COMPUTATIONAL ANALYSIS FOR THERMAL OPTIMIZATION OF SERVER FOR SINGLE – PHASE IMMERSION COOLING

By

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THESIS

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ABSTRACT

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The University of Texas at Arlington, 2019

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Complete immersion of servers in synthetic dielectric fluids is rapidly becoming a popular technique to minimize the energy consumed by data centers for cooling purposes. In general, immersion cooling offers noteworthy advantages over conventional air-cooling methods as synthetic dielectric fluids have high heat dissipation capacities which are roughly about 1200 times greater than air. Other advantages of dielectric fluid immersion cooling include even temperature profile on chips, reduction in noise and addressing reliability and operational enhancements like whisker formation and electrochemical migration. Nevertheless, lack of data published and availability of long-term reliability data on immersion cooling is insufficient which makes most of data centers operators reluctant to implement this technique. The first part of this paper will compare thermal performance of single-phase oil immersion cooled HP ProLiant DL160 G6 server against air cooled server using computational fluid dynamics on 6SigmaET®. Focus of the study are major components of the server like Central Processing Unit (CPU), Dual in Line Memory Module (DIMM), Input/output Hub (IOH) chip, Input controller Hub (ICH) and Baseboard Management Controller (BMC). The second part of this paper focuses on thermal performance optimization of oil immersion cooled servers by varying oil and its inlet temperature and volumetric flow rate.

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Chapter 1 Introduction

1.1 What is Data Center?

Data center is a centralized location rendered with computing resources and crucial telecommunication – which includes servers, storage systems, databases, devices, access networks, software and applications. It stores, manages, processes and disseminates data. Data centers house network's most critical systems and are important for continuity of daily operations. In today's modern world, rapid increase in utilization of servers as well as data centers is due to its wide-spread application in each part of life. Dependency on computer system has arose and it has promoted the continuous growth of data centers in leading industries like banking, education, transportation, social media and many more. Increasing computing demand has led to increase in component densities each year. This results in rise in power requirement and consequently power generation densities. [1]

1.2 Data Center Power Consumption and Cooling Trends

In United States since last five years, capacity of data center has been increased tremendously with little rise in data center total energy consumption, according to the results of new study of data center energy use by US government released on Jun 27th,2016. US data centers have consumed about 70 billion kWh in 2014 representing 2 percent of country's total power consumption. That's equivalent to the amount of electricity consumed by 6.4 million average American homes that year. In United States, total energy consumed by data center is increased by 4 percent during 2010 to 2014, and huge change from preceding five years, total US data center energy consumption increased by 24 percent. Improvement in energy efficiency has played vital role in limiting the growth rate of data center energy consumption. Without these improvement, with the same efficiency level of 2010, data centers would have consumed almost 40 billion kWh more than what they have consumed in 2014 for the same amount of work according to the study conducted by US

Department of Energy with collaboration of researchers of Stanford University, Northwestern University and Carnegie Mellon University. Energy efficiency improvement will have saved almost 620 billion kWh between 2010 and 2020 as per study forecast.

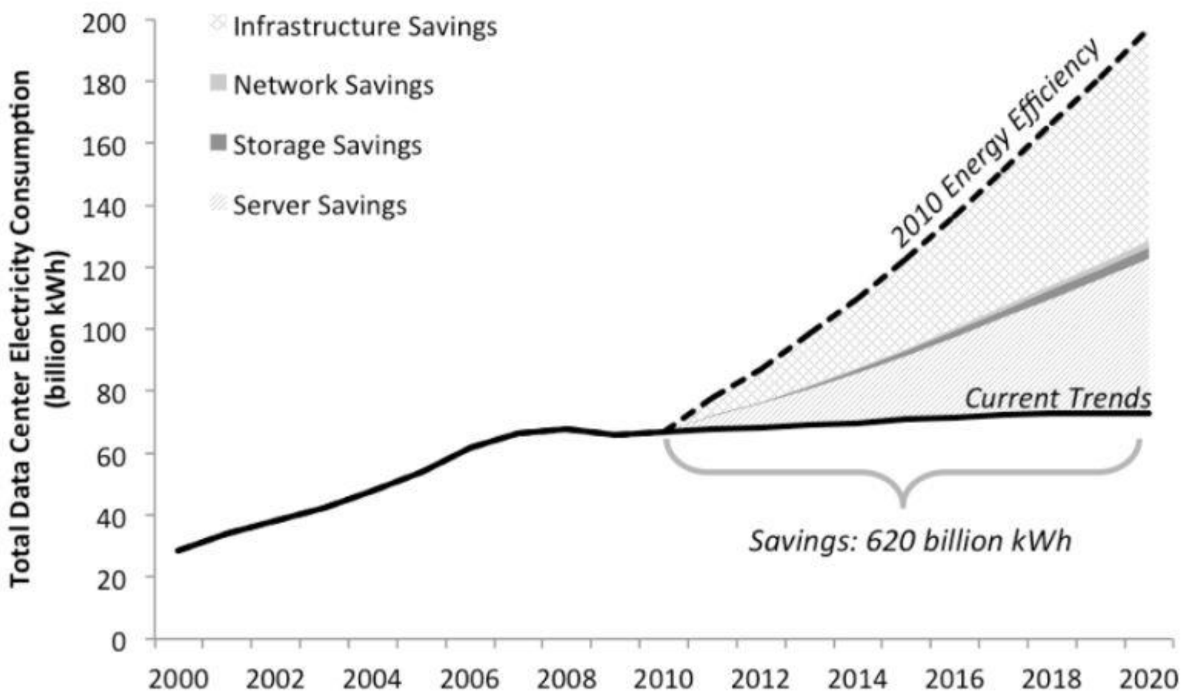

Figure 1 Data Centre Power Consumption [2]

This chart shows past and projected growth rate of total US data center energy use from 2000 until 2020. It also illustrates how much faster data center energy use would grow if the industry, hypothetically, did not make any further efficiency improvements after 2010. (Source: US Department of Energy, Lawrence Berkeley National Laboratory). [3] Below figures shows the breakdown of total energy consumption in data center. From the total power consumed in data center, 33 percent of total power is utilized only for cooling purpose. Hence by improving energy efficiency of current data center cooling methods or using other innovative techniques resulting in increased amount of cooling or improved cooling effectiveness.

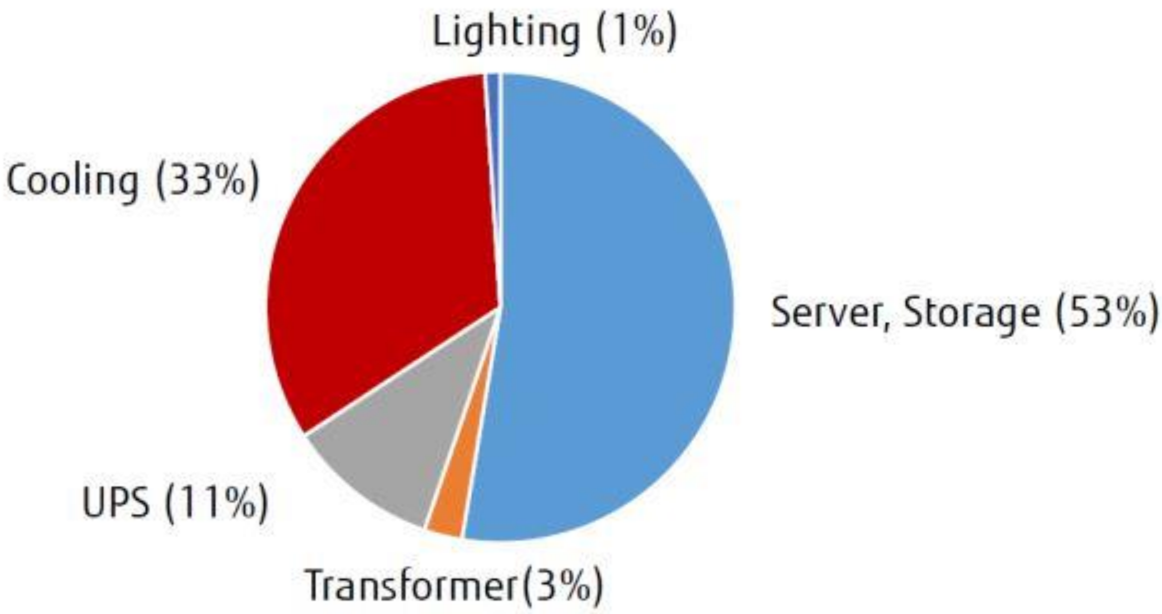

Figure 2 Breakdown of total energy consumption in Data Center [4]

The metric used to determine total power effectiveness of data center is known as Power Usage Effectiveness (PUE), which was developed by Green Grid in 2008. It can be calculated by dividing the total power consumed by data center with total power consumed by IT equipment. So, it is expressed as ratio, with overall improving efficiency as PUE decreases towards 1. It can be represented as,

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

Total Power consumed by IT equipment includes power consumed by servers, data storage systems and telecommunication equipment. Total power consumed by data center is made up of power consumed by IT equipment, cooling system, power delivery systems, battery backups and other miscellaneous power consuming devices throughout the facility. According to a research, it is estimated that 1.5 percent of total electricity generation is consumed by the data centers. The attendant greenhouse gas emissions, some 188 million tons of CO2 per year, match the emissions of about 33 million passenger vehicles Continuously increasing requirement of data centers affects the environment which prompts the engineers to develop energy efficient technology that can be used for data center. Servers are required to be cooled to achieve reliable and efficient operation. [5]

1.3 Need for Data Center Cooling

Server downtime is one of the most commonly and widely used term in the data center industry. Server downtime can be defined as a time during which server cannot be used. It may be because of overloading of memory as well as processors etc. These conditions are caused by absence or insufficient cooling of server. Servers are very critical part of industry and are required to be maintained carefully for its reliable operation. In the server, processors are main source of heat generated in it. To maintain its functionality, processors are required to be operated within certain operating temperature range. Servers tend to generate very high amount of heat within relatively small area. The heat generated by server is extracted by fluid and dissipated to ambient.

Heat dissipated from server is non-uniform and more likely to change frequently. There are various reasons that may result in non-uniformity of power. For example, heat generated by processor depends on percentage utilization of CPU and the time during which it is subjected to high percentage of utilization. Components which are housed in data centers are heat and humidity sensitive components. Most failures are found to occur at chip scale level. Operating temperature of the chip determines the performance of server and at the same time, it also affects the operating life of the chip.

Heat transfer in the server by method of thermal conduction and convection predominates the heat transfer by any other method. The airflow of air through the server chassis determines amount of heat that can be carried away by the air and hence resulting in affecting cooling efficiency. Conduction occurs at chip level while convection occurs at cabinet level. Different other components like heatsinks and fans are used to increase the amount of heat carried away by the process of convections. The amount of air flow through the server determines the cooling efficiency and in addition improve that other cooling solutions like heat-pipes, heat-sinks and vapor chamber can also be used. [6]

1.4 Data Center Cooling Methods

At present, two major techniques that are being used to keep the temperature within permissible limits are,

1. Air cooled servers
2. Liquid cooled servers

1.4.1 Air Cooled Servers

The sole purpose of data center cooling is to remove the heat dissipated by servers. Conventional methods for cooling data centers use air as a primary cooling medium. It is one of the most widely used method for data centers cooling. Server racks are positioned on plenum as per hot aisle and cold aisle arrangement. In this method, floor is raised to certain height accompanied with perforated tiles in order to direct the flow of air from bottom towards top through servers. The cooling air from computer room air condition (CRAC) is made to blow through underfloor plenum and then it is distributed to the cold aisle via perforated tiles. Hence, forced convection of air over the heat-sink is used to extract the heat generated by IT equipment. Heat extracted by air is either rejected to environment resulting in mixing with fresh air or using refrigeration process to cool it down. Air cooling servers used in data center consists of axial fans to manage the volumetric flow of air and heat sink to accelerate the heat transfer from server to air. Heat-sinks are

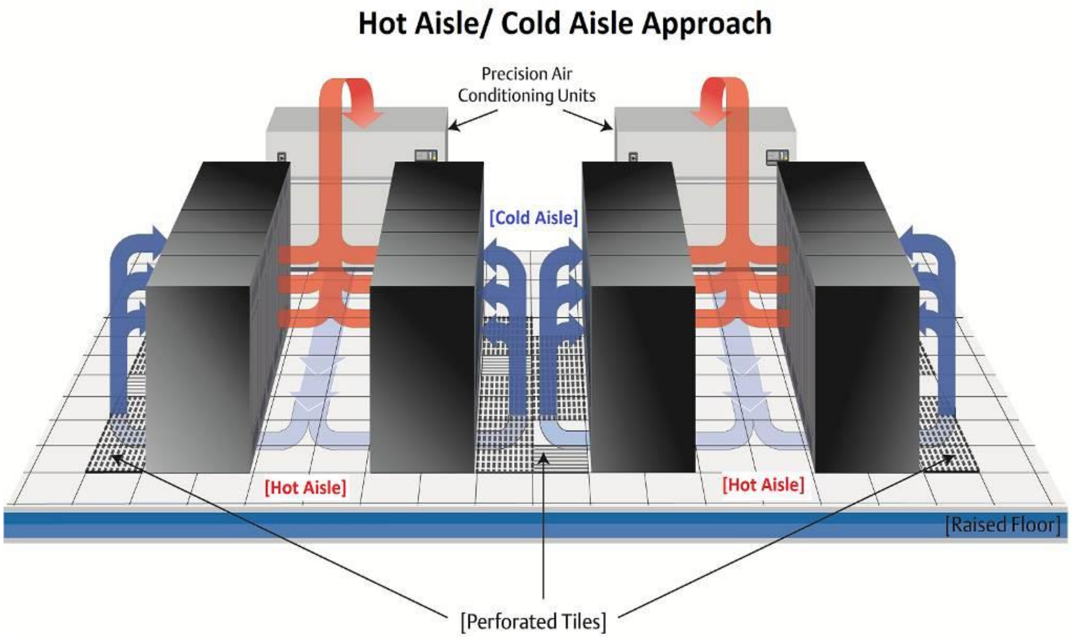

Figure 3 General Setup of Air-Cooled Data Center [26]

designed to increase the heat transfer rate through conduction, convection and through radiation as well. Fans are used to direct the flow of air from inlet to outlet via flowing through servers. Exhaust hot air from server outlet enters the hot aisle and then guided to CRAC (Computer Room Air Conditioning) unit to cool down the air to desired temperature. Once the air is cooled down it will be supplied to the cold aisle and the cycle continues. Design of typical air-cooled data center is as shown in the figure. [7]

1.4.2 Liquid Cooled Servers

Though air cooling is widely used for data center cooling, it is about to reach its limitations due to increasing computing requirements, high powered microprocessors and packaging. As compared to liquid cooled servers, air cooled servers require larger floor area to accommodate CRAC units, ducts, fans and cooling system which manages airflow the data center as well as it requires raised floor to supply the air from bottom for cooling purpose. [5] Hence, having advantages above mentioned points along with having capability to extract higher amount of heat as compared to air cooling method, liquid cooled servers are gaining more importance and are being considered as a future of data center cooling. Liquid cooled servers are further classified into two categories depending on the type of fluid used for cooling. [8]

1. Water cooled servers
2. Oil cooled servers

1.4.2.1 Water cooled servers

Water being an excellent conductor of electricity, it cannot be directly used to contact heat generating components. So, we use a passive heat transfer device named ‘Cold-Plate’. Bottom of the cold plate is made up of copper and it is placed on the top of heat generating components. It is generally used to extract heat from processor. The gap between processor and cold plate is filled with material called heat spreader. Heat from processor is conducted to cold plate resulting in rise of temperature of cold plate. Water is made to flow through cold-plate which extracts the heat from cold-plate. Heated water is directed to chillers to cool it down and so that it can be again used for next cooling cycle. Cold plate can be used in server instead of heatsink. The vital benefit of using cold-plate is the requirement of less space as compared to heatsink resulting in more compact design of server as well as power required to operate cold plate is less as compared to air cooling technique. [9]

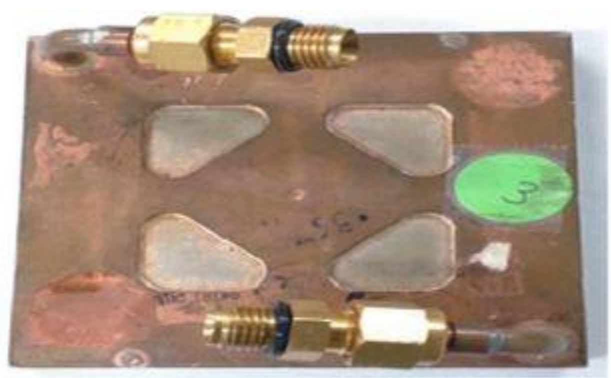

Figure 4 Cold Plate

1.4.2.2 Oil Cooled Servers

Oil Cooling method consists of submerging the servers in the thermally conductive but electrically non-conductive liquid called dielectric liquid. Heat transfer continuously takes place between dielectric liquid and server. The flow of dielectric liquid is maintained with the help of flowmeter. Some most commonly used dielectric liquids are mineral oil, white oil, electric cooling oils and non-purpose oils. Oil immersion cooling can be further classified based on the characteristic properties of dielectric liquid. [8]

1. Single Phase Immersion Cooling
2. Two Phase Immersion Cooling

1.4.2.2a Single Phase Immersion Cooling

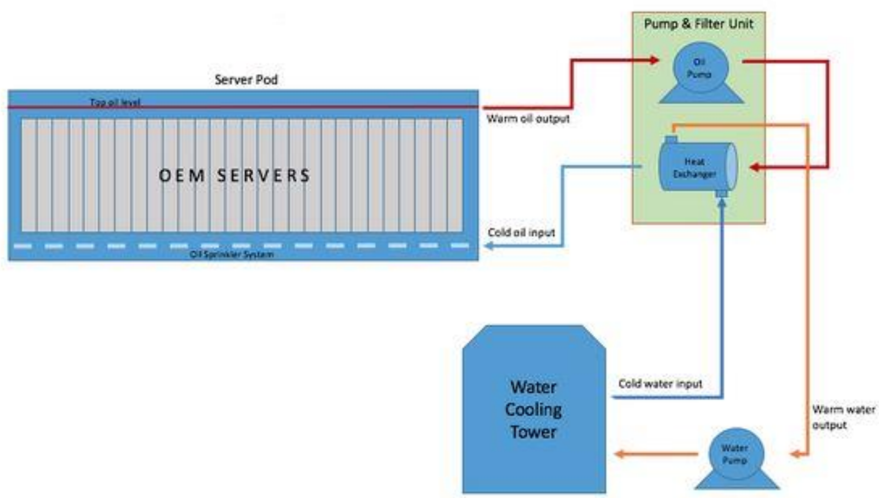

Figure 5 Schematic Diagram for Single-phase Immersion Cooling [10]

In the single-phase immersion cooling, dielectric liquid never changes its state and remains in the liquid state within the working temperature range of the server. Single phase dielectric heat transfer fluid is circulated through the system either actively or passively at very low pressure and volumetric flow rate. Fluid as a working medium extracts heat from the server through convection and warm fluid is sent to heat-exchanger where it cools down by exchanging heat with cold water. Cooling tower is used to cool down the hot water from heat exchanger. It can be operated in open bath condition considering negligible loss of fluid by evaporation. [11]

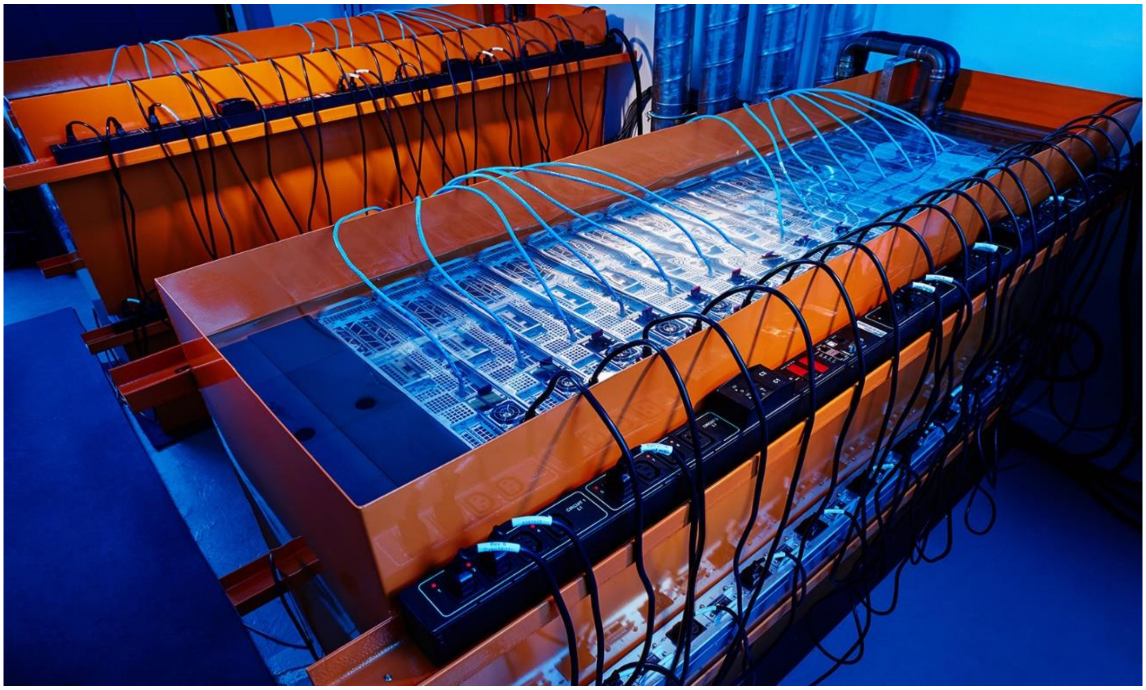

Figure 6 Actual Footage of Single-Phase Immersion Cooling [12]

1.4.2.2b Two Phase Immersion Cooling

In the two-phase immersion cooling system, servers are submerged into a bath of heat transfer liquids having much better thermal conductivity as compared to oil or water or oil. Dielectric fluid boils and hence exists in both state liquid and gas. Dielectric liquid being used as a working medium is having a low latent heat and hence a low boiling point. Working medium gets heated by absorbing heat from server and results in boiling. The gas moving upward encounters condenser coils which is maintained at temperature lower than saturation temperature. Cold water is made to flow through condenser coil. Condenser coil causes the condensation of dielectric fluid vapor and liquid fall back into the fluid pool. It is required to be operated in the form of semi-open bath to avoid the loss of liquid as working fluid changes its state. [13]

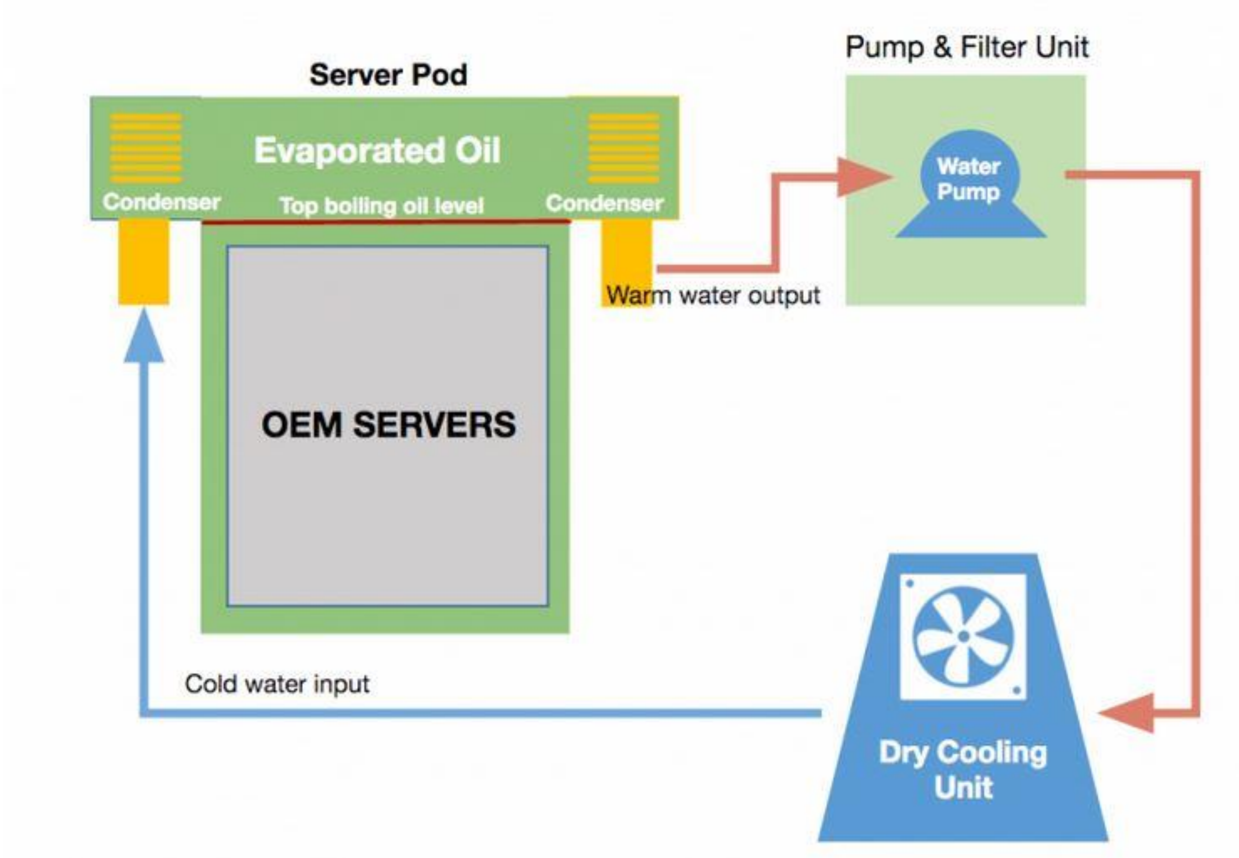

Figure 7 Schematic diagram for Two-phase immersion cooling [10]

1.5 Need of CFD Modeling

The most important factor for improving the cooling efficiency of server is to guide the air through the server so that that air can extract more heat from components by the process of thermal conduction. In order to drive air from one end to other end or basically form the flow of air, pressure drop across the server is must. The finite amount of pressure drop is required to drive the enough volume of air through server which is required to cool it down as well its reliable operation. These parameters can be determined by using CFD analysis and giving it the prediction regarding design capability. These predictions can be determined experimentally also. But, by using CFD analysis we can save the time as well as the money required to carry out experiments to determine those parameters. Optimization of the server requires the extensive use of CFD software in order to carry out analysis with various combinations, different orientation of components, different flow rate as well as fluid flow temperature. The main objective of this study is to design the detailed model of the server and analyze the air flow through the server which can be used for thermal analysis and thermal optimization later. [6]

1.6 Motivation to study

Due to increased power density and computing demand, air cooling methods for data center cooling are about to reach its limit. Single phase immersion cooling helps in thermal optimization of the servers that are being used for air cooled data centers. It also improves space management as servers no longer require the use of fans and other ducts which intended for guiding the airflow through the server.

Chapter 2 Server Description

2.1 Server Overview

The server on which this study is been carried out is HP ProLiant DL160 G6 server. It has two Intel Xeon 5650 six core central processing unit on motherboard with 18 Dual in Line Memory Module slots constituting 1U server. This study provides detailed and accurate CFD analysis of server which provides the information about temperature distribution and fluid flow across the server. System resistance curve and flow rate were obtained using CFD model and then compared with the same data measured experimentally.

This chapter will discuss all the details about the specification of server and specification of all the components that constitutes server including PCB, server chassis, fans, heatsinks and power supply unit (PSU).

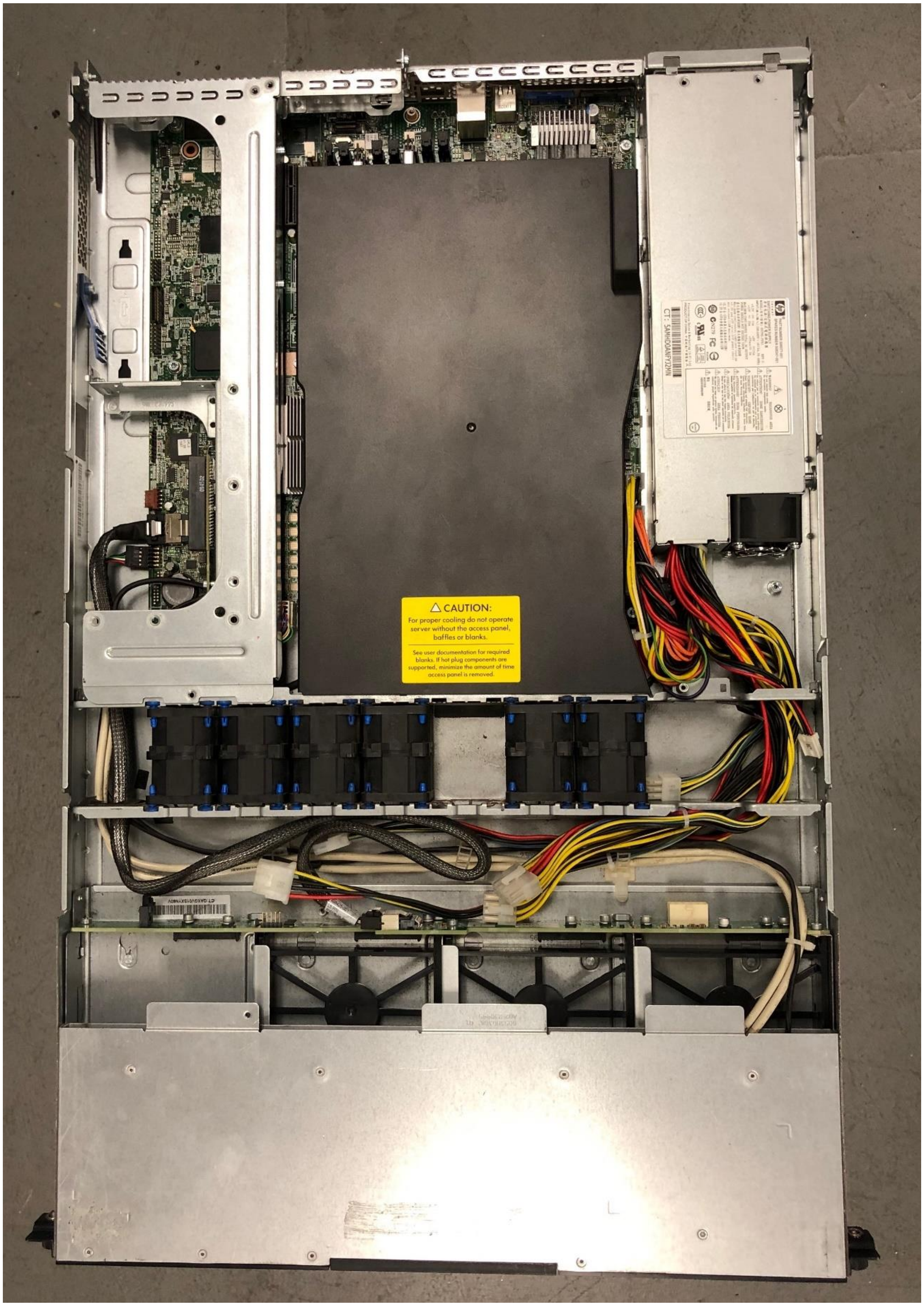

Figure 8 Top View of Server

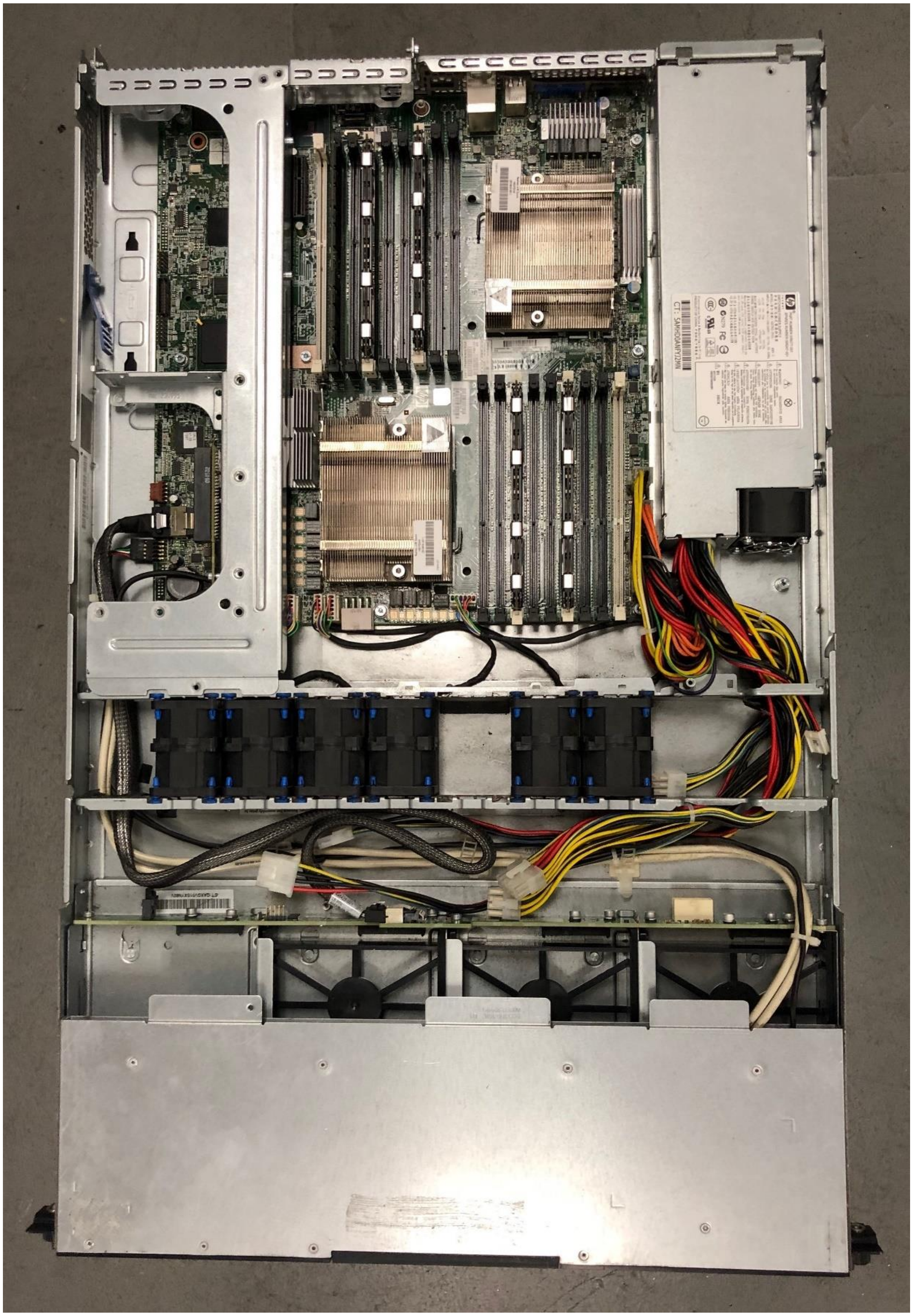

Figure 9 Top View of Server Without Duct

2.1.1 Motherboard

The server we are studying here is HP ProLiant DL160 G6 with two central processing unit Intel Xeon 5650 six core on motherboard along with 18 DIMM slots. This motherboard carries two Intel CPUs each having 95W thermal design power (TDP). Each DIMM 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 I/O 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.

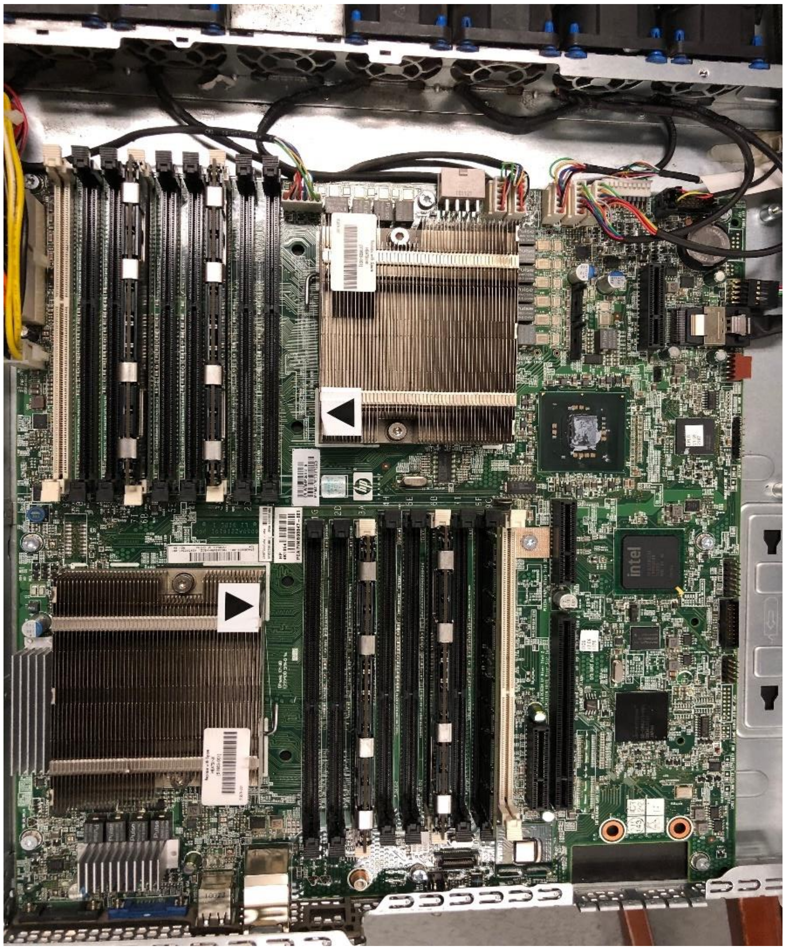

Figure 10 Top View of PCB

2.1.2 Server Chassis

The chassis is 44 mm tall – that's 1U in rack-form factor. As it is compact server, it doesn't allow the use of taller heat sink and larger diameter fans. The server chassis is made of 1.2 mm thick zinc plated corrosion resistant steel within house array of six fans and 4 front mounted hard drives. The server is loaded with snap plungers which reduces the amount to mount or unmount the component.

2.1.3 Server Fans

This server contains 6 Delta 40mm x 40mm x 56mm fans for the purpose of cooling on the front end just after the hard drives. A fan speed control algorithm is used by motherboard to control the speed of fan based on the core temperature of CPUs. The fans are installed as per pull arrangement.

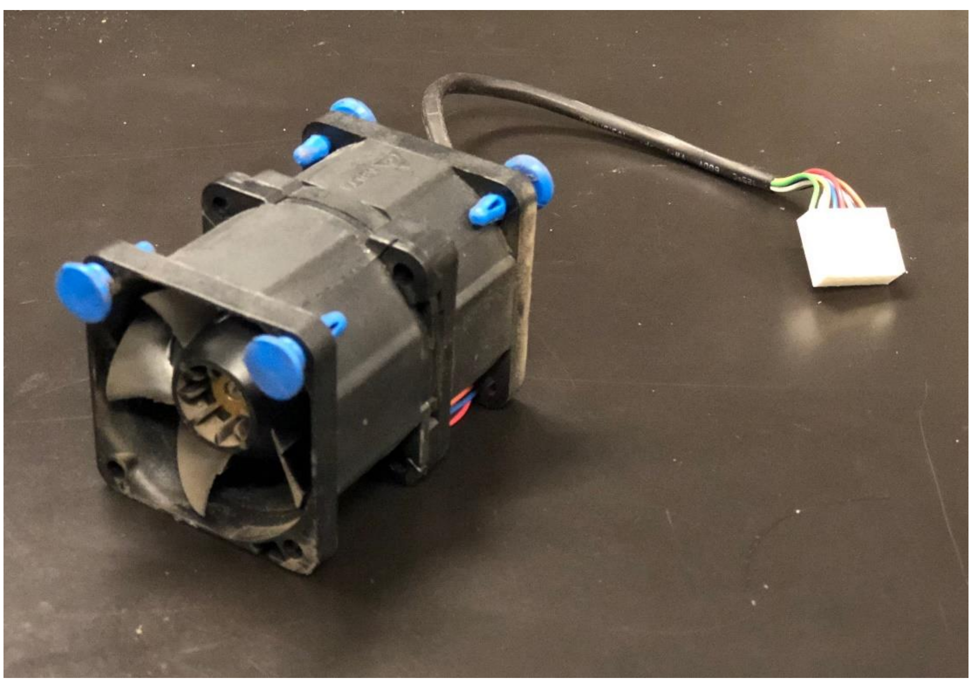

Figure 11 Fan used for HP ProLiant DL160 G6

The fan characteristics are as followed;

ITEM	DESCRIPTION
RATED VOLTAGE	12 VDC
OPERATION VOLTAGE	7.0 - 13.6 VDC
INPUT CURRENT	1.25 (MAX. 1.50) A
INPUT POWER	15.00(MAX. 18.00) W
SPEED	front 15000/rear 11200 R.P.M. (ref.)
MAX. AIR FLOW (AT ZERO STATIC PRESSURE)	0.770(MIN. 0.690) M^3/MIN. 27.30 (MIN. 24.75) CFM
MAX. AIR PRESSURE (AT ZERO AIRFLOW)	41.33(MIN. 37.27) mmH_2O 1.63 (MIN. 1.47) $inchH_2O$
ACOUSTICAL NOISE (AVG.)	59.5 (MAX. 63.5) dB-A
INSULATION TYPE	-------------
INSULATION STRENGTH	10 MEG OHM MIN. AT 500 VDC (BETWEEN FRAME AND (+) TERMINAL)
DIELECTRIC STRENGTH	5 mA MAX. AT 500 VAC 60 Hz ONE MINUTE, (BETWEEN FRAME AND (+) TERMINAL)
EXTERNAL COVER	OPEN TYPE
LIFE EXPECTANCE	--- HOURS CONTINUOUS OPERATION AT 40 °C WITH 15 ~ 65 %RH.
ROTATION	TWO FANS ROTATE IN COUNTER DIRECTIONS SHOWED IN THE NAME PLATE SIDE
OVER CURRENT SHUT DOWN	THE CURRENT WILL SHUT DOWN WHEN LOCKING ROTOR.
LEAD WIRE	UL 1061 -F- AWG #24 BLACK WIRE NEGATIVE(-) RED WIRE POSITIVE(+) BLUE WIRE FREQUENCY(-F00)

Figure 12 Fan characteristics [14]

The dimensions of the fan as provided by manufacturer are;

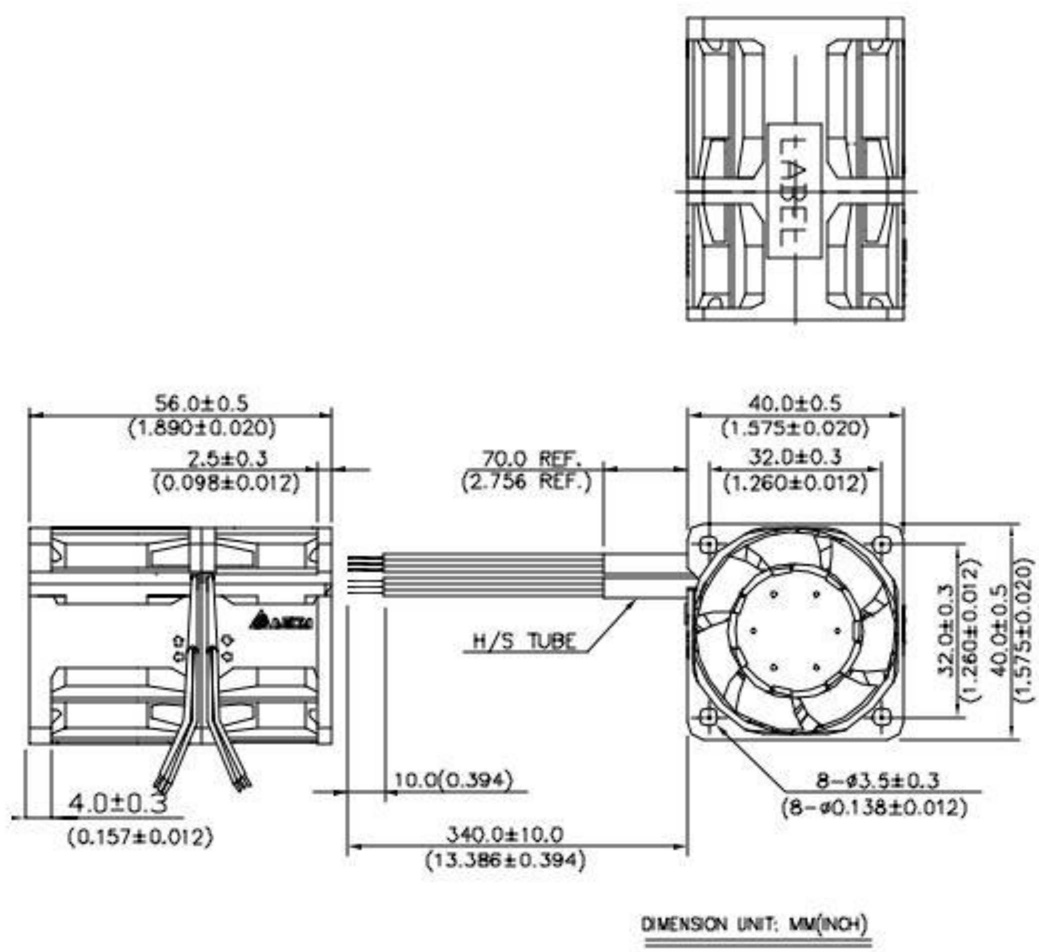

Figure 13 Fan Design Drawing [14]

The fan characteristic curve provided by manufacturer is as followed;

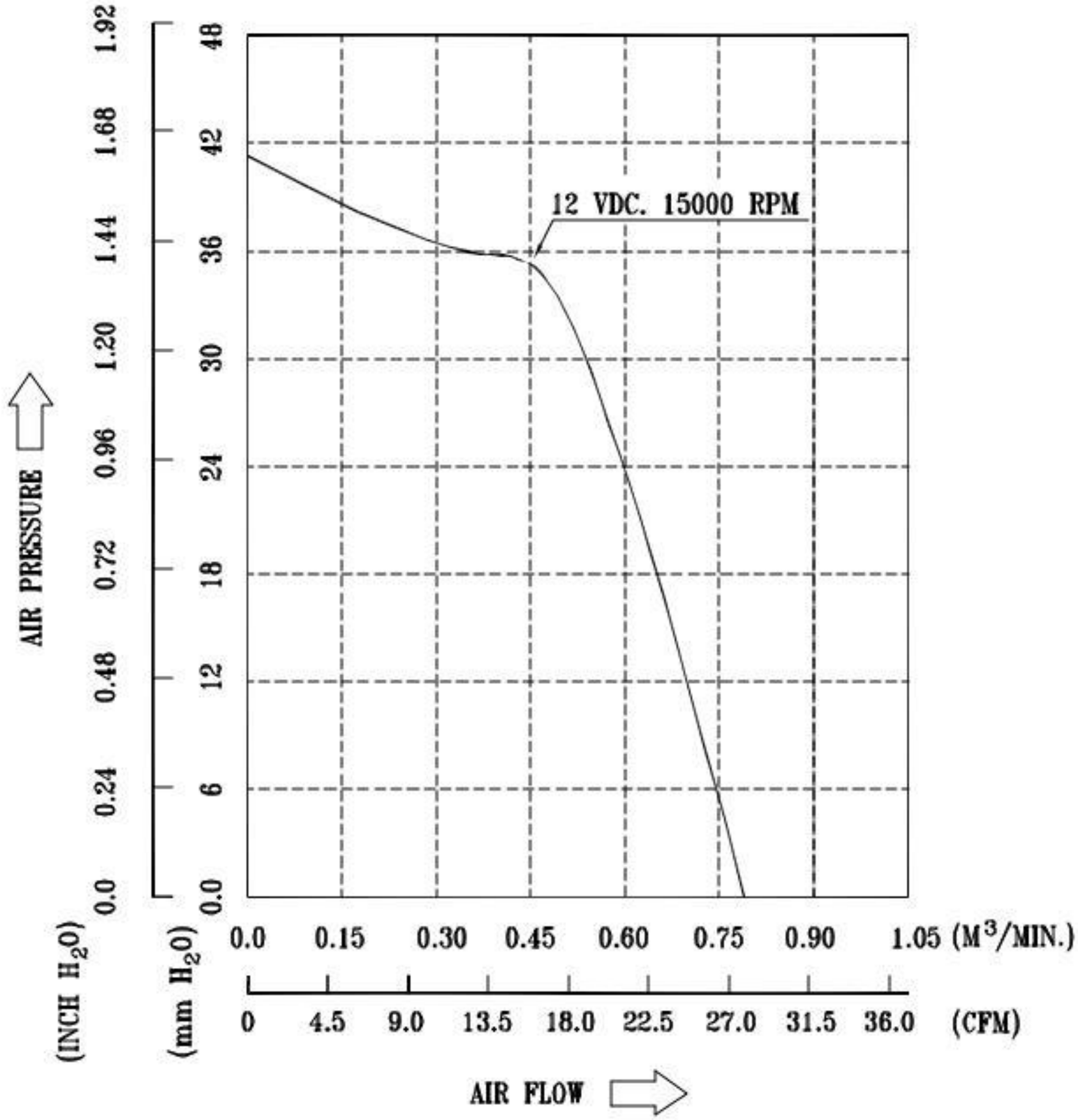

Figure 14 Fan characteristic curve [14]

2.1.4 Heat Sinks

Heat sinks are placed on major heat generating devices which eventually cool down the component by dissipating heat to air by heat transfer convection. This server consists of two straight fins heat sinks one on each processor so that both processors can operate within the operating range. There are two spring loaded screws provided for the mounting purpose on each side. It is mounted on black plate and screw receptacles which constitute mounting assembly.

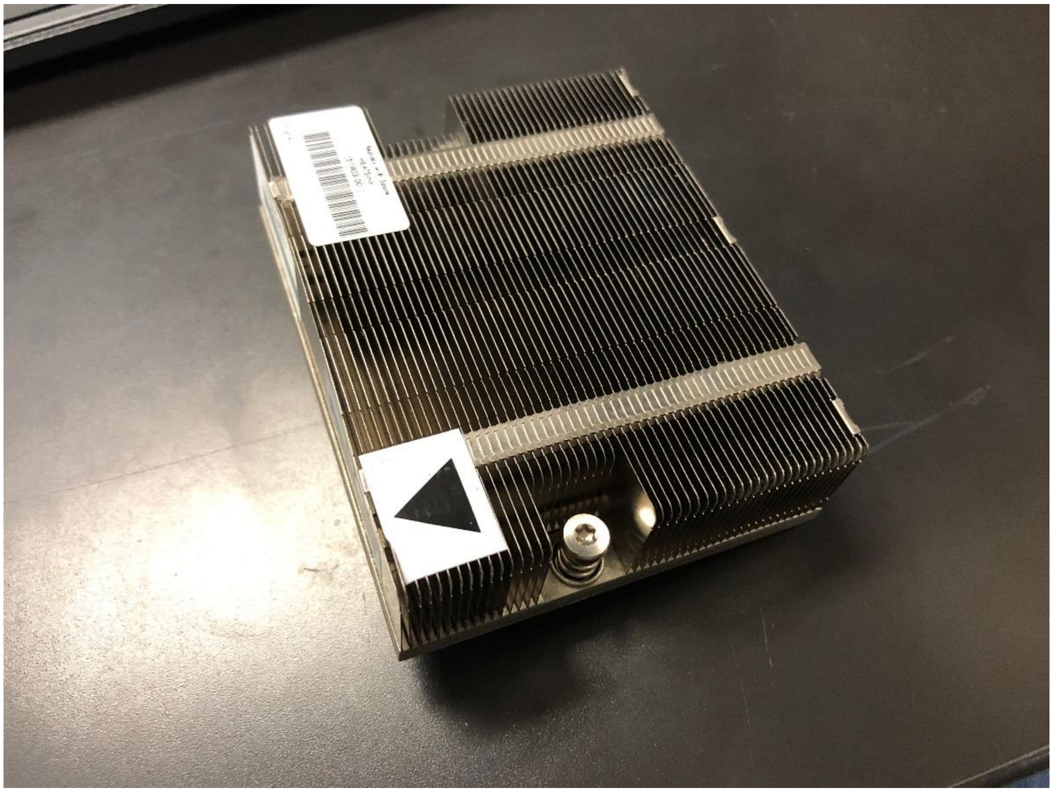

Figure 15 Heatsink to be mounted on CPU

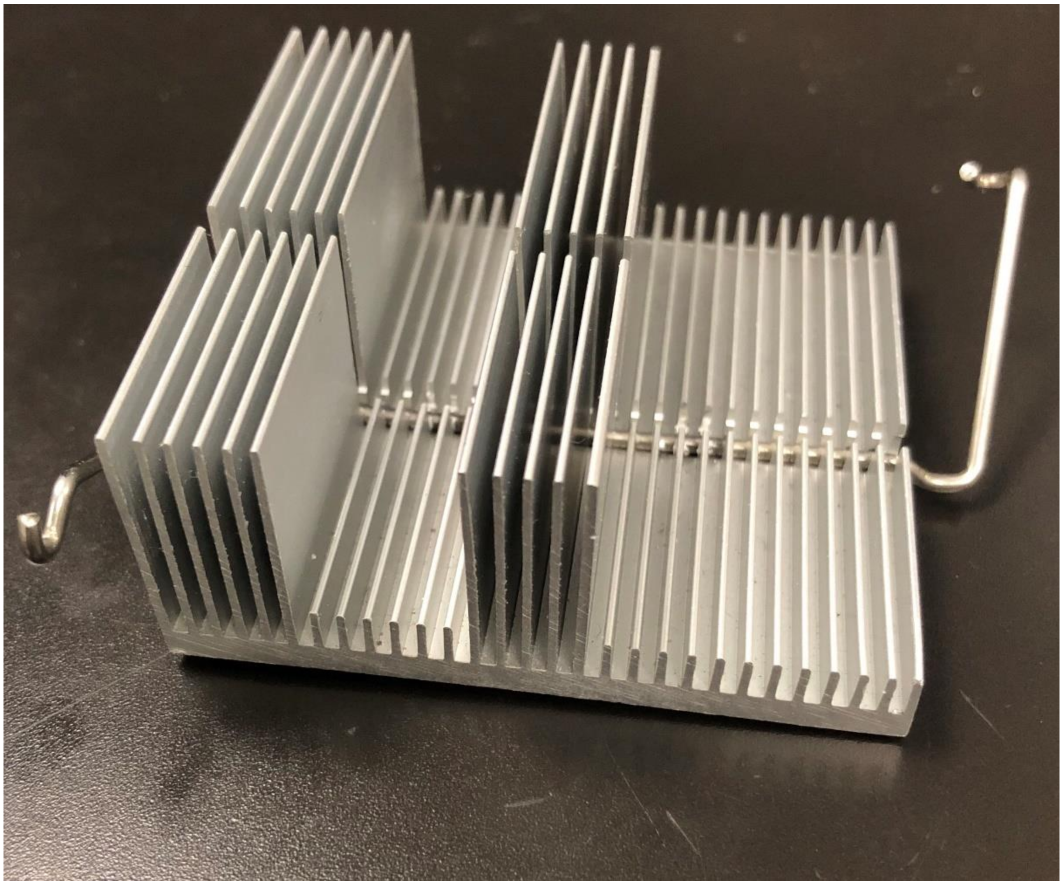

Figure 16 Heatsink to be placed on IOH Chip

2.1.5 Power Supply Unit (PSU)

The power supply unit is a standard 500W non-hot-plug or optional 750W or optional 460W hot-plug PSU with power factor correction factor. This server houses power supply unit on rear panel. It also contains a separate fan for cooling down the power supply unit. The fan used in power supply unit is DELTA fan of size 40mm x 40mm x 29mm. The specification of standard 5oo W power supply unit is as followed;

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 17 Standard 500-Watt power supply unit specification [15]

2.2 Liquid for Single – Phase Immersion Cooling Server Model.

For CFD analysis of single-phase immersion cooled server, Opticool 872552 is used. It is thermally conductive and electrically non – conductive fluid. It is non – toxic, non – hazardous, biodegradable oil. Flash point of Opticool 872552 is 185 ^{0}C. It is cost effective and hence provides safety and thermal stability at low cost. The temperature dependent properties of fluid are given in below table [16].

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	0.0397	2.204	0.1358
50	3.96	0.0307	2.242	0.1352
60	3.22	0.0247	2.28	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	1.7	0.0126	2.43	0.1323

Figure 18 Properties of Dielectric Fluid Used

For mineral oil, it is colorless, odorless, light mixtures of higher alkanes from mineral source, particularly a distillate of petroleum. Mineral oil is having temperature dependent properties but for numerical analysis purpose, constant properties of mineral oil is used. The properties of mineral oil which was used for analysis are [1];

- Density – 849.3 Kg/m^3
- Thermal Conductivity – 0.13W/mK.
- Specific heat – 1680J/KgK
- Thermal Diffusivity – 9.166 x 10^{-8} m^2/s
- Overall heat transfers co-efficient – 30-50 W/m^{2}K

Chapter 3 Validation of CFD Model Considering Different Parameters

3.1 System Impedance (System Resistance)

According to ASHRAE, safe operation of IT equipment requires specific environment which depends on certain parameters like Air inlet temperature, inlet relative humidity, inlet particulate contamination as well as inlet gaseous contamination and there are well developed standards for this also. Even after considering those parameters, it doesn't provide any guarantee of its safe operation. In order to maintain safe operation of server, flow rate through server or any other IT equipment is a major parameter to taken care of. For the flow rate through server, there are not any well-established standards. Basically, flow rate through server depends on its flow resistance characteristics. An IT equipment houses many electronic components like capacitors, voltage regulators and heat rejection devices like heatsinks etc. Such objects provide obstructions to the air flowing through the IT equipment. Due to obstruction, energy loss takes place and usually it is measured in terms of pressure drop and reduction in flow rate. Hence, this resistance offered by the system components to the flow of air is referred as System impedance or system resistance. Graphical representation of system impedance or system resistance is known as a System resistance curve or system impedance curve.

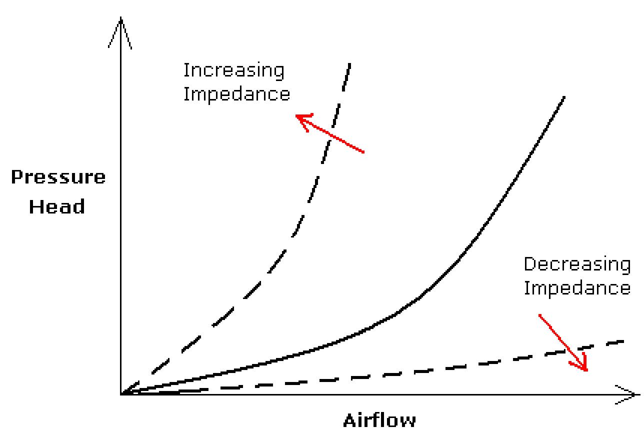

Figure 19 General Representation of System Impedance curve [17]

From graph, we can say that if system impedance curve coincides with horizontal axis then it is having no resistance to the air flowing through it. If system impedance curve coincides with vertical axis, then it is having too high resistance to the air flowing through it and we can consider this system as a blocked and there is no flow possible. As system impedance curve moves towards the horizontal axis, flow resistance decreases and hence pressure drop decreases. Similarly, as system impedance curve moves towards vertical axis, flow resistance increases and hence pressure loss also increases.

3.2 Fan Curves and Static Pressure Drop across the Server

Experimental determination of static pressure drop across the server is a key parameter in the validation of CFD model. Air flow through the system depends on the resistance offered by the system component. System resistance causes the pressure to drop as flow occurs through the system. Decrease in pressure is due to generation of boundary layers as fluid flow through server components. The pressure drop depends on fluid properties and its parameters like its velocity and initial pressure. Hence, basically determination of the flow characteristics of fluid through server components is very important in validating the CFD model.

At the same time, determination of fan performance curve is also very important as from which one can determine the performance of fan at different static pressure conditions. Fan curve for a fan is a graph of airflow rate vs static pressure across the system. By using fan performance curve, one can determine amount of air flow that a fan can generate for a given static pressure across the system. Fan performance curve is different for each fan. In this server, six fans are mounted and all are of similar type. By superimposing the system resistance curve and fan performance curve, we can get the operating point at which the fan will operate by finding the intersecting point.

3.3 Airflow Rate

After determining the pressure drop across the system, it is also required to determine volumetric flow rate through the system at various fan speeds. The fans speed varies depending on the core temperature of CPU. Basically, fan speed is controlled by motherboard depending on the CPU core temperature. So, as core temperature increases, volumetric flow rate through the server also increases to cool down the CPU temperature and keep it within its operating range for its optimum performance.

3.4 Operating Point

Operating point can be defined as intersecting point of two system impedance curve and fan characteristic curve. It is important to note that system impedance curve is not only for a single system and similarly fan characteristic curve is not only for one single fan, it may refer to series or parallel combination of fans. From system impedance curve we can get the idea of flow requirement of server. On the other side, fan characteristic curve shows the capacity of fan to supply air at various static pressures. Hence, the point at which both system impedance curve and fan characteristic curve intersects provides the information about pressure at which server operates.

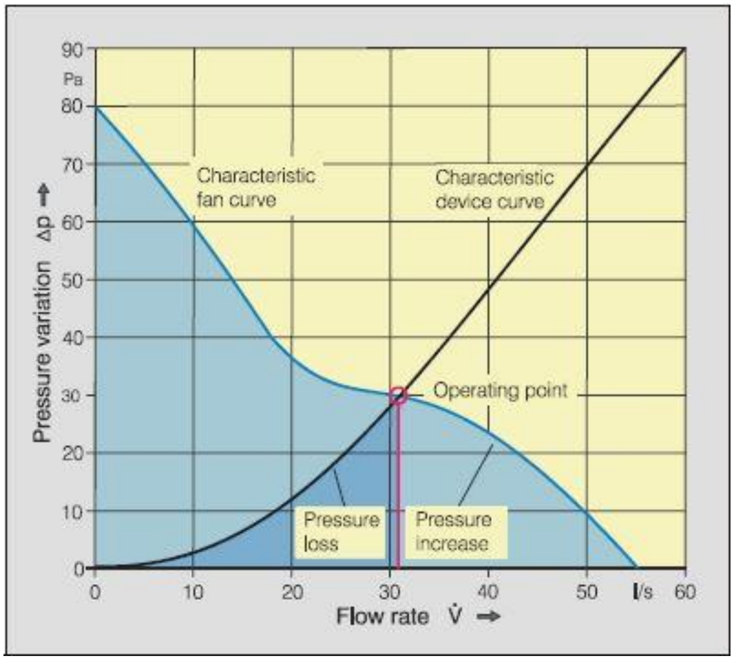

Figure 20 Operating point of a system [18]

Chapter 4 Experimental Methods and Tools

4.1 Airflow Bench Testing

Accurate determination of amount of air required to cool down the server may require the data about heat dissipated as well as the temperature difference across the server. But at the same time, calculating pressure difference required to create air flow across the server is also a difficult task. It is also important to set the fans either for pull consideration or push consideration.

Airflow bench test can be used for accurate determination of static pressure drop across the system as well as volumetric flow rate through the system. It can also be used to determine fan performance curve and system impedance curve or system resistance curve. The air flow bench that we are using for experimentation, was manufactured by Airflow Measurement Systems and designed according to AMCA 210-99. The test chamber can provide wide range of airflow rates by using different nozzle diameters. The chamber enhouses pressure taps which are directly connected in order to measure the static pressure of system. The differential pressure is also measured by pressure taps to flow rate through the system.

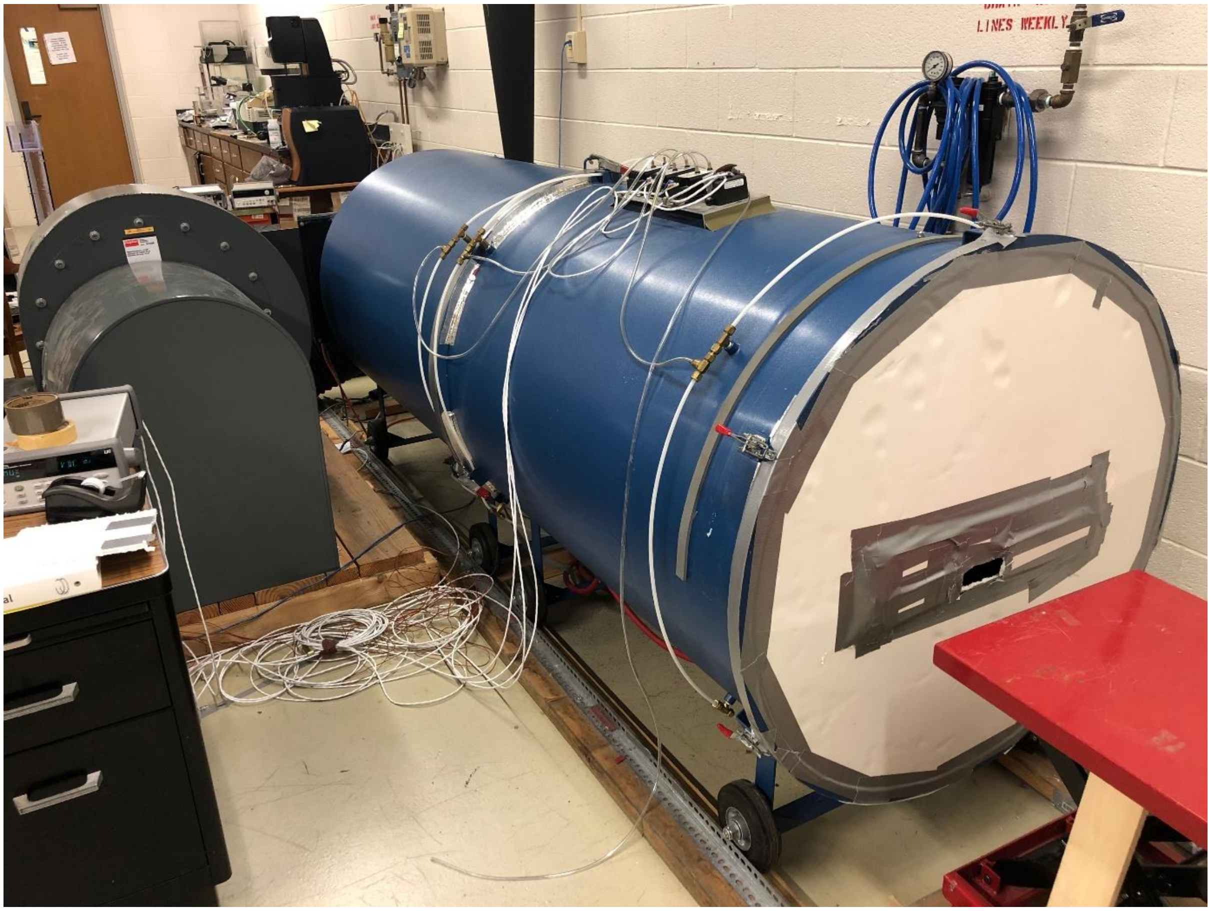

Figure 21 Airflow Bench Setup

4.1.1 Air Flow Bench Test Setup

The airflow bench consists of two chambers which are separated by a nozzle plate placed in between them. In order to determine pressure in the chambers, pressure taps from the chamber are connected to the pressure transducers having differential pressure range from 0 to 5 inch of water. The variable capacitor is been formed by closely placed tensioned diaphragm and insulated electrode. Positive pressure causes the diaphragm to move towards the insulated electrode resulting in increase in the capacitance. Similarly, negative pressure causes the diaphragm to move away from electrode resulting in decrease in capacitance.

A software can be used to convert voltage change (which is obtained from capacitance change) into pressure value.

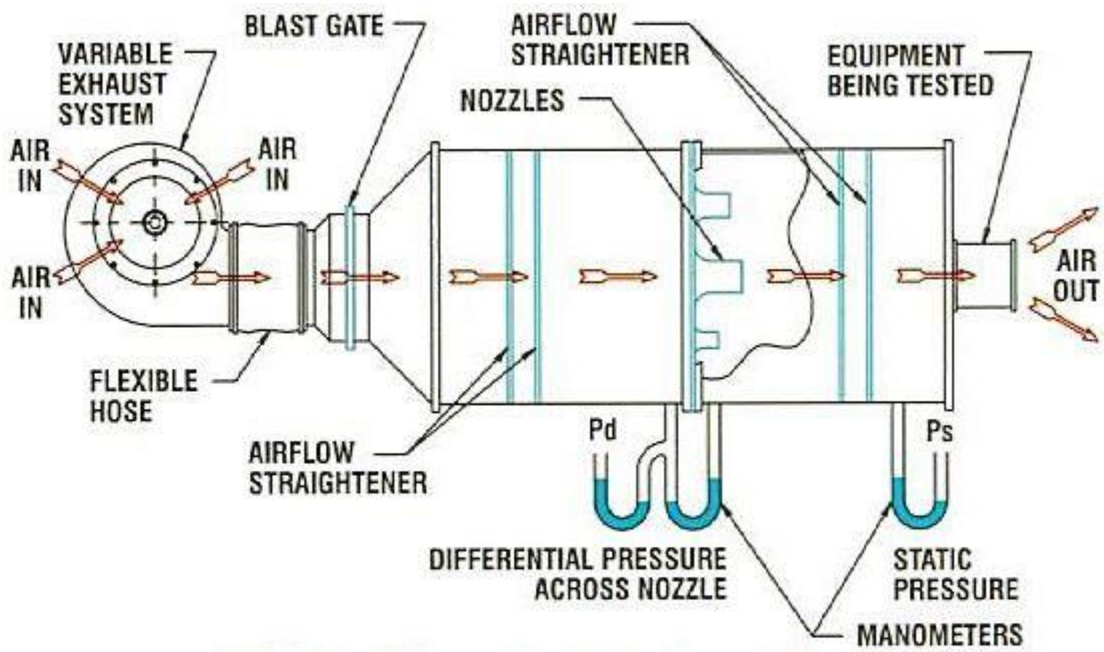

Figure 22 Schematic Diagram of Airflow Bench Setup [19]

Nozzle selection chart is used for selecting a nozzle. The proper mounting is provided for each nozzle size on the nozzle plate. Each nozzle has its flow stopper in order to block the flow through the nozzle when it is not in operation. The wide range of flow rate can be generated using air flow bench testing with different nozzles.

Figure 23 Flexible hose connecting blower with airflow chamber

The airflow chamber is incorporated with a counter blower and counter blower is controlled by speed controller. The airflow provided by blower can be varied by changing the frequency in the speed controller. The flexible hose Is used to supply air from blower to airflow chamber. Blast gate which is a sliding gate valve at the chamber end can also be used to vary the amount of air flow through chamber. According to manufacturer to get a high resolution, the maximum differential pressure caused by flow through the airflow bench should not be more than 3.0 inch of water. In case of any unknown airflow requirement of a device, nozzle with 2-inch diameter should be selected and operated under free delivery condition to get idea about operating airflow range. If differential pressure is higher than 4-inch of water then, nozzle with larger diameter should be used. Similarly, nozzle with smaller diameter should be used if differential pressure is below 1 inch of water.

Figure 24 Blower

As airflow bench setup consists of various parts, airflow bench is subjected to air leakage issues. Any type of air leakage in the system may lead to wrong reading of differential pressure. In order to prevent any air leakage issues, inflatable seals are provided on both side of the nozzle plate as well on the front plate.

4.2 Static Pressure Drop Measurement

The server inlet was placed at the outlet of the airflow bench. Server chassis from server inlet side is placed slightly inside the chamber to avoid any type of losses. The airflow bench on outlet side with inserted server in it is sealed using tacky tapes to make it airtight. Similarly, all the possible leaks must be sealed using tacky tapes. All holes and vents on the server chassis must be sealed or closed except vents at the outlet.

Figure 25 Transducers for pressure measurement

Pressure gauge along with manually working control valve is provided with airflow bench in order to maintain the constant pressure inside the airflow bench test chamber. During the airflow bench testing, pressure inside the chamber is required to be constant. It might decrease due to air leakage in the setup.

Figure 26 Pressure gauge along with valve

The airflow bench was setup on push configuration to blow the air through the server. One end of flexible hose was connected to blower outlet and another end of flexible hose was connected to inlet of chamber. The blast gate was completely open. Orientation of nozzle array was placed towards the flow downstream. Based on required flow rate, selection of nozzle was made. The nozzle stopper was removed from the nozzle that we wanted to utilize. The tubes from the chamber before and after the nozzle array plate were connected to the high and low ports of pressure transducer. Hence, the differential pressure that we are measuring is the pressure difference between the pressure before and after nozzle array plate. The tube near the server inlet was connected to high port of pressure transducer and low port was kept open to atmospheric pressure.

The frequency of the blower is varied, and the static pressure values are recorded for different flow rates. Hence, static pressure values are plotted against the flow rates which gives us the system resistance or system impedance curve.

Figure 27 Setup of server for airflow bench testing

Similar procedure was followed for the power supply unit. After inserting power supply unit slightly inside at the outlet of the airflow bench, tacky tape is used for airtight sealing of outlet of airflow bench. Special care should be taken while sealing the outlet of airflow bench. Any kind of even a small leakage can result in faulty pressure readings. In this study, server motherboard has 6 fans running as per its cooling requirement. While power supply unit has its own fan for cooling and power required for operating the fan is provided by power supply unit. The speed of the fans powered by motherboard is depends on server loads. Power supply unit has its own chassis which enhouses number of components in it. Hence, static pressure drop particularly for power supply unit was figured out separately by using airflow bench testing. These data can be further used to validate the CFD model of power supply unit.

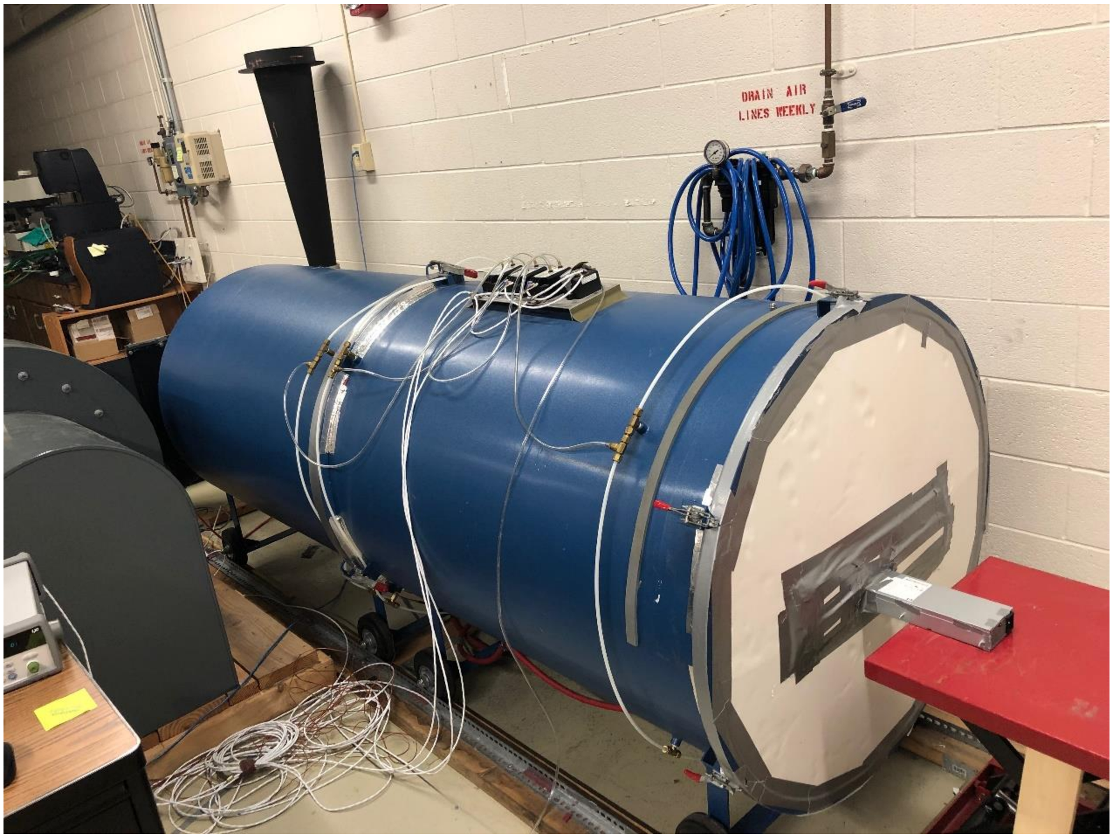

Figure 28 Setup of PSU for Airflow Bench Testing

Chapter 5 CFD (Computational Fluid Dynamics) Analysis and CFD Modeling

5.1 Introduction to CFD

Computational Fluid Dynamics or CFD can be defined as a computer-based simulation or analysis which involves fluid flow, heat transfer and any other related phenomena. It is very powerful technique and is applied in wide range of industrial and non-industrial area. Earlier the application of CFD analysis was limited to aerodynamic application only which include testing of designed aircraft and flow over the aircraft etc. Nowadays, it carries wide range of applications in different fields. It is applied in; [20]

- Aerodynamics of aircraft and vehicles; lift and drag
- Internal combustion engines and gas turbines-based power plants
- Turbomachinery
- Electrical and electronic engineering; cooling of electronic equipment
- Biomedical engineering; characterizing blood flow through arteries
- Chemical Process Engineering
- Hydrology and oceanography
- Environmental engineering

Computational Fluid Dynamics (CFD) can be considered as a branch of fluid mechanics which interacts with numerical simulation and analysis of fluid flow through system, heat transfer characteristics and pressure characteristics. It uses numerical methods to predict, simulate and analyze distribution of various flow parameters like velocity, pressure, temperature. These results can be used to analyze the designed model and helps to optimize the design. [21]

CFD analysis tools works on CFD codes which are structured around numerical algorithms that interacts with fluid flow problems. In order to provide easy interaction between user and CFD software, CFD packages includes excellent sophisticated user interface to provide problem details and parameters and to check the results or for post processing. Hence, coding is done for this purpose and mainly contain major elements: pre-processor, solver and post-processor.

Post-processing of any problem requires user to input the flow problem to a CFD program through user friendly interface and conversion of input data into a form of data that can be used by solver. Post-processing of a includes;

- Definition of a geometry
- Grid – generation
- Selection of physical/ chemical phenomena to be analyzed
- Definition of fluid properties
- Applying boundary condition to the geometry

Solver includes application of different numerical codes to derive the solution of the problem. There are three distinct streams of numerical solution techniques: Finite Element Method, Finite Difference Method and Spectral Methods. Most of the CFD analysis software works on the finite volume method in turn which can be considered as a special case of finite difference method. It is the main concept used in development of CFD codes like: CFX/ANSYS, FLUENT, PHOENICS and STAR-CD. Numerical algorithm on which CFD solver works includes following processes;

- Integrating fluid flow governing equations over finite control volume of domain
- Converting resulting integral equation into a system of algebraic equation
- Solution of algebraic equations by an iterative method like Newton – Raphson Method etc. [20]

Post-processing includes the conversion of data solved by the solver into desired any means of result representation. Nowadays increased use of workstations with outstanding graphics capabilities causes CFD package to be equipped with complex data visualization tools. Data visualization tools includes;

- Vector plots for visualizing velocity, temperature, pressure or other properties within the system

- Streamline plot or particle tracing to visualize flow of fluid through system
- Contour plots
- 2D and 3D surface plots

5.2 Governing Equations

Computational Fluid Dynamics codes are based on Navier-Stokes equation. The numerical solution for the fluid flow and heat transfer based problems is obtained by solving a series of three differential equations. The governing equations of fluid flow are basically mathematical statements of laws of conversation of physics. Laws of conservation can be described as [20];

- Law of conservation of mass;

$$\frac{\partial \rho}{\partial t} + \text{ div } (\rho u) = 0$$

- Law of conservation of momentum;

$$\frac{\partial (\rho u)}{\partial t} + \text{ div } (\rho u \vartheta) = \text{ div } (\mu \text{ grad u }) - \frac{\partial P}{\partial x} + S_M$$

- Law of conservation of Energy;

$$\frac{\partial (\rho i)}{\partial t} + div\ (\rho i \vartheta) = -p\ div\ \vartheta + div\ (k\ grad\ T) + \emptyset + S_i$$

5.3 Turbulence Modelling

Turbulent flow can be described as a flow regime which is characterized by irregular fluctuations in all directions and infinite degrees of freedom in all directions. In the turbulent flow model, rapid changes in fluid flow parameters takes place. Reynolds number is used a matric to determine whether the flow is laminar or turbulent. 6SigmeET uses K – Ɛ turbulence model.

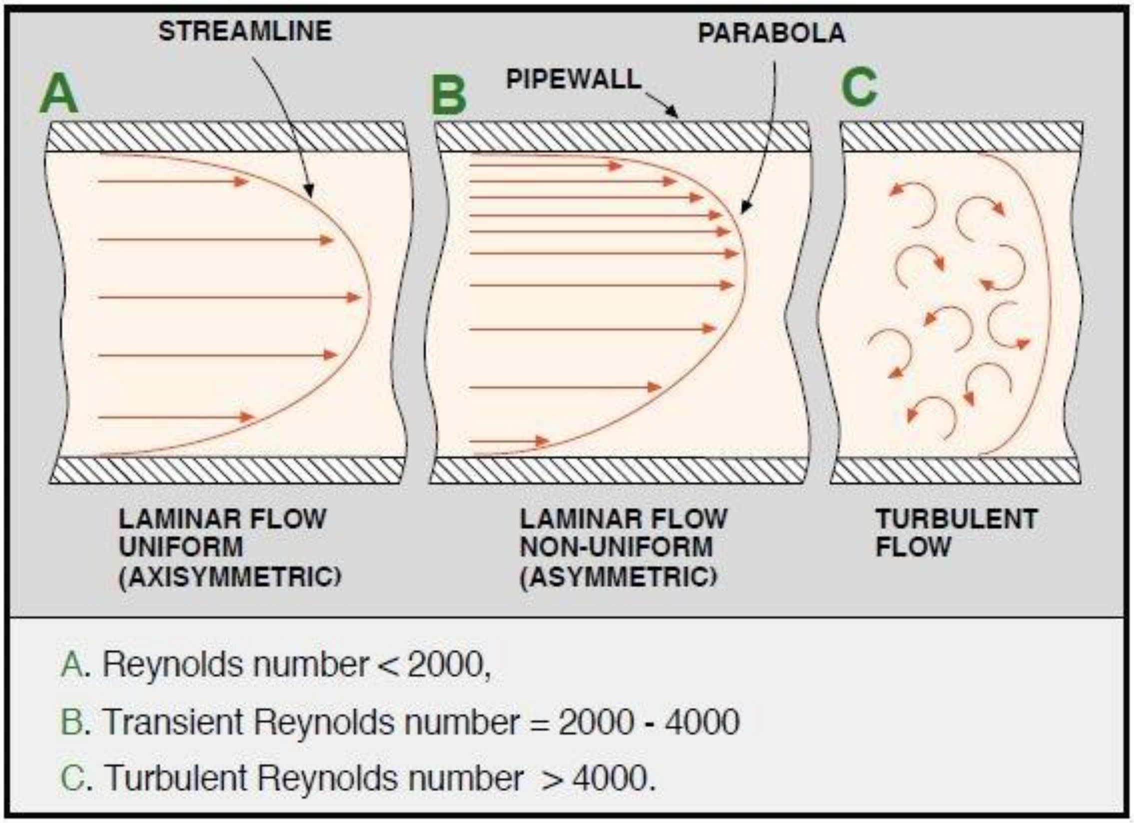

Figure 29 Turbulent flow and Laminar Flow Model [22]

5.3.1 K-Epsilon Turbulence Model

For turbulence flow modeling, K – epsilon flow modeling is widely used turbulent flow modeling which is also known as two equation flow model. It includes two variables; K, kinetic energy of turbulence and Ɛ, rate of dissipation of kinetic energy of turbulence. Specifically, for thin shear layer problems along with recirculating flows, K – Ɛ turbulence model is commonly used. Equation for K and Ɛ can be described as; [20]

$$\frac{\partial(\rho k)}{\partial t} + div\ (\rho k U) = div\ \left[\frac{\mu_t}{\sigma_k}\ grad\ k\right] + \ 2\mu_t S_{ij} S_{ij} - \ \rho\varepsilon$$

$$\frac{\partial(\rho \varepsilon)}{\partial t} + div\ (\rho \varepsilon U) = div\ \left[\frac{\mu_t}{\sigma_\varepsilon}\ grad\ \varepsilon\right] + \ C_{1\varepsilon}\frac{\varepsilon}{k} 2\mu_t S_{ij} S_{ij} - \ C_{2\varepsilon}\rho\frac{\varepsilon^2}{k}$$

5.4 Grid Configuration and Meshing

Grid configuration is for specifying minimum and maximum cells across the model geometry. 6SigmeET uses a cartesian grid. Grid in 6SigmaET is component specific grid. As each component is readily available in object library, it automatically meshes components as per their importance according to pre-defined gridding rules. It automatically decides which grid is best suited for simulation purpose.

5.5 Objects

6SigmaET® is specifically designed for electronic industry and hence it directly provides all the components and sockets those are required to be mounted on PCB. In addition to that it also uses the same nomenclature that is used in industry. Entities in 6SigmaET are parametrically defined and know their function and behavior which makes model too easier to build, mesh and analyze. Objects are readily available that can be used directly and even if further modification required, it is also possible in terms of material properties and thermal properties. Objects like chip socket, components, TIM, heatsink and may other are readily available which makes the things a lot easier. [23]

5.5.1 Test Chamber

Test chamber is kind of faux wind tunnel where model can be developed and tested under number of different flow conditions. It acts as an enclosure to the server chassis. Different environment can be attached to the test chamber or flow can also be prescribed. Different environment corresponds to ambient environment for air cooling and immersion bath for oil immersion cooling. In this case, front and rear end of test chamber are specified as an open hole and top, bottom, left and right side of test chamber are specified as wall.

5.5.2 Server Chassis

As we open the 6SigmaET, default chassis model is created automatically having dimensions of 440mm x 500mm x 1 U height. Then user can change the dimensions as per the modeling requirement. It is hollow cuboidal duct in which PCB, fan assembly, hard drive can be designed. User can change the measuring unit and properties as per modeling requirement. User can assign thickness, material and different environmental condition to each different side of chassis. By selecting a material, specific thermal and surface properties related to that material will be automatically applied to the chassis. It also allows to design the chassis as thick sheet or thin sheet. User can model vent opening on any face of the chassis and can also provide the percentage opening for that vent opening. Everything that user is going to add in chassis directly, will appear under chassis node and can also be organized from here. Chassis node consists of following nodes;

- Cooling – includes fans, blowers, heatsinks
- Electronics – includes PCB and components that can be mounted on it, disk drives and drive bays
- Obstructions – includes different types of obstruction which also includes solid obstruction, porous obstructions, perforated or slotted obstructions etc.
- Sub-chassis – includes chassis which is inside a parent chassis that can be used for creating power supply unit.
- Sensors – includes pressure sensor, temperature sensor, velocity sensor which can be placed anywhere within designed model

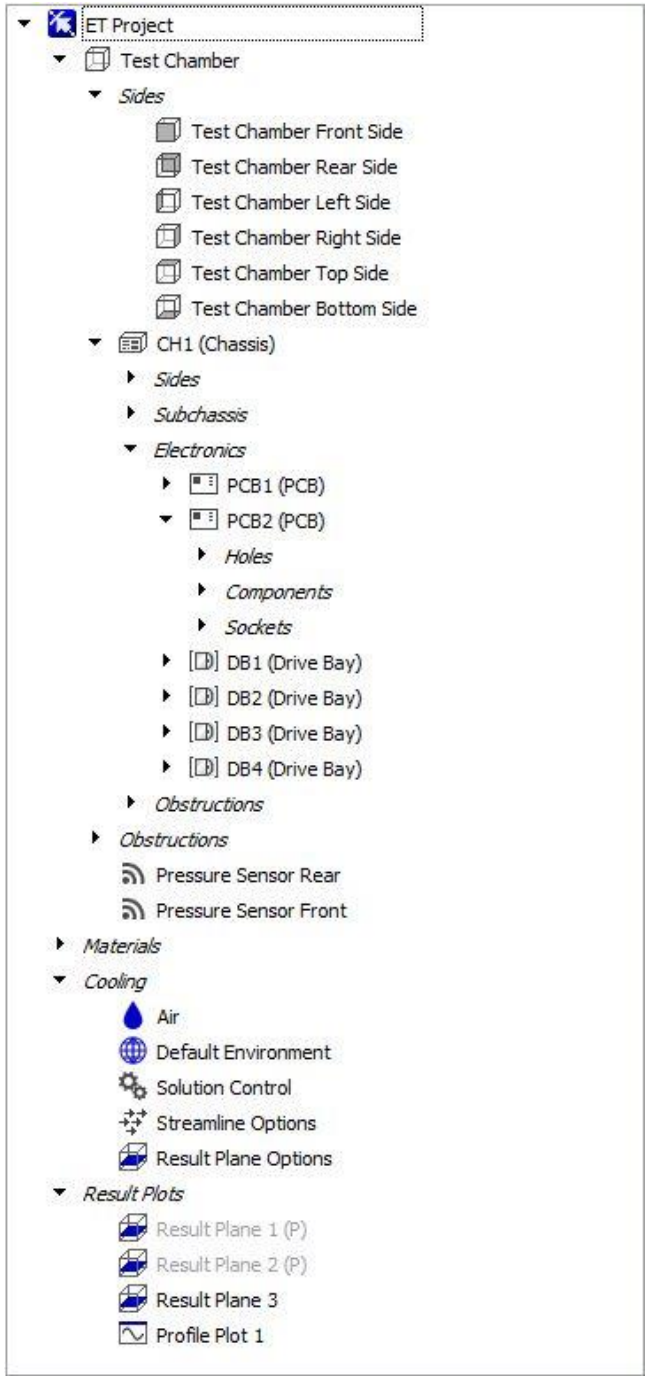

Figure 30Model tree in 6SigmaET

5.5.3 PCB

Printed Circuit Board (PCB) is a composite manufactured from thin copper sheets which is been laminated to the insulating substrate. Using photolithography, conductive paths are produced on the top of it leaving the remaining area non-conductive. Its function is to provide mechanical support to the components to be mounted on PCB and connect those components electrically through the conductive paths traced using photolithography. While modeling PCB, 6SigmaET® carries a feature by using which PCB can be modeled easily.

5.5.4 Sensors

Sensors can be considered as a measurement device which can be used to measure pressure, temperature, velocity and other data about the environment to which it is attached. Sensors can be placed at any location in the solution domain. In this simulation, two sensors are placed one at inlet and other at outlet for measuring the pressure which can be further used for characterizing system impedance curve.

5.5.5 Fans

Fans are flow creating used in server to create enough amount of air flow through the server which is enough to cool down the processor temperature or to maintain the temperature within operating range for the safe operation of the server. Basically, fans convert the torque applied to propeller shaft into the kinetic energy required by air to flow through server. It creates pull configuration on the one side of the server and push configuration on the other side of server. Six fans are placed in array for the cooling purpose in this server. For this type of application, axial fans are most commonly used. Axial fans supply the air flow in the direction parallel to axis of fan rotor. Such axial fans can deliver air with very high volume and low pressure.

5.6 PAC

PAC Study in 6SigmaET® stands for parameterize, analyze and compare, which is used for carrying out parametric analysis for determining results for various alternative cases. It allows us to add number of input parameters and as well as output parameters which can be analyzed. By varying values of input parameters, it will simulate the model and gives us the value of output parameters. By using configure input parameter we can include various parameters as input which can be varied. By using similar feature configure output parameters, output parameters can be added. It reduces time required for comparing different parameters as it shows us the all input and output parameters in a single window named configure PAC matrix. By using PAC study, mesh sensitivity analysis can also be performed with ease. It allows to perform PAC study with different fan speed, different fin configuration, different flow rates.

5.7 Detailed Modeling of Server

6SigmaET® is used for modeling the HP ProLiant Dl160 G6 server. Server enhouses the number of components. Some of which might affect the system resistance and some of them might not. At the same time, it is also very difficult to model each component that is present on the motherboard as they might not affect the system impedance. Similarly, some components present in the server contribute negligible to the total power generated by the server. In order to develop detailed server model, most of the major heat generating and flow restricting components are taken under consideration while modeling the server. Major heat generating components are chosen based on their Thermal Design Power (TDP).

Device	Reference Designator	Thermal Design Power (TDP)
Processors	CPU1	95 W
	CPU2	95 W
DIMMS	DIMMS	2.50 W
Chipsets	ICH chip	4.5 W
	IOH chip	27.4 W
Fans	Fan1	0.7-6 W
	Fan2	0.7-6 W
	Fan3	0.7-6 W
	Fan4	0.7-6 W
	Fan5	0.7-6 W
	Fan6	0.7-6 W
Power Supply Unit	PSU	5 % of server power
Hard Drives	HDD	8 W

Figure 31 TDP of each component [24]

Initially, detailed server model was developed in 6SigmaET®. The airflow takes place from front end of the server to rear end of server. Test chamber of exact dimensions to server chassis was developed in 6SigmaET®. The purpose of creating the test chamber to provide a virtual environment like actual experimental setup.

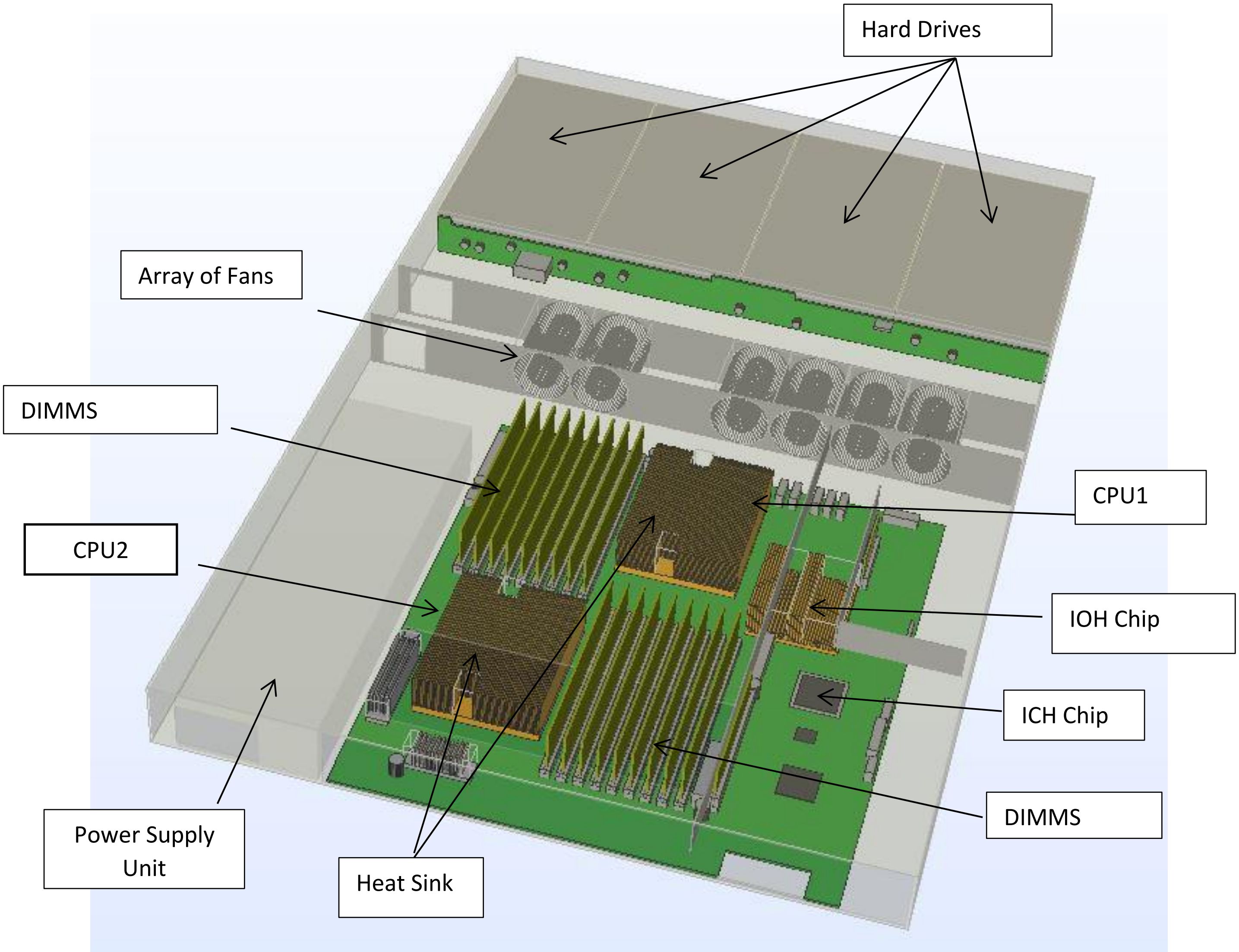

Figure 32 Server Detail Design Model

In this detail model of server developed in 6SigmaET®, all the major components were modeled. The duct provided in actual server was made transparent configuration so that other details can be made visible.

For single – phase immersion cooling model, same PCB was placed inside the container having inlet on one side and outlet on other side. Hard drives were removed from server due to functionality issues as hard drives will not operate if immersed in liquid. Fans are also removed from the server as they were no longer necessary for the single – phase immersion cooling. Below is the picture of single – phase immersion cooling model.

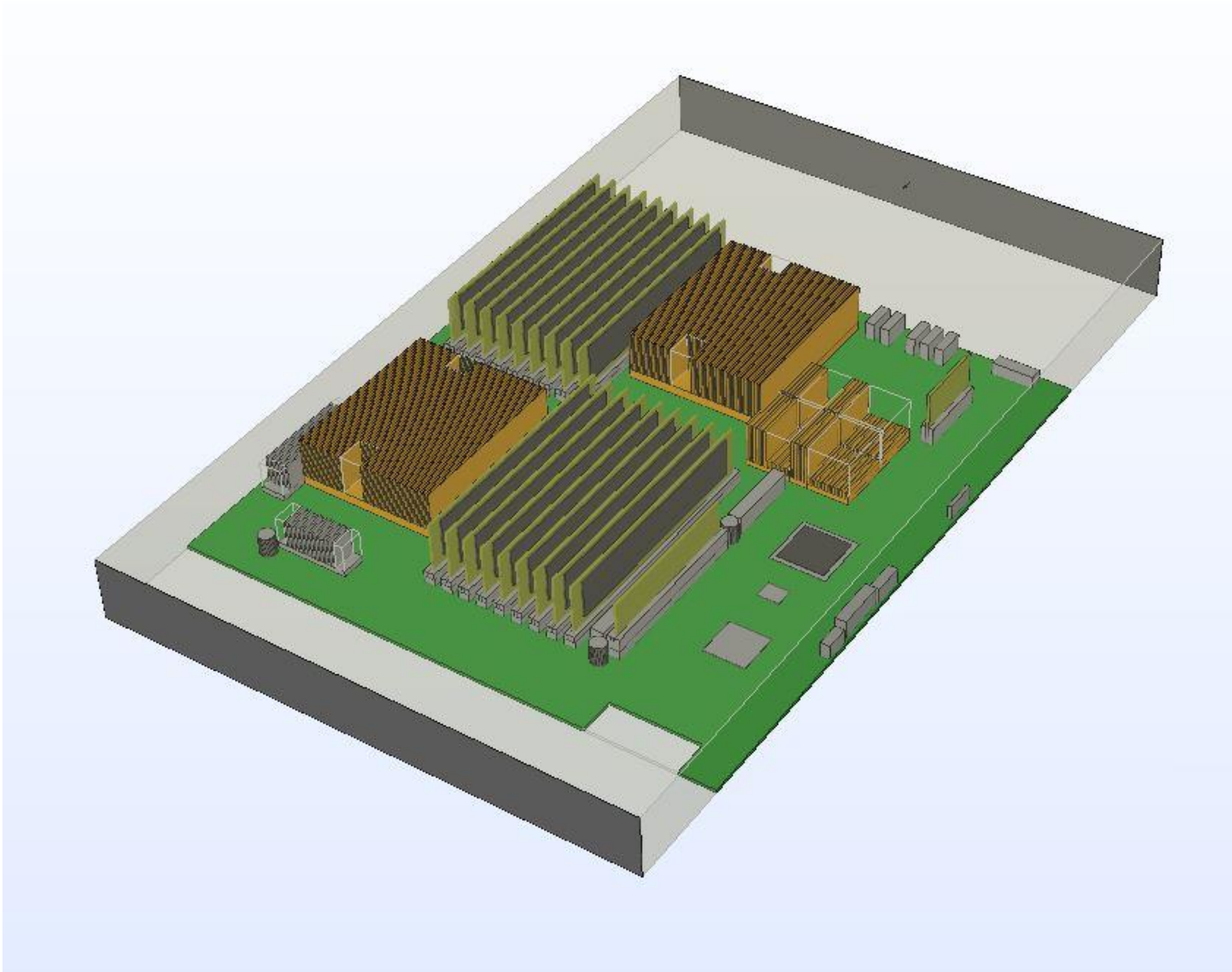

Figure 33 Single - phase immersion cooling model

5.7.1 Heat Sink Model

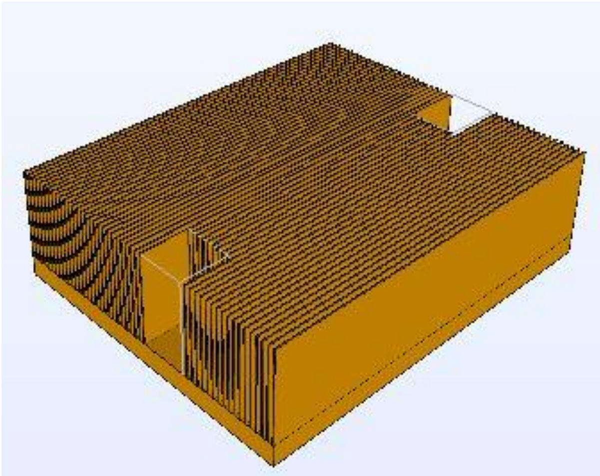

Figure 34 Heatsink to be placed on processors

The detailed model of heat sink was developed which includes each geometric feature like actual heat sink. The dimensions of heat sinks were measured manually by using Vernier calipers. The heat sinks were tested on the air flow bench along with server and system impedance was measured. The model was also simulated to verify the modeling accuracy. The above shown is of heatsink to be placed on the processors.

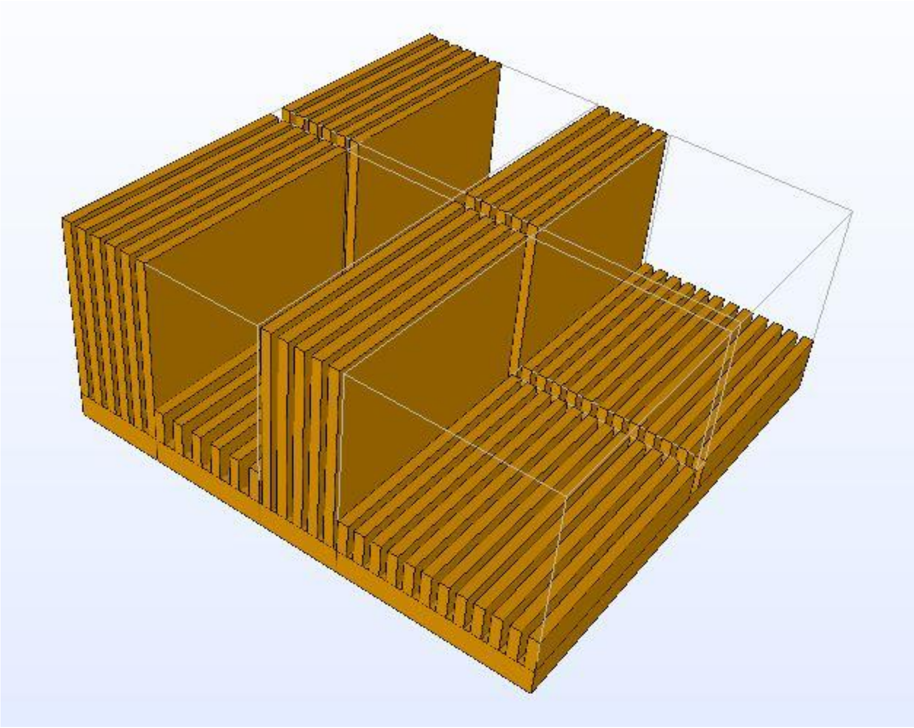

Figure 35 Heatsink on IOH chipset

Heatsink to be placed on IOH chip is having fins of two different heights. It is quite difficult to be designed in 6SigmaET® as it doesn't allow us to model the heatsink with two different fin height at the same time. In order to overcome this limitation, heatsink was designed in two parts separately and then making their assembly will result in the required heatsink.

5.7.2 Server Duct Model

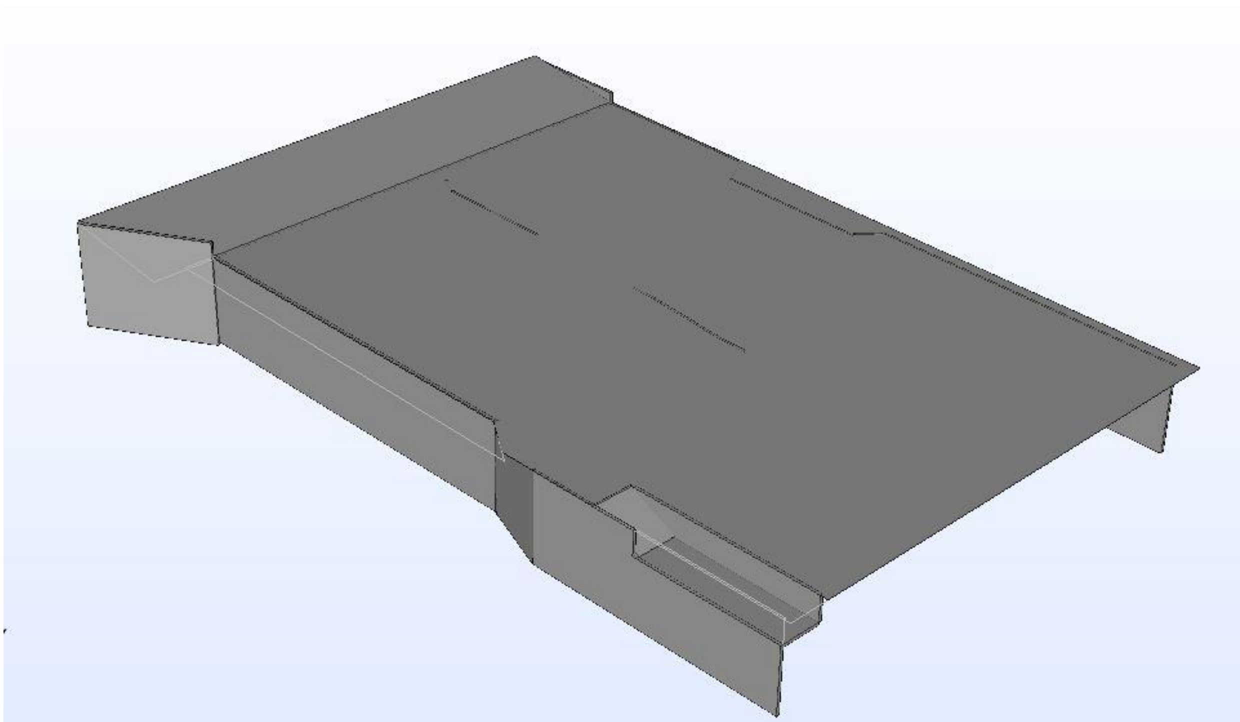

Figure 36 Top view of Duct

Duct inside the server was designed as a solid obstruction. The main purpose of the duct is to guide the air flow towards major heat generating components like heat sinks. It was very difficult in 6SigmaET® to design this complex duct and all the sides of this duct to place closely. The above picture is the top view of duct developed in 6SigmaET® and below picture shows the upside-down view of the duct.

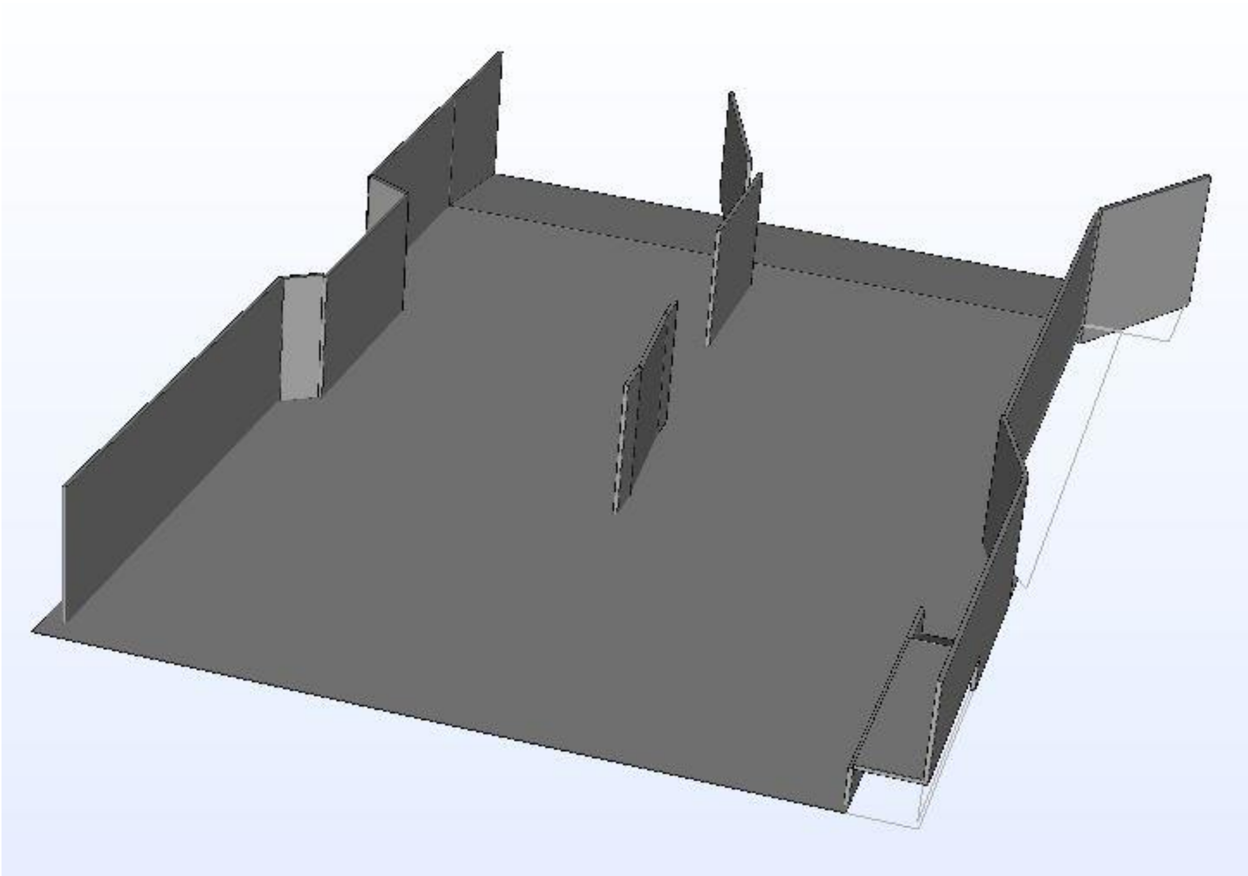

Figure 37 Upside down view of Duct

5.7.3 Dual in Line Memory Module (DIMMS) Model

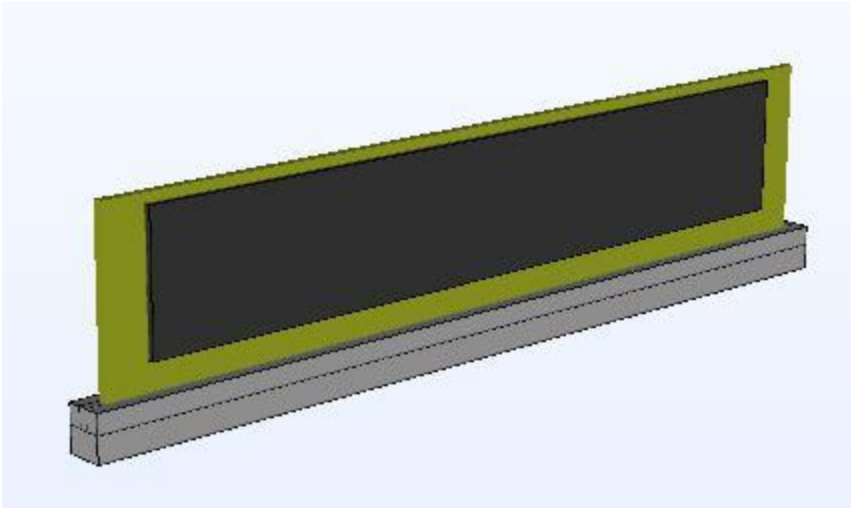

Figure 38 Dual in Line Memory Module

In order to model dual in line memory module in 6SigmaET®, first daughter board socket was modeled as parent on PCB. Then child PCB is modeled and inserted in the daughter board socket and components are created on the child PCB. In order to simplify the model, instead of creating several small components one simplified component is modeled. Total 18 DIMMS model were developed to be placed on PCB.

Chapter 6 Results and Discussion

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6.1 Characterization of System Impedance Curve of Server

As procedure mentioned earlier, system resistance or system resistance curve of server was experimentally characterized in order to validate the CFD model that has been developed using 6SigmaET. The inlet of server was inserted a little inside the outlet of the airflow bench and fixed airflow rate is supplied and static pressure is measured. This same procedure was followed for different flow rates. Below is the graph showing comparison between the system impedance curve obtained experimentally and using CFD analysis in 6SignmaET.

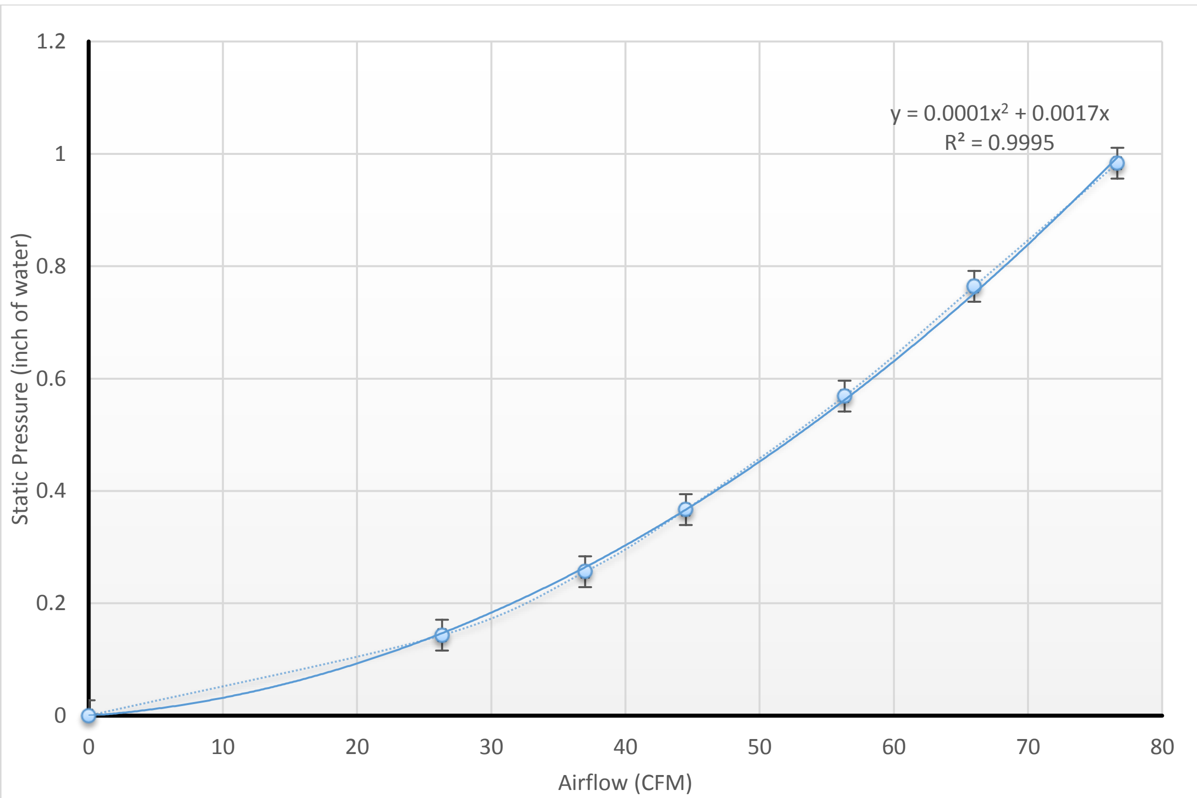

Figure 39 Experimental System Impedance Curve

While doing experimental airflow bench testing, static pressure across the server was measured keeping the flow rate constant. Results were taken by varying airflow rate. Same procedure was followed for three times resulting in minor variations in reading of static pressure. Based on minor variations in static pressure value, error bars also have been plotted on system impedance curve.

For plotting system impedance curve analytically, boundary conditions similar to airflow bench testing were applied to server. In 6SigmaET, setup required to plot system impedance curve is shown the below figure.

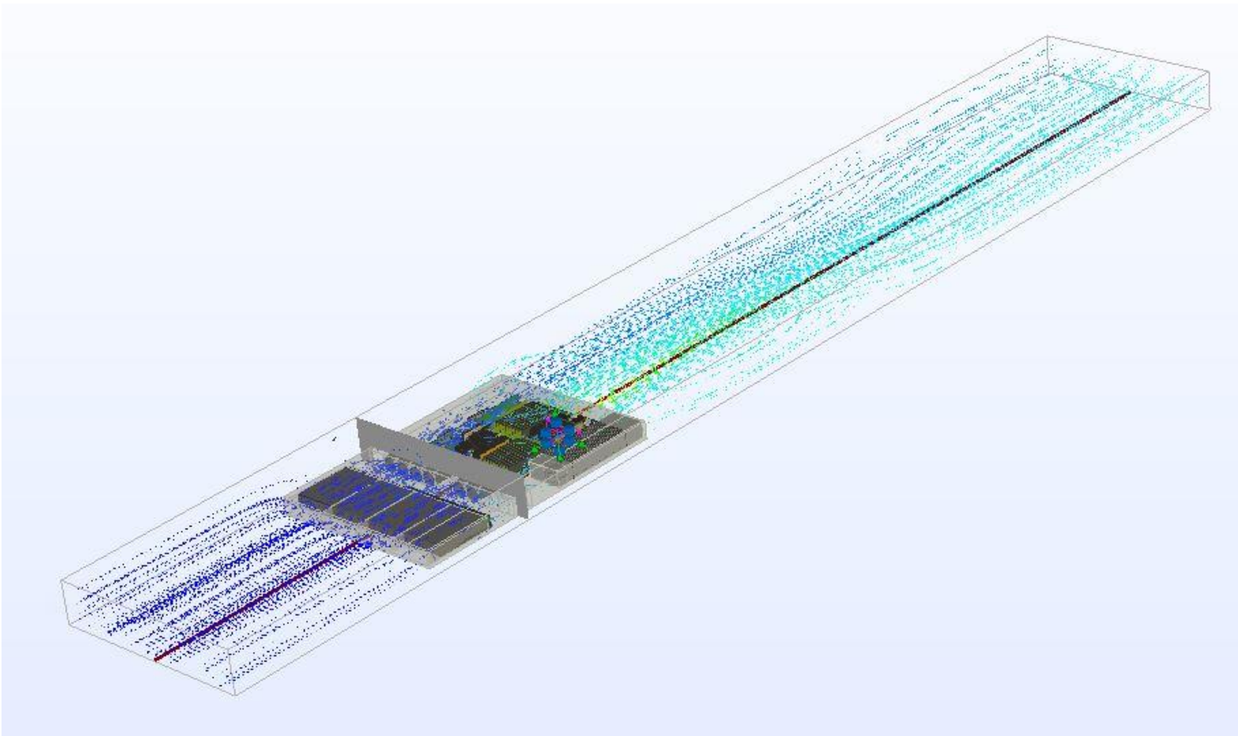

Figure 40 Setup required for plotting system impedance curve

In 6SigmaET, pressure at rear end is measured by providing sensor or using result plane for a given airflow rate. Same procedure is followed to get static pressure data for different airflow rate. System impedance curve plotted characterized from CFD analysis can be seen below.

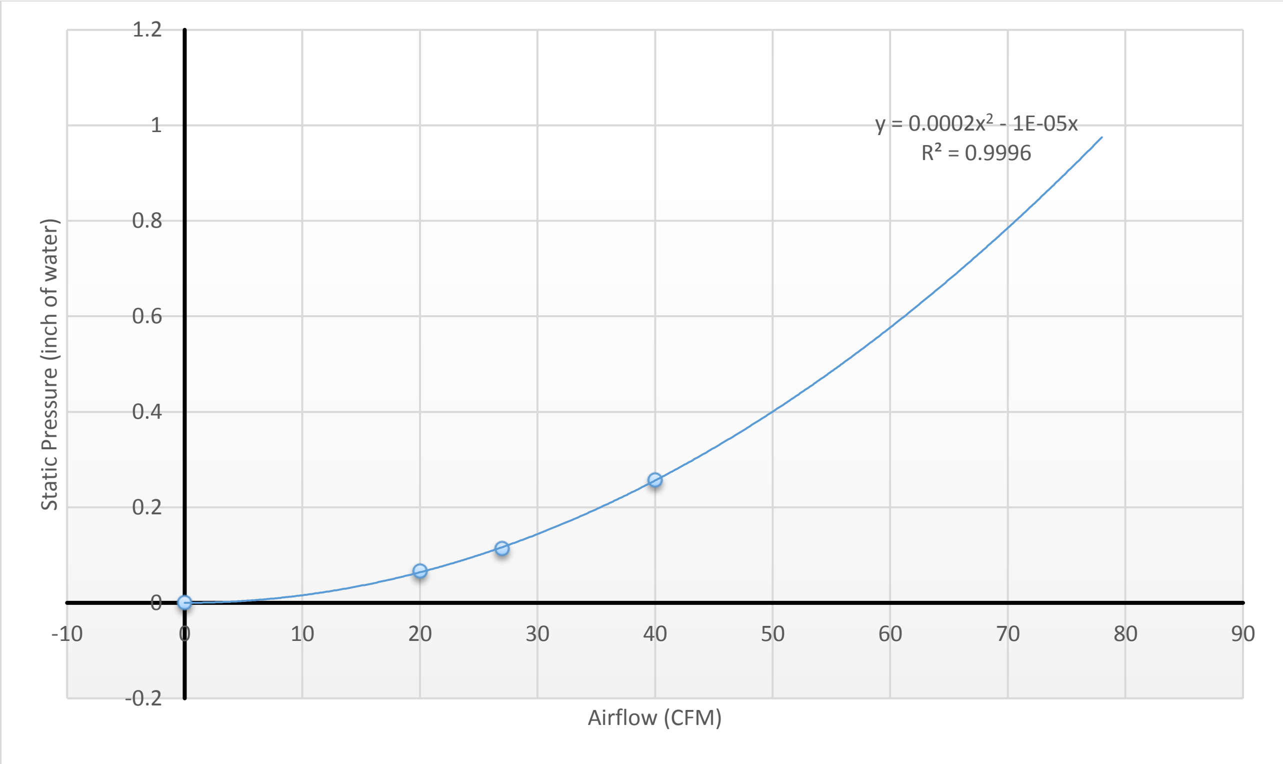

Figure 41 Analytical System Impedance Curve using 6SigmaET

Comparison between the system impedance curve obtained experimentally and analytically using 6SigmaET is been made and overall % variation of system impedance curve obtained using 6SigmaET from experimental system impedance curve is less than 10%.

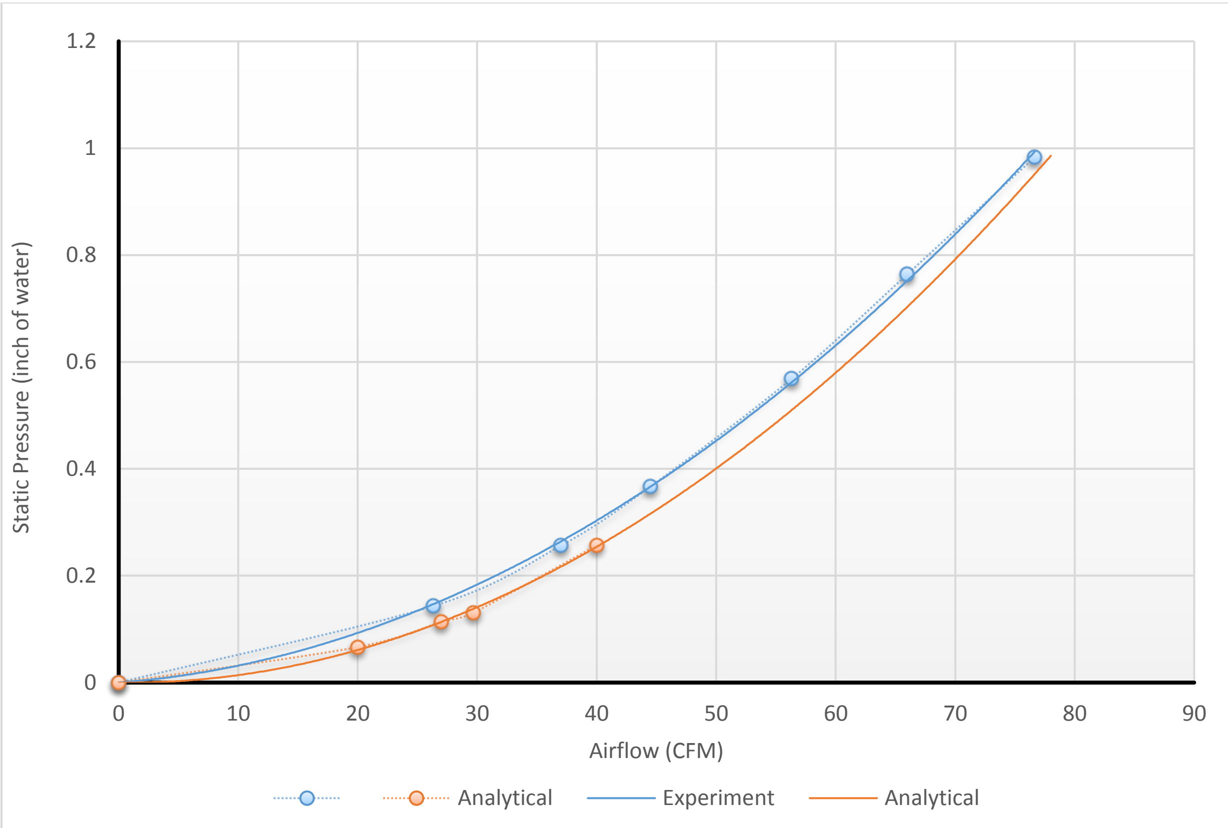

Figure 42 Comparison between Experimental and Analytical System Impedance Curve

6.2 Mesh Sensitivity Analysis for Air Cooled Server

Mesh sensitivity analysis is one of the most important things to be done while doing CFD analysis regardless of software type. Accuracy of results is determined by mesh sensitivity analysis. It is done to check that results are independent of grid size and grid count. The cell count depends on geometry and complexity of model. The grid size depends on the smallest and largest dimension in any direction. With increase in grid count pressure increases and after 10 million grid count pressure is almost constant. It is basically trial and error kind of procedure but, using PAC study mesh sensitivity analysis can be performed easily. Below table contains results of mesh sensitivity analysis;

Solution Control Grid			Pressure Sensor Front Simulation Results
Max Size in X, Y, Z	Cell Count Target	Grid cell count	
5 mm	20000000	21649110	0.1182
10 mm	20000000	14595942	0.1182
20 mm	20000000	10588506	0.1182
25 mm	20000000	8550582	0.1165
30 mm	20000000	7020280	0.1109

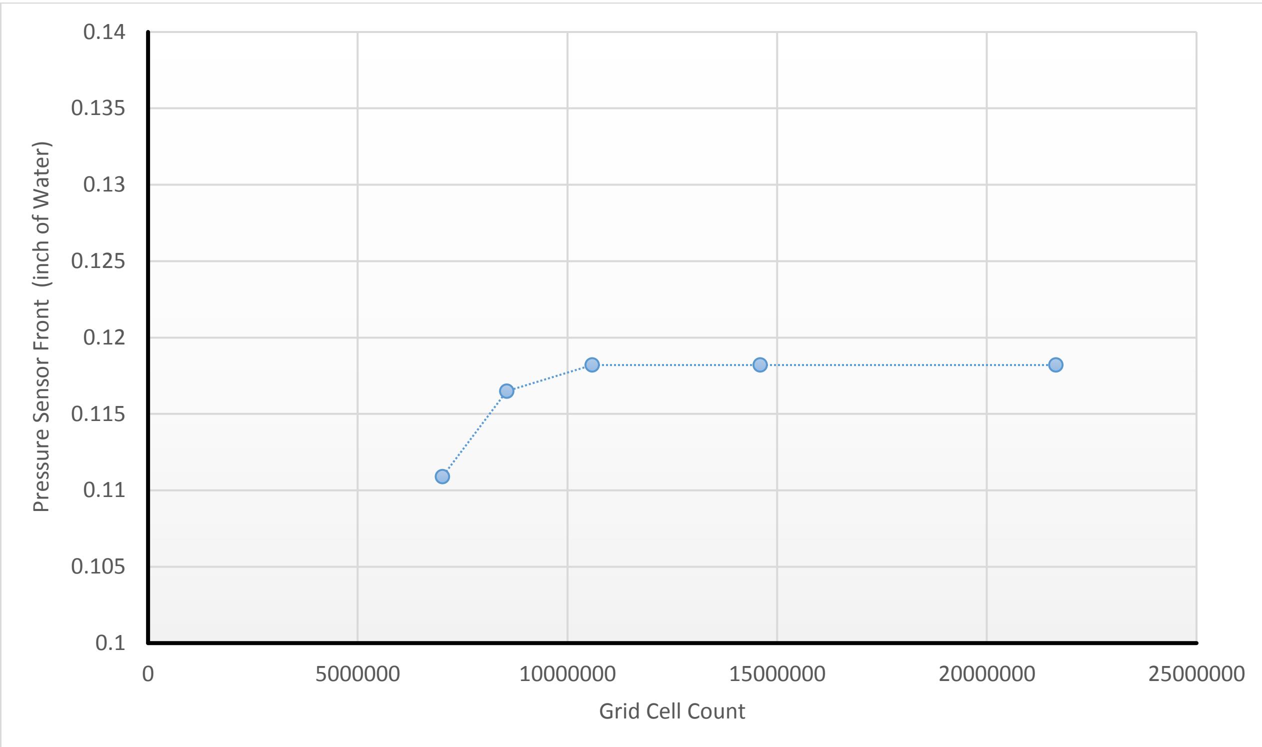

Figure 43 Mesh Sensitivity Analysis for Air – Cooled Server Model

6.3 Operating Point of System

Operating point of the system is the intersecting point of the fan characteristic curve and system impedance curve of the system. Operating point of the system provides the pressure drop across the system and air flow rate required to overcome the resistance due to server components. From the operating point of system, required air flow rate to overcome the system resistance is around 26.67 CFM and pressure drop across the system for the operating air flow rate. Operating point of the system is obtained in the below graph.

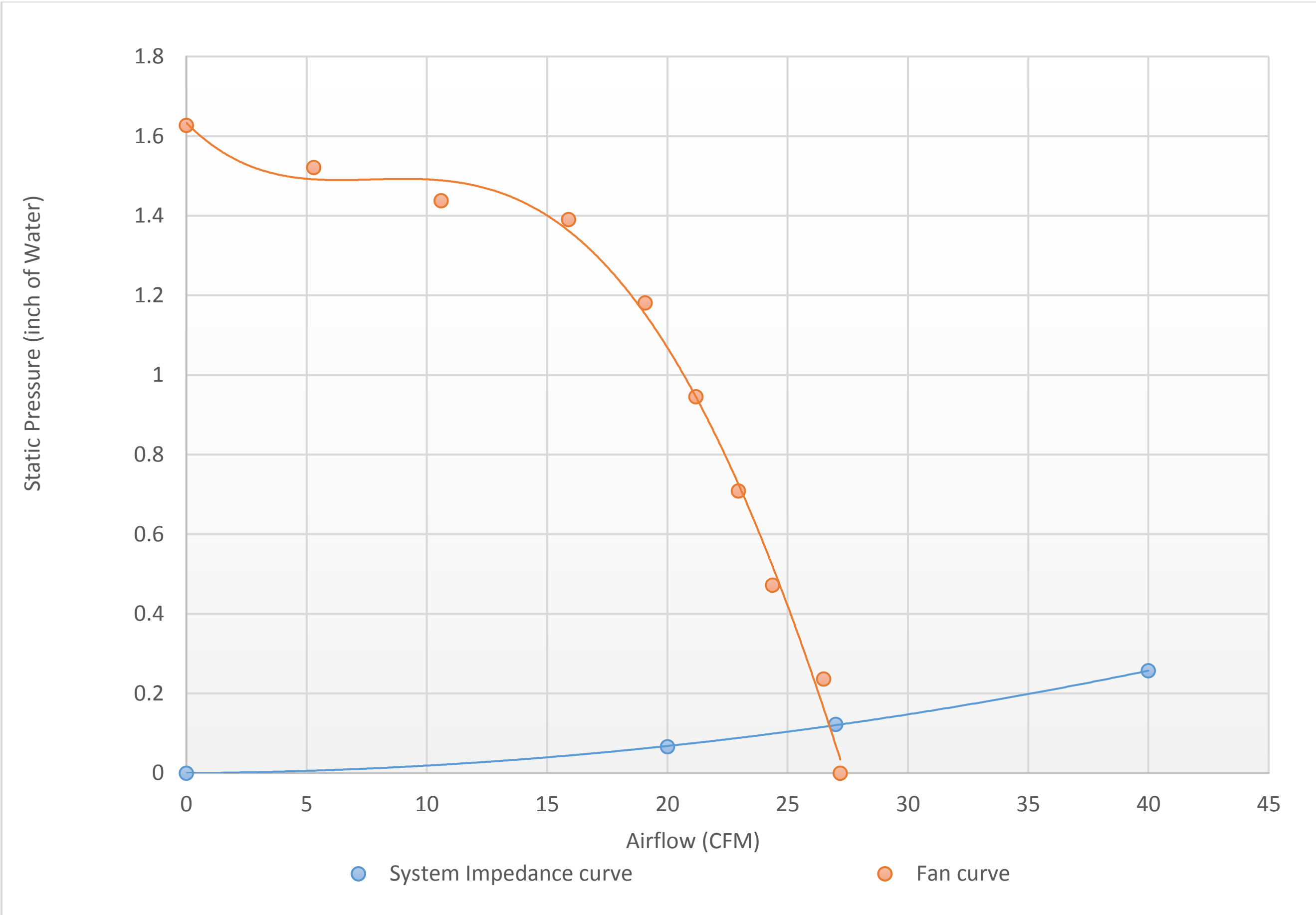

Figure 44 Operating point of the system

6.4 Results for Air Cooled Server Model

By providing the actual flow rate, air cooled server model was simulated. The temperatures for the major the heat generating components were measured.

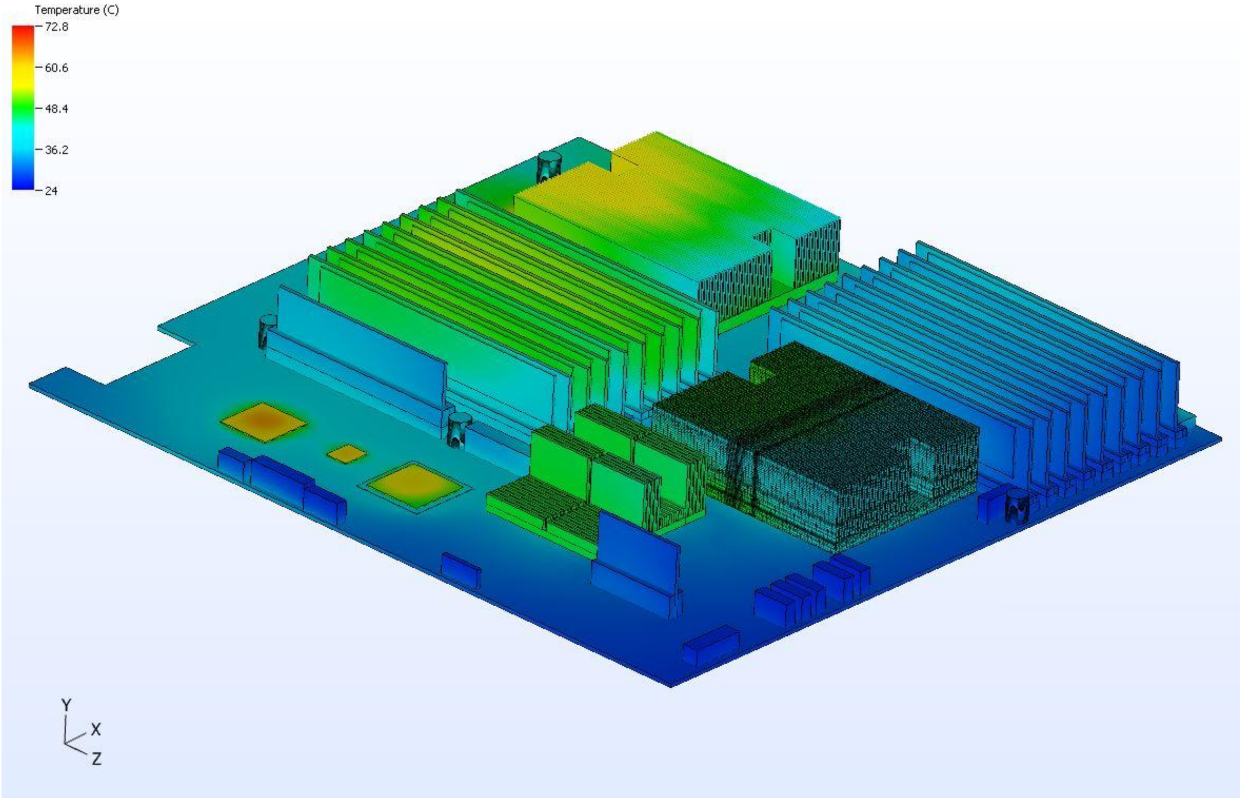

Figure 45 Temperature of different component for air cooled server model

6.5 Mesh Sensitivity Analysis for Single – Phase Immersion Cooled Server Model

Though we used the same model for single – phase immersion cooling, which was designed earlier for air cooled server, mesh sensitivity analysis is must for single – phase immersion cooling also. Same PCB model which was developed earlier was used in single – phase immersion cooling server model. Mesh sensitivity analysis was performed again for single – phase immersion cooled model and results are below;

Solution Control Grid		Pressure Sensor Simulation Results (Pa)	
Cell Count Target	Grid Cell Count	Front Vent	Rear Vent
15000000	25077395	3.8361	3.169
25000000	27003876	3.7409	3.091
27000000	27062985	3.7398	3.087
29000000	27954321	3.7397	3.087

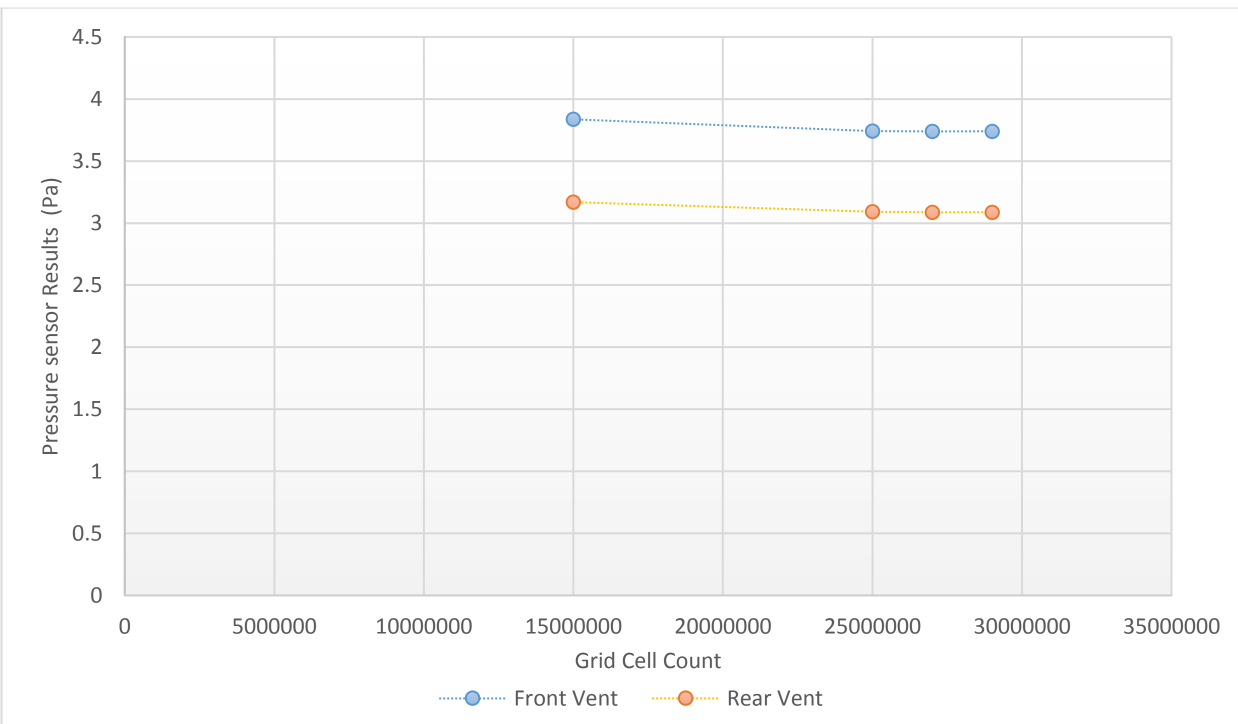

Figure 46 Mesh Sensitivity Analysis for Single - phase immersion cooled server model

6.6 Results for Single – Phase Immersion Cooled Server Model Using EC – 100

By providing different volumetric flow rate and varying inlet temperature of dielectric liquid, temperature of different components on PCB were measured. By varying volumetric flow rate and inlet temperature of dielectric fluid, variation in temperature of different component is plotted below;

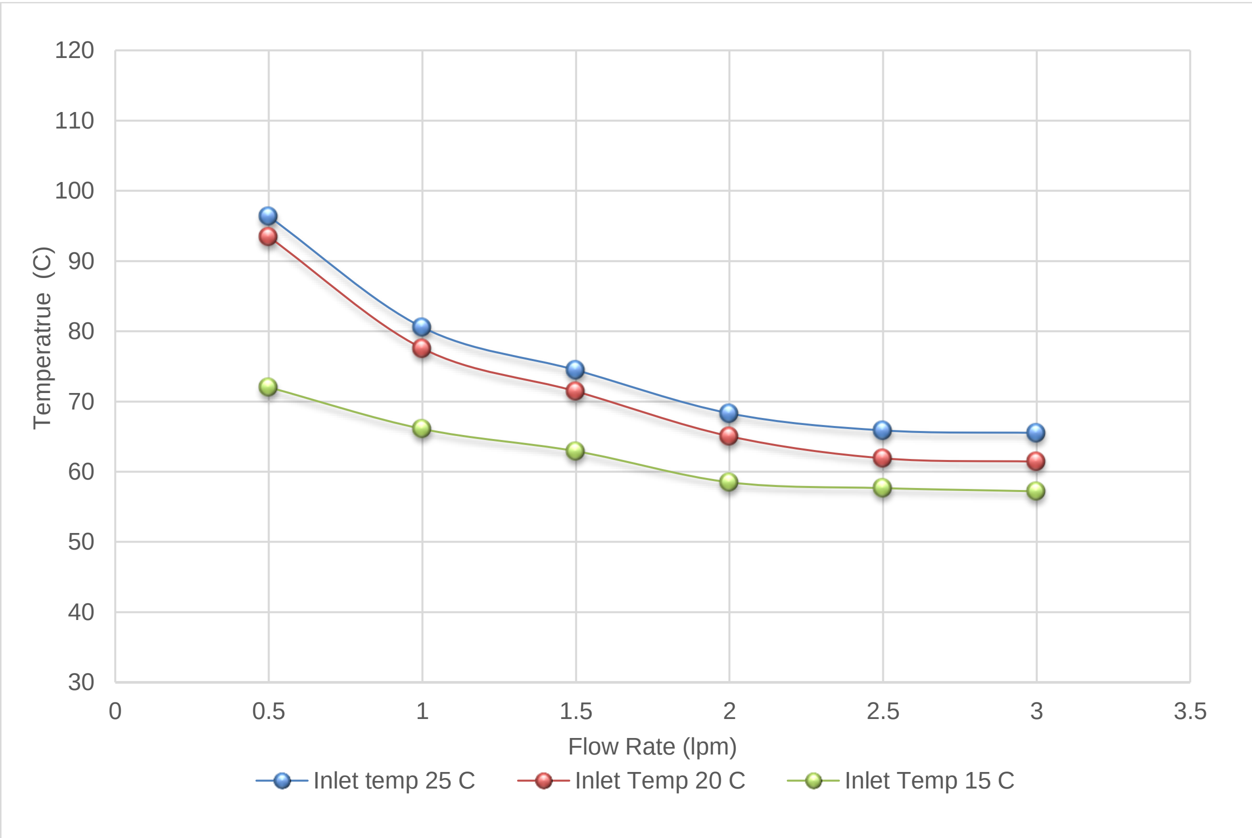

Figure 47 CPU1 Temperature variation in EC - 100

From the plot, with increase in volumetric flow rate and decreasing the dielectric fluid inlet temperature, component temperature decreases. Similar behavior can also be seen for other components.

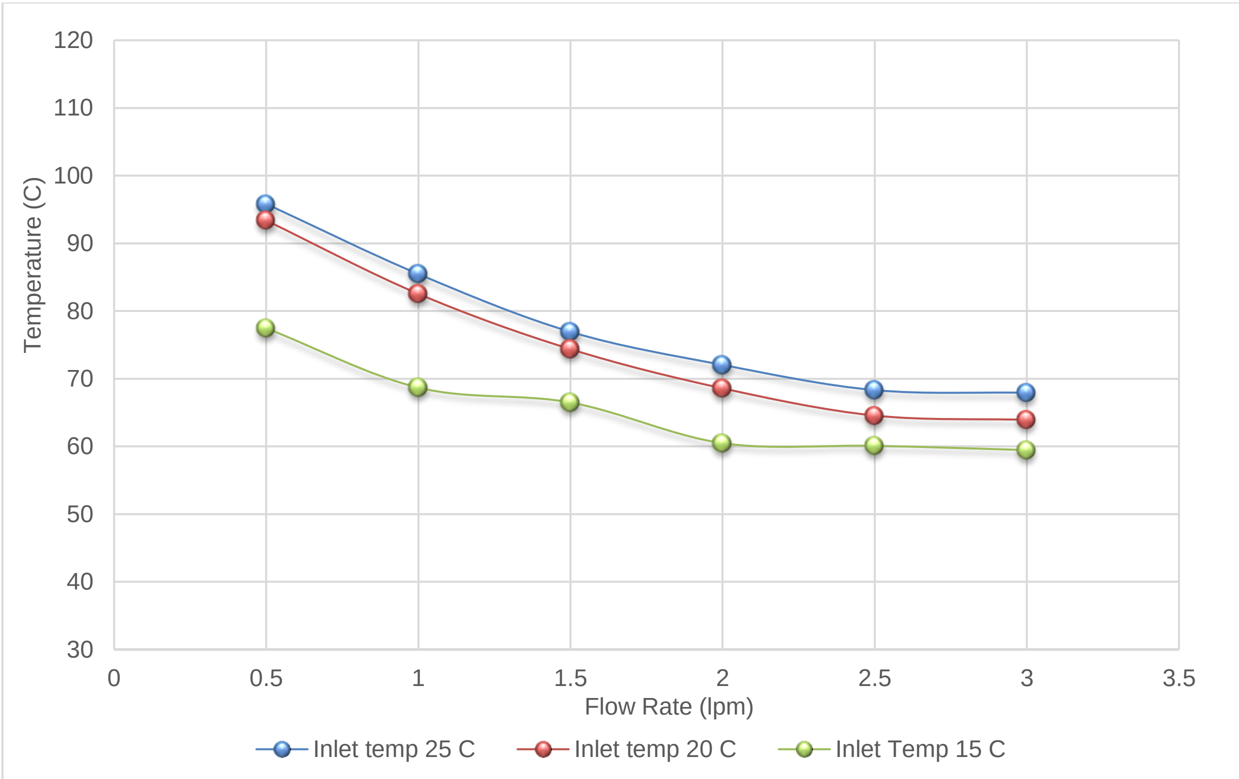

Figure 48 CPU2 Temperature Variation in EC - 100

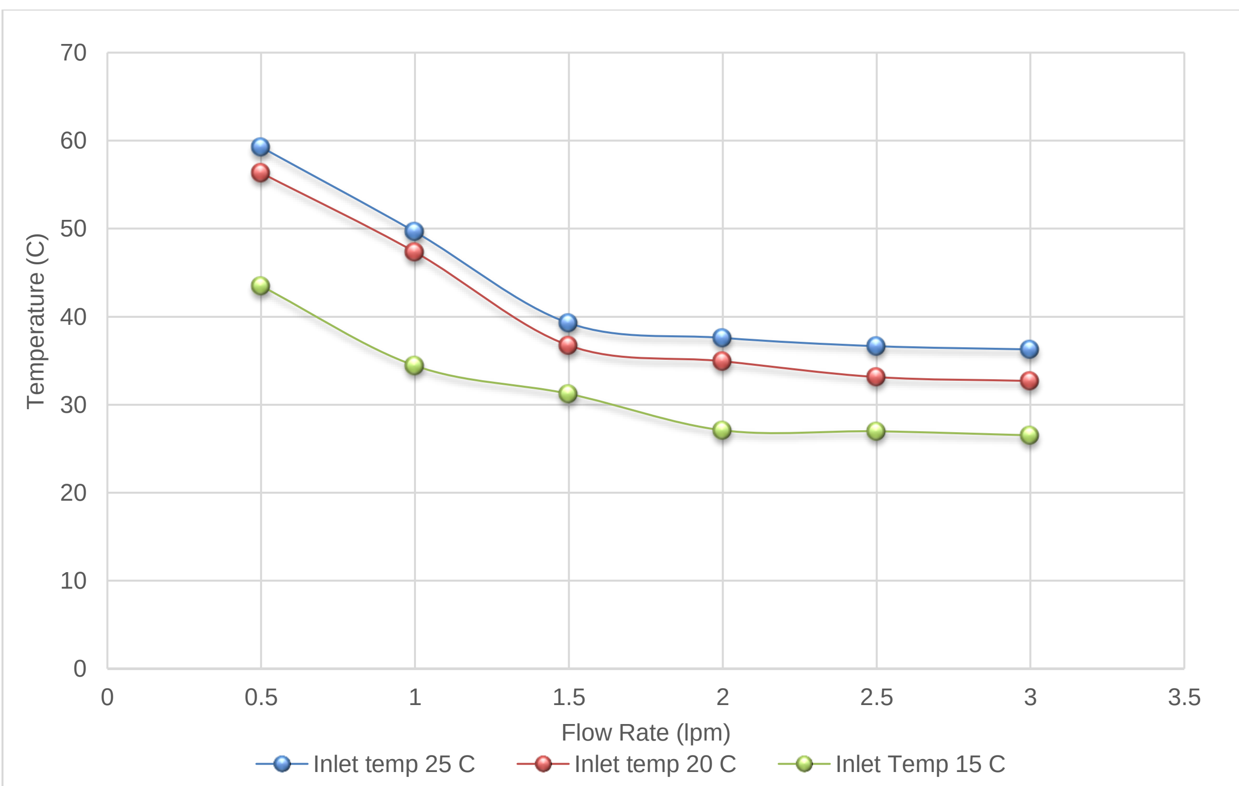

Figure 49 IOH Chip temperature variation in EC - 100

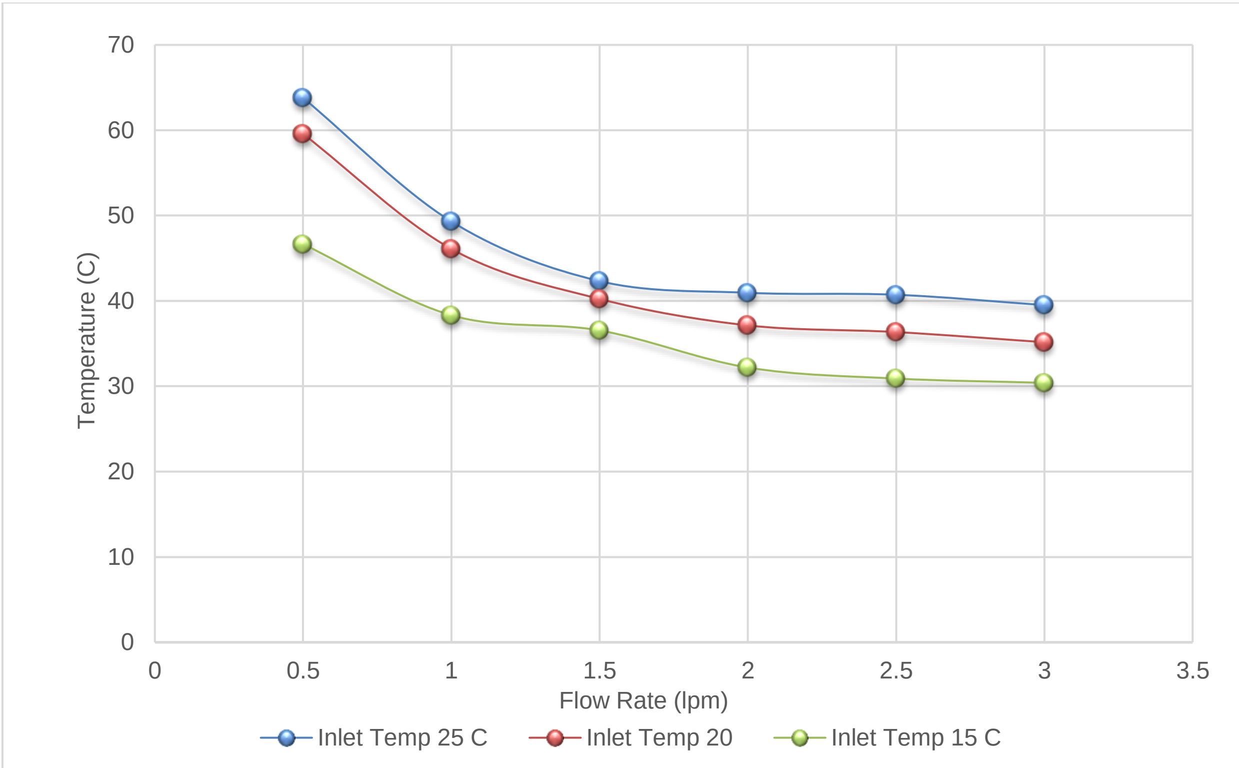

Figure 50 ICH Chip temperature variation in EC - 100

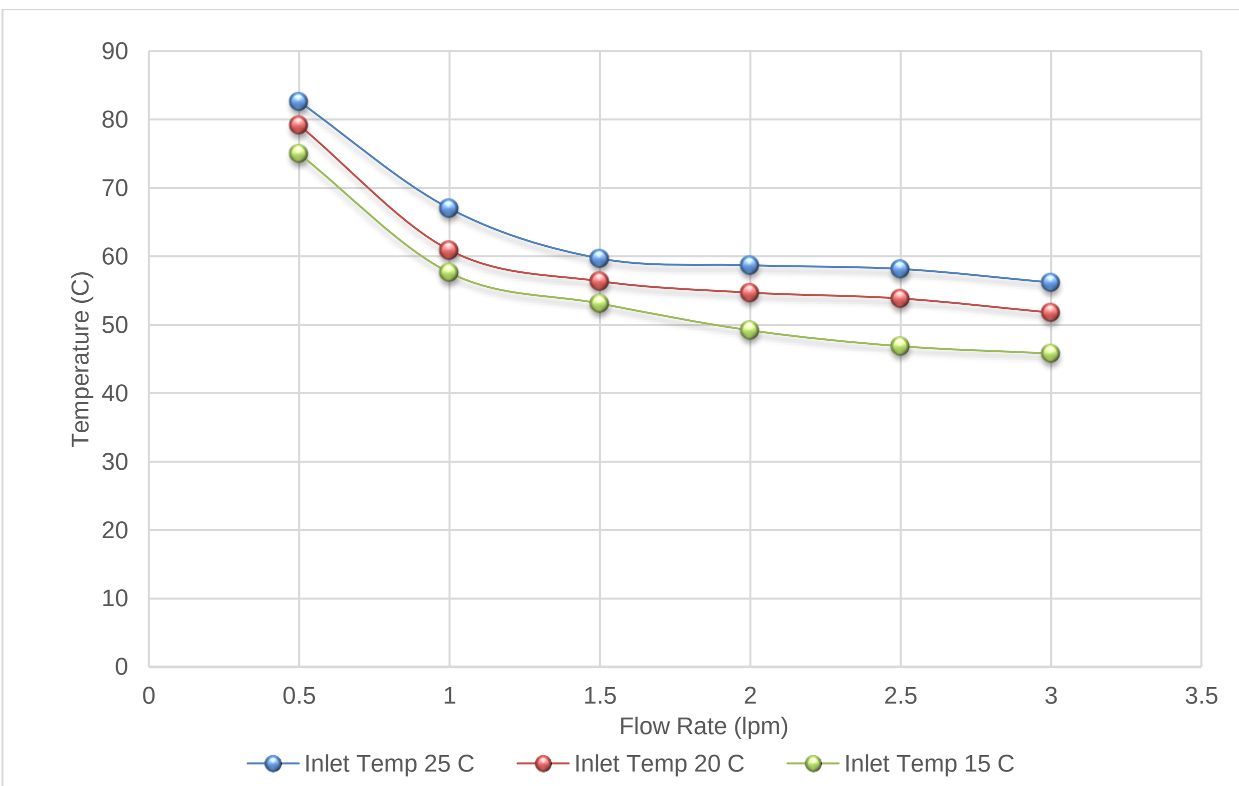

Figure 51 BMC Chip temperature variation in EC - 100

6.7 Results for Single – Phase Immersion Cooled Server Using Mineral Oil

By using different volumetric flow rate and different inlet temperature of mineral oil, temperature of different component was measured using CFD analysis in 6SigmaET®. By varying volumetric flow rate and inlet temperature of mineral oil, temperature results were plotted;

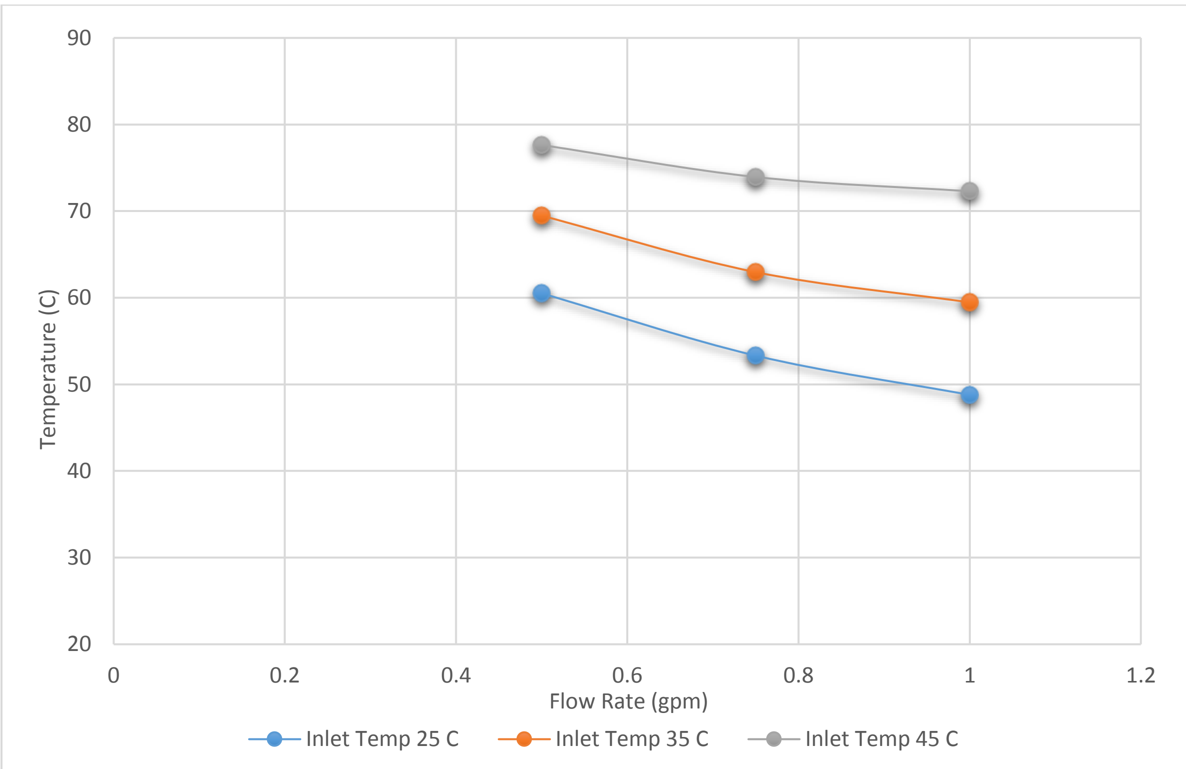

Figure 52 CPU1 Temperature Variation in mineral oil

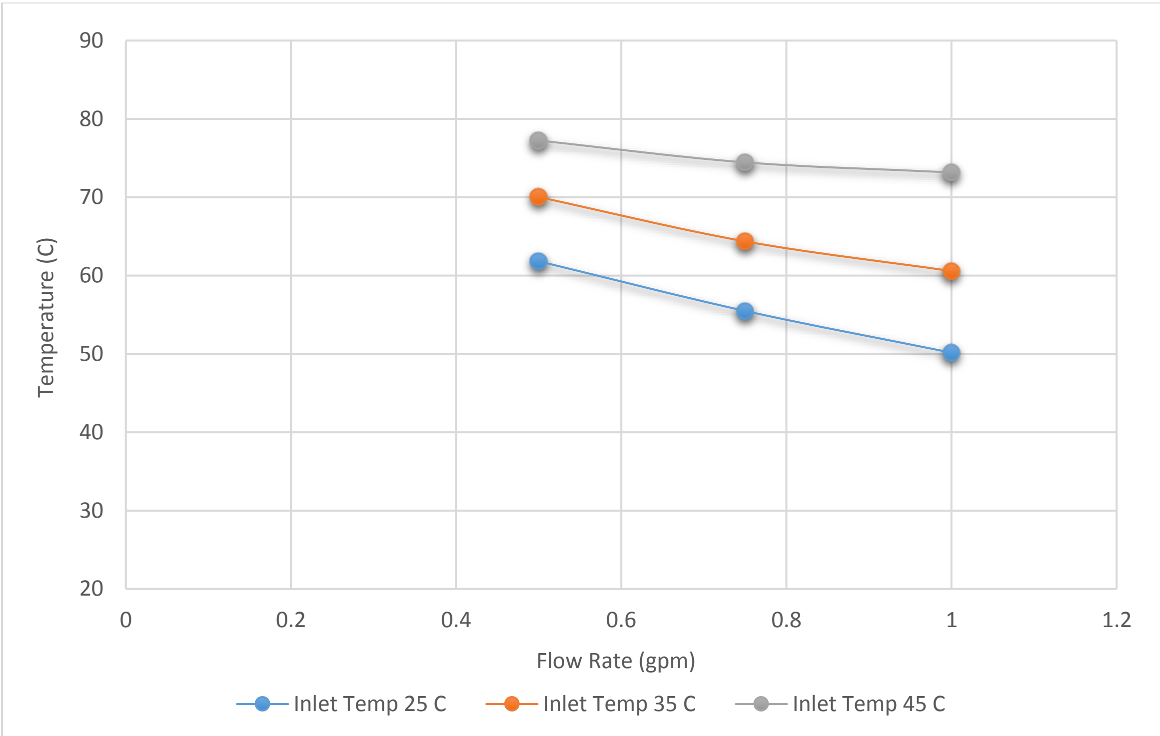

Figure 53 CPU2 Temperature Variation in mineral oil

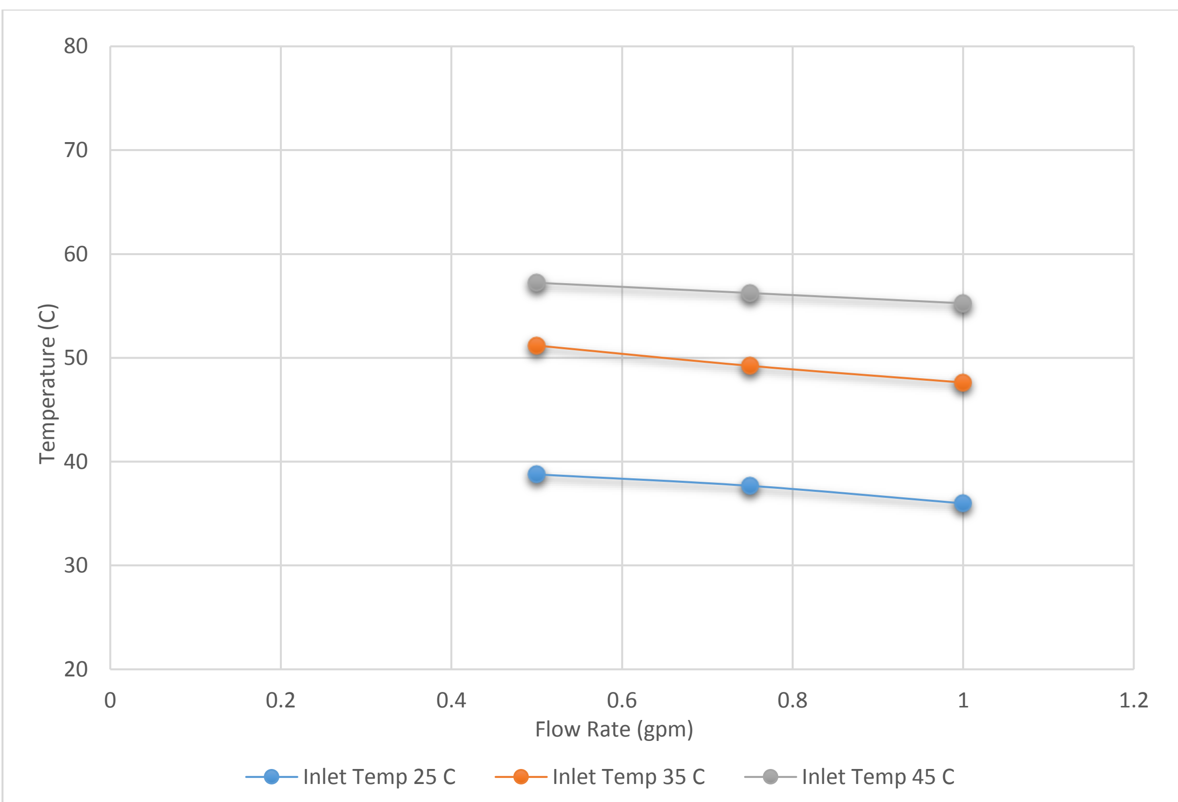

Figure 54 ICH Chip temperature variation in mineral oil

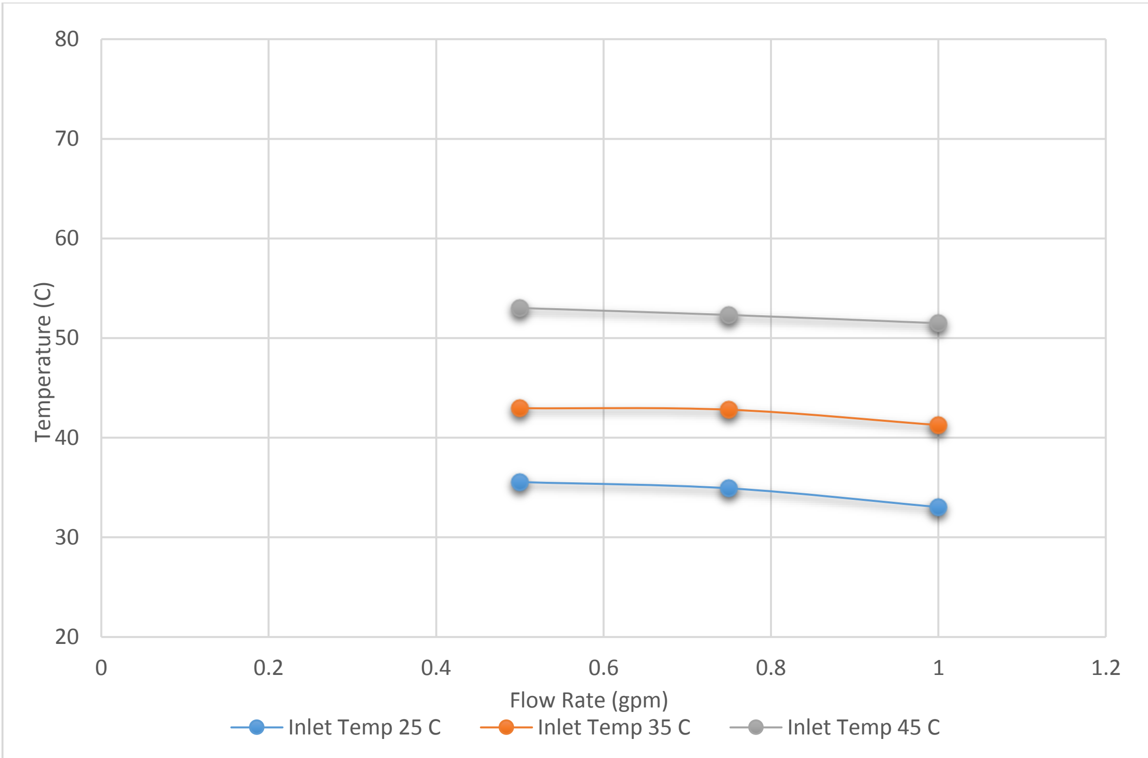

Figure 55 IOH Chip temperature variation in mineral oil

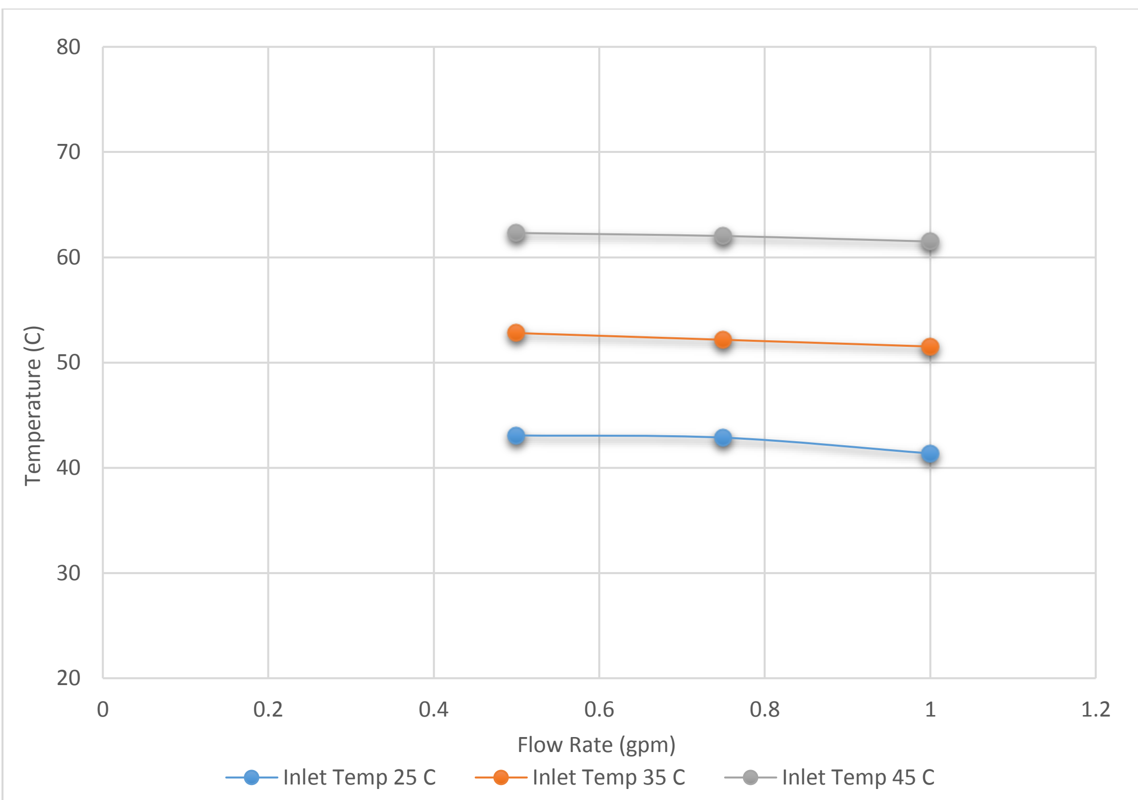

Figure 56 BMC Chip temperature variation in mineral oi

6.7 Comparison between Air cooled and Single – Phase Immersion Cooled Server Model

Temperature of component on PCB in case of air - cooled server model and single – phase immersion cooled server model is compared with each other. By using single phase immersion cooling we can get almost similar temperature to air cooled server model. But power consumption in case of single – phase immersion cooling is less as compared to power consumption in air - cooled server model.

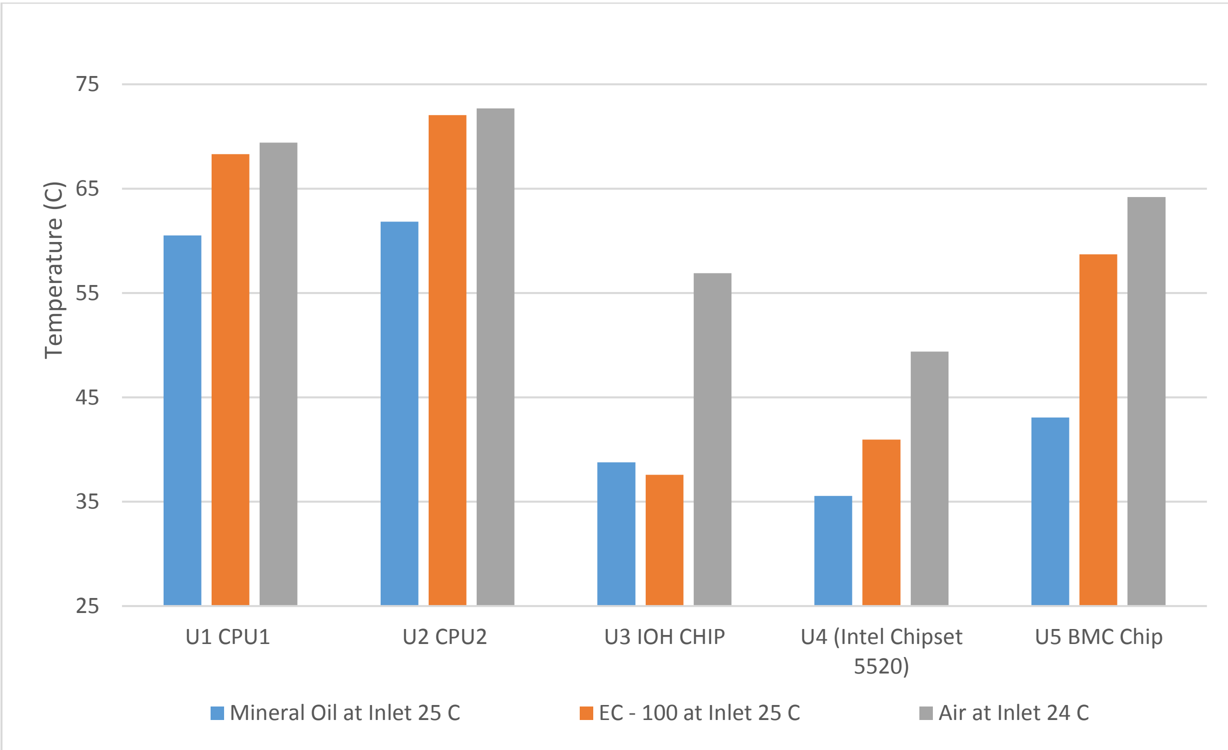

Figure 57 Comparison of component temperature obtained using air - cooled server model and single - phase immersion cooling

6.8 Conclusion

The comparison between experimental and analytical system impedance curve of the server has been made. From comparison we observed that percentage error between system impedance curve obtained experimentally and analytically for server model was as minimum as 3.03 percent to 12.63 percent maximum. The goal of this study was to determine general operating trends that can be observed in single – phase immersion cooled server setup in data center. By complete immersion of server in synthetic dielectric fluid and varying volumetric flow rate and inlet temperature of dielectric fluid, operating conditions were established based on simulation results in 6SigmaET®. From this study, it is possible that dielectric fluid with 25 ^{o}C or even higher temperature can be utilized depending on volumetric flow rate. From comparison between air cooled server with air at 24 C and single – phase immersion cooled server with EC – 100 and mineral oil as working fluid at approx. 2 lpm flow rate, we observed that mineral oil gives the optimum results as compared to other alternatives. Improved accuracy in modelling with 6SigmaET® can improve the simulation result accuracy. Modification in server design and heat sink optimization may increase heat extraction by cooling fluid. Future work in this area can be done by improving heat sink design and determining reliability concerns and maintenance challenges present in this method of data center cooling.

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Biographical Information

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