EXPERIMENTAL CHARACTERIZATION OF HYBRID COOLED CISCO SERVERS INCLUDING THE EFFECT OF WARM WATER COOLING

By

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I thank almighty god for providing me the strength and inspiration.

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Abstract

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The University of Texas at Arlington, 2016

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The information technology (IT) owners are experiencing a greater cooling challenge because of the increase in power density due to modern computational needs. The non-uniform power density in each server is forcing the industry to use hybrid cooling technology. Server components of different cooling requirement needs air water hybrid cooling which offers variable design alternatives. Such hybrid cooling technology cools the high heat generating components by using water or water based fluid, whereas, the rest of the components are cooled by air using internal fans. Conventional air cooling is more than sufficient for the components with less thermal demand. Air cooling is cheap, highly available and it has better serviceability than any other cooling methods.

The objective is to optimize the cooling power of the air cooling loop of such hybrid cooled server. As the major components are cooled by the water based fluid, the other components generate less heat which can be cooled by much less volume of air then supplied in air cooled server. The volume of air supplied is controlled by varying the air flow rate through the internal fans. Also number of fan was reduced to 3 instead of 5 to minimize the power consumption. Parameters like CPU and memory utilization are varied with the flow rate. ASHRAE recommends that the most data centers can be maintained between 20 and 25°C, with an allowable range of 15 to 32°C. But for this type of hybrid cooling servers, the processor is cooled by water. So the servers can operate at much higher inlet air temperature. In this paper the hybrid cooled servers will be characterized also.

The server used for experimental testing has processor with 135 watt thermal design power. Also, the server utilizes distributed pumping i.e. each cold plate has its own pump. The test matrixes consider supply and return water temperatures, flow rate of coolant for optimizing the cooling power consumption. The supply inlet water temperature was varied by LabView code. Further, processor and outlet temperature was monitored for better understanding the case scenario. The relation between supply water temperature and different power utilization gives the data for modeling different cooling infrastructure. This in turn, will give an idea of power savings by utilizing such energy efficient hybrid solution for cooling servers in a datacenter.

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Chapter 1

Introduction

A Data Center is a facility where large number of IT Equipment such as computer systems, data storage units and telecommunication devices are stored. The server is the main equipment of data center where the processes takes place. The equipment such as server are mounted in a standardized cabinets called rack. These racks of servers constitute many number of IT equipment. Data center requires uninterrupted power and cooling. To maintain the required temperatures the Heating, Ventilation and Air Conditioning (HVAC) provides the necessary cooling.

1.1 Data Center: Energy usage and cooling efficiency

Data center consumes huge amount of energy to maintain a certain temperature. There is an increment of power consumption by data centers which is about 56%. In USA it is reported about 36% by J. Koomey [1] in the New York Times. He also mentioned that electricity uses by data center is 2% of total electricity use for USA. The increase in energy usage is a concern for environmental agencies in the U.S., European Union, China and other countries. In order to satisfy requirements new cost-cutting measures need to be taken. This includes use of ambient air and warm water cooling etc.

American Society for Heating Refrigeration and Air Conditioning Engineers (ASHRAE) TC 9.9 [2] Committee has developed a guidelines for design, operation, maintenance, and efficient energy usage of data centers. The recommended temperature zones are from 18°C (64.4°F) to 27°C (80.6°F). The humidity should be less than 60%. Also ASHRAE A3 envelope allows IT equipment to operate at 24˚C temperature and 85% relative humidity [3]. Anything outside of the region might show a deleterious effects on reliability, acoustics, or performance [4].

Power usage effectiveness (PUE) has become the new metric to measure data center efficiency. Power Usage Effectiveness (PUE) is a ratio of the total energy to the energy consumed by IT equipment. The global average PUE of data centers is between 1.8 and 1.89 [3]. Almost an equal amount of energy is spent in non-IT power like cooling.

1.2 Thermal Management of Data Centers

Computer based application requires faster and improved communication. To meet with the loads, efficient servers are necessary for processing. A substantial amount of energy is required to cool of the servers with high heat generating components.

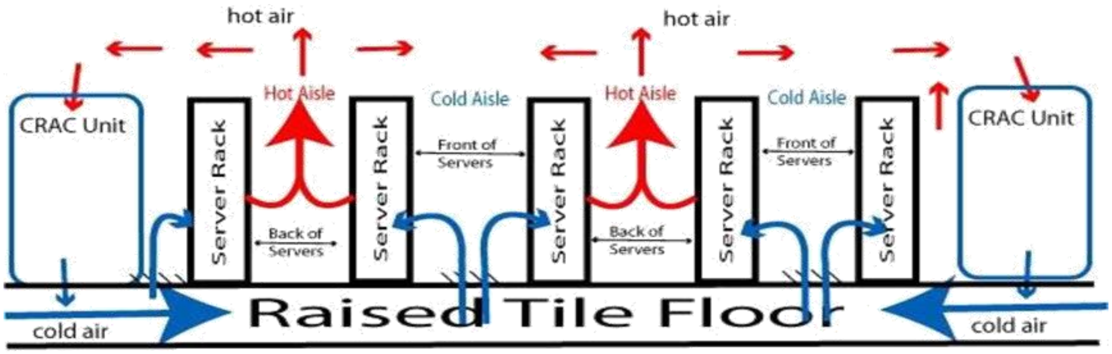


Figure 1-1 Typical thermal layout of a data center [5]

Thermal management of data center is multi-scaled. The different levels of thermal management which needs consideration are chip level, server level, rack level and room level. The primary heat generates at chip level and disperses into the data center which is cooled by the CRAC unit.

Chip level thermal management includes design of effective heat sink, use of thermal interface materials and heat spreader. At server level, heat rejection from the printed circuit board like fan installation and ducting air-delivery pathway to the heat sinks. Rack level optimization enhances airflow rate in cabinets and servers. Computer room air-conditioning (CRAC) unit deliver cold air through perforated tiles thus room level cooling is done. At the rack level, the placement of servers, rear-door heat exchangers and liquid cooling are very important. Various distribution configurations are used to control airflow delivery by air mixing and dispense air to the loads [6].

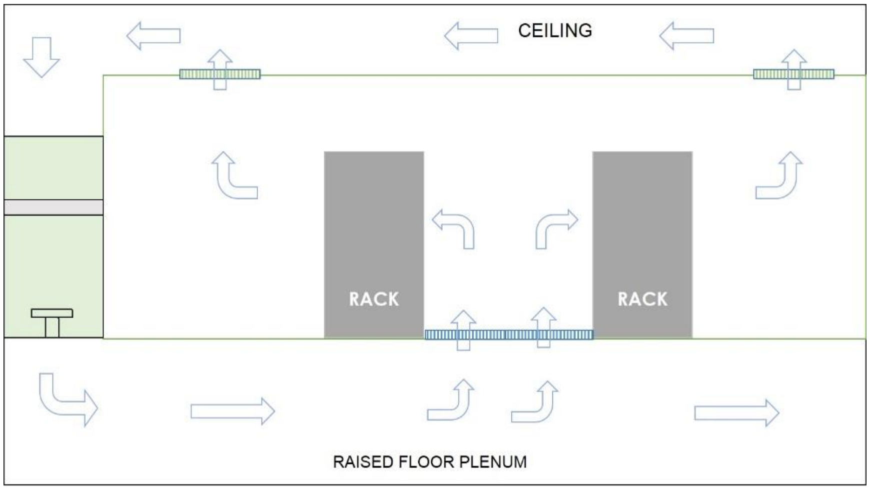


Figure 1-2 Raised-Floor Supply and Dropped-Ceiling Return Architecture

Figure 1-2, is a common data center architecture. A raised-floor is used to supply cold air and dropped-ceiling is used to return air with the CRAC. The airspace is divided into cold and hot aisle. A cooling system should include all levels of thermal management in a data center.

1.3 Data Center Cooling Provisioning

Any cooling system must ensure that microelectronic component meets its thermal specification. For silicon devices reach their functional limits generally in the 85°C to 105°C range and experiencing 15°C to 25°C increase can damage and shutdown the component. The operating ranges for both air and water cooling are illustrated in Figure 1-3.

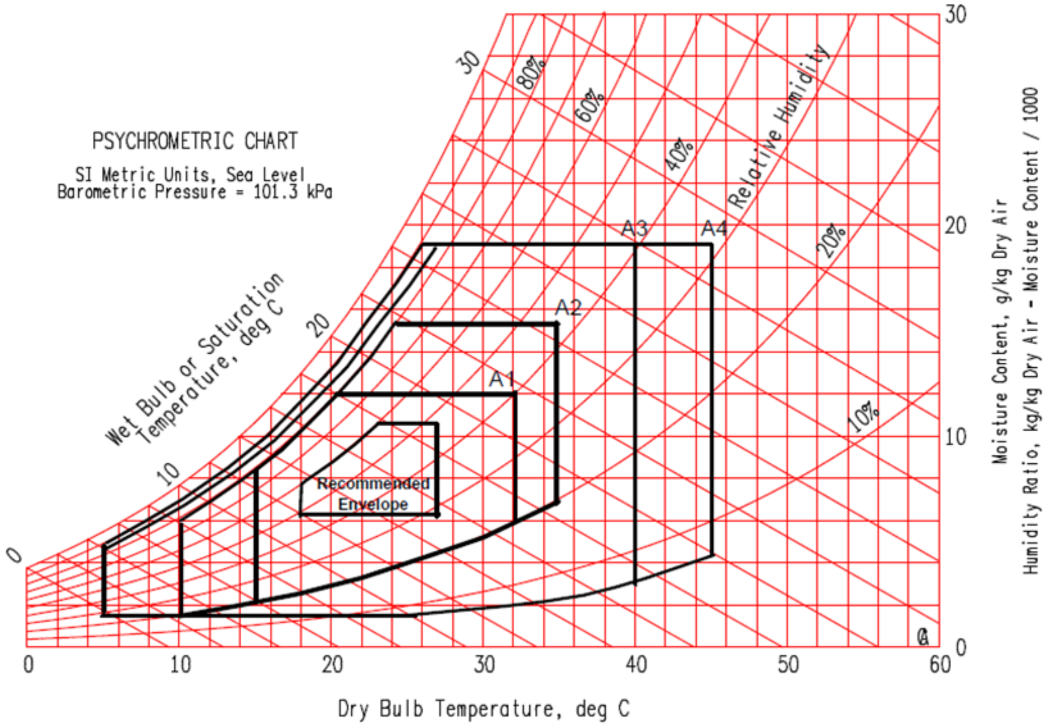


Figure 1-3 Environmental envelopes based on the class of data center [7]

The component temperature is determined by the inlet air or liquid temperature to the system in air cooled or liquid cooled server. While placement of the component is determined by electrical circuitry considerations but often the thermal optimization is ignored.

The fans are selected to match the server's resistance and provide required volumetric flow rates for best cooling performance, power consumption, acoustic noise, fan reliability and redundancies [8]. Dynamic solutions means the amount of cooling required to maintain component operating temperatures. Component thermal sensors provide the dynamic control over the cooling units. As the inlet temperature increases the fan unit reacts by functioning at higher speeds.

1.4 Motivation

Microsoft has millions of servers in their data center and this was mentioned by S. Balmer [9]. A small power savings can scale up to a huge number in these type of companies. In search of efficient cooling technology in data centers, the industries are looking for innovative ideas such as hybrid cooling. Pressure difference in a cold aisle and hot aisle is necessary to improve efficiency in a data center [10].

Usually IT servers are typically designed assuming there is a zero differential pressure between inlet and exhaust. But in reality, any change in fan speed control results in varying volume of air through the server. Dynamic response is necessary to counter this variation.

Liquid cooling has acceptance for cooling novel, high-powered microelectronic device [11]. Cold plates using water as the coolant are one of the widely used liquid cooling solutions available. The cold plate is used to remove the heat dissipated by chips mounted on the glass ceramic substrate. As the module powers is increasing, liquid cooling is once again being considered for thermal management of microelectronic devices [12].

Water has many advantages over air cooling such as greater heat carrying capacity, targeted delivery and lower transport power. Also, when operating at higher utilization, servers are more energy-efficient [13]. To respond to non-uniform heat dissipation by the processor, it is necessary to use the cold plates.

This work seeks to understand the impact of air flow rate on the thermal performance and energy consumption within a server. This information will be helpful in optimizing the hybrid cooled server to achieve the most energy efficient use of cooling resources.

1.5 Scope of Work

It is very important to minimize the power consumption by chassis fans because they are parasitic loads attached to the server. The objective of this work is to reduce cooling power of server by reducing flow rate and removing chassis fans in the server. The overall objectives of this study are as follows:

- Characterize a hybrid cooled server
- Upon variation of the flow rate, the impact on server cooling efficiencies and thermal performance
- Optimize the air cooling of the server by reducing the number of fans
- Study how to change the inlet temperature of liquid cooling loop
- Experiment the effect of warm water cooling on the hybrid servers

Chapter 2

2.1 Fans in IT Equipment

The main purpose of fan is to move air. Fans can supply at a certain flow rate and static pressure. Axial fans are mostly used in IT equipment. Axial fans can provide high flow rate and it can work against low static pressure. Blowers are mostly used in laptops and it works against higher static pressure.

2.2 Fan Curve

Fan curve is a graphical representation of capacity of a fan. The graph is plotted static pressure(y - axis) vs. flow rate (x - axis) and static pressure. Figure2-1 [23], is representation of fan curve. When the static pressure is zero, it's called free flow condition and flow rate is maximum. When the flow rate is zero, it's called stall condition and static pressure is maximum.

In air flow bench, any kind of fan curve can be produced. In the air flow bench flow rate can be changed by changing the blower speed. At different blower speed a static pressure can be measured across the fan.

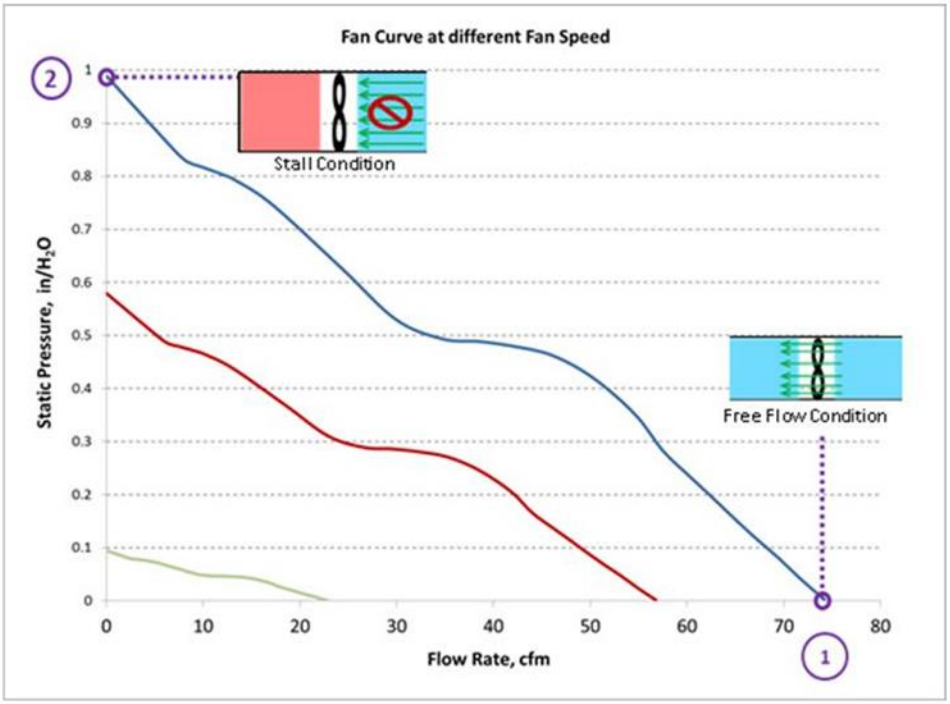


Figure 2-1 Fan Performance Curve [23]

2.3 Fan Laws

There are three fan laws that can be used to interpolate flow rate, static pressure. The flow rate, static pressure and power depends on the fan speed and fan impeller diameter [24].

Fan Law 1: $\frac{Q1}{Q2} = \left(\frac{N1}{N2}\right)\left(\frac{D1}{D2}\right)^3$

Fan Law 2: $\frac{\Delta P1}{\Delta P2} = \left(\frac{N1}{N2}\right)^2\left(\frac{D1}{D2}\right)^2$

Fan Law 3: $\frac{P1}{P2} = \left(\frac{N1}{N2}\right)^3\left(\frac{D1}{D2}\right)^5$

Figure 2-2 Three fan laws [24]

Where Q is Flow Rate, ∆P is Pressure Drop, P is Air Power, N is fan speed in RPM and D is Fan Impeller Diameter. As derived by Jorgenson and Bohanon [25], the laws for incompressible version can be obtained by setting compressibility coefficient ratio equal to unity.

2.4 Fan in series and parallel

When the fans are in series, the static pressure will increase by the number of fans and the flow rate will stay constant. On the other hand when the fans are in parallel, flow rate will increase by the number of fans and the static pressure will stay constant. If there is a system of higher resistance then fans are used in series. If there is a lower system resistance then fans are used in parallel.

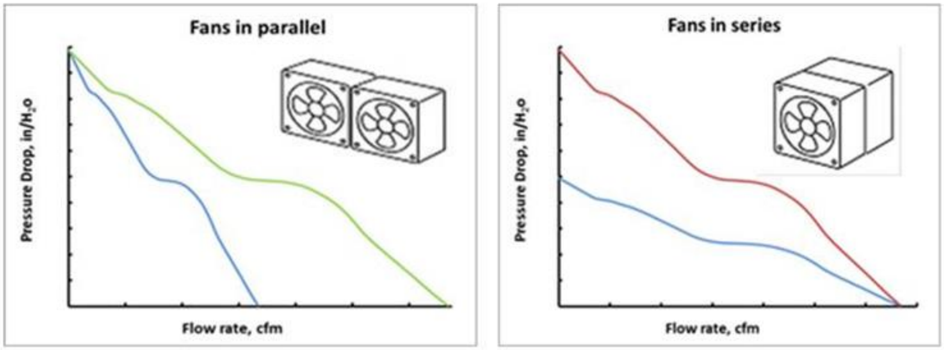


Figure 2-3 Fans in Parallel and Series combination [23]

2.5 System Resistance

When there is an obstruction in the flow, energy loss occurred that can be expressed in terms of pressure drop. When air passes though IT equipment, air has to go over electronic components like capacitors, voltage regulators and heat sink. Figure 2-4 shows the flow resistance of the system which is known as system resistance curve.

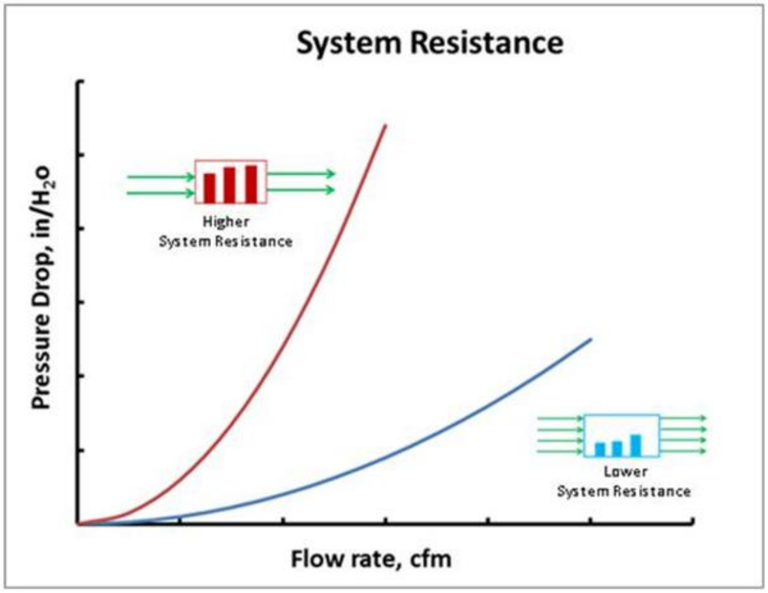


Figure 2-4 High and low flow resistant system [23]

If a system resistance curve coincides x axis, there will be no resistance to flow. On the other hand, if a system resistance curve coincides with y axis, there will no flow. As system resistance curve tends to move towards the vertical axis, it represents higher resistive flow [23].

Chapter 3

Experimental Set-up and Testing

The main idea for this experiment is to simulate the real world data center conditions. To observe the effect of lower flow rate it was placed in the air flow bench where static pressure was zero to depict an ideal condition. To experiment the effect of warm water cooling outside room temperature was considered 25^{0}C.

3.1 Server under Study

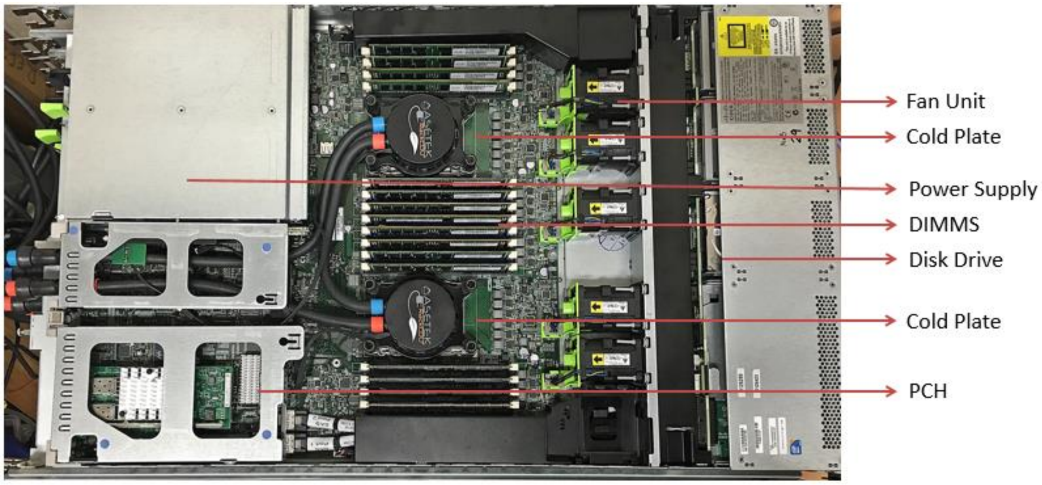


Figure 3-1 Cisco Server with retrofitted Asetek Cold Plate

Figure 3-1 shows a Cisco USC C220 M3 server based on Intel motherboard used in this study [14]. The height of the server is 1U rack mount unit and customized cold plates for the primary heat generating components (CPUs). The critical temperature below which the CPUs need to be operated is 88°C. In this work, the analysis of airflow over components except CPUs and fan power consumption of the servers was done.

Five 40mm x 40mm x 56mm DC fans are located at the intake of the servers which pull conditioned air through the server and are driven based on a 25 kHz pulse width modulation (PWM) signal that is prescribed by CPU die temperatures.

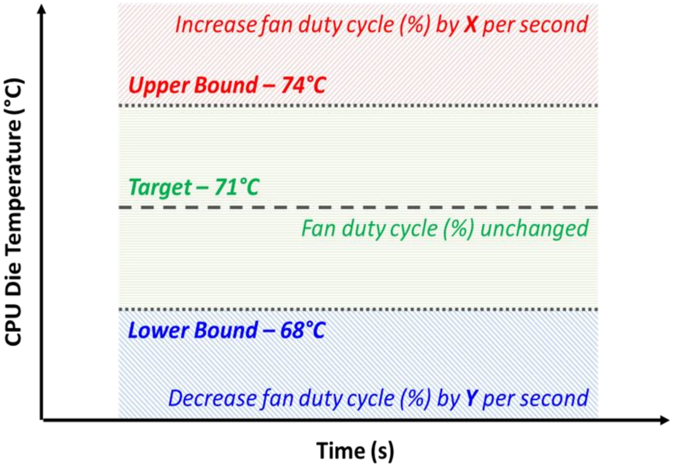


Figure 3-2 Deadband control limits

The two processors are the principal heat load with a thermal design power of 135W and their temperatures drive the fan speed control algorithm based on a dead band control scheme as shown in Figure 3-2 to ensure cooling. The power supply unit has an integrated 40mm fan that modulates the airflow based on inlet temperatures.

3.2 Test Setup

The airflow provisioning configuration modulates the temperature and pressure differences through the server rack. The velocity streamlines that are exiting perforated floor tiles are not straight into the servers and racks have non-uniform pressure difference between front and back of the rack [15].

A Cisco server was used to run the experiment. An Air Flow Bench was used as a test chamber and that air flow bench worked as a pseudo cold aisle shown schematically in Figure 3-3. The inlet of the rack was mounted on the airflow bench with the outlet exhausting into the room ambient. This scenario is an ideal case because it assumes uniform pressure difference between the servers and flow goes straight into the server. The streamline of the flow is parallel with the server which is an ideal scenario.

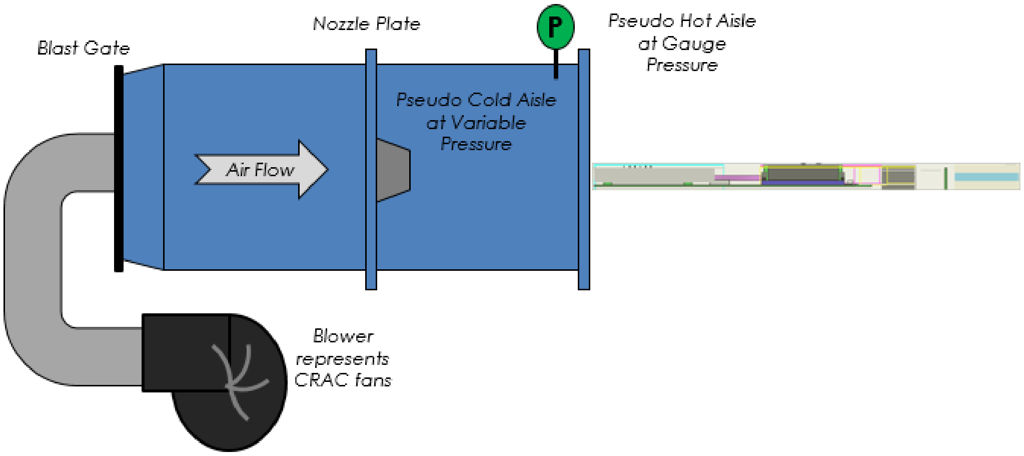


Figure 3-3 Schematic of experimental setup to control inlet static pressure to server

An external 12VDC power supply was used to power all the 40mm DC fans that helps to measure the fan power. Each fan is connected onto a breadboard using four pin connectors. The four pins replicate the functions of ground, power, tachometer and PWM control. Figure 3-4 depicts the control and data acquisition setup.

The fan speeds are sensed using IPMI tool in the server. The fans are controlled by an external PWM signal generator. The fan speeds are varied by changing fan duty cycles [16]. As the fans were still externally powered but internally sensed, there was no need of dummy signal for the motherboard. The ground signal from server and fan was shared between all the monitoring and control equipment.

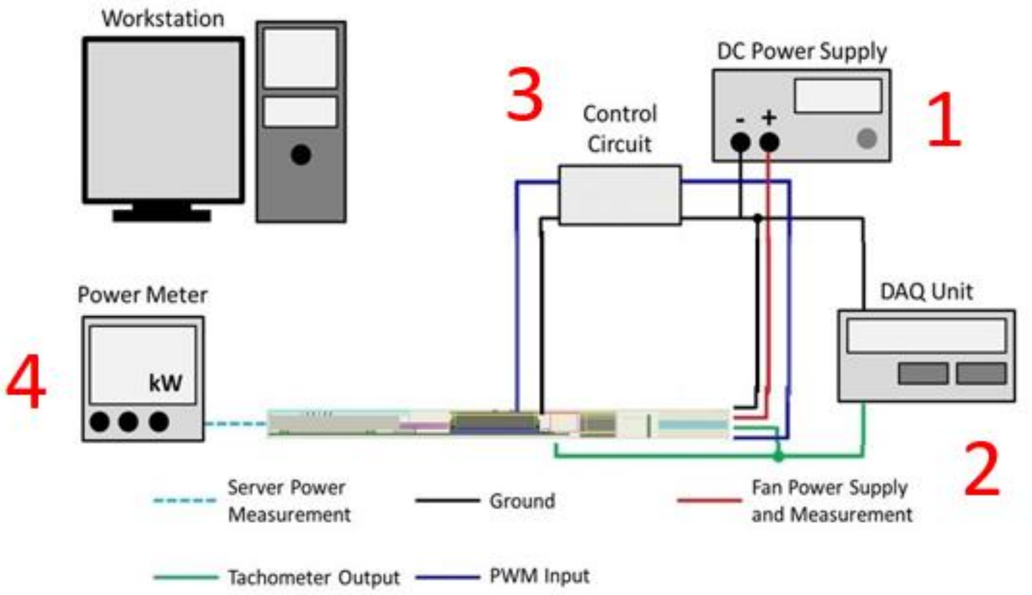


Figure 3-4 testing setup and data acquisition

A Yokogawa CW121 power meter is used to measure the power drawn by the server. Omega OM-EL-USB-1-LCD temperature loggers are used to measure the room ambient temperature. The inlet temperature of 25°C ± 1.0°C is observed during testing. UBUNTU operating system was used in the server to get the temperature measurement. A workstation is used to store all the result and analyze the data.

For the liquid cooling part, a penetrable K-type thermocouple was used in the inlet and outlet of the tubes. The diameter of the thermocouple is negligible to the flow.

Figure 3-5 K-type Penetrable Thermocouple

Foam tape was used to seal any kind of leakage after the penetration of the thermocouple. One more advantages of the foam tape is it seals the hole after removing the thermocouple. All these setup was required as the quick connects were charged with water based coolants.

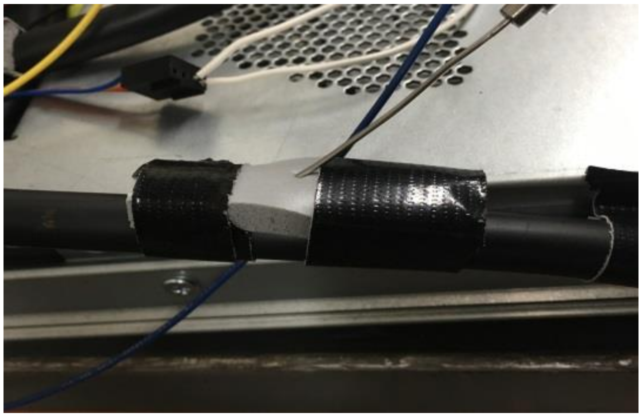


Figure 3-6 Thermocouple inserted with foam tape

Also to prevent heat dissipation though the tubes, Styrofoam was used. Styrofoam will work as a thermal insulator. Styrofoam covers the whole tube.

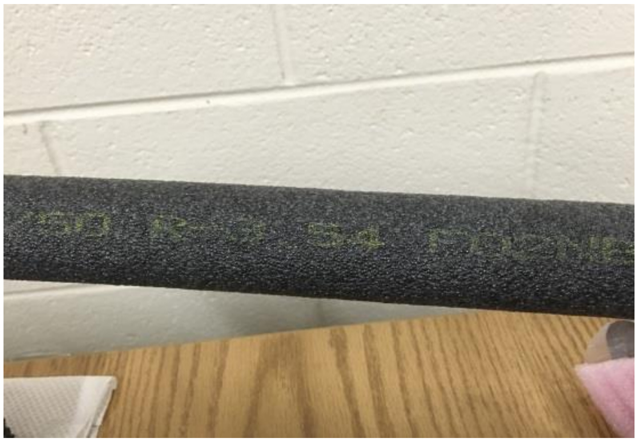
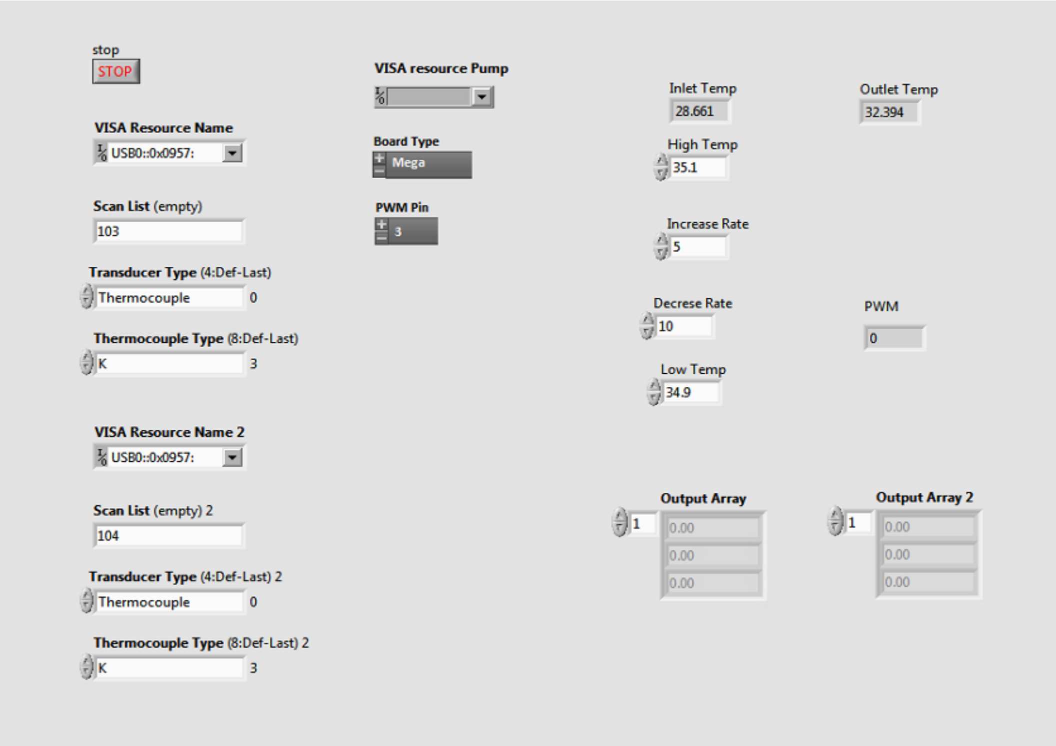


Figure 3-7 Styrofoam for tubes

A labview code was used to control the inlet temperature of the liquid coolant. To control the temperature, the speed of the dry cooler fan was varied. First the inlet temperature was measured though a DAQ and the DAQ is connected to the labview code. According to that temperature labview sends a PWM signal to the fans through Arduino.



VISA Resource Name
USB0::0x0957:

Scan List (empty)
103

Transducer Type (4:Def-Last)
Thermocouple 0

Thermocouple Type (8:Def-Last)
K 3

VISA Resource Name 2
USB0::0x0957:

Scan List (empty) 2
104

Transducer Type (4:Def-Last) 2
Thermocouple 0

Thermocouple Type (8:Def-Last) 2
K 3

VISA resource Pump

Board Type
Mega

PWM Pin
3

Inlet Temp
28.661

High Temp
35.1

Increase Rate
5

Decrese Rate
10

Low Temp
34.9

Output Array
1
0.00
0.00
0.00

Outlet Temp
32.394

PWM
0

Output Array 2
1
0.00
0.00
0.00

Figure 3-8 Front Panel of Labview

3.3 Procedures

The Airflow Bench allows to measure volumetric flow rates for varying pressure drops across the server. Air flow bench contains a blower which can be set in the push or pull configuration. The speed of the blower can be varied. The test bench has two chambers with a nozzle plate in the middle allowing the static pressure taps installed across them to record differential pressures [17].

Figure 3-9 shows the test bench used for this study. The static pressure was monitored using the static pressure transducer. The measurement represents the pressure drop across the server. By varying the blower speed, the flow rates and pressure drops across the server was measured with a DAQ unit. Any system or air mover is characterized on the test bench complying to the standard referenced in [28].

The server is utilized using a synthetic load generator tool called lookbusy [29] to create various workloads. A bash script is used to run the test for 18 hours. Native Linux command IPMItool was used to measure the temperature of components such as CPU, DIMMs and PCH [20]. Other native Linux commands mpstat [21] and free [22] are executed to measure CPU utilization and memory usage during the stress. The ability to change the flow rate allows parametric study of cooling efficiency of the fans.

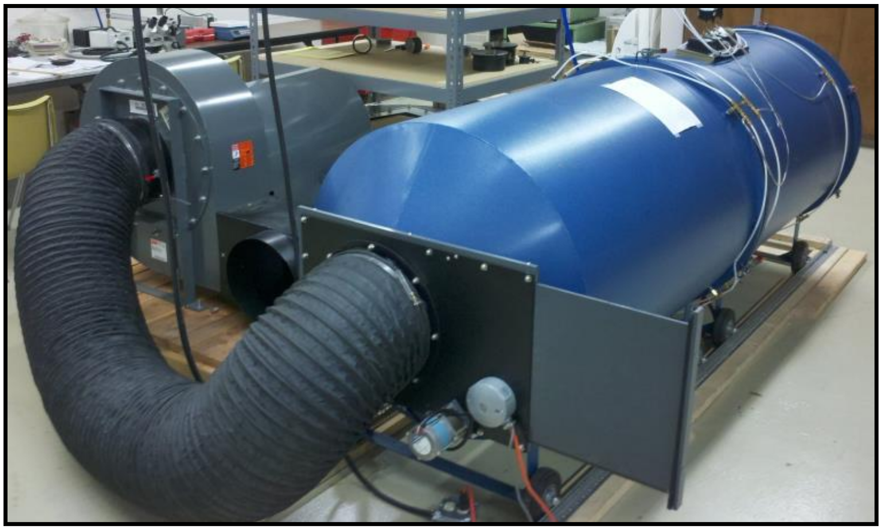


Figure 3-9 Airflow Test Bench

Chapter 4

Impact of Flow Rate Reduction

Flow rate was reduced by reducing the number of fans and the thermal performance of the server is evaluated.

4.1 Flow rate reduction test procedure

For initial testing, the system resistance of the server was measured. For measuring the system resistance, flow rate of the blower was varied. The pressure difference between front and back of the server measured with a help of pressure transducer. After that, flow rate was measured at different fan speeds. Then one fan was removed and flow rate was measured. Subsequently one more fan was removed and flow rate was measured.

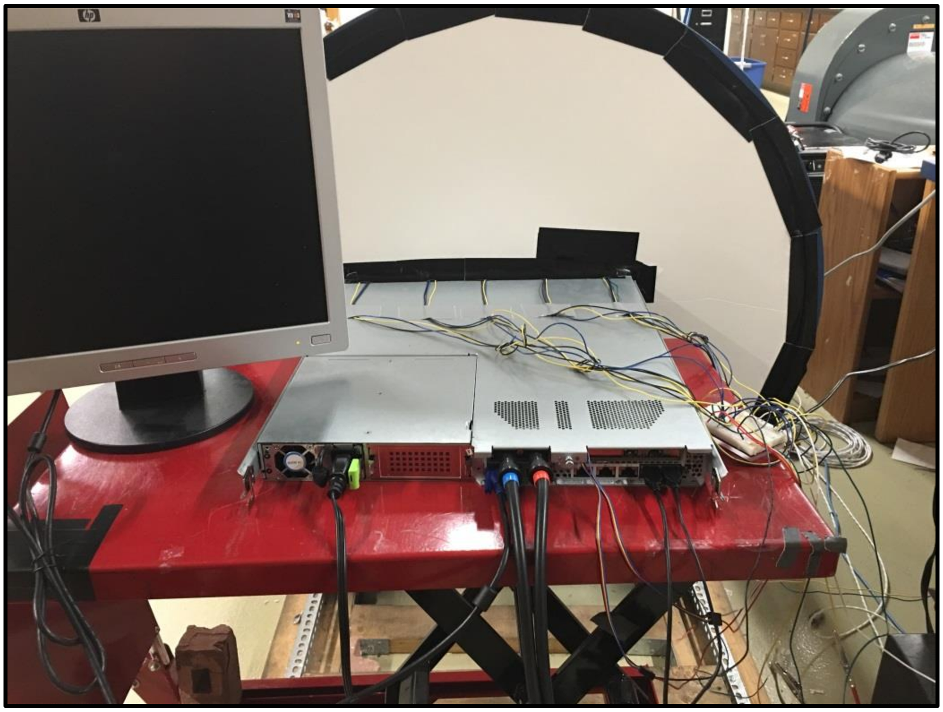


Figure 4-1 Server attached to the Airflow Bench

Also, the power consumption of the fans were measured at different flow rate or fan speed.

To measure the thermal performance, the server fans were at idle. For the testing, a synthetic computational load is applied to the server using a free software package, lookbusy [19]. The flow rate was reduced by reducing the number of fans and the effect on component temperature was observed. While operating the fans were at idle speed which is the minimum flow rate and the blower to the Air Flow Bench was adjusted to achieve zero static pressure.

At each run, the server was provided a synthetic computational workload of idle, 30%, 50%, 70% and 98% CPU utilization with the lookbusy. Each workload was run for 30 minutes and repeated three times in total for repeatability. The results gathered here are taken from the average values over the last 10 minutes of each computational workload as this is when steady state component temperatures were achieved [17].

Again, the server was provided a synthetic computational workload of idle, 30%, 50%, 70% and 98% memory utilization with the lookbusy. Again, each workload was run for 30 minutes and repeated three times in total for repeatability. The results gathered here are taken from the average values over the last 10 minutes of each computational workload as this is when steady state component temperatures were achieved [17].

4.2 Results

In the Figure 4-2, the system resistance curve of the hybrid server is shown. The curve is similar to any 1U servers. The replacement of heat sink to cold plate doesn't make that much difference in the system resistance curve.

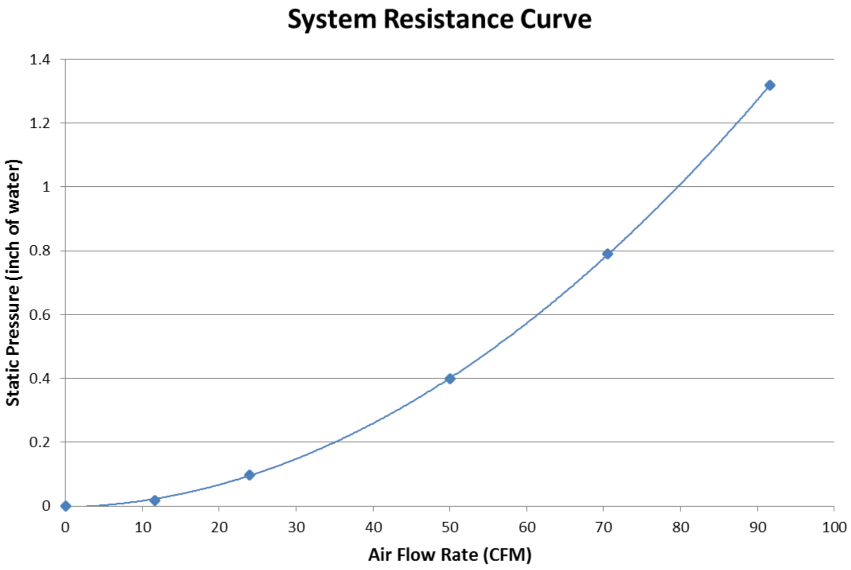


Figure 4-2 System Resistance Curve

Figure 4-3 represents different flow rate at different fan speed. The fan speed was varied by changing the PWM through the function generator. This experiment was done for 5, 4 and 3 fans. All the curves seems similar with some offset.

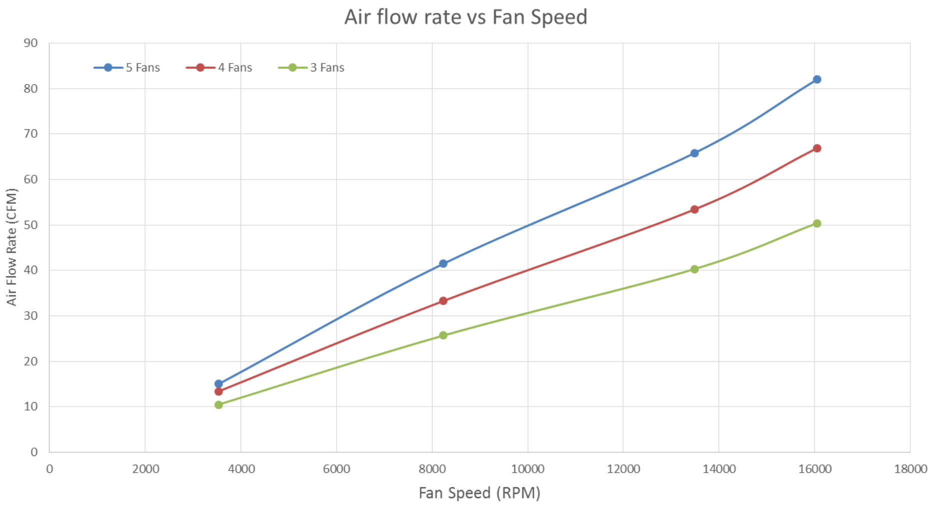


Figure 4-3 Flow Rate vs. Fan Speed

Figure 4-4 shows the same graph as before but this is flow rate vs. PWM of the fans. The PWM of the fans were controlled by the function generator. It has the same pattern as the previous graph.

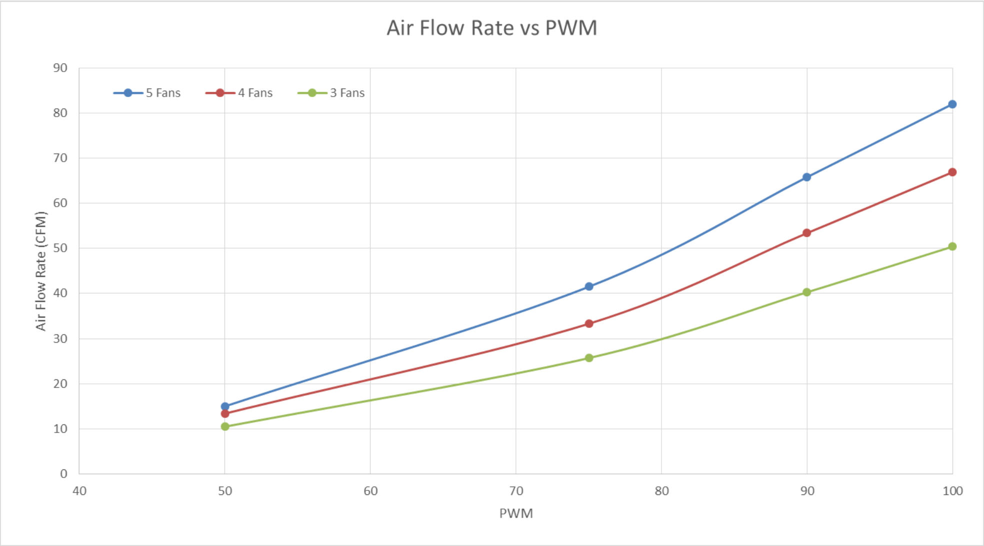


Figure 4-4 Flow Rate vs. PWM

To compare the power consumption by the fans at different fan speeds Figure 4-5 has been shown. As from fan law we know higher flow rate requires more power consumption for 3 fans rather than 5 fans. For an example, if 50 CFM is required 5 fans will consume around 25 watts whereas 3 fans will consume around 50 watts. But for this kind of hybrid server, the required air flow rate is very low. Around 10 CFM is sufficient to cool the other components. For this reason, 3 fans will save more power rather than 5 fans.

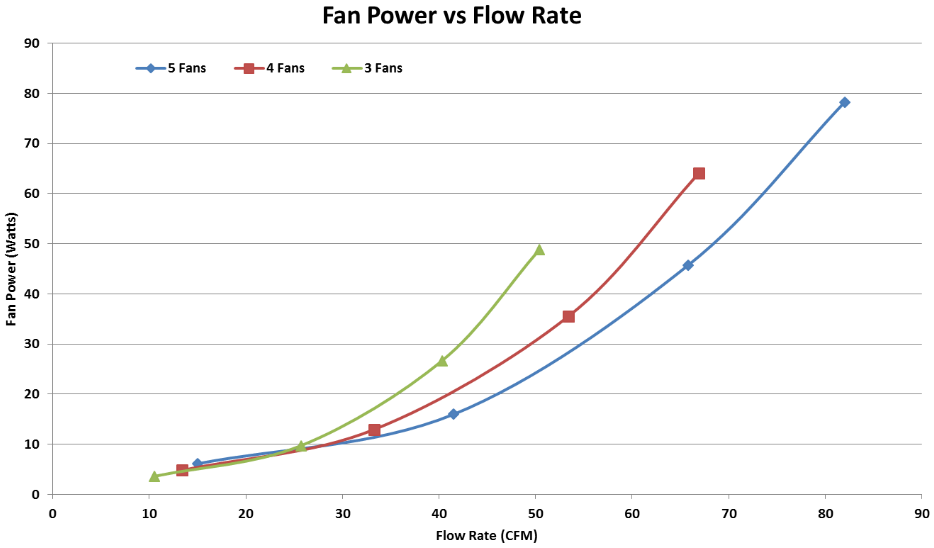


Figure 4-5 Fan Power vs. Flow Rate

For evaluating the thermal performances of the server, CPU was stressed from idle to 98% and different component temperature was measured. For measuring the DIMMs temperature, the average value of 8 DIMMs were taken which are associated with CPU0 or CPU1. Also, PCH temperature was measured.

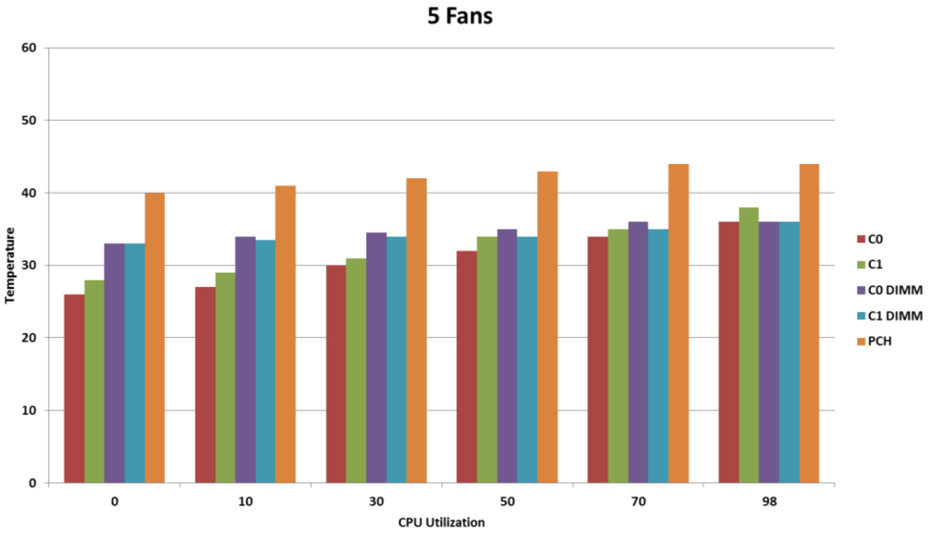


Figure 4-6 Temperature vs. CPU Utilization with 5 fans

From the Figure 4-6 it can be observed that CPU temperature doesn’t increase that much because of the cold plate. But the other component shows significant temperature increase. The DIMMs temperature increase with the utilization. Also, there is a significance increase seen in the PCH temperature.

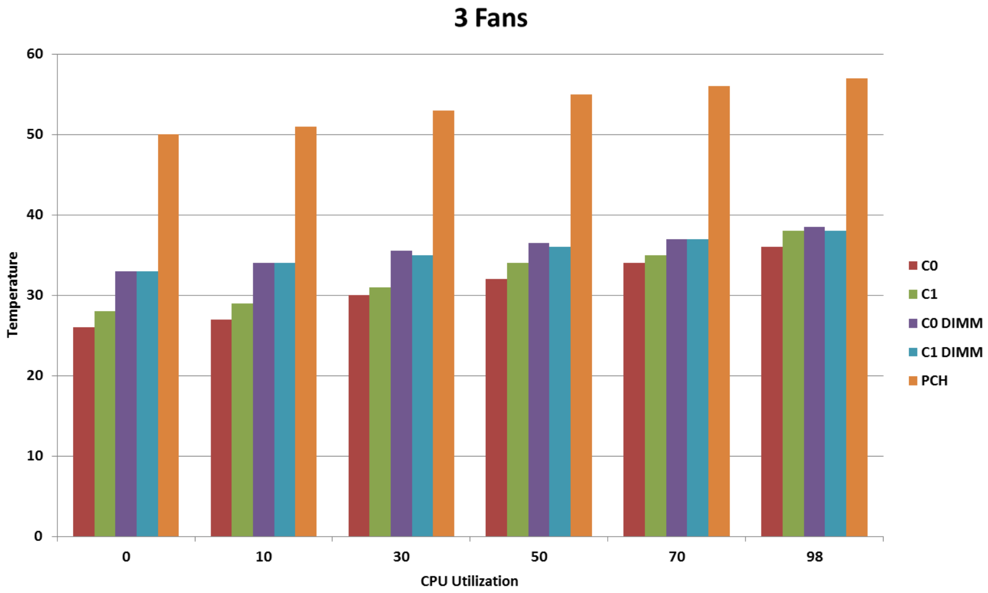


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Figure 4-7 Temperature vs. CPU Utilization with 3 fans

After that, 3 fans were used instead of 5 fans to reduce the flow rate. When using the 3 fans the flow rate was 10 CFM. When using 3 fans same processor temperature was observed. The maximum CPU temperature was 38°C. But the temperature of DIMMs and PCH was increased. Figure 4-7 illustrates the higher PCH temperature. As the CPU utilization increases the PCH temperature increases. The maximum PCH temperature was 57°C.

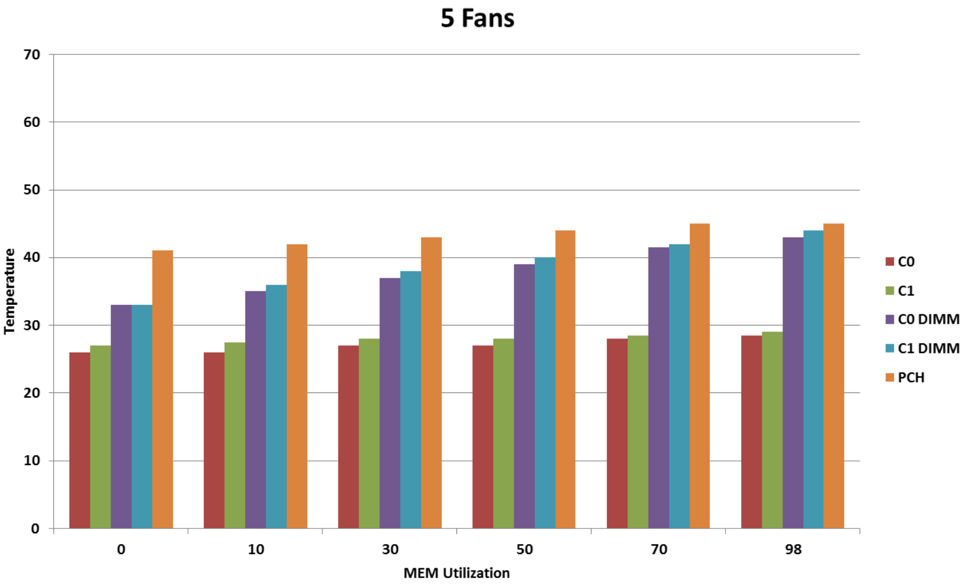

Figure 4-8 Temperature vs. Memory Utilization with 5 fans

In this case instead of CPU, memory was utilized from idle to 98% with help of lookbusy. CPU temperature was similar as the previous cases. But higher DIMMs temperature was observed. As the memory utilization increased the DIMMs temperature increased too. The maximum DIMM temperature was 44°C. Also, The PCH temperature was 46°C. All the temperatures are way below the critical temperature which make sure the reliability and performance of the components.

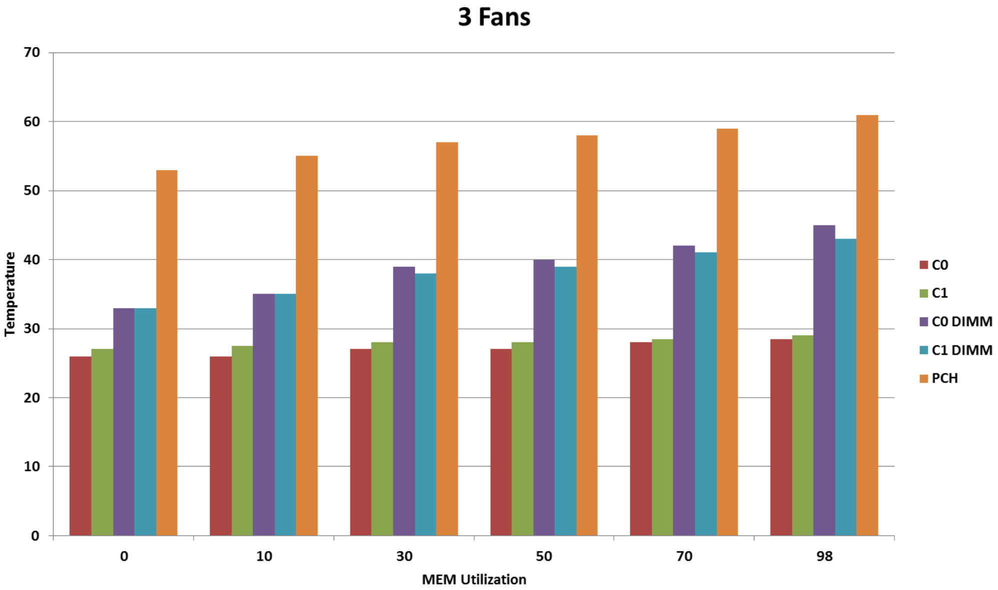

Figure 4-9 Temperature vs. Memory Utilization with 3 fans

In the Figure 4-9, 3 fans were used to reduce flow rate. A little bit higher temperature was observed for the DIMMs. But while using 3 fans, much higher temperature was observed for PCH. The maximum PCH temperature was 61°C. So, it can be seen that while reducing the number of fans, the PCH temperature is a major concern.

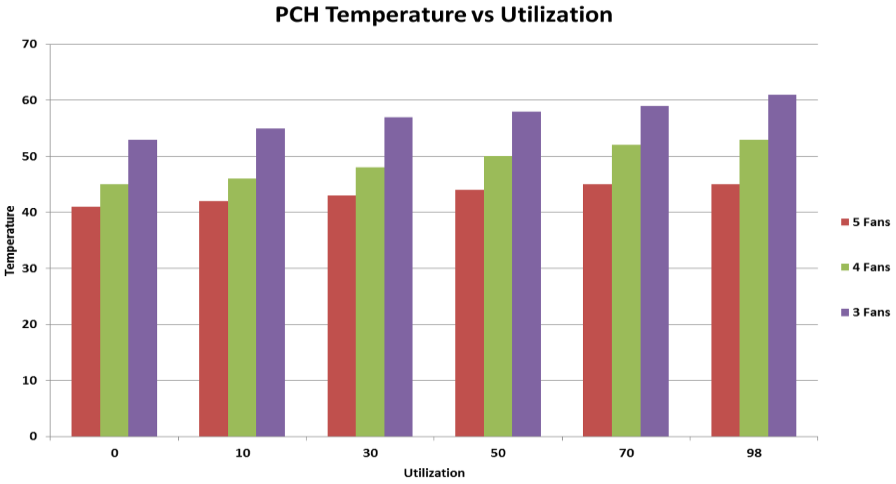

Figure 4-10 PCH Temperature vs. Utilization

Figure 4-10 represents PCH temperature with different utilization. PCH temperature with 5, 4 and 3 fans were observed. With 5, 4 and 3 fans the flow rate was 14, 12 and 10 CFM respectively. When the server was running with 3 fans maximum PCH temperature was 61°C. The critical temperature for PCH is 90°C. So it seems that PCH will operate pretty well with 3 fans only.

Chapter 5

Impact of Warm Water Cooling

5.1 Testing Procedure

Understanding the impact of warm water cooling is very important for this kind of processor which has very high heat generating capacity. The CPU was stressed with lookbusy. The temperature was measured by IPMItool. The fans were at idle speed.

A synthetic workload of 98% CPU utilization with the lookbusy was given to the server. Each workload was run for 30 minutes and repeated three times in total for repeatability. The results gathered here are taken from the average values over the last 10 minutes of each computational workload as this is when steady state CPU temperatures were achieved.

To maintain steady inlet temperature labview code was used. First, the inlet temperature was measured with a penetrable K-type thermocouple. Then the temperature value was used in the labview code. A dead band control was used to monitor the temperature and give output signal accordingly. If the temperature was higher than the target temperature, an output signal of higher PWM generated. On the other hand if the temperature was lower than the target temperature, an output signal of lower PWM generated. Then the output PWM signal was sent to the miniature dry cooler fan with the help of Arduino. Arduino was connected to the labview code. All of these process was automated.

5.2 Results

The inlet temperature of the cold plate was varied from 30°C to 50°C with an increment of 5°C. The output parameters that were monitored are outlet temperature, CPU0 and CPU1 temperature. CPU0 was in the upstream and CPU1 was in the downstream.

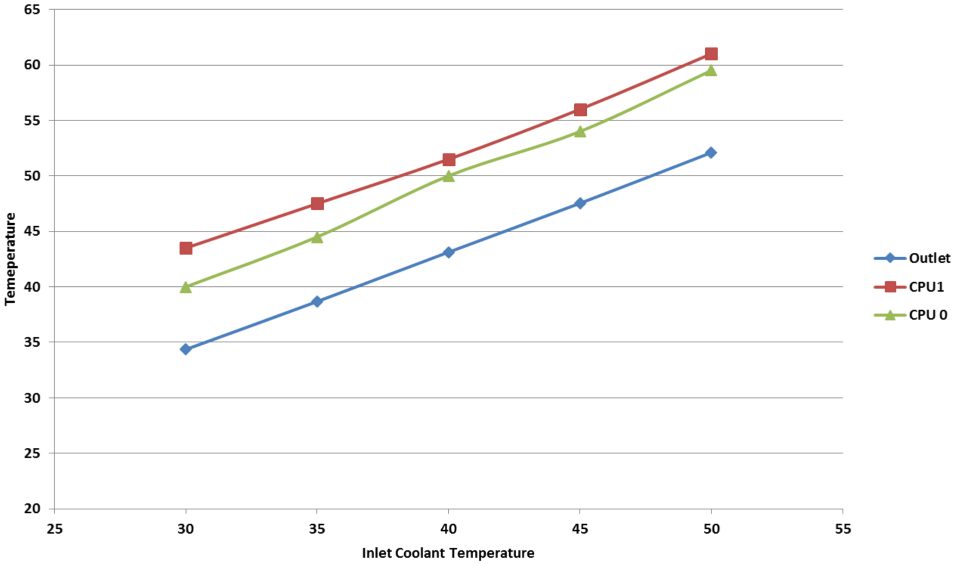

Figure 5-1 Temperature vs. Inlet Temperature

From the above figure it can be seen that outlet temperature has a straight line trend. At 30°C inlet temperature the outlet temperature is 34°C whereas at 50°C inlet temperature the outlet temperature is 52°C. So, with the increase of inlet temperature, the heat carrying capacity reduces significantly. As for the CPU temperature, at 30°C inlet temperature the CPU0 temperature is 40°C and CPU1 temperature is 44°C. The temperature increase has a linear trend. With the higher inlet temperature, the difference between CPU0 and CPU1 decreases. At, 50°C inlet temperature, CPU0 temperature is 59°C and CPU1 has 61°C. The critical temperature for the processor is 88°C. So even at 50°C inlet temperature the processor should work fine. The performance and reliability should not be an issue at this temperature.

Chapter 6 Conclusions and Future work

6.1 Conclusions on Air Cooling

In this study the effects of different airflow rate going through the server is studied. In the process of reducing the air flow rate, the number of fans were also reduced. This study will a new idea of optimizing hybrid cooled server. A truly optimized system will require balancing between air cooling part and liquid cooling part as well. From the results showed in here it is clear that hybrid cooled server required a reduced amount of air flow then air cooled server.

The overall goal of the study is to minimize the total cooling power consumption. Some significant overall conclusions can be drawn from the experimental study performed on the Cisco servers. There can be an overall 40% energy savings when using 3 fans.

Each fan consumes a maximum of 9W. If it is possible to reduce 2 fans that will save around 18W. Reducing 2 fans will reduce the flow rate which can cause an increase in component temperature.

The power saving greatly depends on the fan control algorithm. In this case fan algorithm is set based on the processor temperature but it needs to set on the basis of PCH temperature because the main heat generating component is the PCH as the processor is cooled by the liquid cooling.

From the experiments it can deduced that, Using 3 fans at idle speed will cause the enough air cooling for the components. It can be seen that the maximum PCH temperature was 61°C. Other components like DIMMs were way below the critical temperature. The maximum DIMM temperature was 46°C.

Also it was seen that PCH usually generate a constant heat. It doesn't change that much with CPU or memory utilization. For redundancy, 3 fans can always ramp up and produce enough air flow. The maximum air flow for 3 fans is 50 CFM. In a sense that will require more power than 5 fans but when they are running at idle 3 fans will require less power. For all of this a dynamic fan control algorithm is required.

6.2 Conclusions on Liquid Cooling

On the other hand, for the liquid cooling experiment it can be deduced that these servers can run at a much higher inlet temperature. It was observed that flow rate was critical parameter to consider when warm water cooling experiment was done.

From the experiment, the inlet temperature was at 50°C and the maximum processor temperature was 61°C which is way below the critical temperature. The critical temperature for this kind of processor is 88°C. So it is safe to say that these server can run at 50°C inlet temperature as well.

As we know cooling rate or flow rate is important factor in warm water cooling. The flow rate was at maximum when the inlet temperature was at 50°C. That's why the processor temperature was under 65°C.

6.3 Future Work

- To find the optimized position for the fans
- Introducing a ducting system so that more air can go through the PCH heat sink
- Study the effect of raised inlet air temperature
- Study the tradeoff between cooling power and leakage current
- Experiment with reduced coolant flow rate
- Study the failure case scenario of fans and pumps as well

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Md Malekkul Islam, has received her Bachelor of Science in Mechanical Engineering degree from Bangladesh University of Engineering and Technology, Dhaka, Bangladesh. He has completed her Masters of Science in Mechanical Engineering from the University of Texas at Arlington in May 2016.

Malek has always been interested in Computational Fluid Dynamics, HVAC systems and Machine design. His research interests have always been into Fluid flow and Heat Transfer, Thermal Sciences and Design.

During his Master’s program he has worked in thermal management of data centers. He has associated himself with various industry collaborated research projects and studied various topics like air cooling, liquid cooling and direct/indirect evaporative cooling etc. He has worked in experimental and CFD characterization of Cisco servers, thermal power optimization technique and determination of die temperature. He has gained theoretical background knowledge of CFD and worked data center specific CFD codes like 6SigmaDC, Icepak and FloTherm.