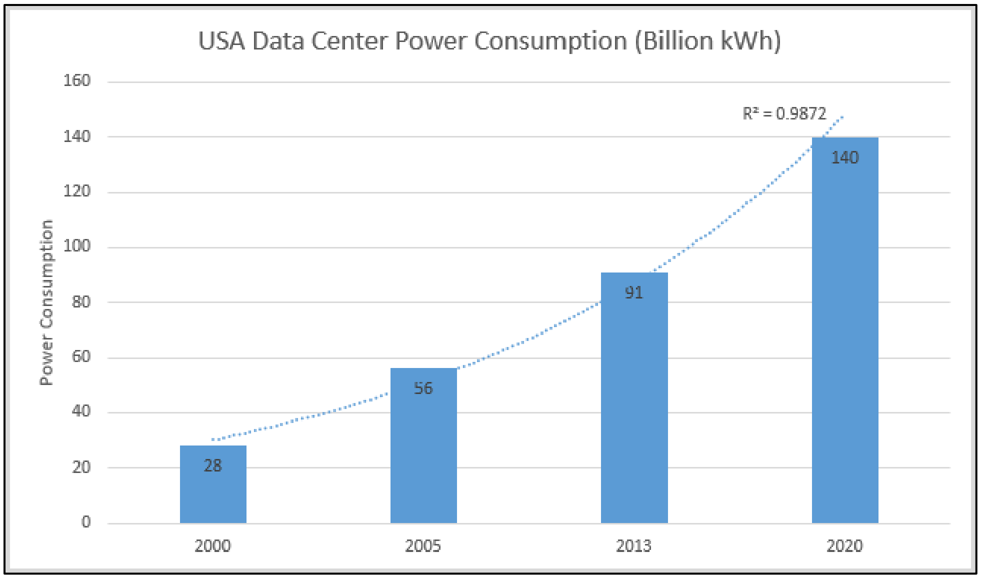


Figure 1: USA Data Center Power Consumption [2]

The energy consumed by a data center can be broadly categorized into two parts [3]: energy use by IT equipment (e.g., servers, networks, storage, etc.) and usage by infrastructure facilities (e.g., cooling and power conditioning systems). The amount of energy consumed by these two components depend on the design of the data center and the efficiency of the equipment.

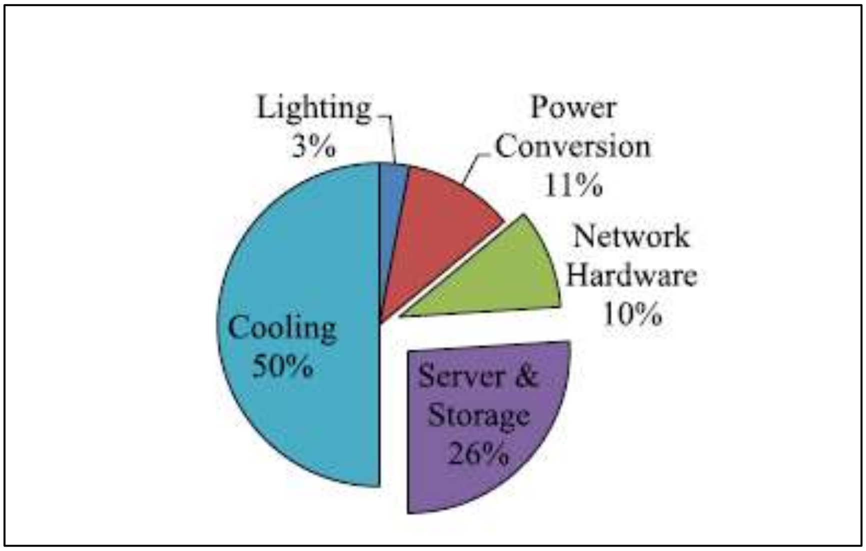


Figure 2: A breakdown of energy consumption by different components of a data center [5]

For example, according to the statistics published by the Infotech group (see Fig. 2), the biggest energy consumer in a typical data center is the cooling infrastructure (50%) [4], [5], while servers and storage devices (26%) rank second in the energy consumption hierarchy.

To find effectiveness of a data center, a metric called power usage effectiveness, were introduced by Green Grid. Using PUE as a measurement helps understand how efficient a datacenter is and compare with similar datacenters in similar locations or with similar environmental conditions, to determine whether there are areas that could be improved by adopting new technology and by applying best practices and architectural choices [6].

$$PUE = \frac{Total\ Power\ Consumed\ by\ Data\ Center}{Total\ Power\ Consumed\ by\ IT\ equipment}$$

PUE	**Level of Efficiency**
3.0	Very Inefficient
2.5	Inefficient
2.0	Average
1.5	Efficient
1.2	Very Efficient

Table 1: PUE and Level of Efficiency [6]

1.3 Data Center Cooling Methods

The most common techniques used for cooling of data centers are

1. Air cooled servers

2. Liquid cooled servers

1.3.1 Air Cooled Servers

The purpose of cooling in a data center is to remove the heat dissipated by the servers. Air cooling is one of the most widely used cooling techniques. In this technique, the heat generated is removed by the forced convection of air over the heat transfer component called heat sink. Fans are provided to manage the airflow from inlet to outlet and are controlled according to the change in the temperature of server components.

The first method within air-based cooling is the ‘‘Cold Aisle/Hot Aisle’’ system. In this method simply cold air is separated hot air. It is done by facing cold sides of the server cabinets away from hot sides. This produces a cooling convection system where the server cabinets can cool themselves. This convection system is not always efficient, so the data center managers need to push more cold air into rooms [7].

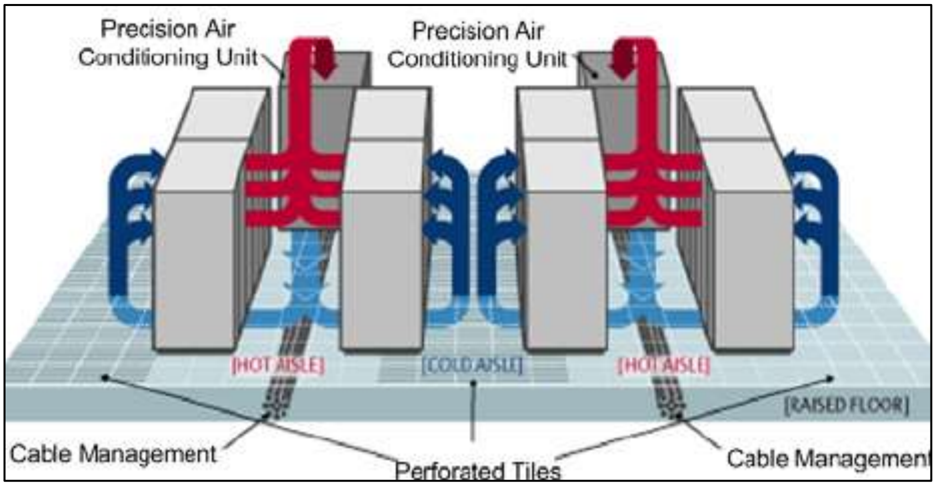


Figure 3: Cold Aisle/Hot Aisle System

Another air-based system is called “cold or hot air containment.” This method advances the cold aisle/hot aisle method by actually containing the servers, so the hot and cold air don’t mix. Driving the air directly from the CRAC unit helps achieve this method. Although this system works satisfactory, this method still faces the problems with hot spots within the server [7].

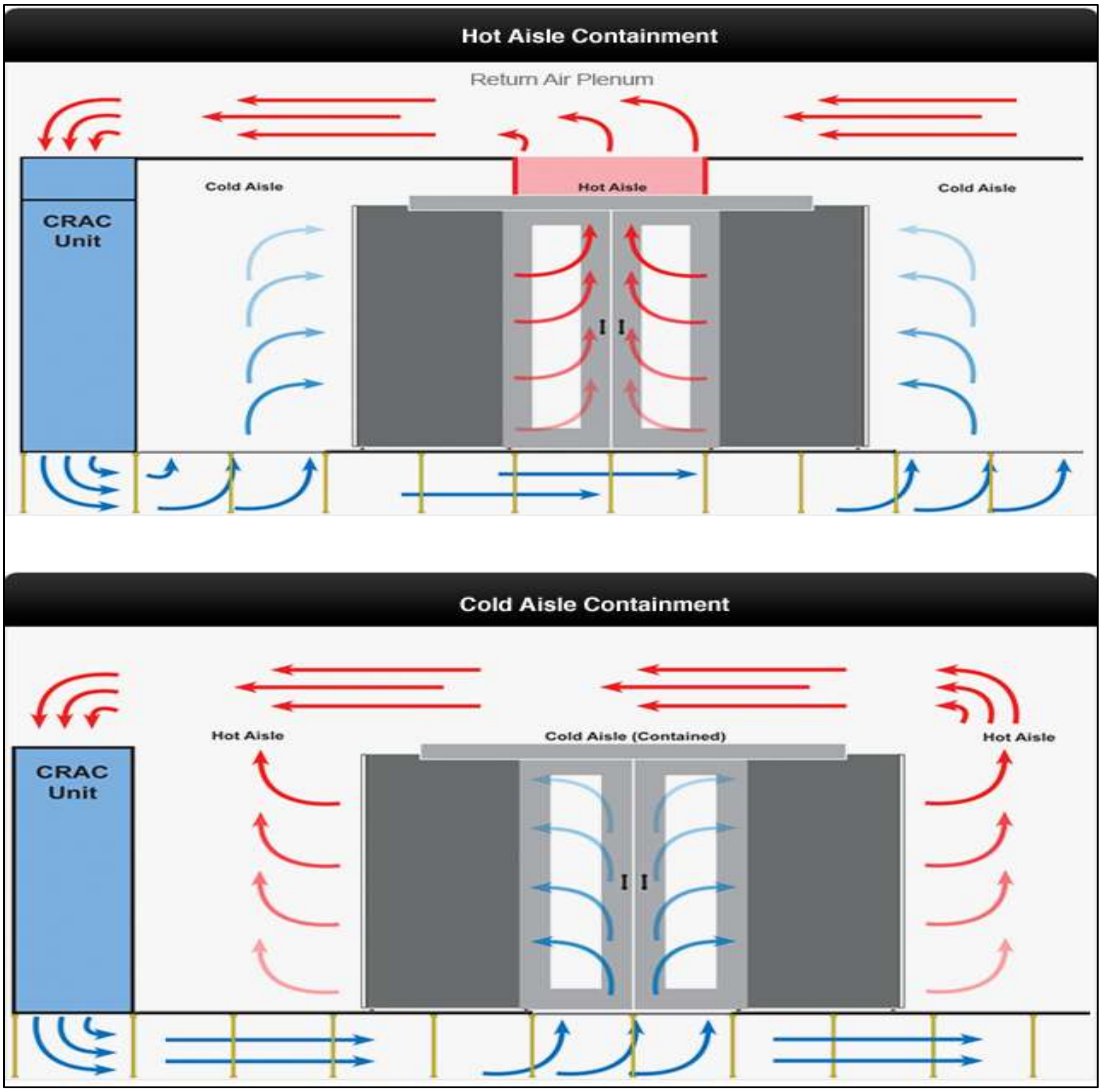


Figure 4: Cold and Hot air containment.

1.3.2 Liquid Cooled Servers

Even though air cooling is widely used technique, it has limitation when it comes to high power computing. Due to comparatively low conductivity of air than oil, we need to provide bigger fins and improved ducting to dissipate more heat. The ducting system, the fans and the heat sinks occupy large space in server. To compensate these limitations, industries looking towards liquid cooling methods as a better option.

The liquid cooling methods divided into two types

1. Water Cooled Servers
2. Oil Cooled Servers

1.3.2.1 Water Cooled Servers

Water is good conductor of electricity, so we can not use it to cool electronic components directly. So we use passive heat transfer device called cold plate. Bottom of a cold plate is made up of a copper, which is placed on heat producing components. Heat is transferred to cold plate from heat generating componenets through a heat spreader. Water flows over the cold plate and heat is transferred to cold plate by conduction. And then cold plate to water using covection. Now this heated water is sent to chillers to cool down and recycled. The advntage of using cold plate are compact design of server and less server power requirement.

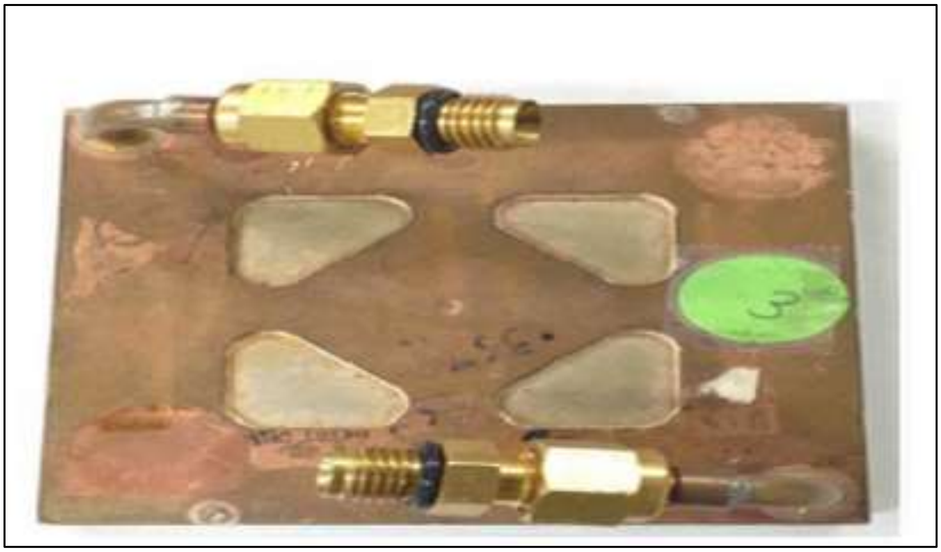


Figure 5: Top view of the Cold Plate

1.3.2.2 Oil Cooled Servers

In this method, servers are cooled by submerging into thermally conductive dielectric oil. Heat transfer take place in between servers and dielectric oil. The flow is measured by a flowmeter. Most frequently used cooling liquids are white mineral oil, electric cooling liquids and non-purpose oils. Oil immersion cooling can be classified as:

A. Single Phase Immersion Cooling

B. Two Phase Immersion Cooling

1.3.2.2a Single Phase Immersion Cooling

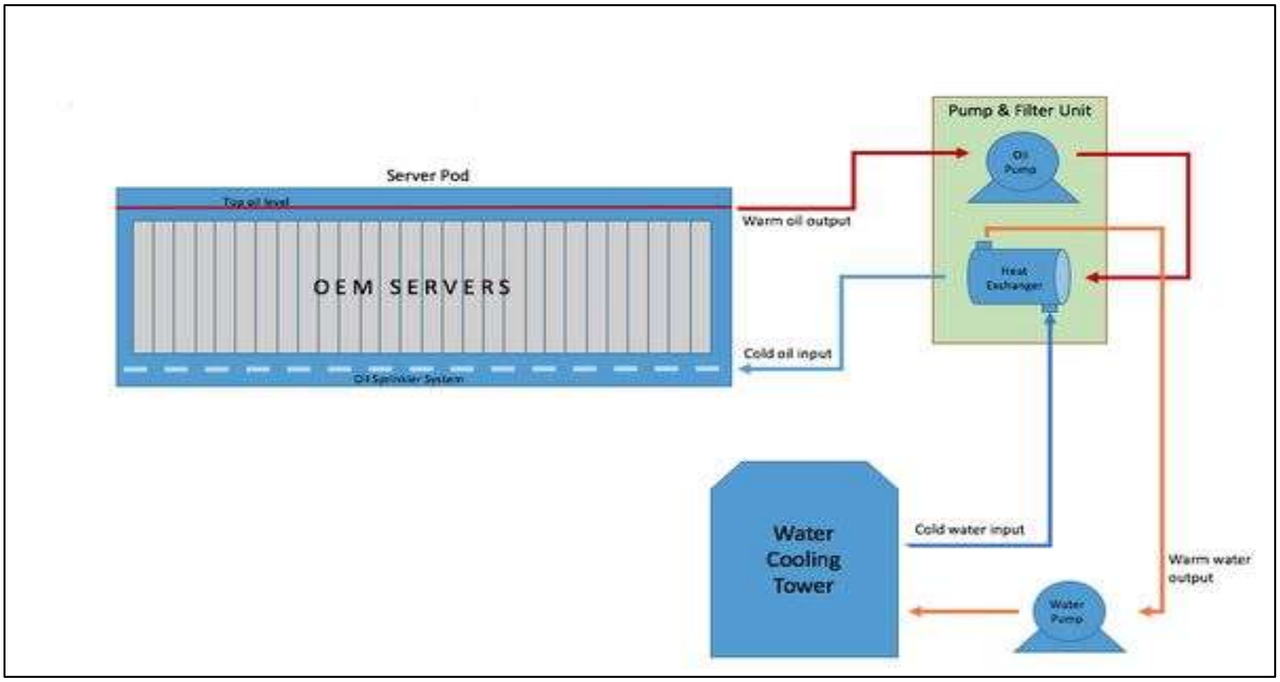


Figure 6: Schematic Diagram for Single-phase Immersion Cooling

In single phase immersion cooling, dielectric oil remains in liquid phase throughout of its working. Dielectric thermally conductive oil is circulated throughout the system with low pressure. While working heat is transferred to fluid through convection then this fluid is passes through heat exchanger to cool down. Cooling tower is used to cool down the hot water from heat exchanger.

1.3.2.2b Two Phase Immersion Cooling

In this method, throughout its working oil changes its physical state from liquid to gas and then liquid. In this method servers are submerged into the of thermally conductive dielectric oil bath. Dielectric fluid used in this method has low boiling point, hence when heat is transferred from server to fluid, it starts boiling and converts into gaseous form. This gaseous formed oil moved to the condenser coil where it turned into liquid form and moved back to the oil bath. It requires to be operated into the semi open bath to avoid the loss of liquid while changing its phase.

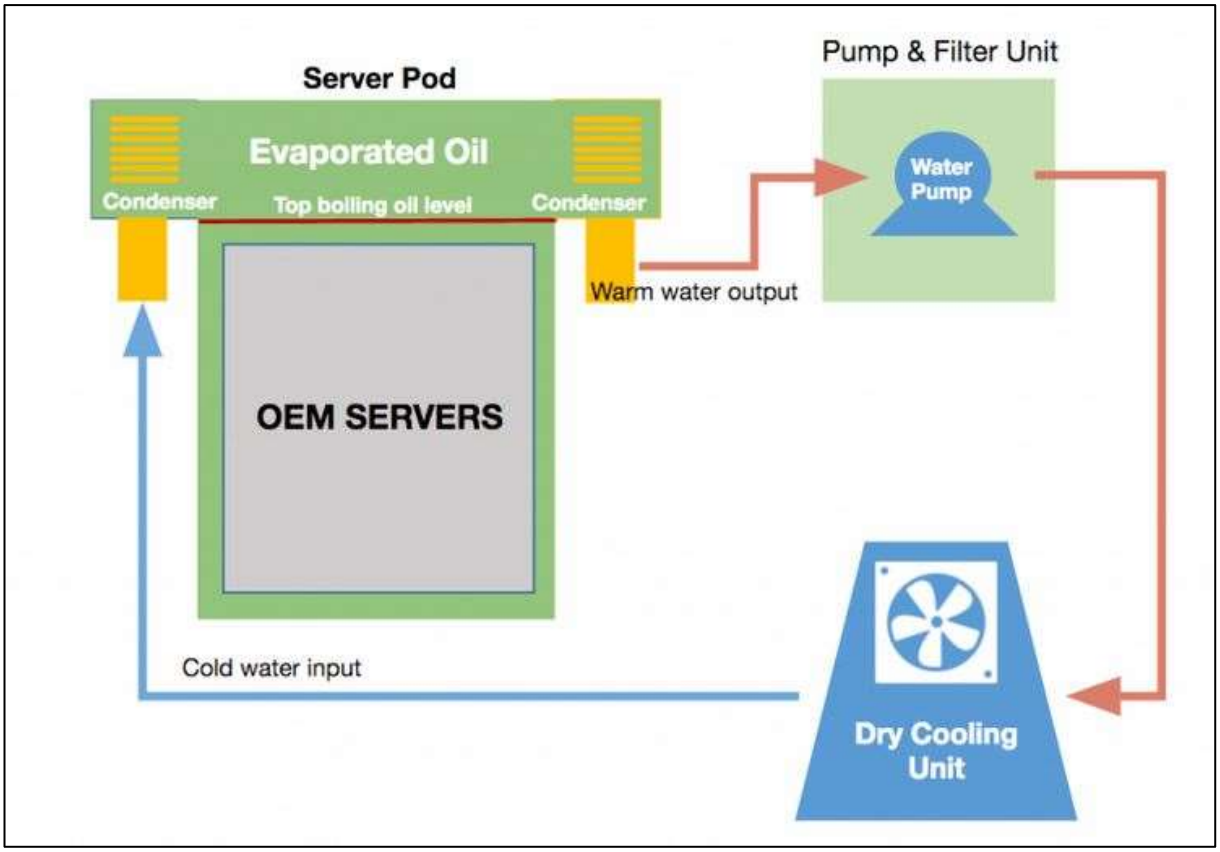


Figure 7: Schematic Diagram for Two-phase Immersion Cooling

Following table explains different fluids and their physical properties.

Type of Fluid	Heat Capacity (KJ/Kg K)	Density (Kg/m3)	Kinematic viscosity (X 10−6 m2/s)	Heat Conductivity (W/m K)
Air	1.01	1.225	0.016	0.02
Water	4.19	1000	0.66	0.58
White Mineral Oil	1.67	849.3	16.02	0.13
Synthetic fluid (EC-100)	2.165	803.78	13.22	0.1378

Table 2: Fluids and Properties

Chapter 2

Immersion Cooling Experimentation

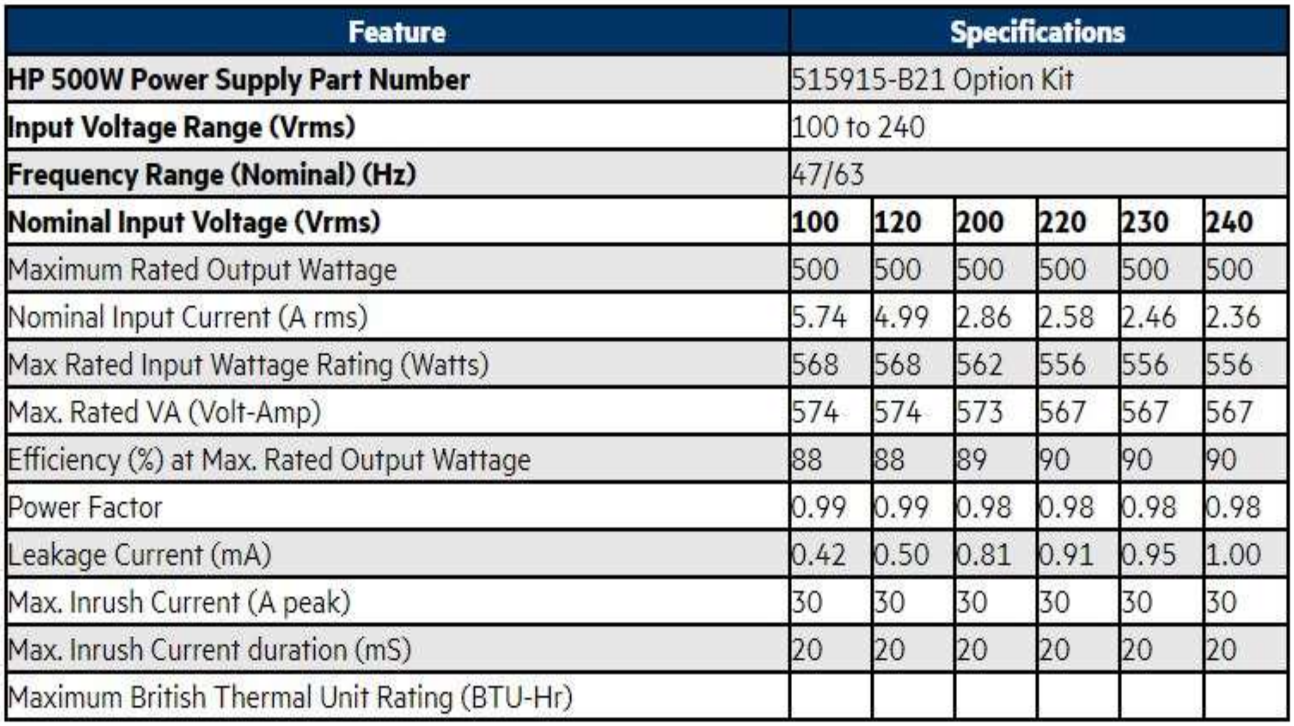
Submerging servers and IT equipment completely in a dielectric medium for cooling provides substantial energy savings as it accommodates heavy energy loads and density as its heat capacity by volume is 1120-1400 times greater than air [8], [9], [10]. This helps to keep the temperature constant even if there are any changes in server workload which mean that the server is in a good isothermal environment. Single-phase oil-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 turns maintains the server hygiene [11]. In regular air-cooling with airside economization, some dust and dirt particles enter the facility. These dirt and dust particles get accumulated inside the chassis with the computers and cause mechanical failure [12], [13], [14]. Immersion cooling also minimizes and eliminates many common operational issues like solder joint failures, oxidation or corrosion of electrical contacts. Other advantages are no moving parts like fans, no sensitivity to humidity or any temperature condition. Operating expense of this equipment is exceptionally low [9].

The primary goal of this experiments is to establish general operating conditions, in terms of volumetric flow rate per server and oil inlet temperature, which can be expected for the safe operation of servers in an oil immersion cooling configuration. For this work, an HP ProLiant DL 160 G6 server, Figure 8, was experimentally tested and characterized. Initially, baseline operating conditions and components temperatures were established by operating the server in the standard air-cooled configuration with internal server fans. Next, the server was taken out from its standard chassis and placed in a sterilite container and submerged in white mineral oil. Although the complete experimental set-up is not entirely reflective of an actual data center facility implementation in fully built-out conditions, the data does provide strong evidence to support continued research in this area.

2.1 Server Specification

The Server will be studied in this experiment is HP ProLiant DL 160 G6 server. It consists of two Intel Xeon 5650 six core central processing unit on motherboard with 18 Dual in Line Memory Module (DIMM) slots constituting 1U server. The motherboard carries two CPU which has 95 W thermal design power (TDP). Each DIMM on the motherboard slot can carry DDR3 RAMs up to 16 GB. It houses three DDR3 RDIMMs per channel per CPU and hold up to 9 RDIMMs per CPU. The motherboard also consists of Intel 5250 Input-output Hub chipset. They operate on 12.5 VDC supply delivered by power supply unit. The motherboard also powers four hard drives using traditional 4-pin floppy connector. This server contains 6 Delta 40mm x 40mm x 56mm fans for the purpose of cooling on the front end of the server, just after the hard drives. The Fan speed is controlled by the motherboard algorithm which is based on CPU core temperatures.

The power supply unit is standard 500W with power correction factor, which is at the rear end of the server. It is provided with separate fan for cooling. The fan used in power supply unit is DELTA fan of size 40mm x 40mm x 29mm. The specifications of PSU are as follows,



Feature	**Specifications**					
HP 500W Power Supply Part Number	515915-B21 Option Kit					
Input Voltage Range (Vrms)	100 to 240					
Frequency Range (Nominal) (Hz)	47/63					
Nominal Input Voltage (Vrms)	**100**	**120**	**200**	**220**	**230**	**240**
Maximum Rated Output Wattage	500	500	500	500	500	500
Nominal Input Current (A rms)	5.74	4.99	2.86	2.58	2.46	2.36
Max Rated Input Wattage Rating (Watts)	568	568	562	556	556	556
Max. Rated VA (Volt-Amp)	574	574	573	567	567	567
Efficiency (%) at Max. Rated Output Wattage	88	88	89	90	90	90
Power Factor	0.99	0.99	0.98	0.98	0.98	0.98
Leakage Current (mA)	0.42	0.50	0.81	0.91	0.95	1.00
Max. Inrush Current (A peak)	30	30	30	30	30	30
Max. Inrush Current duration (mS)	20	20	20	20	20	20
Maximum British Thermal Unit Rating (BTU-Hr)						

Figure 8: Standard 500-Watt power supply unit specification [15]

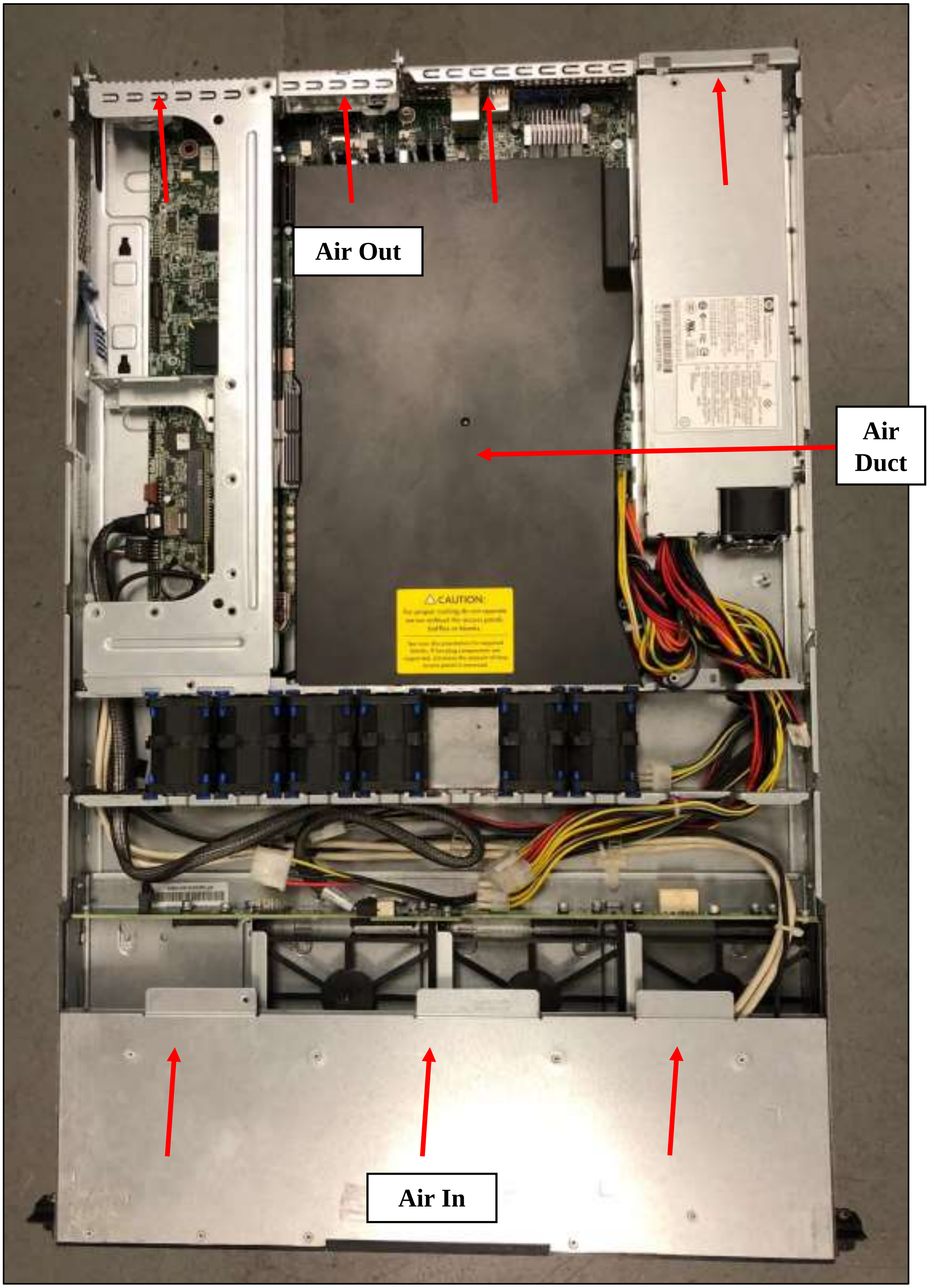


Figure 9: Top View of Server

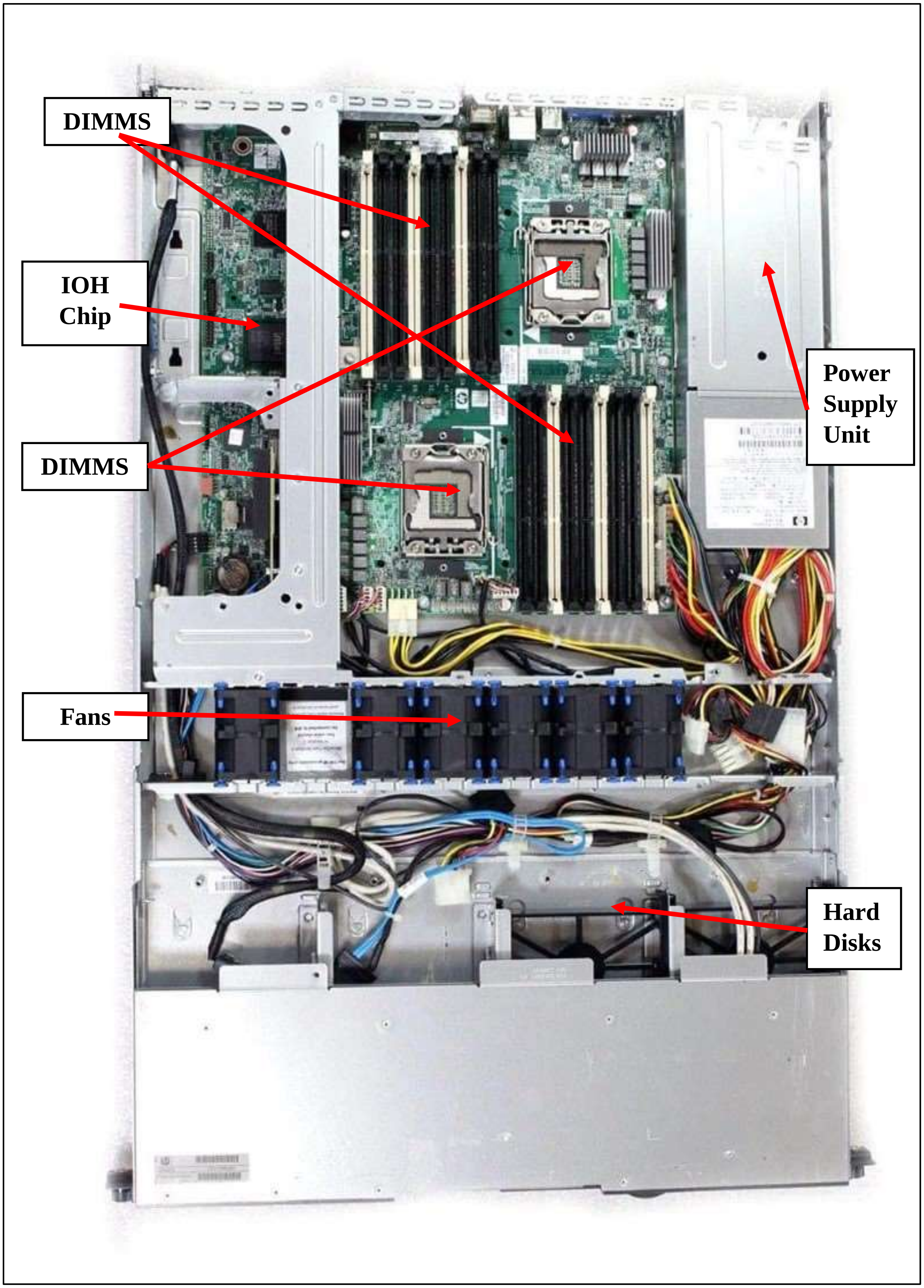


Figure 10: Top View of Server Without Air Duct

2.2 Test Setup

This research work gives the detail idea about oil immersion cooling of a server with experimental results. Whole experiment was conducted in two steps.

Step 1: Testing of HP ProLiant DL 160 G6 server with pre-installed fans on it. So basically, experiment will be conducted for air cooling which will be considered as a base test. Oil immersion experiment results will be compared to these air-cooling results.

Step 2: Testing of the server for oil immersion cooling. In this step, server will be prepared for oil immersion cooling with new modification in server. It involves preparation of experimental setup, server modification and conducting the oil immersion experiment.

Results of air cooling and oil cooling will be compared. More experiments will be performed on oil cooling with varying flow rate and inlet temperature conditions.

2.3 Instrument Setup

Linux operating system is used in the server. To execute, monitor and record the data, different scripts are used. Different equipment was used during the experimentation.

2.3.1 Test Case Parameters

In this experiment, server is tested with % CPU utilization which starts from 25% to 99% with the interval of 25 along with % memory utilization. For comparison study fluid inlet temperature kept 25°C. For oil experiments, experiment is performed with different inlet temperature as well as different flow rate.

2.3.2 Temperature measurement instruments

- Omega thermocouples

Temperature of all major heat generating components is measured by omega thermocouples. So, for that, T-type, copper insulated thermocouple of Omega Engineering is used. It has range up to 480°C. In testing, thermocouples are attached to major heat generating components like CPU’s, VRDs, DIMMS, I/O chip, PCH (power controller hub). Thermocouples with the connection can be seen in the figure 10.

Figure 11: Thermocouple Connections in the Server

- USB data logger

These data loggers are used to measure temperature at inlet and outlet of the server and it also gives idea of relative humidity and ambient condition in the test. It is places at the front and rear of the server.

- Agilent E3640A data logger

All the thermocouple that connected to major heat generating components in the server, are connected to different ports in multiplexer. This multiplexer gets fixed in the Agilent E3460A data logger. Multiplexer and data logger are shown in figure 12 and 13. By using pre-installed Agilent data logging software in the system, we can monitor the surface temperature of all the parts at a specific interval of time continuously. All temperature data can be saved automatically.

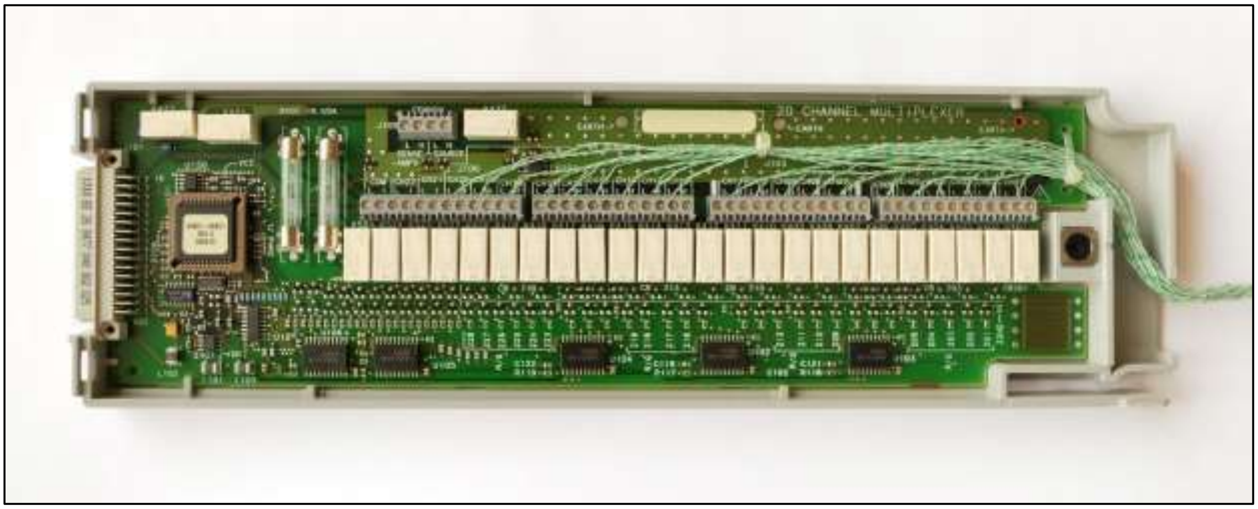


Figure 12: Multiplexer

Figure 13: Agilent E3640A Data Logger

2.3.3 Power Measurement

- ‘P3 P4400 Kill A Watt’ Power Meter

To measure the total power consumption of the server ‘P3 P4400 Kill A Watt’ is used, as shown in the figure 14. It supports single phase-three phase connection and can measure up to 500W. The data is logged and recorded.

Figure 14: ‘P3 P4400 Kill A Watt’ Power Meter

2.3.4 Di-electric Coolant

As in oil immersion cooling. Oil works as a coolant and the server will be kept inside the oil bath, so it is important to use di-electric oil. The main reason behind is if oil is electrically conducive and if it touches the electrically powered components of motherboard then it would cause short circuit. Figure 15 shows the big container of a white mineral oil of technical grade.

Figure 15: White Mineral Oil

2.3.5 Hydraulic Pump

For doing the experiments by the principle of forced convection some external forces required to move the di-electric viscous fluid over the test server. Fluid can be circulated by any hydraulic pump. For this experiment centrifugal hydraulic pump is used. But before using any pump some parameters need to be consider like flow meter, suction head, mass density, viscosity of the mineral oil. After doing some hand calculations, it decided to use Laing D5-38/720B Vario DC Circulator Pump from manufacturer named Laing Thermotech, as shown in figure 16. It's a compact hydraulic pump with variable speed control which gives us the maximum 4 GPM flow rate. Technical specification and calculations are given below,

1) Nominal voltage: 25 VDC
2) Maximum head: 14 Ft
3) Maximum flow rate: 4 GPM
4) Temperature range: up to 230 Degree F
5) Maximum pressure: 150 psi
6) Maximum power: 35 watts

2.3.5.1 Pump Power Calculation

Equation: $Ph = q \rho g h / (3.6 * 10^6)$ (Where Ph = hydraulic power in KW)

(Assume max flow rate Q= 0.33 GPM, Total head required is 0.5 ft, Mass density = 855 KG/m^3 and Viscosity = 70 SUS [*From technical data sheet of oil] putting in this equation Pump power required is 3 watts)

Figure 16 : Laing D5-38/720B Vario DC Circulator Pump

2.3.6 Heat Exchanger

During experimentation oil gets warmer due to the heat generation of components, so cooling of oil is necessary to assure better cooling. So, we need to use a heat exchanger in the experiments. It is liquid to air heat exchanger. Different parameters such as temperature difference required, total amount of heat required and heat capacity of mineral oil. After some hand calculations it is decided to use MCRx20-QP from SWIFTECH. This is low noise, heavy duty radiator which has 3 fans with 120 mm diameter for throwing air to fins, as shown in figure 17.

2.3.6.1 Heat Exchanger Calculation

Equation: $Q = m \cdot cp \cdot \Delta T$ Where (Q= Heat removal required)

Let say we want maximum temperature difference of around 20°C and heat capacity of mineral oil is 1.67 KJ/kg K and Q= 300 watts, consider as maximum server power consumption so we want to remove this much amount of heat from radiator. After using all this data in equation, we got mass flow rate of 0.33 GPM which is valid as after compared with hydraulic pump calculation

Figure 17: MCRx20-QP Pump

2.3.7 Flow Meter

Flow meter is one of the essential equipment used in this experiment, as flow rate of di-electric oil is get affected by temperature variation. So, for better performance, we need to keep sense of the oil flow rate throughout the experimentation. We cannot use flow meter that are used for water as water and oil has different viscosities. For this experiment we are using FPD-2003 from OMEGA. It is specially made for viscous fluids such as oil and works on the principal of positive displacement, as shown in figure 18. Specification are given as follows,

1) Accuracy: ±0.5%
2) Analog output: 4 to 20 mA
3) Supply voltage: +10 to 28 VDC
4) Maximum Liquid temperature: 204°C (400°F)
5) Repeatability: ±0.1%
6) Supply frequency: 0.25 Hz to 5 KHz

Figure 18: FPD-2003 Flow Meter

2.3.8 Software Used

- Lookbusy:

It is a simple application for generating synthetic load on a Linux system. It can generate fixed, predictable loads on CPUs, keep chosen amounts of memory active, and generate disk traffic in any amounts you need [18]. For this study load of 25%, 50%, 75%, and 99% were chosen.

Command to initiate the program is as follows. According the following command CPU processors will be stressed to 25% with memory stressing of 20 GB.

Command: `lookbusy -c25 -m200000000`

- Lm_sensors:

Lm_sensors 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. The temperature readings are very accurate as the software is collecting 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 an external circuit located to report temperature; all core temperature values are stored in the processor. Lm_sensors software can access and provide a real-time reading. This method eliminates any kind of inaccuracies [19] [12].

Command to initiate the program is as follows. According the following command, we will see actual core temperature of CPU processors at real time. And using a script we can record the data at a required interval of time.

Command: `watch sensors`

Chapter 3

Experimental Setup and Procedures

3.1 Air Cooling

In this experiment HP DL160 G6 server of 1U form factor is tested with conventional air-cooling method. For this experiment, we don’t need to do any modification in server, so server will be running with all six fans. Server is connected to a local desktop computer with a LAN connector and then a script is deploying command codes. The script contains all the information about the test such as total time of the test, all the commands of the all the software needed to use, pre-determined cooling period with all % loading conditions. Entire test run period was around 24 hours. Each test run for 7 hours and then this test repeated for 3 times. Each test ran for 30 minutes including pre-cycle and post-cycle period. The reason for pre-cycle and post-cycle is cool down the server and reach at initial condition.

The Lookbusy and Lm_sensors software used with a script. It contains commands to record the data at 5 second of interval of time, along with the different percentage utilization of CPU ranging from 25% to 99% and memory. The total RAM used in this experiment is 98 GB. Simultaneously systems monitor the core temperatures and records it at interval of 5 seconds. The server has in built sensors to measure and record the temperature data of major heat generating parts. A separate script is deployed to record these data and compare it to the actual thermocouple data.

The server is attached with 18 Omega thermocouples to measure the surface temperature of major heat generating components. Agilent E3640A data logger keeps the record of the surface temperature data throughout the test for a interval of 5 seconds. Ambient temperature and humidity is recorded by USB data loggers which are placed in front of the server.

‘P3 P4400 Kill A Watt’ power meter shows the actual power consumption of the server which is recorded at the interval of 10 seconds.

Both CPUs are attached to the two extruded heat sink which are designed for this server and thermal interface material of Shin-Etsu X-23-7783D is used in between the heat sink and heat spreader to reduce the air gap between them and to improvise the thermal performance of heat sink. In each test total power consumption, surface temperature, % CPU, % memory is measured and recorded and average of all three is calculated and plotted. And this data is considered as a base line test for other tests.

Figure 19: Air-Cooling Experiment Setup

A baseline for comparison is established, by testing the server in the standard air-cooled configuration as shown in Figure 19. The server motherboard consists of two CPUs each with a rated thermal design power (TDP) of 95W. These components are the primary heat sources in the system and are cooled by two extruded aluminum heat sinks. The key features which enable efficient air cooling are six fans, an air duct that directs airflow over the temperature critical components (i.e. processors and memory or RAM chips), and minimal system resistance. The internal server fans are controlled by a BIOS fan speed control. This fan speed control is done by using pulse width modulation (PWM) to achieve a target CPU die temperature. In this manner, the fan speeds and die temperatures typically oscillate with some over- and undershoot of a targeted value [10]. Over the duration of the test cycle, an average value is reported. The server draws the air from the ambient laboratory environment for cooling. A synthetic computing workload is applied, and internal monitoring tools are used for data collection.

3.2 Single Phase Oil Immersion Cooling

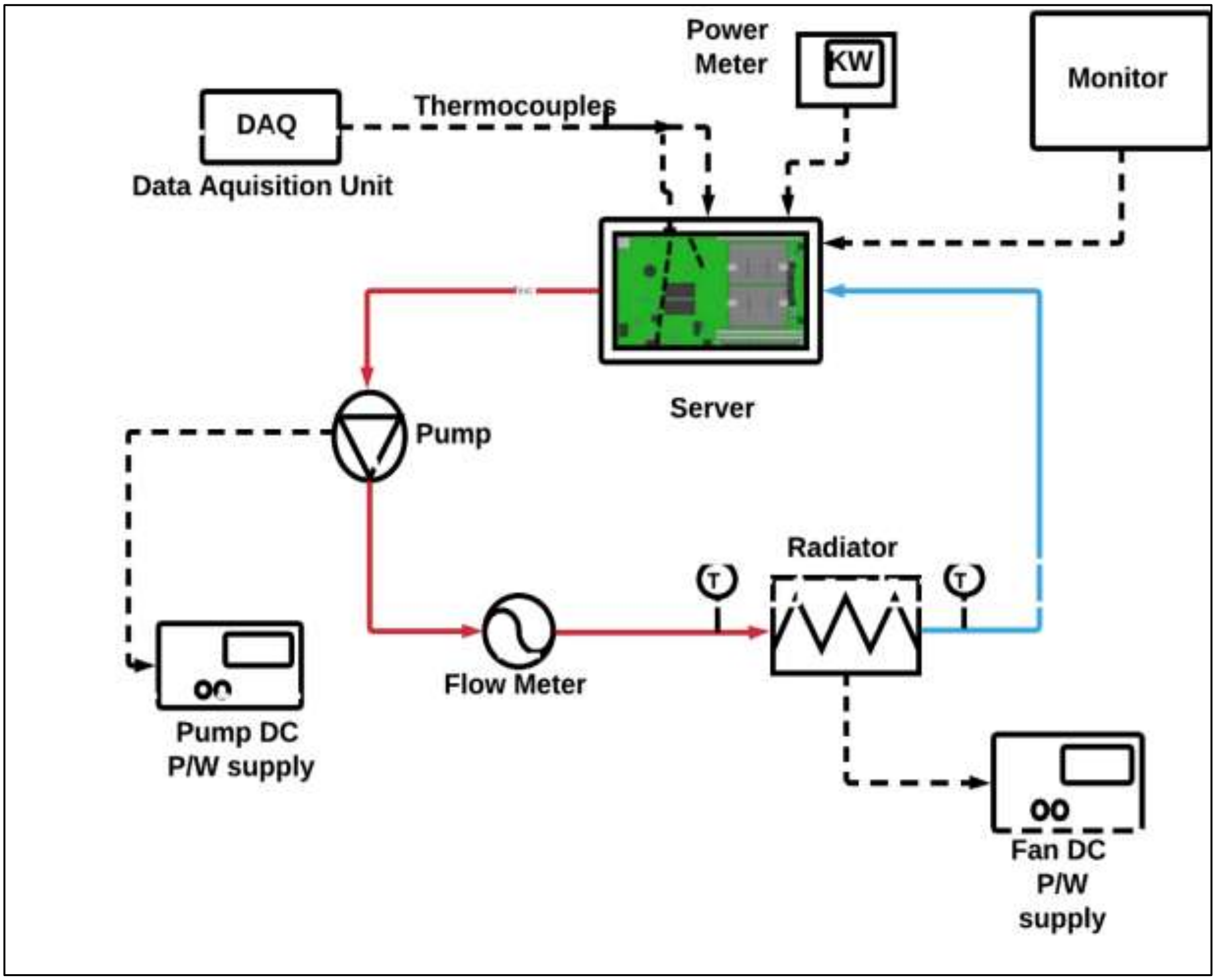


Figure 20: Schematic of Test Setup and Data Collection Equipment

The oil immersion test setup used in the experiment consists of the following major components as shown in Figure 20 and 21 and discussed below.

A single HP ProLiant DL 160 G6 server motherboard is placed horizontally in an immersion tank. Some modifications are made to the server and the container, to enable testing in the container available and to enable operation in oil. The server motherboard is removed from the metal chassis to reduce its size to fit in the test container available. The air duct is kept for the oil experiments, as it is helpful into directing oil flow over the CPU heat sinks. Internal server fans of the server were removed from their respective locations and kept outside the oil container. The hard disk drive (HDD), incapable of operating when submerged, is placed outside the tank. From here, the HDD is cooled by natural convection only and represents a small portion of the total IT heat load that is not removed by oil (approximately 3.5%) [10]. The thermal interface materials (TIM) applied on the CPUs are removed and replaced with indium TIM foil.

The motherboard of the server of size 33 x 30in is placed in sterilite container of size 24 x 16 x 7in. Two 0.5in diameter ports are tapped into the container, one serving as an inlet to the tank and other as an outlet.

Figure 21: Experimental Setup with all Components

The inlet and outlet ports are strategically placed with ball valves are directly in-line with the center of the base of the CPU heat sinks. Due to which the highest velocity flow is directed straight across the CPU heat sinks. A small centrifugal pump with 8-25 V located on the outlet side of the tank circulates fluid through the system. A DC power supply delivers a constant voltage signal to the pump. The pump has speed controlling settings using which flow rate of the system can be controlled.

Heat is rejected from the oil to the environment via radiator constructed of two-pass. The Radiator is equipped with four 120mm 12V DC brushless motor fans. A DC power supply delivers a constant voltage signal to the fans. A function generator is used to control the speed of the fans to achieve the desired inlet temperature to the tank containing the server. An Omega FPD-2003 in-line flow meter is used to record the volumetric flow rate of the oil. The flow meter has a scale accuracy of ±5%. The meter is rated for oils with a specific gravity of 0.873. This leads to a correction factor of 1.0% for the oil used in the current system. The flow meter is placed midway between the outlet and inlet sections of the immersion tank.

The oil inlet temperature of the tank is measured using T-type thermocouples placed at the exit of the radiator. These thermocouples have an accuracy of ±0.5°C and are used to maintain the tank inlet temperature to within ±0.5°C of the desired value. Similar thermocouples are placed at the inlet of the radiator to measure the temperature difference of the oil across the server.

The material specifications of the technical grade white mineral oil are given in Table 1. In total, 11.4L (3gal) of oil is used to fill the system (tank, radiators, and tubing). This allows the tank to be filled to a height of 3.0in, completely submerging the server to just above the top of the extruded heat sinks. This leaves an air column height of 4.0in between the top free surface of the oil and the lid of the container.

Specific Gravity	0.8555
Density	0.8493 g/cm3
Kinematic Viscosity	< 16.02 mm2/s ASTM D445
Kin. Viscosity Temperature	40 °C

Table 3: Mineral Oil Physical Properties

T-type thermocouples are attached with thermal tape to the surface of 18 different locations across the motherboard. The components monitored represent a range of component types (chipsets, voltage regulators, DIMM chips, CPU heatsinks) to provide a survey of the thermal performance of the two cooling methods being tested. These thermocouples have error limits of ±1.0°C and are connected to a data acquisition system which records their values in five-second intervals.

The total server power consumption is measured using a ‘P3 P4400 Kill A Watt’ power meter by connecting voltage and current clamps to the incoming power feed to the server. Power consumption data is recorded in five-second intervals and logged on the workstation.

3.2.1 Server Modification

As this server is made for cooling so we can not use it directly for the oil immersion cooling by submerging it directly in the oil. All the modifications are necessary for this testing. The modification process is quick and inexpensive.

3.2.1.1 Removal of Fan

Use of the fans in a server is to cool down the heat generating components by circulating air throughout the server. In oil immersion cooling as fluid media is an oil which is circulated by mean of a hydraulic pump, to cool the components, so we don’t need fans in the server. Fans usually consumes around 3 to 5 % of the total server power. Figure 22 shows the removal of fans from the server. Serve can not work with fans as its been manufactured for air cooling purpose. So we need to connect the fans but have to keep them outside the oil.

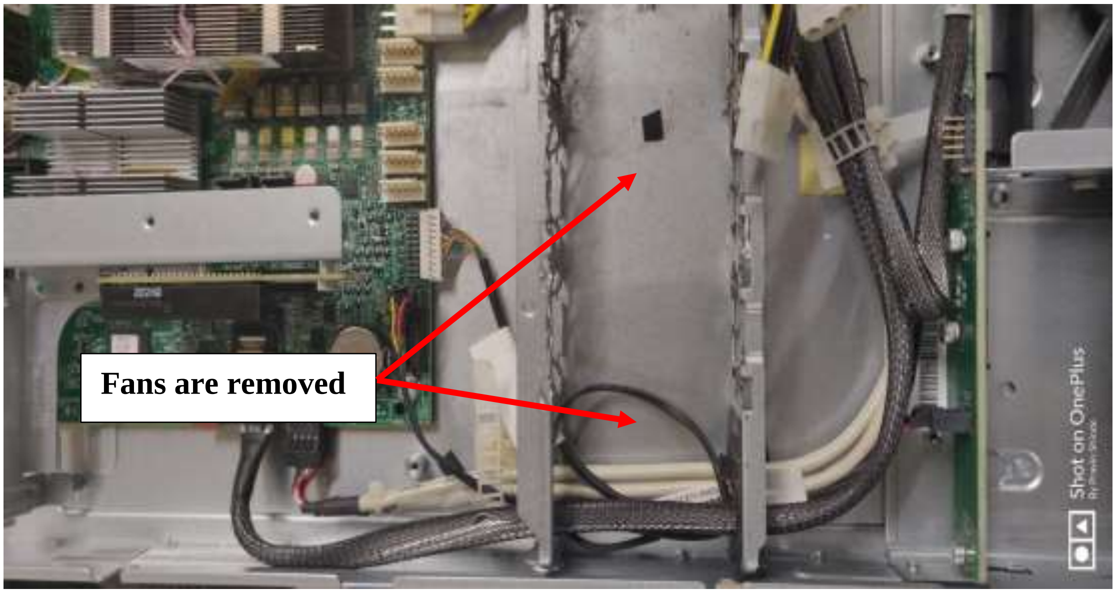


Figure 22 : Fans Removed from the Server

3.2.1.2 Hard-Drive Removal

Just like fans hard-drives also needed to be taken out, as fans can not work well in the oil media. So, we cannot submerge HDD in the mineral oil. But we need HDD for the data recording and saving it. So, HDD will be connected to the server motherboard but will be kept out. Still we must make sure that oil doesn't spilled on HDD. Figure 23 shows that HDD is kept outside of the oil and its connection to the motherboard.

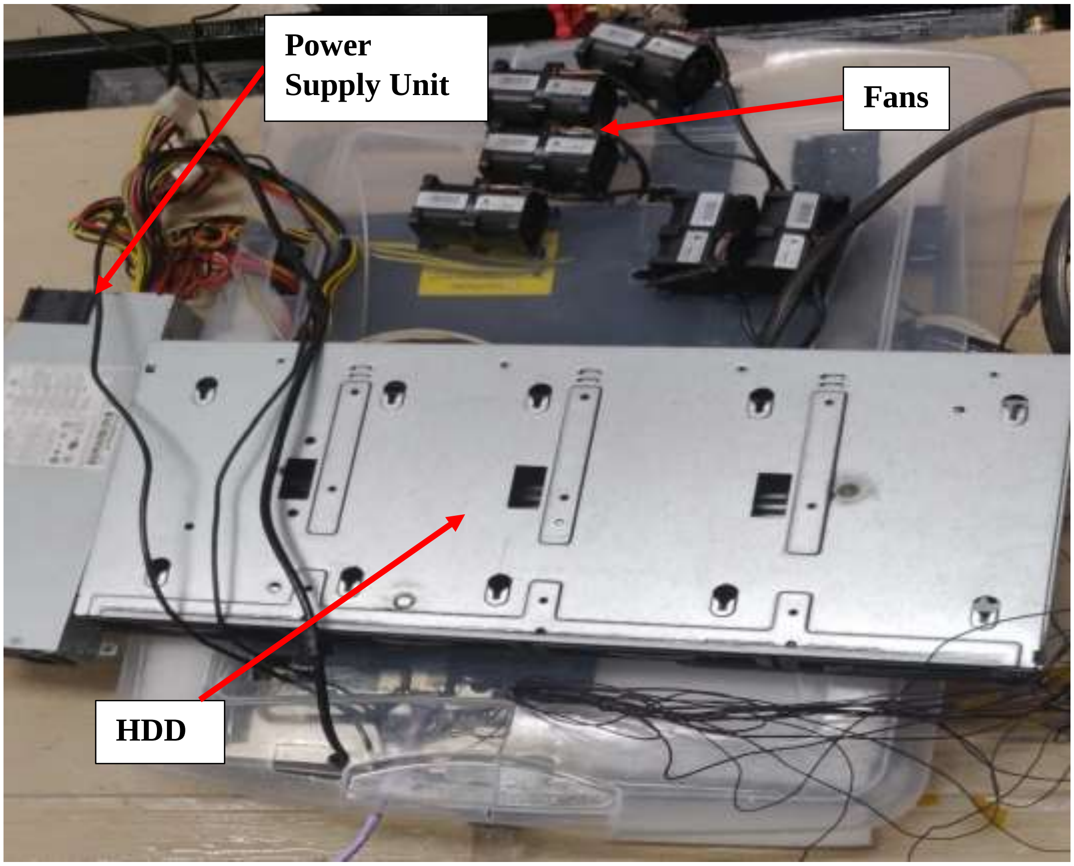


Figure 23: HDD and PSU Removed from the Server

3.2.1.3 Power Supply Unit Removal

Power supply unit (PSU) supplies the power to the motherboard of the server. But we can not submerge it into the oil immersion setup. So, we kept the PSU outside the setup while keeping it connected to the motherboard. Figure 23 shows the connection of PSU while it kept outside.

3.2.1.4 Thermal Interface Material (TIM) Removal

Thermal interface material is useful in filling out the gap in between heat sink and the CPU, and it increases the heat transfer because of the high thermal conductivity, figure 24. As it mostly likely to get dissolve in the di-electric mineral oil, so we can not use it because of the contamination. We will remove the original TIM, figure 25 and replace it with the indium TIM foil, figure 26.

Figure 24: Original TIM before

Figure 25: CPU Processor without the TIM

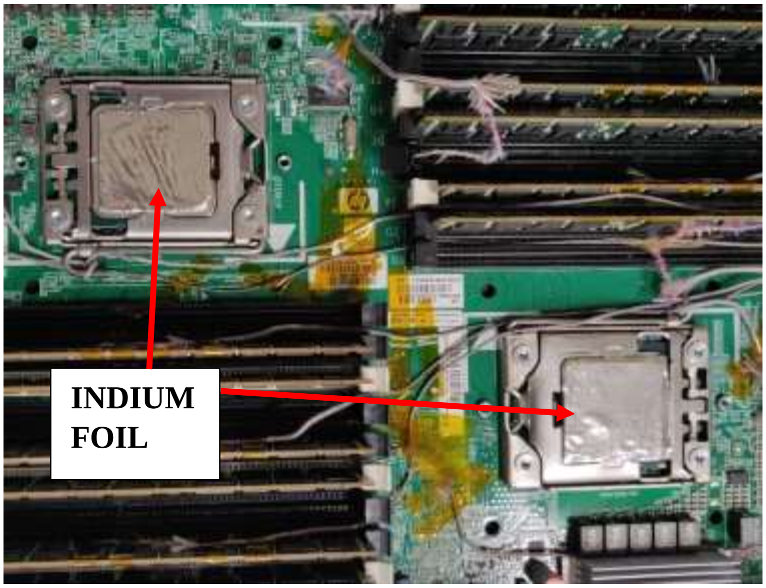


Figure 26: CPU Processor with Indium as TIM

3.2.2 Experiment Preparation

After indium is applied as a TIM on processor and other modifications as mentioned above, server motherboard is placed in the oil immersion container. All thermocouples were attached to the multiplexer and then it is inserted into the Agilent data logger. All the connections such as hydraulic pump, radiator, power supply unit were completed as shown in figure 28.

It can be seen from the figure 27, that specific arrangement is done inside the container for the motherboard. This arrangement is done to ensure the good flow over the major heat generating components. Baffle that is used in air cooling is also used in oil cooling in order to deviate the oil flow over the heat sink of the processors.

Once above arrangement is done and all connection are made like LAN, internet and power supply, server is turned on once the oil is poured in the experiment setup. In this experiment approximate four gallons of white mineral oil is required. Oil is poured until it reaches the top of the heat sink.

Now as server is turned on, we can proceed with experimentation. As soon as server is turned on, using Lm_sensors, core temperature is looked over. Once it made sure that server is working fine, actual experiments can be started.

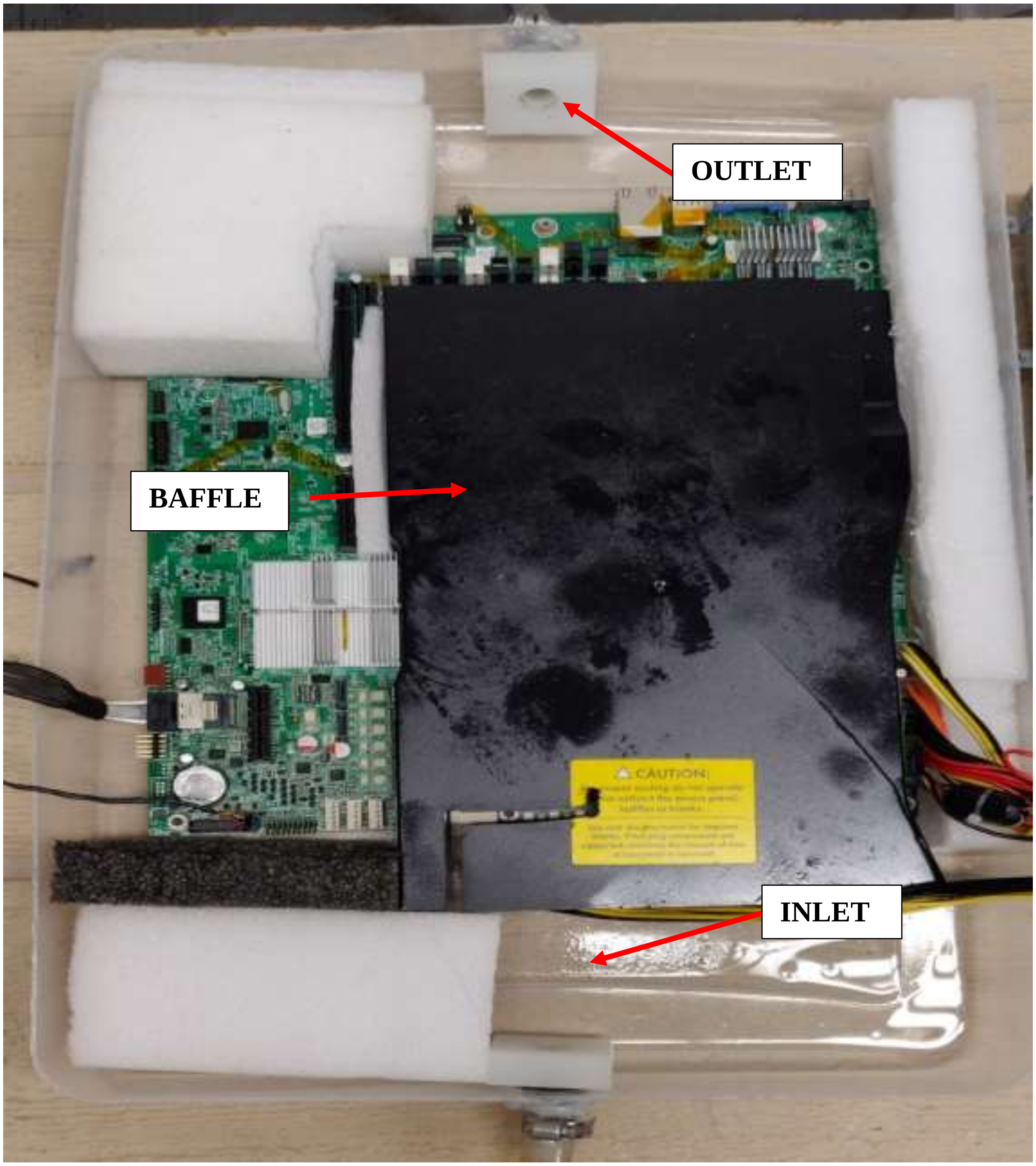


Figure 27: Motherboard in Container

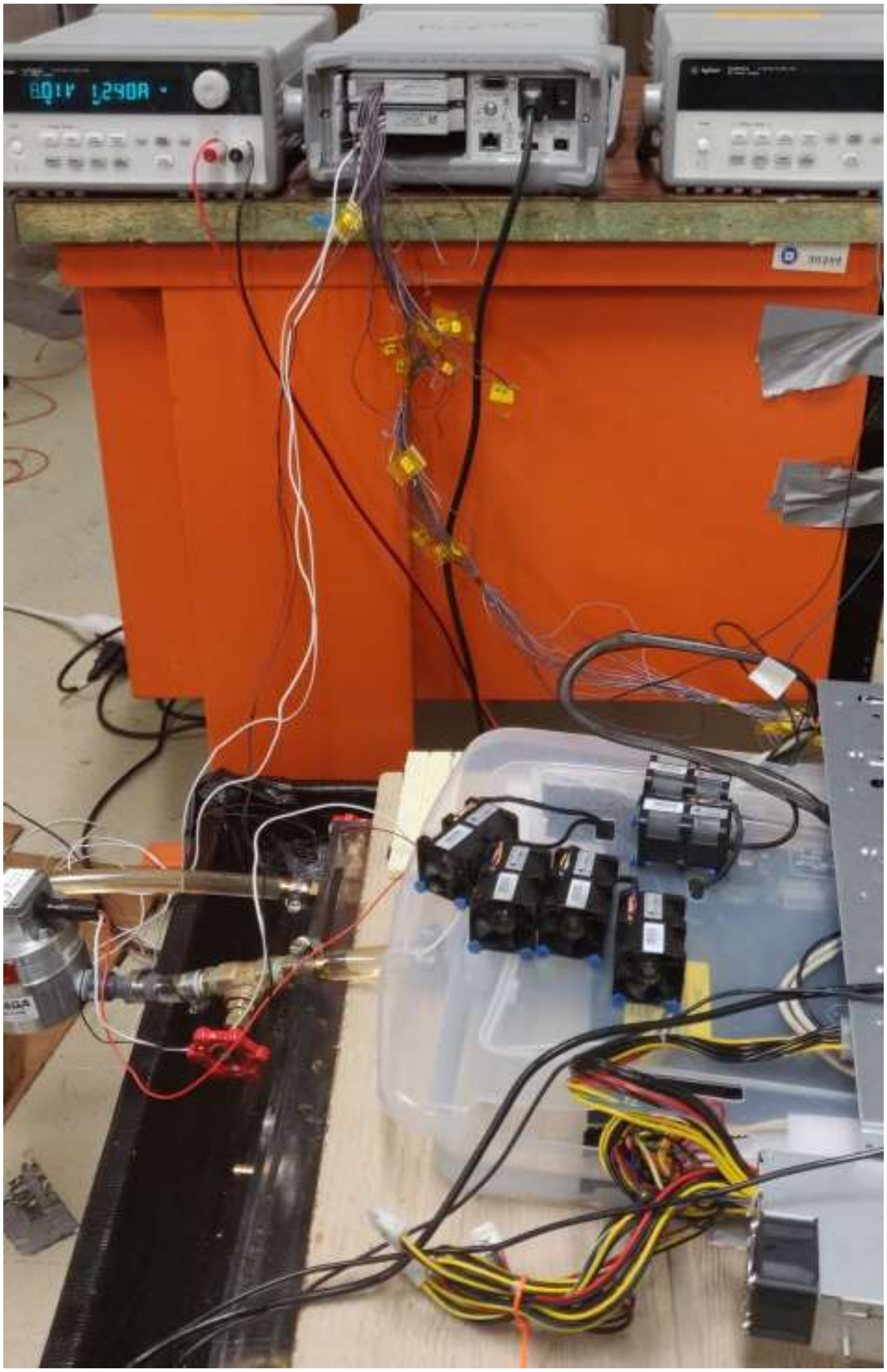


Figure 28: Motherboard connections to DAQ

Chapter 4

Results and Comparison

4.1 Air Cooling vs Oil cooling

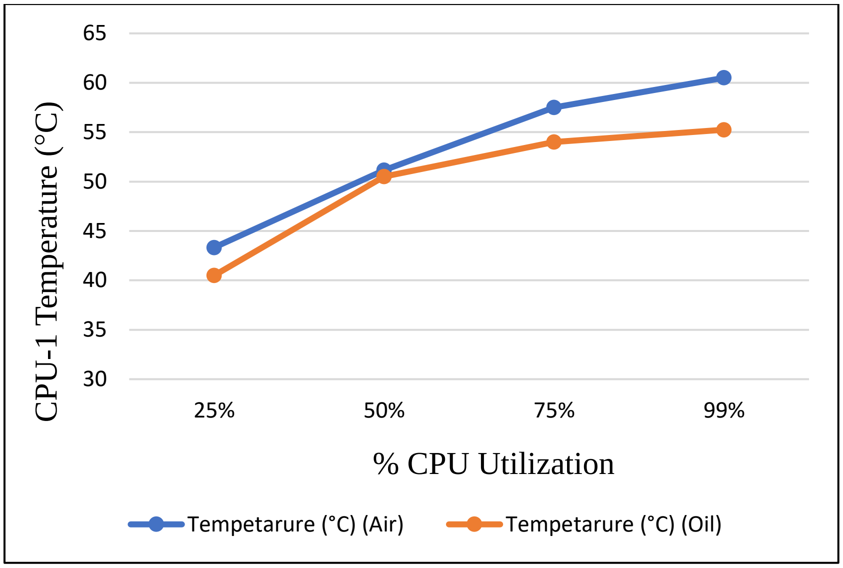


Figure 29: CPU-1 Temperature Vs % CPU Utilization

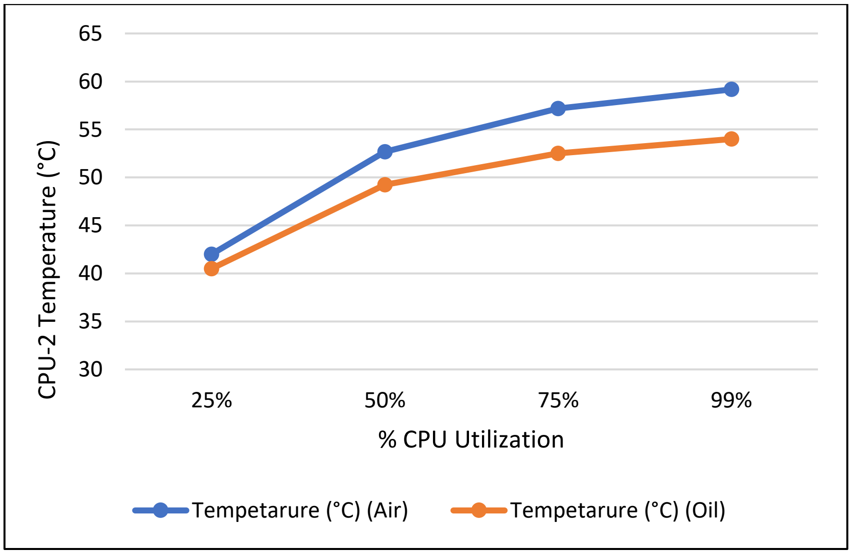


Figure 30: CPU-2 Temperature Vs % CPU Utilization

Component	**Air (°C) (Baseline)**	**Oil (°C)**	**Percent Reduction %**
CPU 1	60.5	55.25	8.68%
CPU 2	59.17	54	8.74%
IOH chip	44.997	37.832	15.92%
PCH	42.412	36.203	14.64%
DIMM 1	39.719	36.056	9.22%
DIMM 2	38	32.941	13.31%

Table 4: Percent Reduction in Temperature

Figure 29, 30 represents a variation of CPU (1, 2) temperature with respect to percentage CPU and memory utilization between air cooling and single-phase oil immersion cooling. During air cooling, CPU 2 has 59.17°C which drops to 54°C in oil cooling, with the reduction of 8.78% in temperature.

Table 2 lists the major heat generating components, with percentage reduction in temperature. For CPU1 maximum core temperature recorded in air, cooling is 60.5°C, whereas in oil cooling it drops to 55.25°C which is 8.68% reduction in temperature. Also, other major heat generating components shows around 8 to 16 % reduction in temperature.

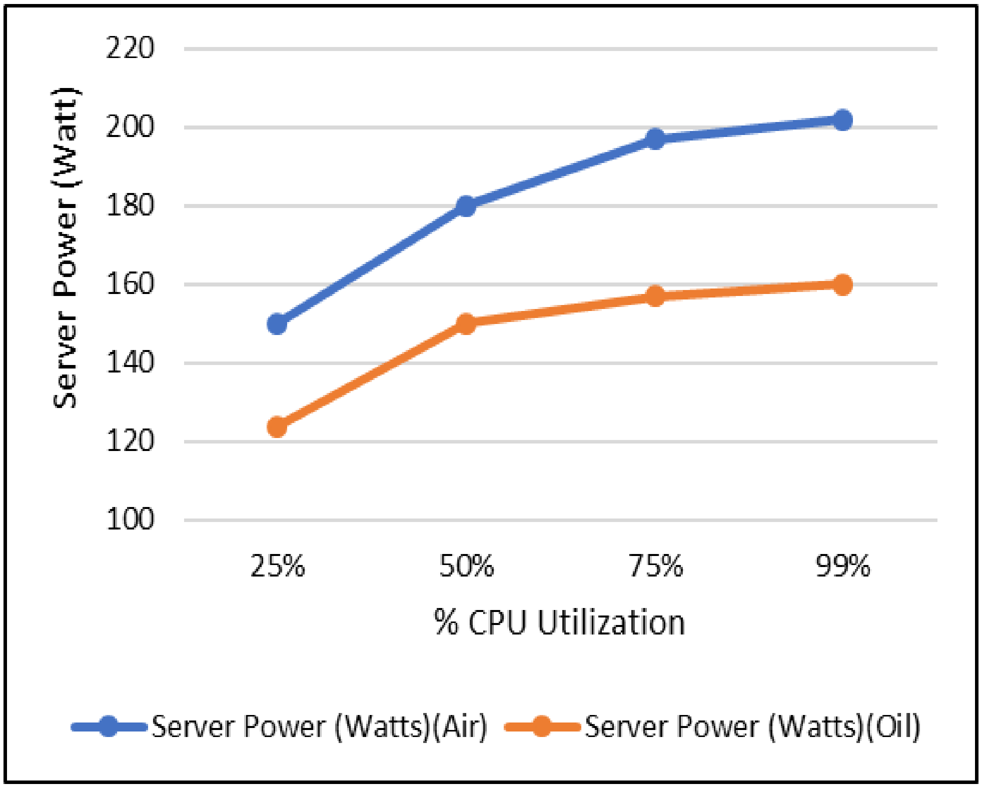


Figure 31: Server Power Vs % CPU Utilization

% CPU Utilization	Air (Watt) (Baseline)	Oil (Watt)	Percent Power Reduction %
25 %	150	132	12 %
50%	180	157	12.78 %
75 %	198	164	17.17 %
99 %	202	168	16.83 %

Table 5: Percent Reduction in Server Power

Figure 31 shows server power Vs % CPU and memory utilization. Also, table 3 represents a percent reduction in power at different percent of CPU and memory utilization. In oil immersion, cooling fans which count for around 5% of server power are not required [10]. At full load, in oil cooling server uses 168 watts whereas in air cooling it is 202 watts, which shows 16.83% percent reduction in server power usage.

For this comparative study, oil flow rate kept at 1 GPM, whereas in air cooling, fans were controlled by BIOS of motherboard.

4.2 Varying Oil Flow Rate and Inlet Temperature

For this experiment, the different oil inlet temperature of 25°C, 35°C, 45°C and a flow rate of 1 GPM and 0.5 GPM is considered.

4.2.1 At 25°C Inlet Oil Temperature

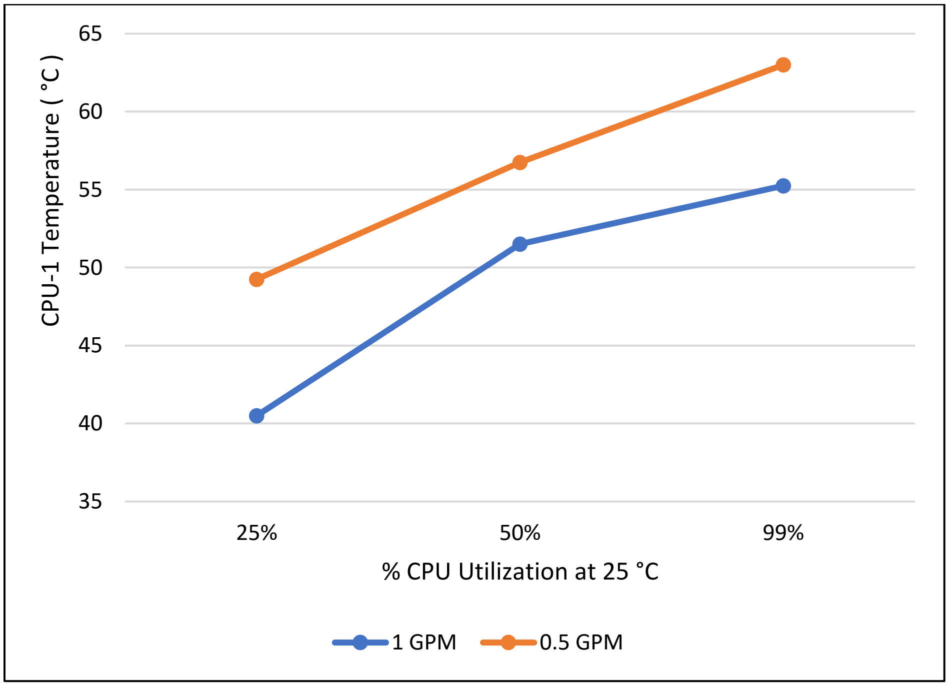


Figure 32: CPU-1 Temperature Vs % CPU Utilization

Figure 32, 33 shows CPU 1 and 2 core temperature Vs percent CPU and memory utilization. Graphs are the plot for two different flow rates of 1 and 0.5 GPM at 25°C inlet oil temperature. With an increase in flow rate, oil was able to cool down the CPU effectively.

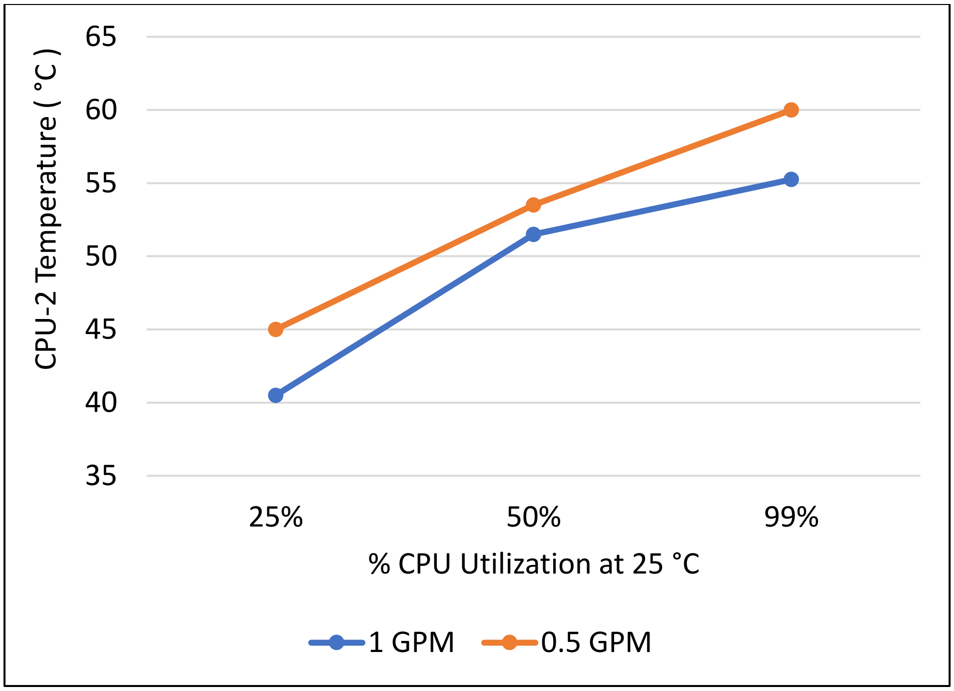


Figure 33: CPU-2 Temperature Vs % CPU Utilization

Component	Oil Temp. At 0.5 GMP (°C)	Oil Temp. At 1 GMP (°C)	Percent Reduction (Full Load) %
CPU 1	63	55.25	14.02 %
CPU 2	60	55.25	7.91 %

Table 6: Percentage Reduction in CPU Core Temperature

Table 6 shows percent reduction in CPU core temperature at 25°C with a flow rate of 1 GPM and 0.5 GPM. With an increase in flow rate, CPU core temperature shows 7 to 14 % of reduction in temperature.

4.2.2 At 35°C Inlet Oil Temperature

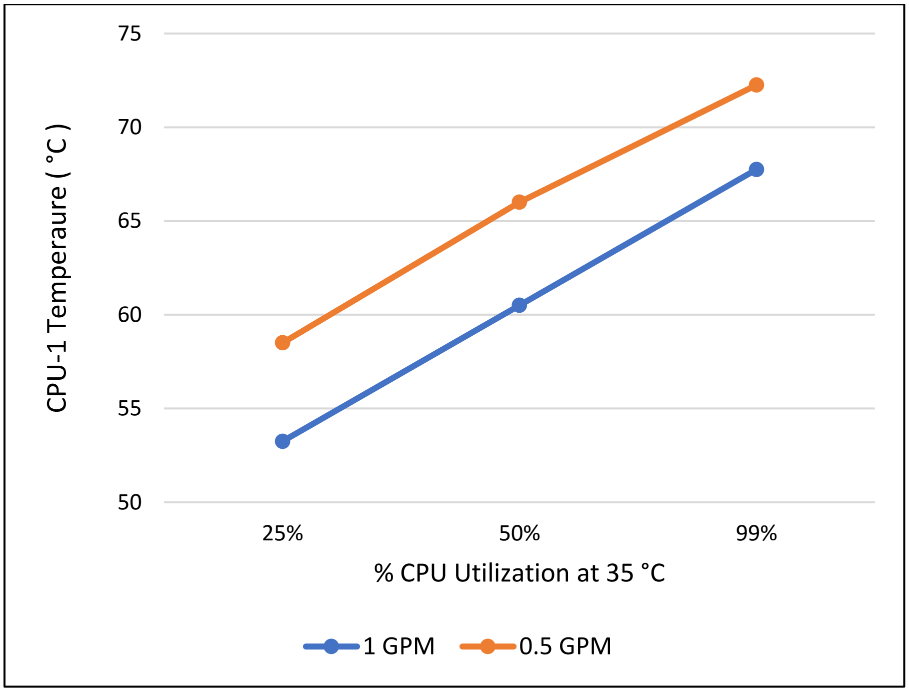


Figure 34: CPU-1 Temperature Vs % CPU Utilization

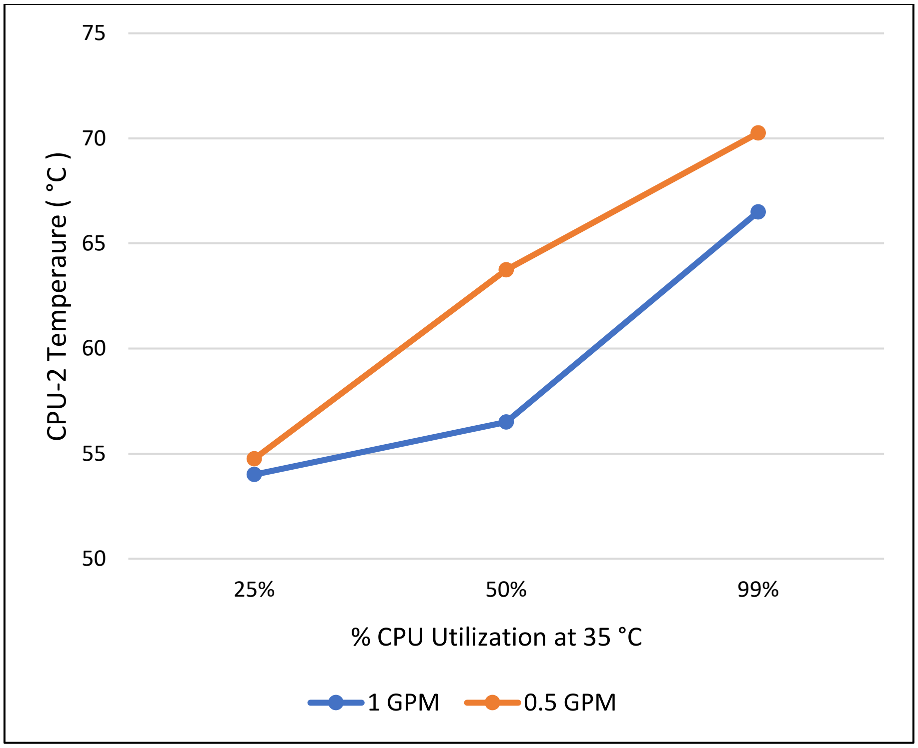


Figure 35: CPU-2 Temperature Vs % CPU Utilization

Component	**Oil Temp. At 0.5 GMP (°C)**	**Oil Temp. At 1 GMP (°C)**	**Percent Reduction (Full Load) %**
CPU 1	72.25	67.75	6.23 %
CPU 2	70.25	66.50	5.34 %

Table 7: Percent Reduction in CPU Core Temperature

Figure 34, 35 shows CPU 1 and 2 core temperature Vs percent CPU and memory utilization. Graphs are the plot for two different flow rates of 1 and 0.5 GPM at 35°C inlet oil temperature. With an increase in flow rate, oil was able to cool down the CPU effectively.

Table 7 shows percent reduction in CPU core temperature at 35°C with a flow rate of 1 GPM and 0.5 GPM. With an increase in flow rate, the CPU core temperature shows a 5 to 6 % reduction in temperature.

4.2.3 At 45°C Inlet Oil Temperature

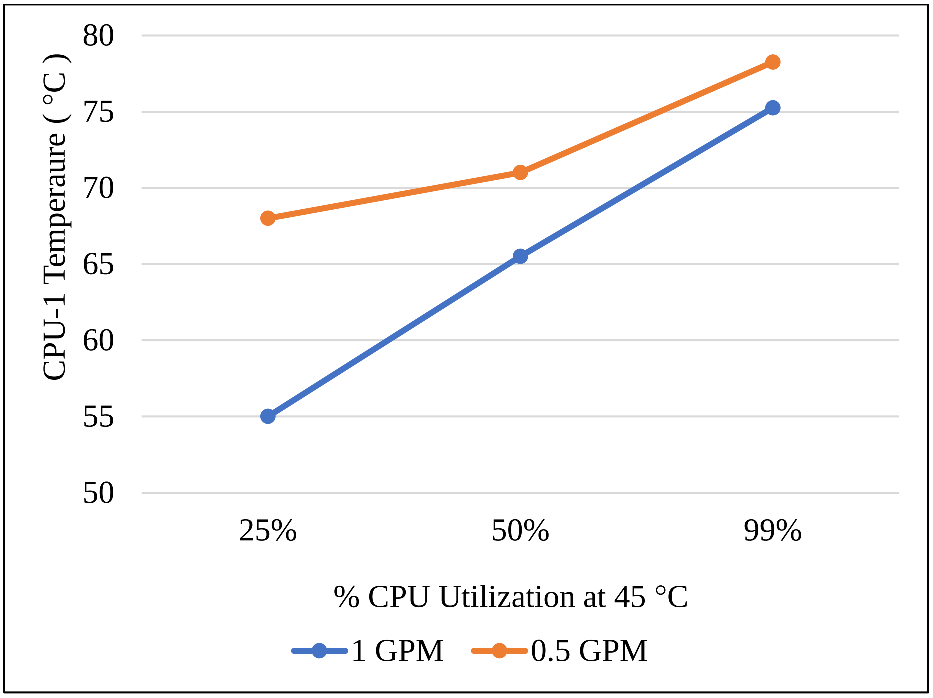


Figure 36: CPU-1 Temperature Vs % CPU Utilization

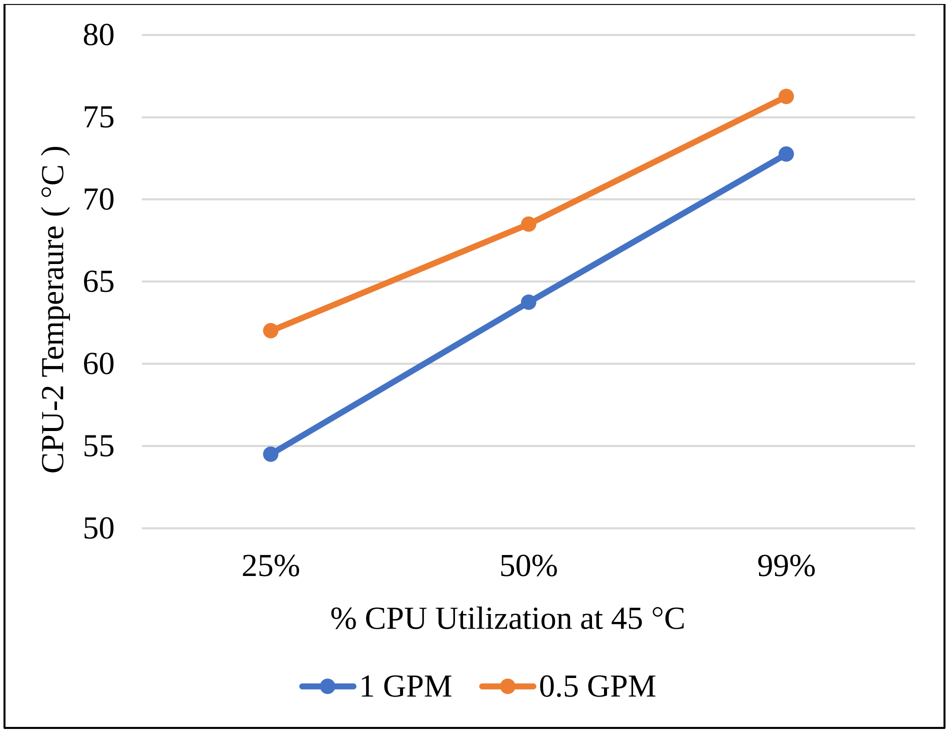


Figure 37: CPU-2 Temperature Vs % CPU Utilization

Figure 36, 37 shows CPU 1 and 2 core temperature Vs percent CPU and memory utilization. Graphs are the plot for two different flow rates of 1 and 0.5 GPM at 45°C inlet oil temperature. With an increase in flow rate, oil was able to cool down the CPU effectively.

Component	**Oil Temp. At 0.5 GMP (°C)**	**Oil Temp. At 1 GMP (°C)**	**Percent Reduction (Full Load) %**
CPU 1	78.25	75.25	3.83 %
CPU 2	76.25	72.75	4.59 %

Table 8: Percent Reduction in CPU Core Temperature

Table 8 shows percent reduction in CPU core temperature at 45°C with a flow rate of 1 GPM and 0.5 GPM. With an increase in flow rate, the CPU core temperature shows 3 to 4 % reduction in temperature.

4.3 Component Temperature with Varying Flow Rate and Inlet Oil Temperature

		1 GPM		
		Temperature of Components at Different Inlet Oil Temperature		
No.	**Components**	**25°C**	**35 °C**	**45 °C**
1	**CPU 1**	55.25	53.25	75.25
2	**CPU 2**	54	54	72.25
3	**DIMMs 1**	36.056	46.374	54.474
4	**DIMMs 2**	32.941	44.78	53.999
5	**IOH Chip**	37.832	46.166	55.095
6	**PCH**	36.203	46.865	55.029
7	**VRD 1**	34.956	45.568	53.936
8	**VRD 2**	33.571	45.082	53.565

Table 9: Component Temperature at Different Inlet Oil Temperature for 1 GPM

		0.5 GPM		
		Temperature of Components at Different Inlet Oil Temperature		
No.	**Components**	**25°C**	**35 °C**	**45 °C**
1	**CPU 1**	63	72.25	78.25
2	**CPU 2**	60	70.25	76.25
3	**DIMMs 1**	38.055	49.985	55.459
4	**DIMMs 2**	32.174	47.914	54.223
5	**IOH Chip**	39.901	50.385	56.021
6	**PCH**	38.994	50.225	55.73
7	**VRD 1**	37.779	49.85	55.51
8	**VRD 2**	37.25	48.4	54.036

Table 10: Component Temperature at Different Inlet Oil Temperature for 0.5 GPM

Table 9 and 10 shows component temperatures at different inlet oil temperature with varying flow rate. With an increase in inlet oil temperature, there is an increase in component temperature. It is also seen that, with an increase in flow rate, the component temperature reduces by a noticeable amount. At 1 GPM, CPU 1 is showing a temperature of 75.25°C, whereas at 0.5 GPM it is 78.25°C. As the flow rate decreases, CPU core temperature increases.

4.4 Server Power with Varying Inlet Oil Temperature

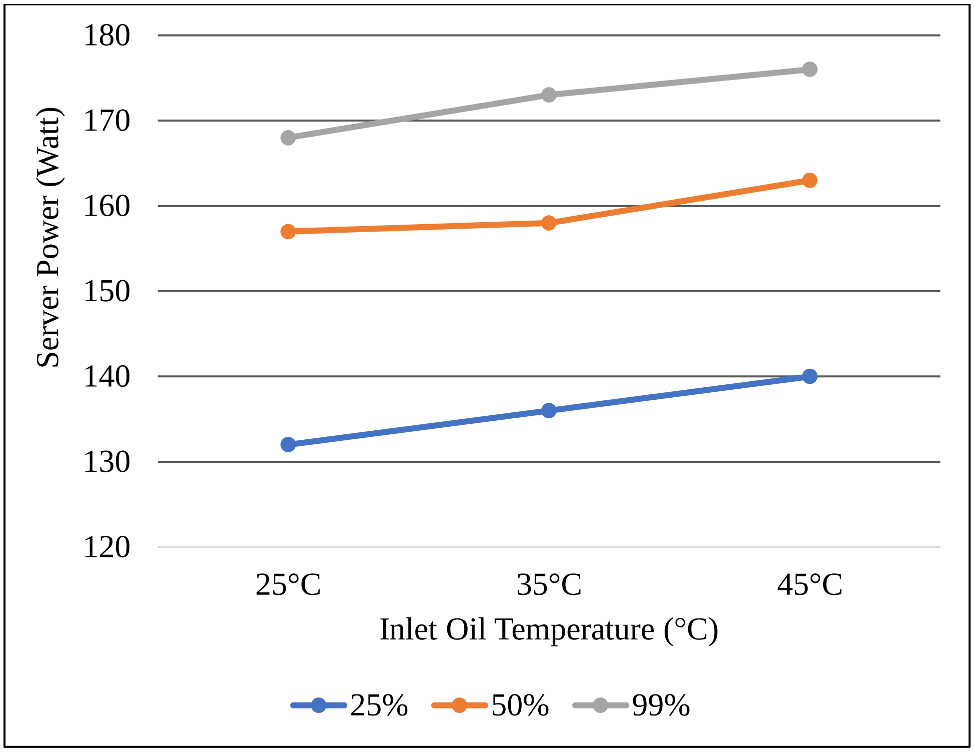


Figure 38: Server Power Vs Inlet Oil Temperature of Server

Figure 38 shows the server's power consumption in watt with varying inlet oil temperature conditions at different percent utilization of CPU and memory.

The server is stressed at different loading conditions, with different inlet oil condition. As inlet oil temperature increases, server power utilization also increases. Power utilization didn't cross 180 watts, even at 45°C when the server was stressed to the full load, whereas during air cooling power utilization is seen crossing 200 watts.

4.5 Partial PUE

Power Usage Effectiveness (PUE) has been widely adopted and used throughout as the standard efficiency metric for data centers. PUE determined as the total power consumed by the data center divided by the power consumed by the IT load (useful work of the data center). Partial PUE (pPUE) metrics can be developed to understand the efficiency of specific subsystems and subsets of the data center. pPUE of cooling systems can be expressed as follows:

$$pPUE_{cooling'} = \frac{Cooling\ Power + Server\ Load}{Server\ Power} \qquad (1)$$

$$Cooling\ Power = Pump\ Power + Radiator\ Cooling\ Power \qquad (2)$$

	PUE at Different Oil Inlet Temperature and Flow Rate (Full Loading Condition)		
	25°C	**35 °C**	**45 °C**
0.5 GPM	1.099	1.0952	1.0930
1 GPM	1.10	1.0975	1.095

Table 11: PUE With Varying Temperature and Flow Rate

Chapter 5

5.1 Conclusion

The primary purpose of this experiment to establish general boundary condition for the server HP DL160 G6 in single phase oil immersion cooling. By operating a single server in fully immersed oil immersion setup, flow rate and inlet oil temperature conditions were established. CPU core temperature did not increase beyond operating critical temperature of 85°C for inlet oil temperature 45°C. From the results, it is possible to efficiently cool down the server with the inlet oil temperature of 45°C for cooling. A reduction in component temperature and server power achieved. $pPUE_{cooling'}$ values ranging from 1.093 to 1.10 were achieved in the current oil experimental setup. Improvement in the system and hardware may increase efficiency the of the use of oil immersion technology for data center cooling. Future work in this area may be rack level analysis with high temperature as well as lowest inlet heat temperature. PUE analysis of single server er as well as at rack level. Studying the effect of different dielectric fluid on the server performance.

5.2 Future Work

- Running a rack level analysis with higher inlet temperatures as well as lowest inlet temperatures.
- PUE analysis for single server as well as at rack level.
- Studying the effects of different dielectric fluid on the server performance.
- Change in properties of mineral oil due to thermal overstressing.

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Biographical Information

Pravin Shinde was born in Pune, Maharashtra, India in 1993. He received his B.E in mechanical engineering from Savitribai Phule Pune university, Pune, India in July 2015, and his M.S. in mechanical engineering from The University of Texas at Arlington in May 2019.

He had been involved in number projects related in area of electronics cooling techniques. His research includes immersion cooling method for data center servers and actively involved in number of projects like leakage current analysis for servers, testing of servers with different types of heat-sinks, fan characterization to determine fan curve of multiple systems, testing servers in different ambient condition using related instruments like environmental chamber, Air-flow bench.

He joined EMNSPC research team under Dr. Dereje Agonafer in fall 2017 and been involved in projects related to packaging level to server level.