RACK LEVEL STUDY OF HYBRID COOLED SERVERS USING WARM WATER COOLING WITH VARIABLE PUMPING FOR CENTRALIZED COOLANT SYSTEM

by

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Abstract

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The University of Texas at Arlington, 2017

Supervising Professor: Dereje Agonafer

As the worldwide demand for the data centers grows, so does the size and load placed on data centers which leads to the applied constraints on power and space available to the operator. Cooling power consumption is a major contributor of the total energy consumption of the system. In the process of optimization of cooling energy consumption per performance unit, liquid cooling technology has emerged as one of the most viable solutions.

In this rack level study, 2OU (Open U) hybrid cooled web servers are tested for an evaluation of warm water cooling in centralized coolant system. Effects of higher inlet temperatures of the coolant in terms of device temperatures as well as IT and cooling power have been observed as a part of the evaluation. The study discusses the significance of variable pumping in centralized coolant system for its more efficient use.

The experimental setup for cooling consists of 1/3rd sized mini rack capable of housing up to eleven liquid cooled web servers and two heat exchangers. The cooling configuration is centralized and has two redundant pumps placed in series with heat

exchanger at the rack. CPUs of each server are liquid cooled with using passive micro-channel cold plates while rests of the components are air cooled.

Synthetic load has been generated on each servers for thermal stress testing and observed performance characteristics such as device temperatures and cooling power consumption of servers. Centralized redundant pumps are separately powered using an external DC power supply unit. The pump speed is varied with variable voltage supply ranging from 11V to 17V across the armature. The experimental testing is carried out at higher inlet temperatures ranging from 25°C to 45°C which falls within the ASHRAE liquid cooled envelope W4.

Variable pumping at higher inlet temperatures has been achieved to evaluate to operating temperatures of device components for reliability and reduction in operational cooling power consumption of the servers.

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Chapter 1

INTRODUCTION

Nowadays, cooling system has become a vital need of an almost every single industrial product. Though cooling systems for electronic devices are designed in accordance with micro-scale heat transfer, their energy consumption is significant. Especially, in data center facilities IT equipment must be maintained at a certain temperature below the critical for reliability purposes [1]. The total energy consumption by data centers in USA is reported to be around 70 billion kilowatt-hours of energy each year which itself is more than 2% of the total energy consumption [2]. The significant increase in power trend continues as the demand for data center grows with advances in computing technologies. More and more number of people are connecting through internet and coming into the mainstream by extensive use of social media, emails, mobile applications etc.

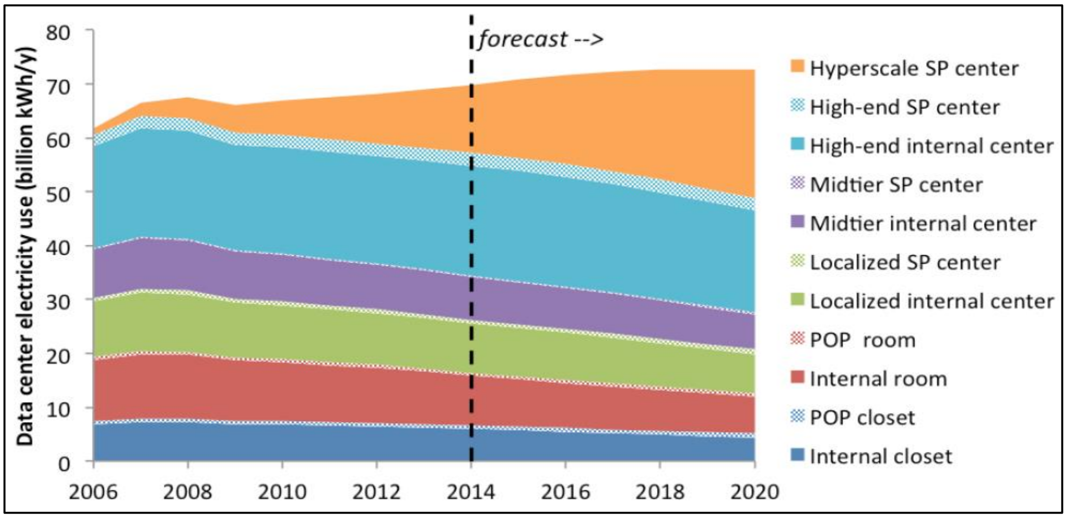


Figure 1-1 The Portion of Energy Use Attributed to Data Centers of Various Types Over Time and Estimated Energy Usage in Future Years [2]

The power consumption by data centers for cooling purposes is around 31% of the overall energy. The cooling power is typically a summation of HVAC Cooling and HVAC Fans [3].

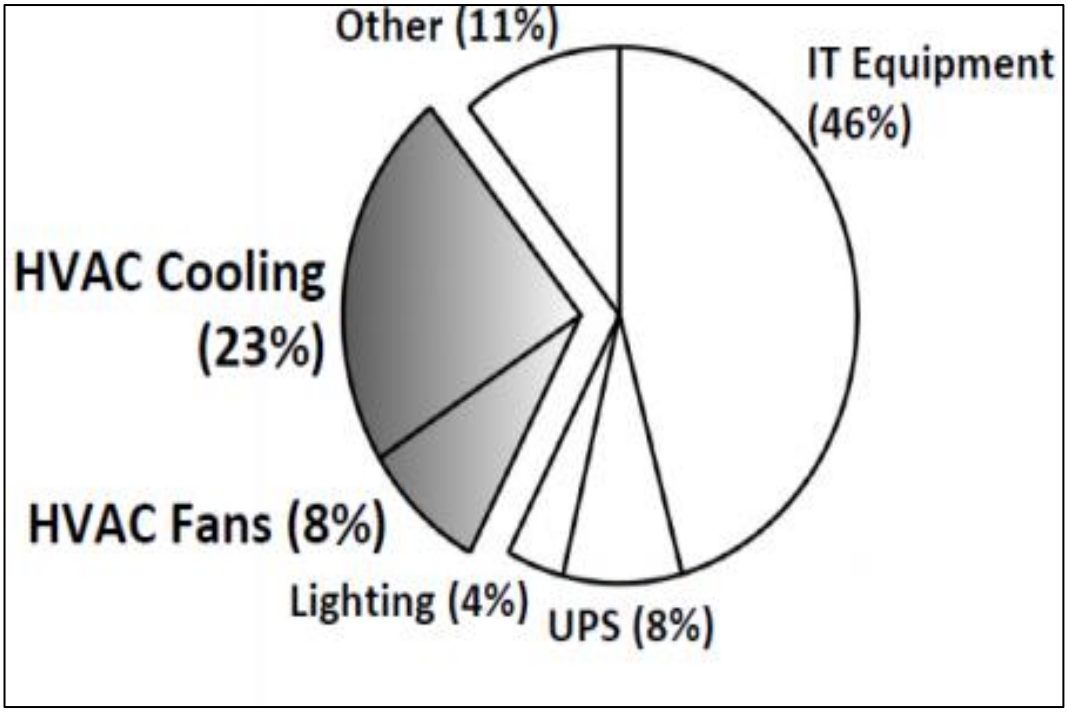


Figure 1-2 A Common Data Center Power Allocation [3]

1.1 Motivation

The conventional method of data center cooling is air cooling of the IT equipment. But air cooling technology has its own disadvantages.

- Air has very poor heat transfer properties compared to the liquids.
- There is a possibility of formation of large hot spots, low pressure pockets in case of air cooling of IT equipment at data center facility.
- The CRAC units, chillers and compressors consume higher amount of energy to maintain desired inlet temperature and pressure.

Figure 1-3 Infrastructure for Air Cooling of Server Racks in Data Center at UTA

- Racked systems in data center facility controls the airflow within the system. Thus it collectively requires a different amount of volume air flow than the CRACs can provide. This may lead to either high pressures and more re-circulation or inadequately provided air cooling in the room as shown in Figure 1-4 [4].
- In the coming future of data centers, IT equipment will might have high performance chips with heat fluxes of 150W/cm^2 to match the high computational performance demands. This can increase heat loads at the server and facility level [4].

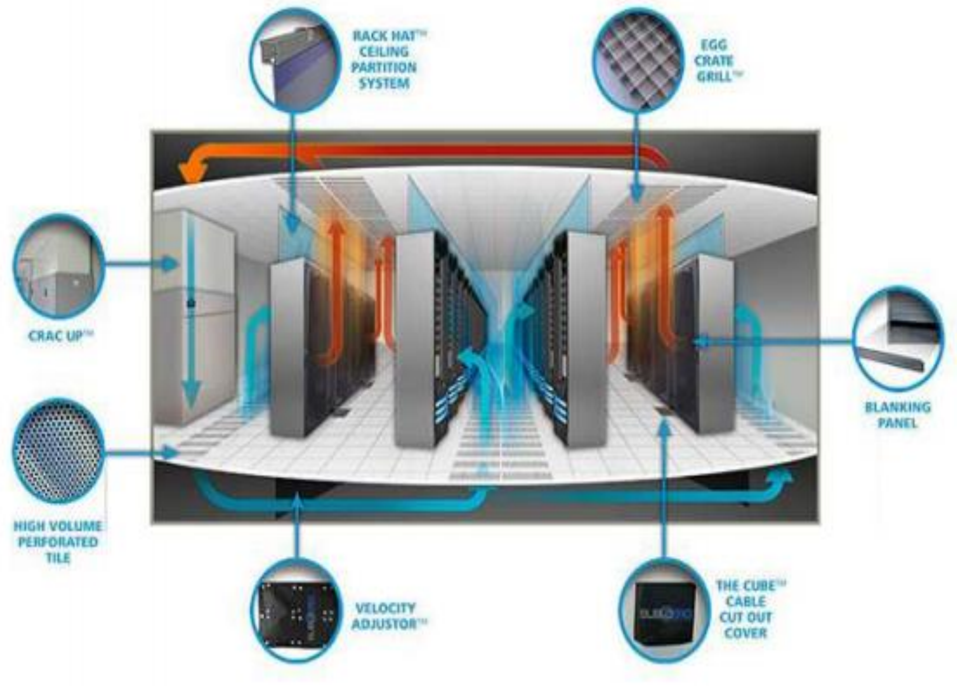


Figure 1-4 Air Cooling in Data Center

Liquid cooling technology provides legitimate solution to the most of these critical issues associated with conventional way of air cooling.

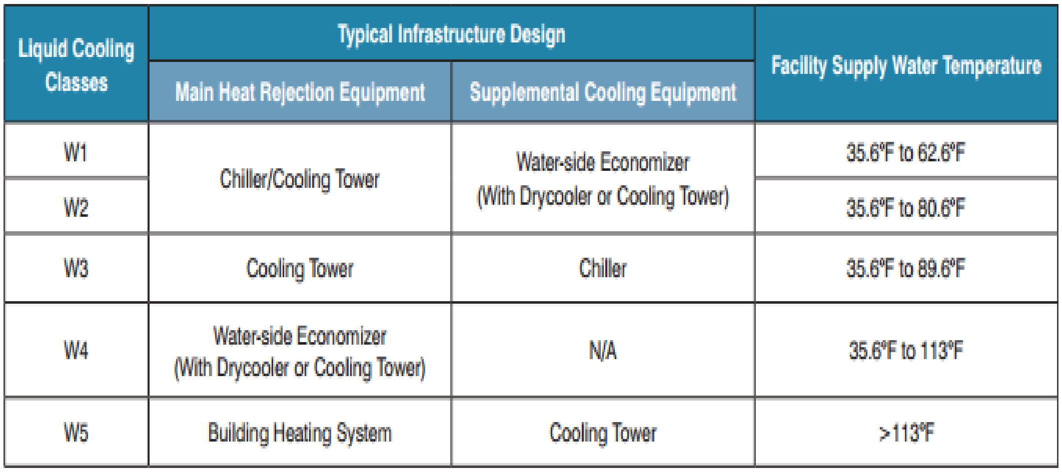
- Liquids have better heat transfer properties compared to the air.
- If we move the liquid source closer to the heat dissipating devices, the formation of hot spots at room level in data center facility can be minimized which leads to an improvement in the effectiveness of the cooling [5].
- Streamline flow of liquid coolant through cooling channels can prevent the formation of low pressure pockets.
- Liquid cooling solution also gives a flexibility in operating within wider range of inlet temperatures with using warm water cooling which may lead to the partial or complete elimination of Computer Room Air Conditioning (CRAC) units reducing cooling power consumption significantly [6].
- The energy consumption by refrigeration chiller compressor contributes around 50% of the total energy consumption by data centers for cooling purposes. Facility level study in liquid cooling of data center may lead to eliminate these chiller compressors with using liquid economizers [6].
- An efficient use of the exhaust in liquid cooling system can help in heat recycling [7].
- On the other hand, liquid cooling systems face few difficulties as leakage becomes a threat to the IT equipment, more infrastructure is required to contain the liquid. Thus Liquid cooling postures greater methodological and economic challenges than air cooling. But its significant cooling performance makes it necessity for high density applications [4].

Accounting the advantages discussed above, rack level evaluation of centralized cooling of hybrid cooled servers have been studied for its more efficient use considering reliability aspects of each device component.

1.1.1 Warm Water Cooling

Liquid cooling solution opens doors to the improvements in data center cooling, but encouraging use of warm water cooling gives wide options for selecting desired inlet conditions.

- According to ASHRAE liquid cooling guidelines, W4 envelope allows the cooling system to operate within a wide range of 2°C-45°C in case of direct contact liquid cooling which improves energy efficiencies [8].



Liquid Cooling Classes	Typical Infrastructure Design		Facility Supply Water Temperature
	Main Heat Rejection Equipment	Supplemental Cooling Equipment	
W1	Chiller/Cooling Tower	Water-side Economizer (With Drycooler or Cooling Tower)	35.6°F to 62.6°F
W2			35.6°F to 80.6°F
W3	Cooling Tower	Chiller	35.6°F to 89.6°F
W4	Water-side Economizer (With Drycooler or Cooling Tower)	N/A	35.6°F to 113°F
W5	Building Heating System	Cooling Tower	>113°F

Figure 1-5 ASHRAE Liquid Cooling Classes [8]

- The data center community is reluctant to operate cooling system beyond 15°C-25°C but there are many ways to run the cooling system smoothly even at higher temperatures below the critical with using warm water cooling which can potentially eliminate CRAC units.
- The higher inlet temperatures in case of warm water cooling enables the pairing of liquid cooling with a water-side economizer (dry cooler) which can partially eliminate chiller compressors.

- The heat carrying capacity of the water is around 25 times of the air which results in lowering mass flow rate, overall power draw and lower temperature rise [4]. This may lead to the energy efficient solution in data center cooling technology and can potentially lower the system noise by lowering the fans speed.
- The use of ethylene glycol based water solution can prevent the possibility of corrosion of various components of the cooling system.
- The use warm water cooling in direct contact cooling system can reduce the junction temperature by around 10% [4]

Figure 1-6 Liquid-based Cooling at IBM [4]

1.2 Objective

Rack level evaluation of the various coolant systems for hybrid cooled servers using direct contact liquid cooling can be carried out in many ways to understand energy efficiencies and component performances.

- In this research topic, centralized coolant system has been evaluated with using variable speed pumping.
- The centralized coolant system has been evaluated with variable inlet conditions such as different fluid flow rates and higher inlet temperatures.
- The implementation of hybrid cooling of servers in centralized coolant system, the ethylene glycol base water at temperatures above ambient conditions (25-45) is utilized to cool the majority of heat dissipating components i.e. CPU and rests of the components such as Hard-disk drives (HDD), Platform Controller Hub (PCH), Dual in Line Memory Module (DIMM) etc. are air cooled in order to reduce an energy required to cool electronic equipment.
- The study involves an observation of rise in operating temperatures of device components with increase in inlet coolant temperatures and cooling energy evaluation in each case of experimentation.
- The objective of the study was to discuss the operating temperature rise of the device components in accordance with the reliability measures and thermal shadowing effect.
- The study also focuses on obtaining trade-off between cooling energy efficiencies and IT performance.

Chapter 2

EXPERIMENTAL SETUP

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2.1 Server Configuration

Winterfell hybrid cooled servers are being tested for centralized cooling system by means of variable pumping.

- Each server tray includes mainly an Intel v2.0 motherboard [10], hard disk drive (HDD) and bus bar clip shown in Figure 2-1.
- The chassis dimensions are 804x171x88 mm³. The cover has internal ducting as shown in Figure 2-2.

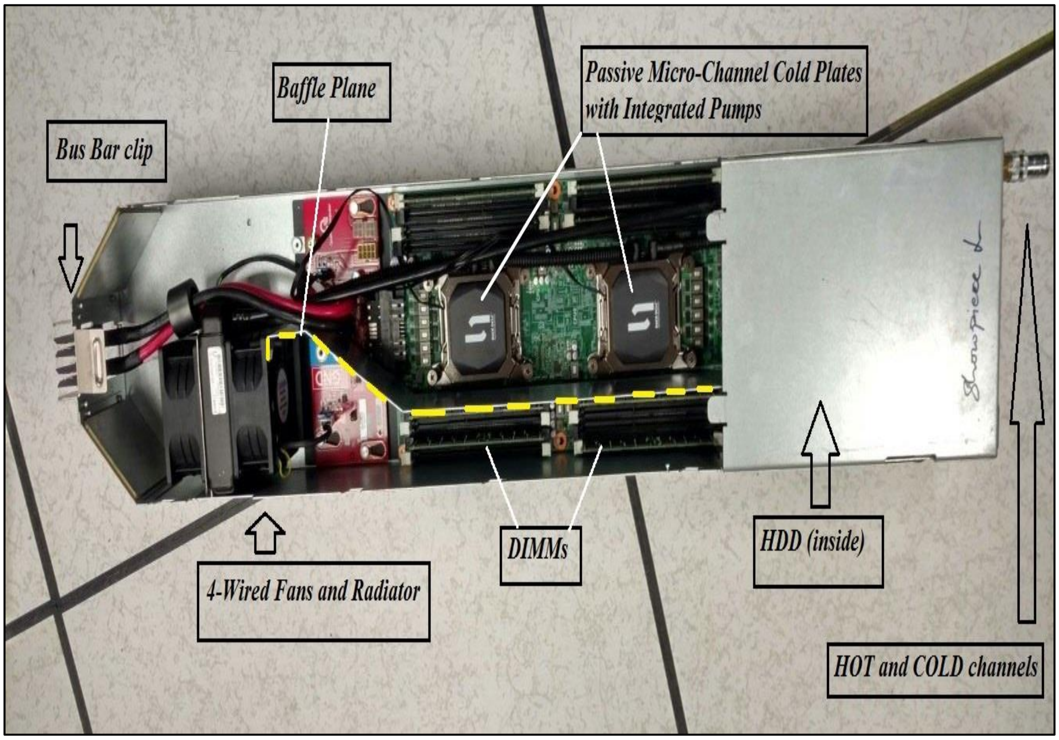
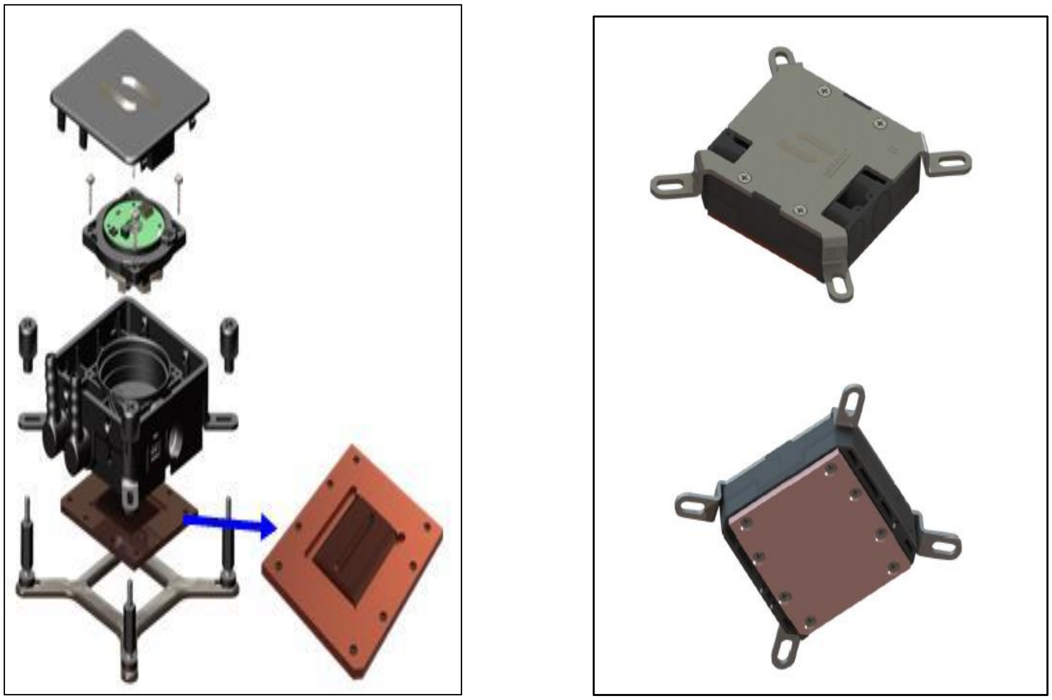


Figure 2-1 Hybrid-Cooled Winterfell Server

Figure 2-2 Internal Ducting (Baffle Plane)

- The internal ducting is a baffle plane which isolates the air flow to cool the auxiliary components in more efficient way
- The motherboard has two CPUs (CPU 0 and CPU 1) and up to 16 DIMMs of installable memory. Each CPU has a TDP rated up to 115 W [10].
    - TDP is a thermal design power, sometimes called thermal design point. It is the maximum amount of heat generated by a computer chip or component (often the CPU or GPU) that the cooling system in a computer is designed to dissipate in typical operation [11].
- In our case of hybrid cooling of a server, CPUs are mainly being liquid cooled while rests of the components are being air cooled.
- Each server is equipped with two passive micro-channel cold plates mounted on CPUs for an indirect cooling. The cold plates are integrated with brushless motor liquid coolant pumps shown in Figure 2-3 [12].



(Figure 2-3.1) (Figure 2-3.2)

Figure 2-3.1 & 2-3.2 Passive Micro-Channel Cold Plates Integrated with Brushless Motor Liquid Coolant Pumps [12]

- The coolant enters the chassis through cold channel passes through the radiator and two cold plates in series before exiting through hot channel.
- The distributed pumps integrated with the cold plates are disconnected from power source to study centralized cooling system. The flow is driven across the system by means of centralized redundant pumps.
- The server tray also has a fan-assisted radiator which re-circulates air within the server for cooling the rest of the heat dissipating auxiliary components. The only fluid exchange from the server is liquid coolant other than that the server is isolated.

- The fans are 4-wire pulse width modulation (PWM) controlled with 975 to 10000 rpm range [13]. The baffled air flow from the fans cools DIMMs present on left hand side (LHS) by forced convection as shown in Figure 2-4.

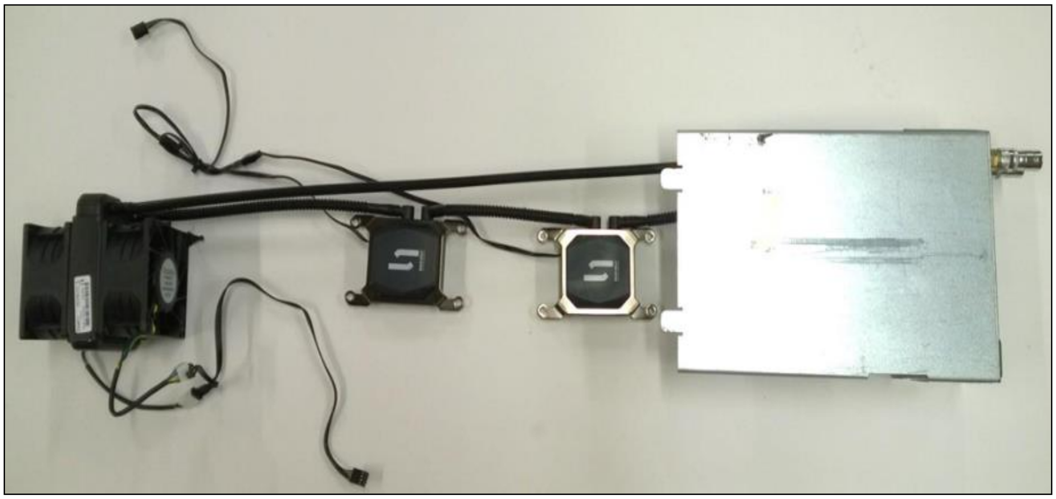


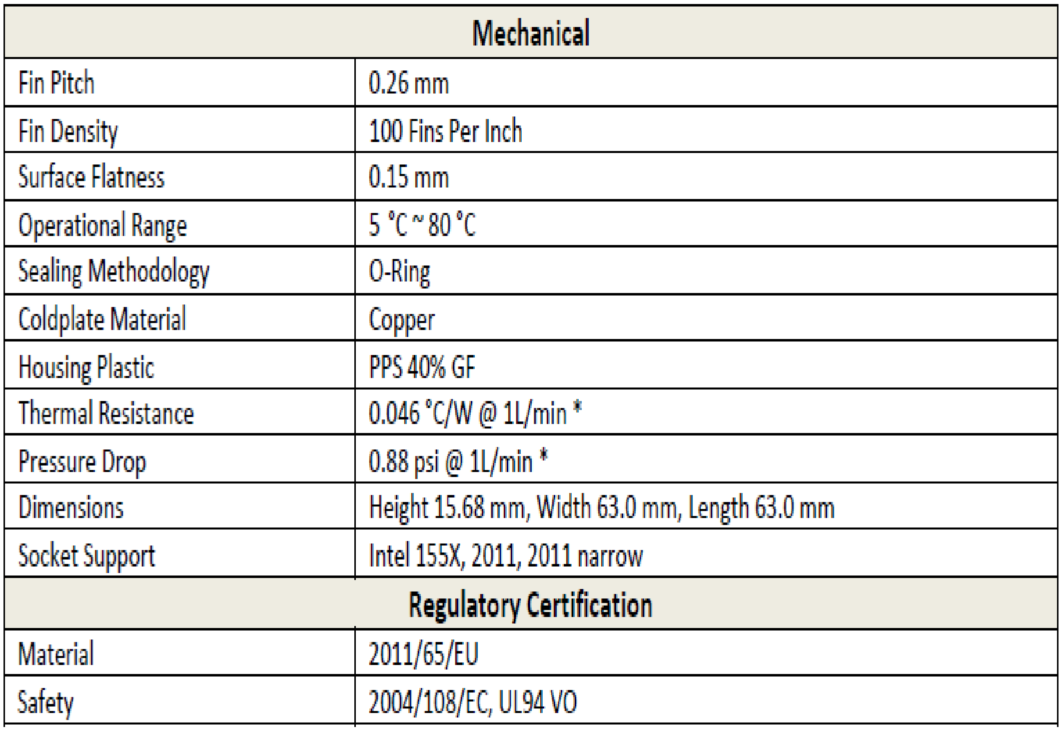
Figure 2-4 Installation of Passive Micro-Channel Cold Plates Integrated with Brushless Motor Liquid Coolant Pumps

2.1.1 Cold Plates (Liquid Cooling)

The R3 cold plate is a passive complete technology employed by CoolIT in centralized pumping architectures. The R3 system is purpose-designed to accommodate lower profile footprints such as blades and other custom chassis.

The CoolIT Systems reference cold plate is a solid copper component that leverages several CoolIT design optimizations including a unique V-Groove micro-channel construct that maximizes performance for today’s high thermal density applications [12].

- The specifications of the cold plates are as follows:



Mechanical	
Fin Pitch	0.26 mm
Fin Density	100 Fins Per Inch
Surface Flatness	0.15 mm
Operational Range	5 °C ~ 80 °C
Sealing Methodology	O-Ring
Coldplate Material	Copper
Housing Plastic	PPS 40% GF
Thermal Resistance	0.046 °C/W @ 1L/min *
Pressure Drop	0.88 psi @ 1L/min *
Dimensions	Height 15.68 mm, Width 63.0 mm, Length 63.0 mm
Socket Support	Intel 155X, 2011, 2011 narrow
Regulatory Certification	
Material	2011/65/EU
Safety	2004/108/EC, UL94 VO

Figure 2-5 CoolIT R3 Cold Plate Specification [12]

- P-Q Curve:

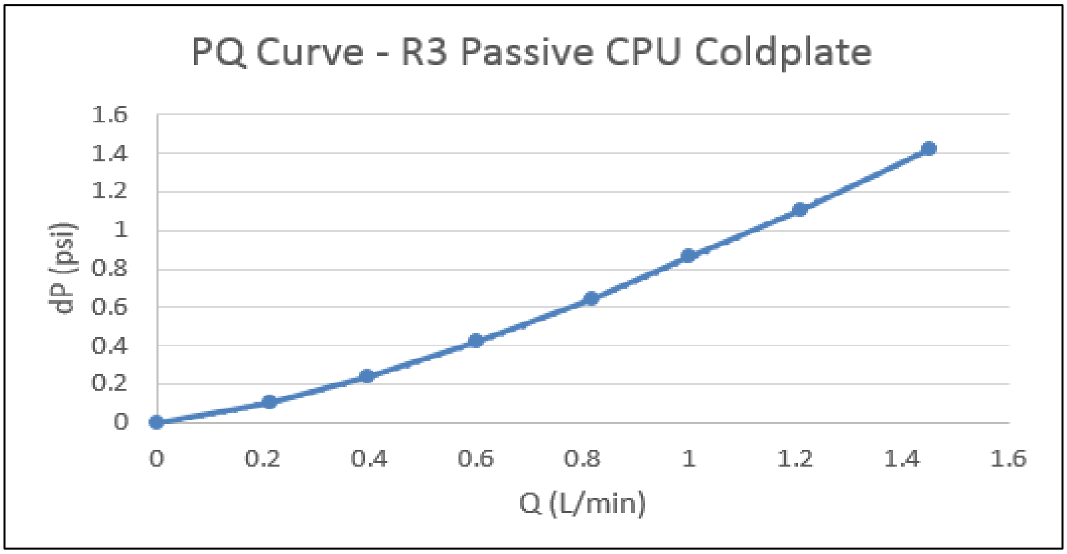


Figure 2-6 CoolIT R3 Cold Plate P-Q Curve [12]

- Thermal Resistance Curve:

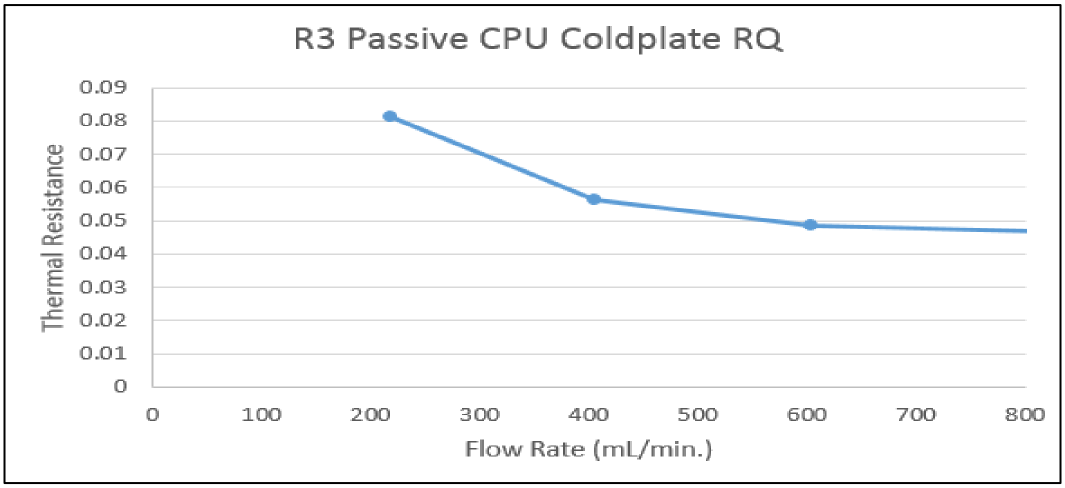
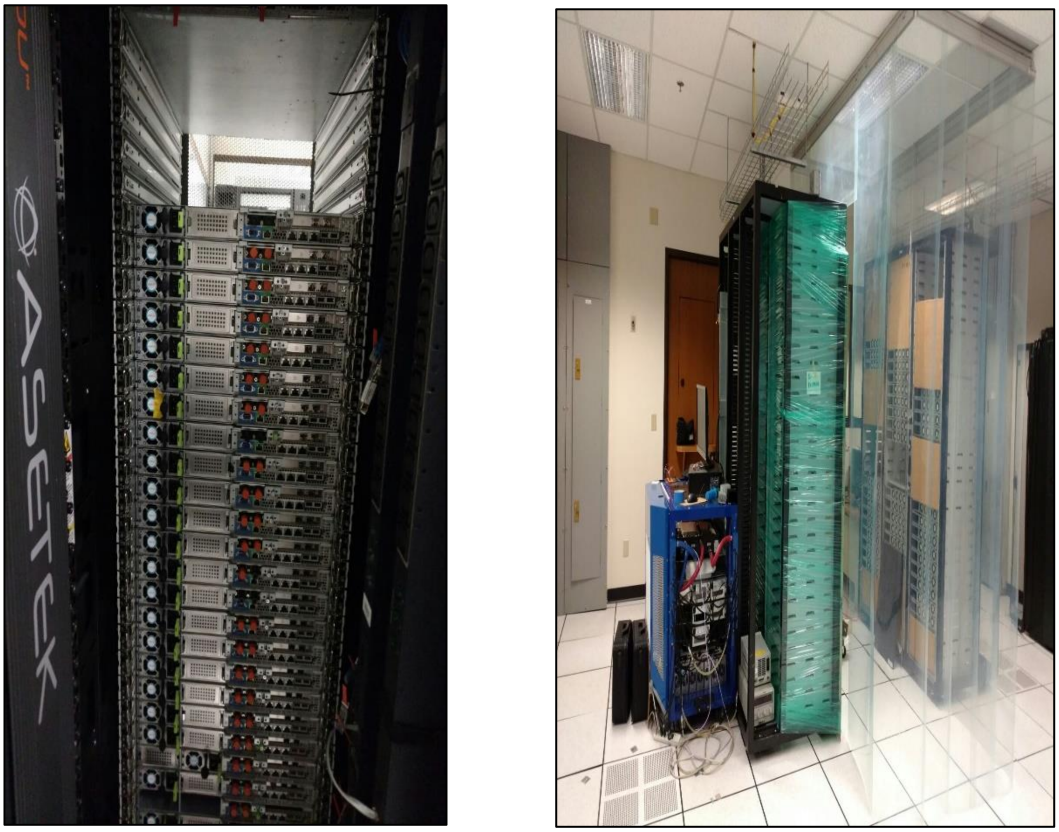


Figure 2-7 CoolIT Cold Plate R-Q curve

2.2 Rack Configuration

The test bed data center room is equipped with CRAH Unit and 3 Open compute 45U racks filled with 1U resistive heaters. The resistive heaters are used to maintain certain room temperature so as to obtain desired inlet temperature. The data center room is equipped with Facebook’s Winterfell, Freedom and Cisco servers for experimental testing. The testing rack is placed in the test bed data center.



(Figure 2-8.1) (Figure 2-8.2)

Figure 2-8.1 & 2-8.2 Thermal Resistive Heaters and Rack Infrastructure in Data Center Lab at UT Arlington

- The experimental setup includes one-third size of an Open Rack V1.0 [15] with a network switch, power shelf and four 2 OU slots as shown in Figure 2-10.
- The rack is equipped with two heat exchangers, a liquid-to-liquid heat exchanger (CHx40) and a side car liquid-to-air heat exchanger (AHx).
- The rack has inlet manifold for distribution of already cooled liquid into each server and outlet manifold for collecting hot coolant from each server. CHx40 unit is placed on the top of the servers and AHx unit is on the side of the server slots. There are total 12 server slots capable of housing up to eleven servers. The power tray is present at the bottom to power the servers and liquid cooling rack.
- Each of the heat exchangers is incorporated with a corresponding coolant reservoir and a control system. The AHx control system helps in varying the inlet temperature of the facility liquid by controlling the fans and pumps.

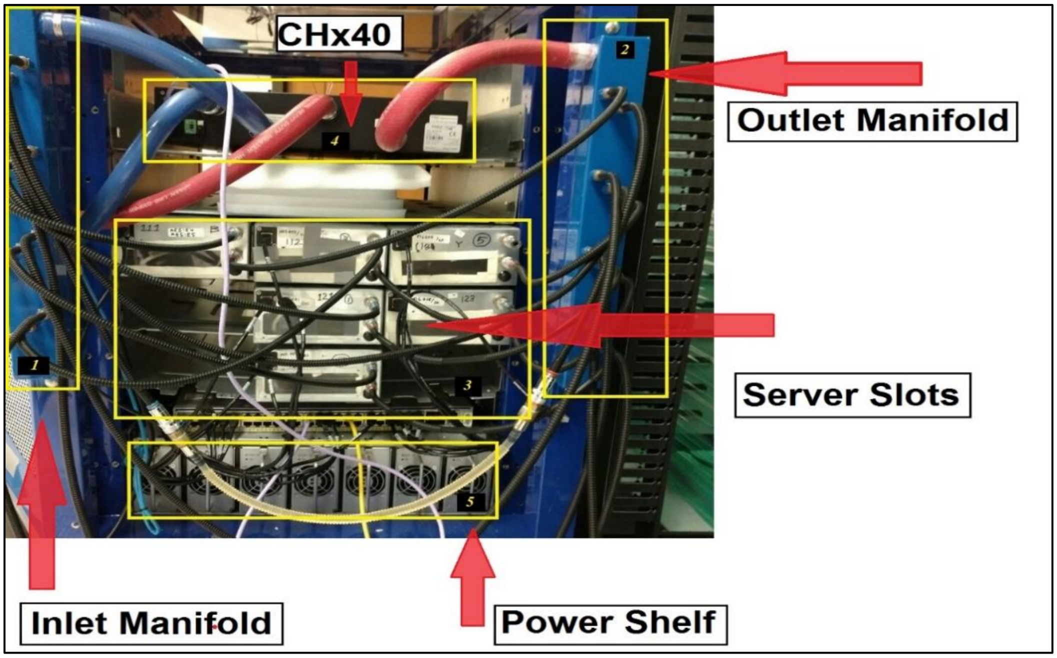


Figure 2-9 Front View of the Open Rack V1.0

2.2.1 CRAH Unit:

A Computer Room Air Handler (CRAH) is a device used in data centers to deal with the heat produced by IT equipment. CRAH uses fans, cooling coils and a water-chiller system to remove heat from inlet air unlike a Computer Room Air Conditioning (CRAC) unit which uses mechanical refrigeration to cool the air introduced to a data center [14].

Figure 2-10 CRAH Unit in Data Center lab at UT Arlington

2.2.2 CHx40 Unit and AHx (Liquid-to-Air Heat Exchanger)

- Chx40 unit is 19” 2U rack mount appliance sled on top of the servers and manages around 40kW+ cooling capacity per rack. It consists of two centralized redundant pumps connected in a series with the liquid-to-liquid plate heat exchanger as shown in Figure6. It has an ability to operate with ASHRAE W3-W5 (2ºC-45ºC) warm water cooling [16].

Figure 2-11 CHx40 Unit by CoolIT Systems [16]

- AHx unit consists of twenty 4-wire fans with 1200 rpm and two HFD5 pumps [17].

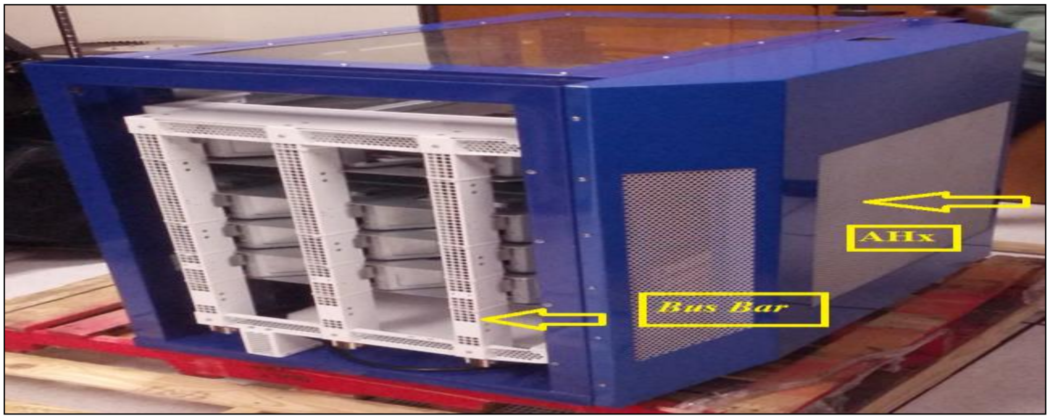


Figure 2-12 AHx Unit by CoolIT Systems [17]

Chapter 3

COOLING PROCESS

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Essentially, there are two cooling liquids which operate the cooling cycle; the liquid that flows through the passive cold plates (drive loop) inside the server is secondary coolant and the liquid with which secondary coolant exchanges heat by means of the liquid-to-liquid plate heat exchanger (supply loop) is called as primary coolant i.e. facility liquid. The coolant used in the system is ethylene glycol based water solution [16].

- The secondary coolant which is already cooled in liquid-to-liquid heat exchanger enters the server through cold aisle. It enters the radiator first and utilized to cool the CPUs. The hot secondary coolant from CPUs then exits through hot aisle.
- The other auxiliary components such as DIMMs, PCH and HDD are air cooled using fan assisted radiator as a result of forced convection

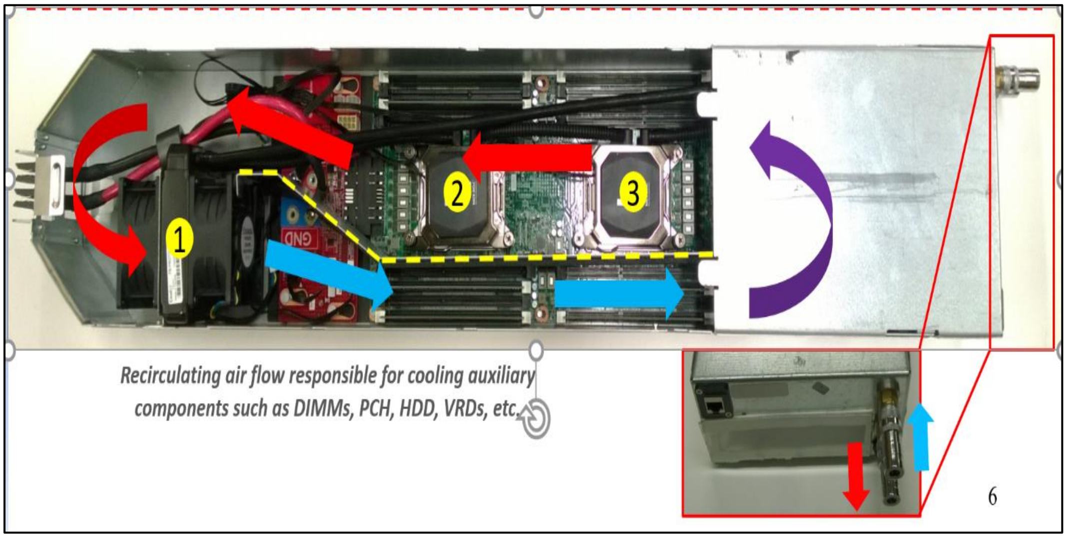

Figure 3-1 Flow of Secondary Coolant and Air within the Server

- Hot secondary coolant from each server is then collected in an outlet manifold. The hot secondary coolant from the outlet manifold then enters liquid-to-liquid plate heat exchanger (CHx40) where it exhausts heat to the already cooled primary coolant as shown in Figure 3-3.

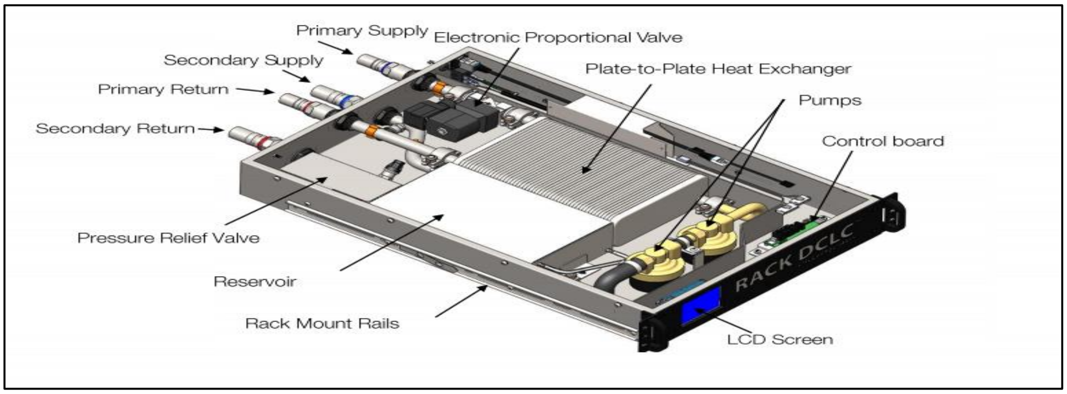

Figure 3-2 CHx40 Unit (2U Centralized Pumping Module Integrated with Liquid-to-Liquid Plate Heat Exchanger) [16]

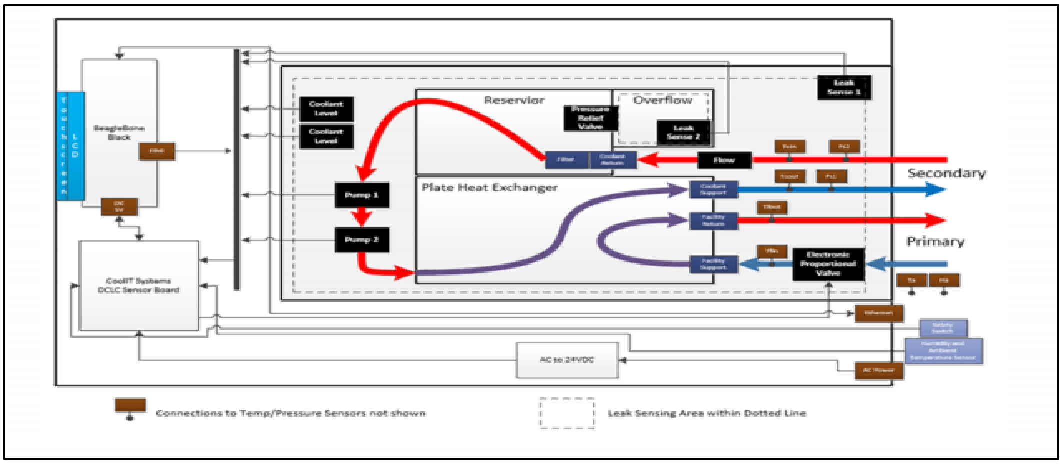

Figure 3-3 Cooling of Secondary Coolant by Means of CHx40 unit (Liquid-to-Liquid Plate Heat Exchanger) [16]

- The cooled secondary coolant enters the inlet manifold and distributed to the servers as shown in Figure 3-4. On the other hand, hot primary coolant enters liquid-to-air heat exchanger (AHx) and exhaust heat to the colder air by means of 4-wire fans cooling the AHx coil.

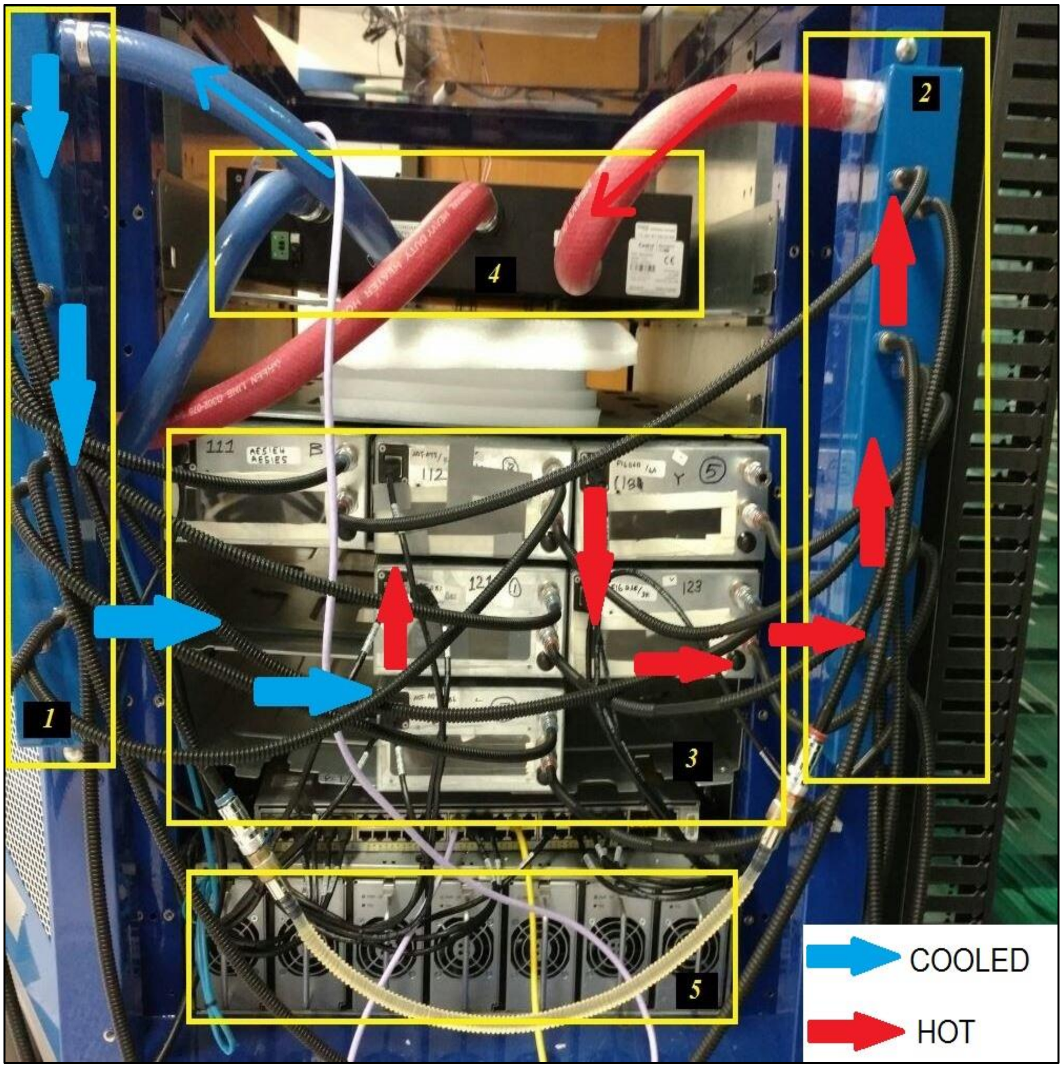

Figure 3-4 Flow Distribution of Secondary Coolant through the Liquid Cooling System

Chapter 4

EXPERIMENTAL PROCEDURE

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Our primary goal is to evaluate cooling power consumption at rack level and component temperatures associated with each server at different inlet temperatures ranging from 25ºC to 45ºC. The Power consumption of hybrid cooled servers is the summation of fan power and pump power; thereby both are measured separately. In our case, the centralized pumps are redundant and constant flow type [16] and the variation in pump power consumption is observed because of variable pumping. The fans are variable speed control; we observe the variation in fan power consumption triggered by PCH temperatures.

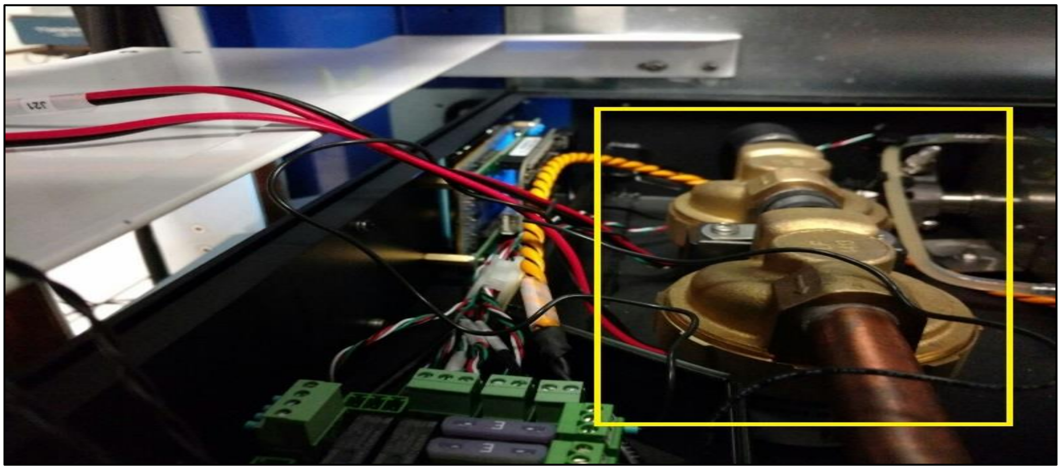
4.1 Redundant Pump

In case of pump redundancy, if one pump goes offline then the other pump which is redundant can kick on to handle peak flow of the system. In our case of study, both the centralized pumps are connected to the liquid-to-liquid plate heat exchanger in series. Thus we can fail a pump singularly if needed [18].

4.2 Variable Speed Pumping

- The integrated pumps inside each server are disconnected to drive fluid flow through the entire system by using centralized pumps.
- The centralized redundant pumps are powered externally by DC supply unit as shown in Figure8. The variable input voltage ranging from 11.5V up to 16.5V (11.5V, 13V, 15V and 16.5V) has been supplied to the pumps in each case of study.

- The pump power has been calculated for respective voltage supply from the DC power supply readings.
- On the other hand, pump rpm is varied by means of variable voltage supply to the pumps [19]; consequently, varying the fluid flow rate.



(Figure 4-1.1)

(Figure 4-1.2)

Figure 4-1.1 and Figure 4-1.2 Externally Powered Centralized Redundant Pumps

4.3 Desired Coolant Temperature

- The initial step of the testing is to achieve the desired inlet temperature of the secondary coolant starting from 25°C till 45°C with increments of 10°C. An allowance of ±1°C in the temperatures is considered for the tests.
- The negative temperature coefficient (NTC) type thermistors are used to measure the primary and secondary coolant temperatures.
- A control system is developed using LABVIEW software [20] to regulate the coolant inlet temperature as shown in Figure9. The desired set point of inlet temperature; e.g. 25°C, is achieved by controlling the AHx PWM of 4-wire fans.

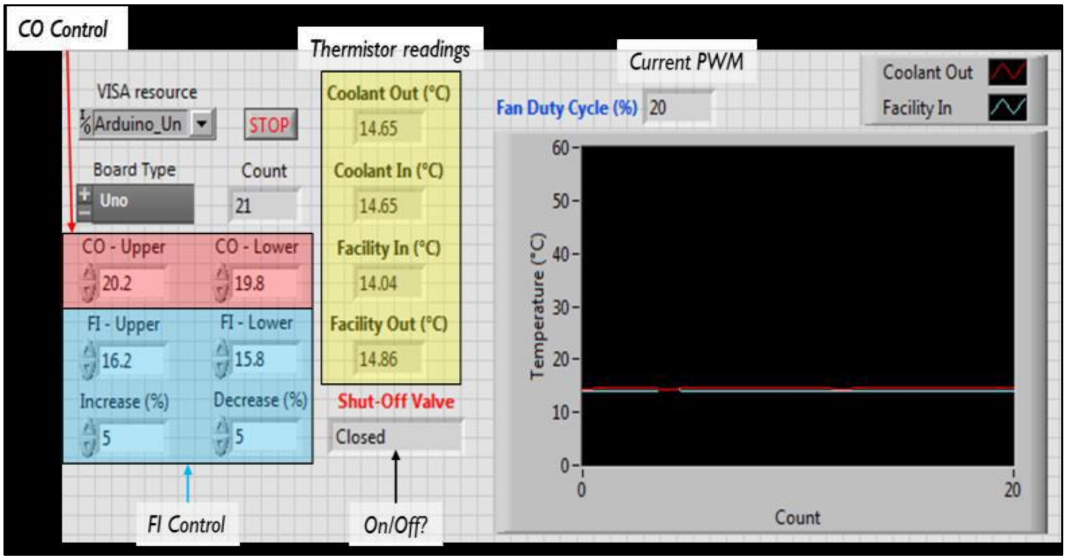
4.3.1 Negative Temperature Coefficient (NTC) type Thermistor

Thermistors are basically temperature-sensing components made up of semiconductor material. Thermistors are sintered in order to display large changes in resistance parameter proportional to small changes in temperature. The resistance can be measured using a voltage drop when direct current is passed through the thermistor [21]

Figure 4-2 Typical NTC Thermistor [21]

4.3.2 LabVIEW Interfacing with Arduino UNO

The software works as an interface between the control parameters and the desired set point temperature. It reads the input from the thermistors that measure the inlet and outlet temperatures of the secondary coolant and primary coolant i.e. facility liquid by means of an Arduino UNO interfaced with CHx40 control circuit and adjusts AHx fans speed based on target temperatures by means of Dead Band Control VI.

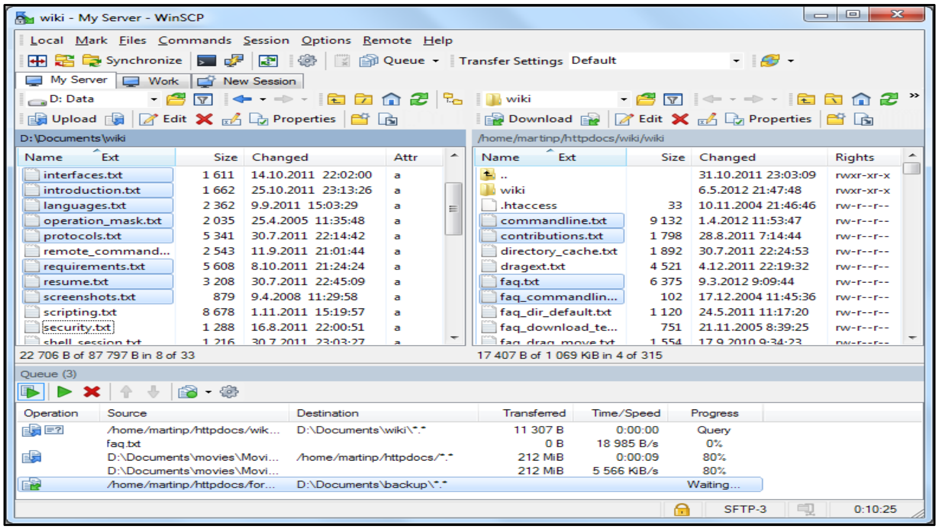


VISA resource: Arduino_Un
Board Type: Uno
Count: 21
CO - Upper: 20.2
CO - Lower: 19.8
FI - Upper: 16.2
FI - Lower: 15.8
Increase (%): 5
Decrease (%): 5
Coolant Out (°C): 14.65
Coolant In (°C): 14.65
Facility In (°C): 14.04
Facility Out (°C): 14.86
Shut-Off Valve: Closed
Fan Duty Cycle (%): 20

Figure 4-3 LabVIEW interface showing input and control parameters.

4.3.3 Synthetic Load generation

- A total of 4 hybrid-cooled servers are tested simultaneously in the rack. A communication to each server is established through software WinSCP by means of the static IP address allocated to each server as shown in Figure 4-4. The operating system of the servers for communication is Linux. The servers are referred and positioned in the rack as shown in Figure 4-5.



D:\Documents\wiki

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introduction.txt	1 662	25.10.2011 23:13:26	a
languages.txt	2 362	9.9.2011 15:03:29	a
operation_mask.txt	2 035	25.4.2005 11:35:48	a
protocols.txt	5 341	30.7.2011 22:14:42	a
remote_command...	2 543	11.9.2011 21:01:44	a
requirements.txt	5 608	8.10.2011 21:24:24	a
resume.txt	3 208	30.7.2011 22:45:09	a
screenshots.txt	879	9.4.2008 11:29:58	a
scripting.txt	8 678	1.11.2011 15:19:57	a
security.txt	1 288	16.8.2011 22:00:51	a
shell_session.txt	1 216	30.7.2011 23:03:27	a

22 706 B of 87 797 B in 8 of 33

/home/martinp/httpdocs/wiki/wiki

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commandline.txt	9 132	1.4.2012 11:53:47	rw-r--r--
contributions.txt	1 798	28.8.2011 7:14:44	rw-r--r--
directory_cache.txt	1 892	30.7.2011 22:24:53	rw-r--r--
dragext.txt	4 521	4.12.2011 22:19:32	rw-r--r--
faq.txt	6 375	9.3.2012 9:09:44	rw-r--r--
faq_commandlin...	102	17.12.2004 11:45:36	rw-r--r--
faq_dir_default.txt	1 120	24.5.2011 11:17:20	rw-r--r--
faq_download_te...	751	21.11.2005 8:39:25	rw-r--r--
faq_drag_move.txt	1 554	17.9.2010 9:34:23	rw-r--r--

17 407 B of 1 069 KiB in 4 of 315

Queue (3)

Operation	Source	Destination	Transferred	Time/Speed	Progress
	/home/martinp/httpdocs/wik...	D:\Documents\wiki*.*	11 307 B	0:00:00	Query
	faq.txt		0 B	18 985 B/s	0%
	D:\Documents\movies\Movi...	/home/martinp/httpdocs/*.*	212 MiB	0:00:09	80%
	D:\Documents\movies\Movi...		212 MiB	5 566 KiB/s	80%
	/home/martinp/httpdocs/for...	D:\Documents\backup*.*			Waiting...

SFTP-3 0:10:25

Figure 4-4 WinSCP Interface

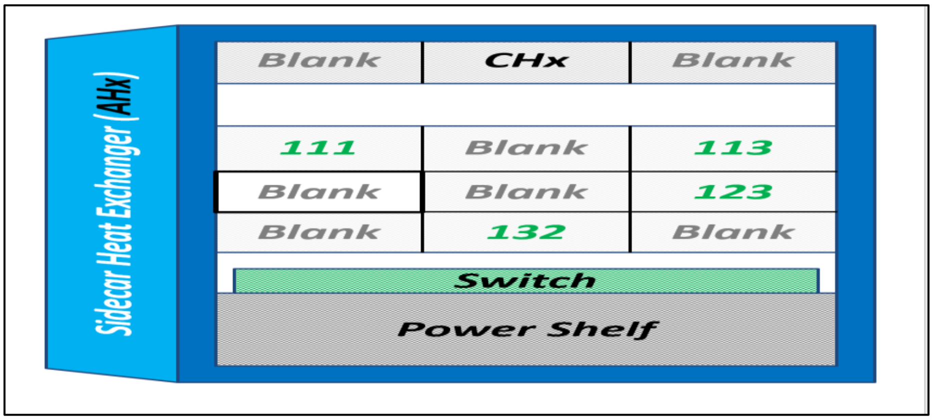

Figure 4-5 Four Servers Tested in the Rack

- The next step of the testing is to load each server computationally at different CPU power levels varying from idle to 100% using power thermal utility (PTU) tools [22]. For example, 60% of the CPU cores are loaded at CPU power level of 60% while all cores (8 in our case) are loaded computationally at 100% power level of CPUs; thereby heating the components to the respective desired temperatures.

Chapter 5

TESTING PROCESS

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- The centralized pumps are powered externally with DC supply unit with variable voltage starting from 11.5V up to 16.5V for thermal stress tests. For an instance, at 25°C total four tests are carried out with variable input voltage (11.5V, 13V, 15V and 16.5V) to the pumps.
- After powering the pumps and fans externally using DC power sources, the secondary coolant inlet temperature is set to the desired set point using the control interface.
- This test runs for about six hours and is repeated for three times to account for repeatability.
- Total 12 tests are carried out which includes a set of 4 tests at each inlet temperatures viz. 25°C, 35°C and 45°C.
- Variable speed pumping at each inlet temperature results into variable fluid flow rate of the secondary coolant.

Inlet Temperature	Voltage Supply to Pumps	Flow Rate
25°C, 35°C and 45°C	16.5 Volts	5.4 LPM
	15 Volts	4.8 LPM
	13 Volts	4.0 LPM
	11.5 Volts	3.4 LPM

Figure 5-1 Various Testing Conditions

- Different parameters like temperatures of CPU, PCH, memory modules and rpm values of the fan and pumps etc. are monitored by the internal digital temperature sensors and tachometer signals [23].
- Data is collected in each test using IPMI and PTU tools for fan and pump speeds, total server power consumption and chipset temperature [24].
- The data collection in last 30 minutes of each test is to be accounted, since steady state is expected to reach during that period. For an instance, the fan speeds may fluctuate within the specific band width (±10% PWM signal). Hence, the average steady state values obtained from all the repeated tests have been used for analysis.

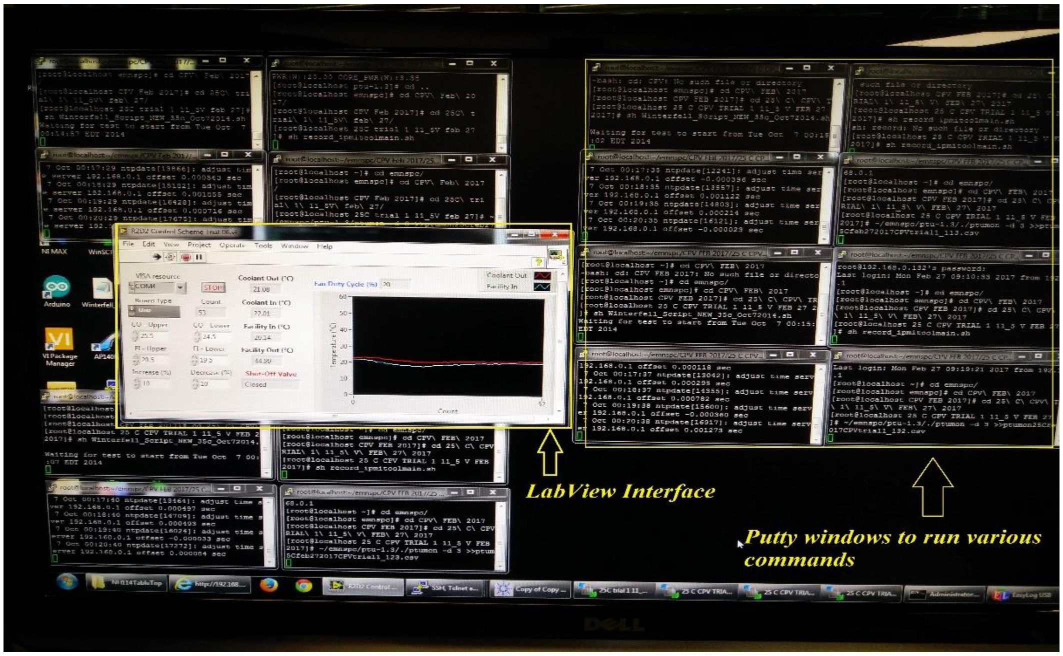

Figure 5-2 Commands in Putty Software for Data Collection using IPMI and PTU tools

Chapter 6

RESULTS

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The objective of the experimental testing of centralized coolant system for hybrid cooled servers was to study the performance characteristics such as device component temperatures (includes temperatures of CPUs, DIMMs, PCH and other auxiliary components) and cooling energy consumption associated with each inlet condition.

The results of the experimental testing discusses the IT performance at different inlet conditions for reliability purposes and variation in cooling power consumption in accordance with total power consumption to realize cooling energy efficiencies.

6.1 IT Performance: Liquid Cooled Device Components (CPUs)

The maximum core temperatures of CPUs (CPU 0 and CPU 1) at 100% computational loading are recorded at each inlet temperatures viz. 25°C, 35°C and 45°C of secondary coolant with lowest and highest fluid flow rate i.e. 3.4 LPM and 5.4 LPM respectively.

- Critical temperature of CPU is (T_j_max= 100°C)

6.1.1 Flow Rate vs CPU Core Temperature

The result discusses about the rise in maximum core temperatures of CPUs with rise in inlet coolant temperatures with reduced fluid flow rate in order to investigate reliability of the component.

The difference between temperatures of each of the CPUs at different inlet conditions has been calculated to understand the effects of variable fluid flow rates on heat carrying capacity of the coolant.

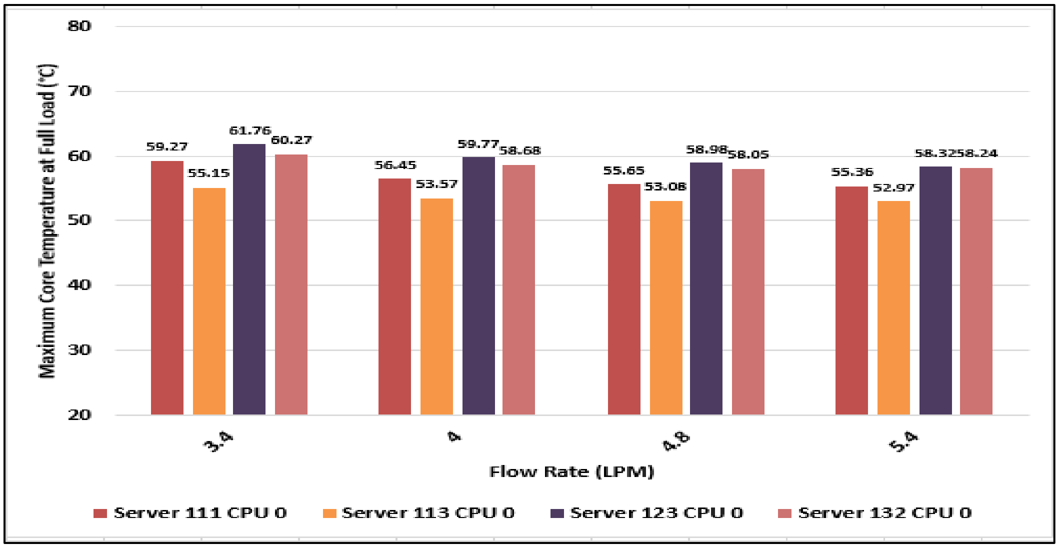


Figure 6-1 Variation in Maximum Core Temperature (CPU 0) with Respect to Change in Flow Rate at an Inlet Temperature of 25°C

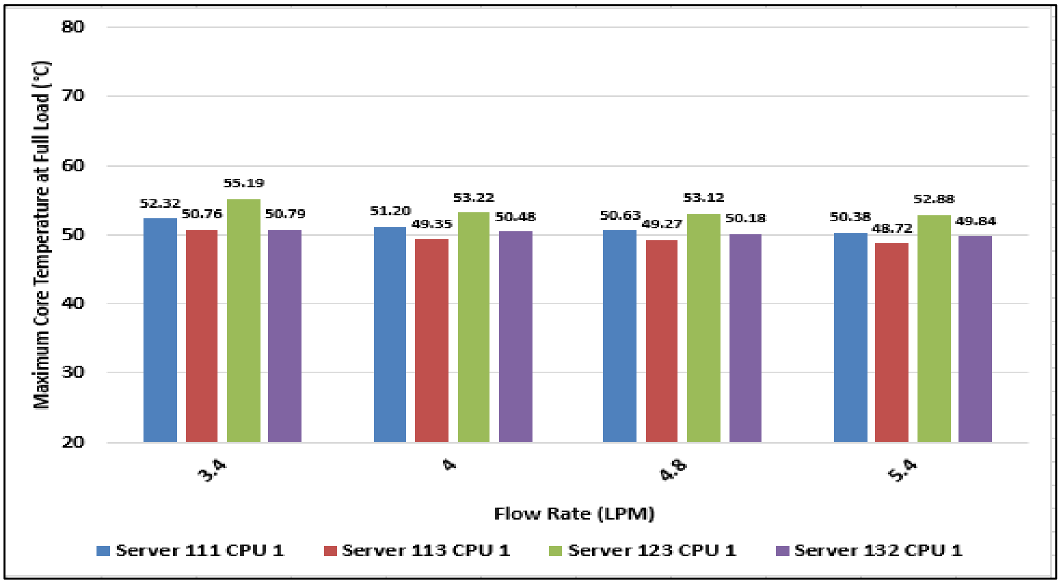


Figure 6-2 Variation in Maximum Core Temperature (CPU 1) with Respect to Change in Flow Rate at an Inlet Temperature of 25°C

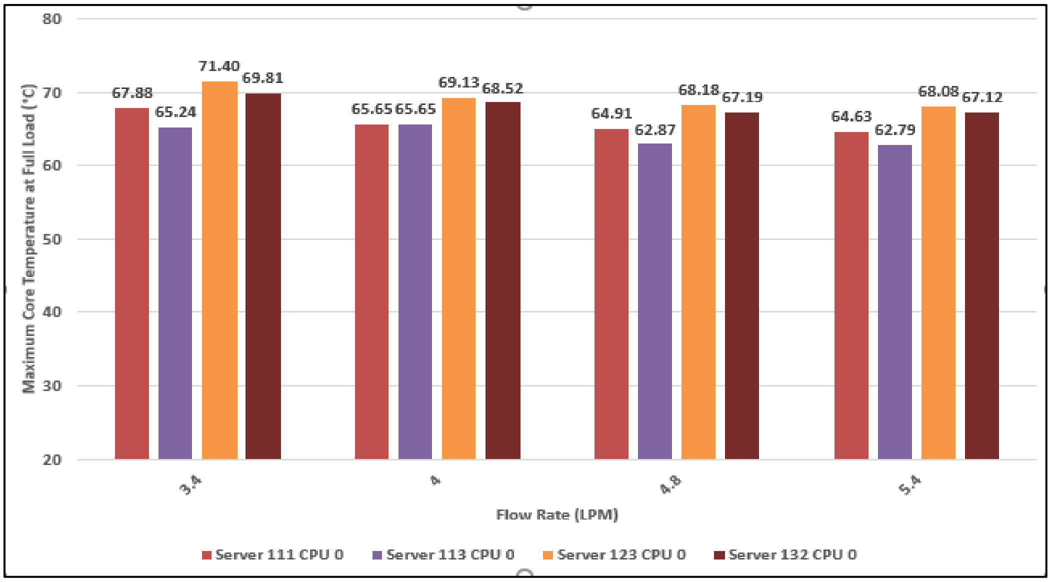


Figure 6-3 Variation in Maximum Core Temperature (CPU 0) with Respect to Change in Flow Rate at an Inlet Temperature of 35°C

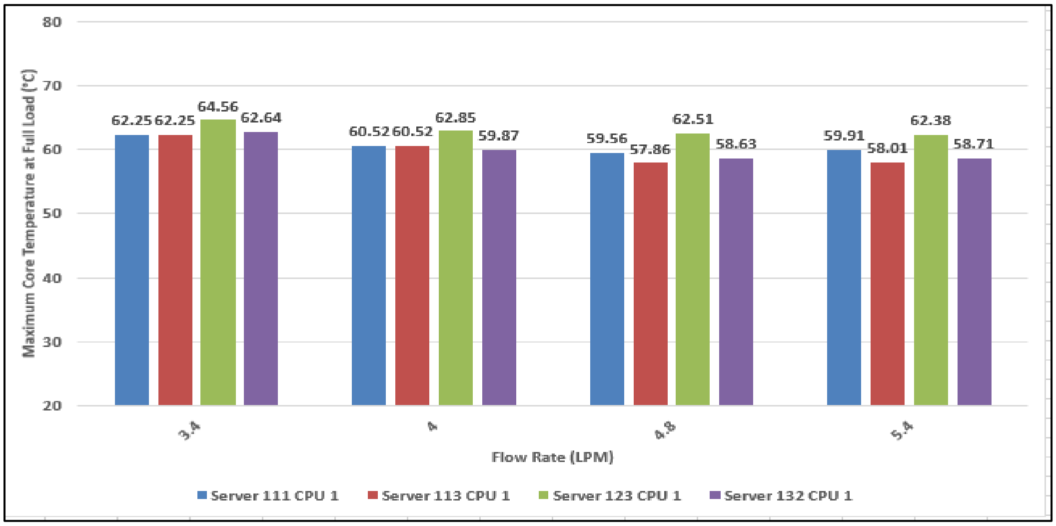


Figure 6-4 Variation in Maximum Core Temperature (CPU 1) with Respect to Change in Flow Rate at an Inlet Temperature of 35°C

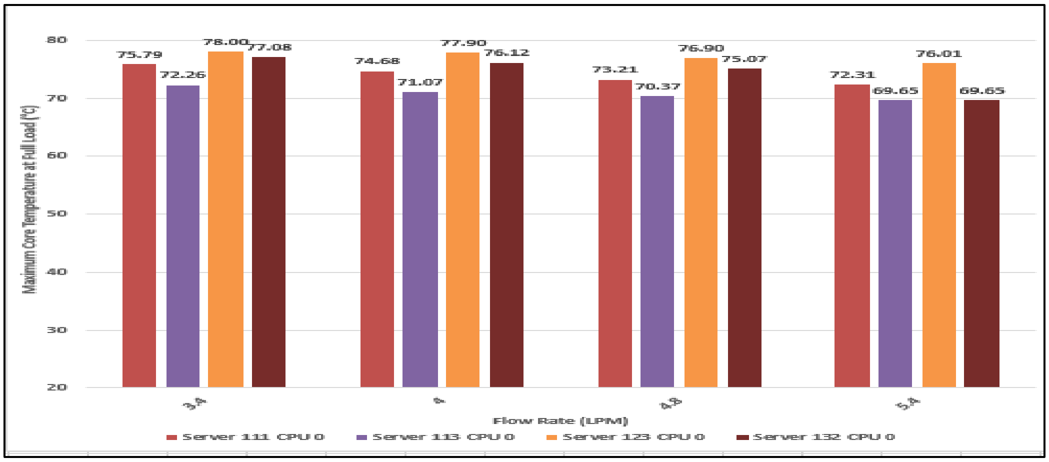


Figure 6-5 Variation in Maximum Core Temperature (CPU 0) with Respect to Change in Flow Rate at an Inlet Temperature of 45°C

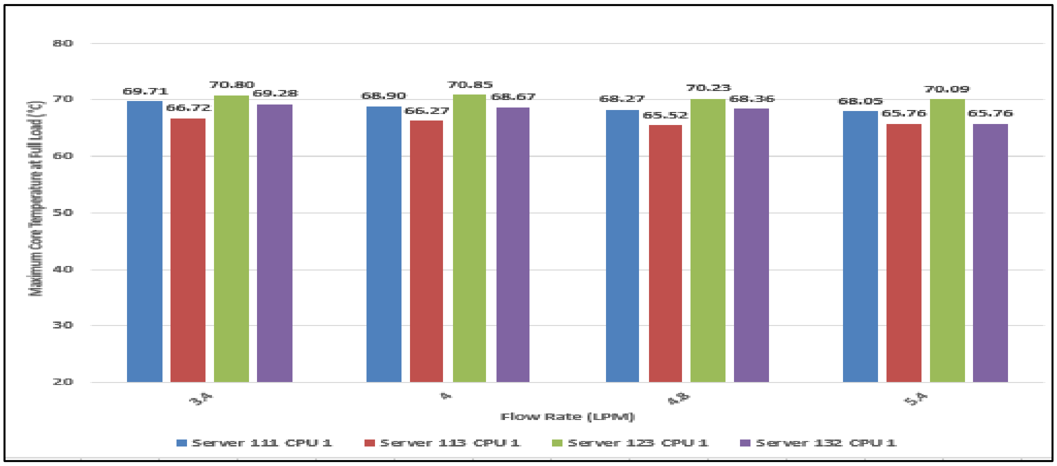


Figure 6-6 Variation in Maximum Core Temperature (CPU 1) with Respect to Change in Flow Rate at an Inlet Temperature of 45°C

- It has been observed that, the difference between the maximum core temperatures of each server (ΔT) with lowest and highest flow rates is approximately 2°C to 4°C at each inlet temperature.

6.1.2 Inlet Temperatures vs CPU Temperatures

The result discusses the pattern of the temperature difference between the CPUs in series with every decrement of fluid flow rate at various inlet temperatures to understand thermal shadowing effect.

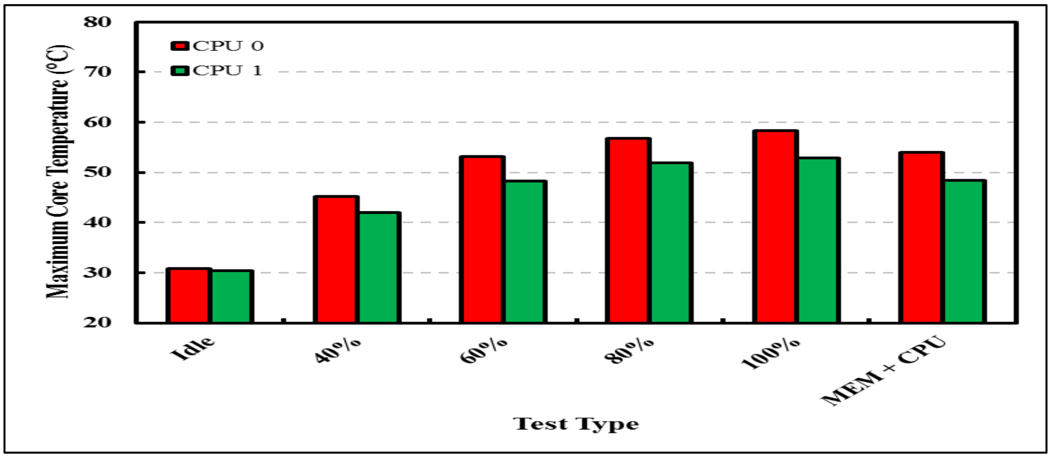


Figure 6-7 Maximum Core Temperature with Highest Flow Rate (5.4 LPM) at an Inlet Temperature of 25ºC

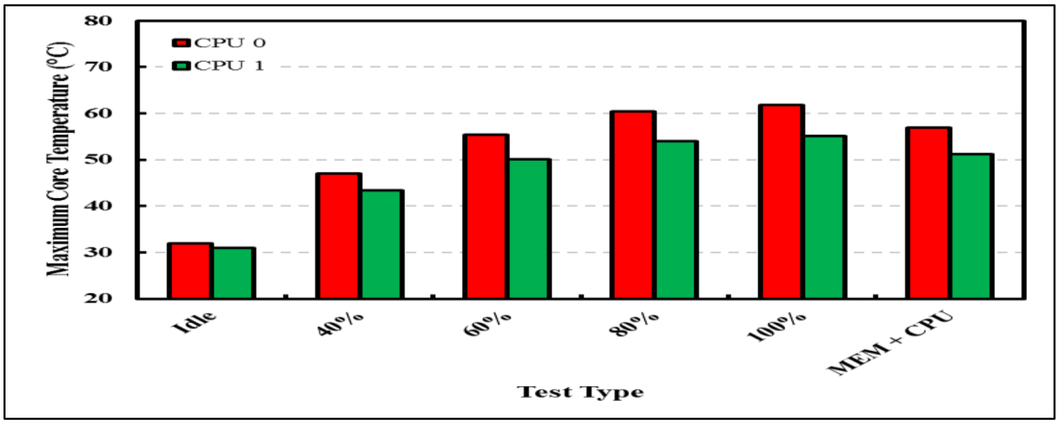


Figure 6-8 Maximum Core Temperature with Lowest Flow Rate (3.4 LPM) at an Inlet Temperature of 25ºC

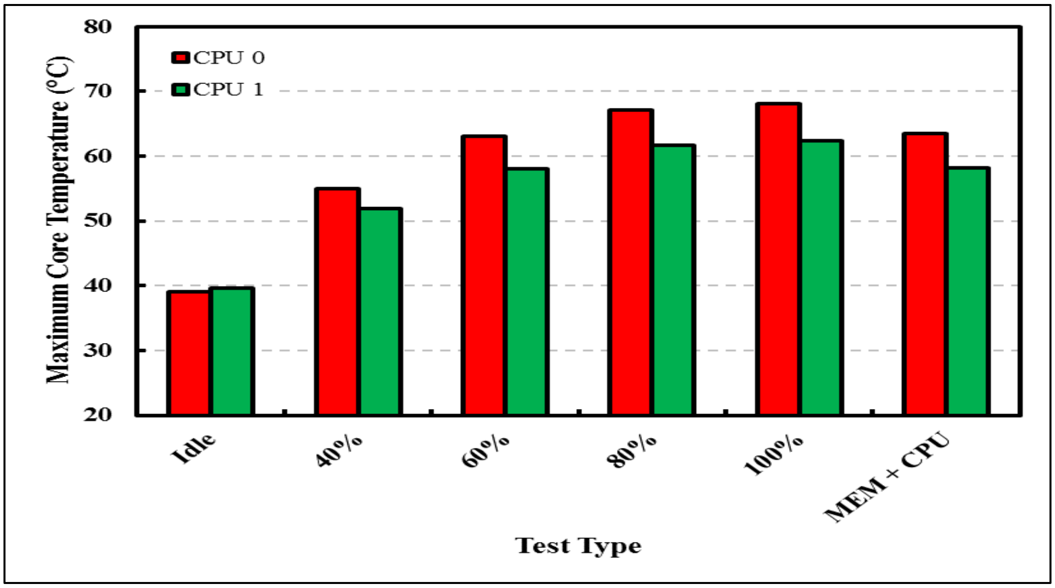


Figure 6-9 Maximum Core Temperature with Highest Flow Rate (5.4 LPM) at an Inlet Temperature of 35ºC

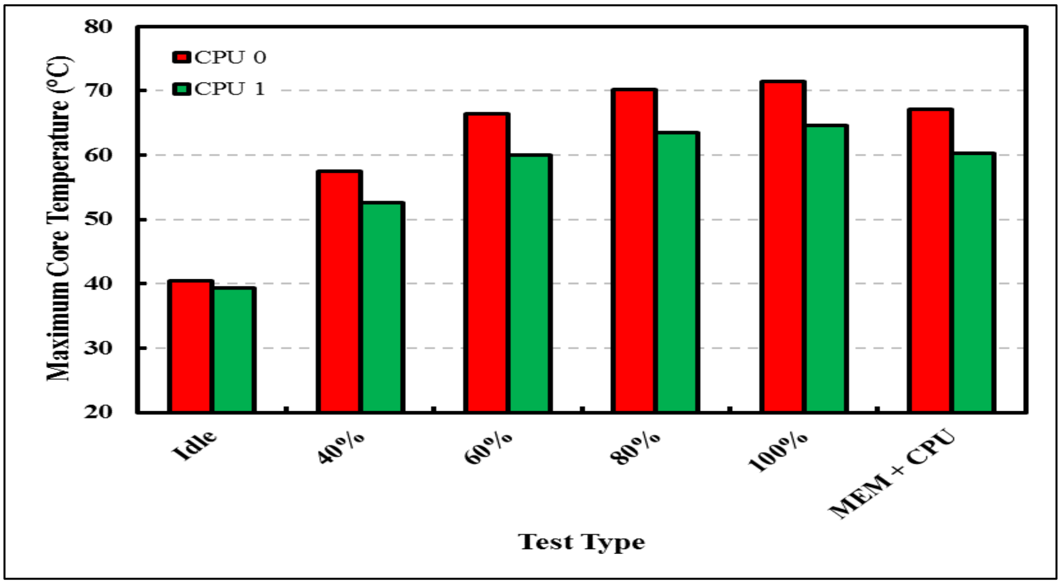


Figure 6-10 Maximum Core Temperature with Lowest Flow Rate (3.4 LPM) at an Inlet Temperature of 35ºC

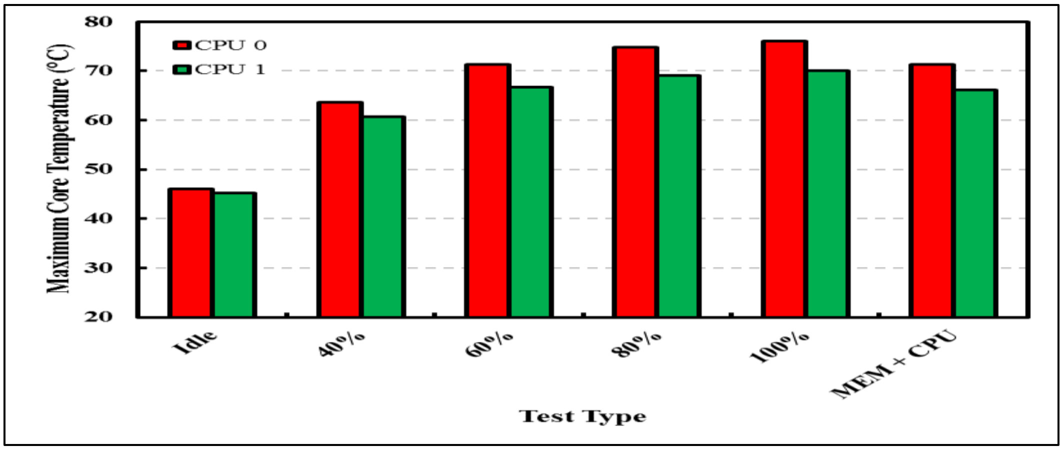


Figure 6-11 Maximum Core Temperature with Highest Flow Rate (5.4 LPM) at an Inlet Temperature of 45ºC

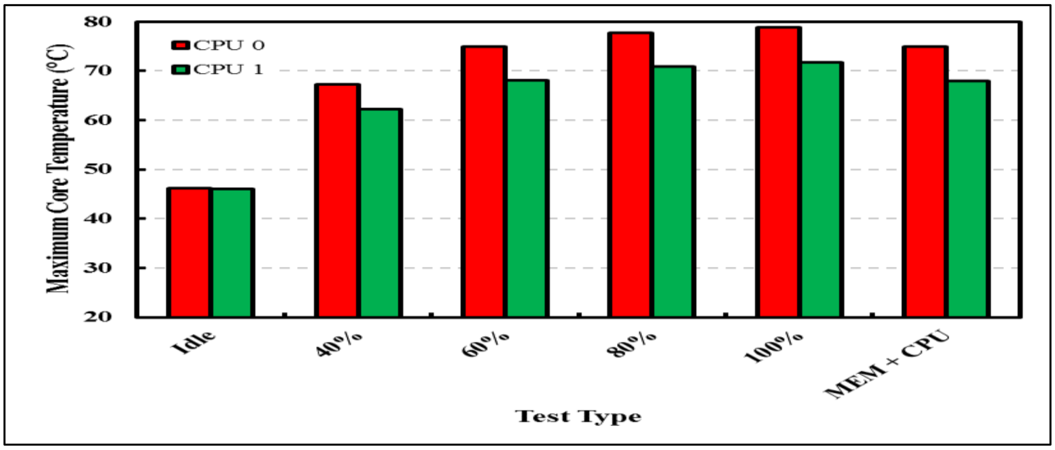
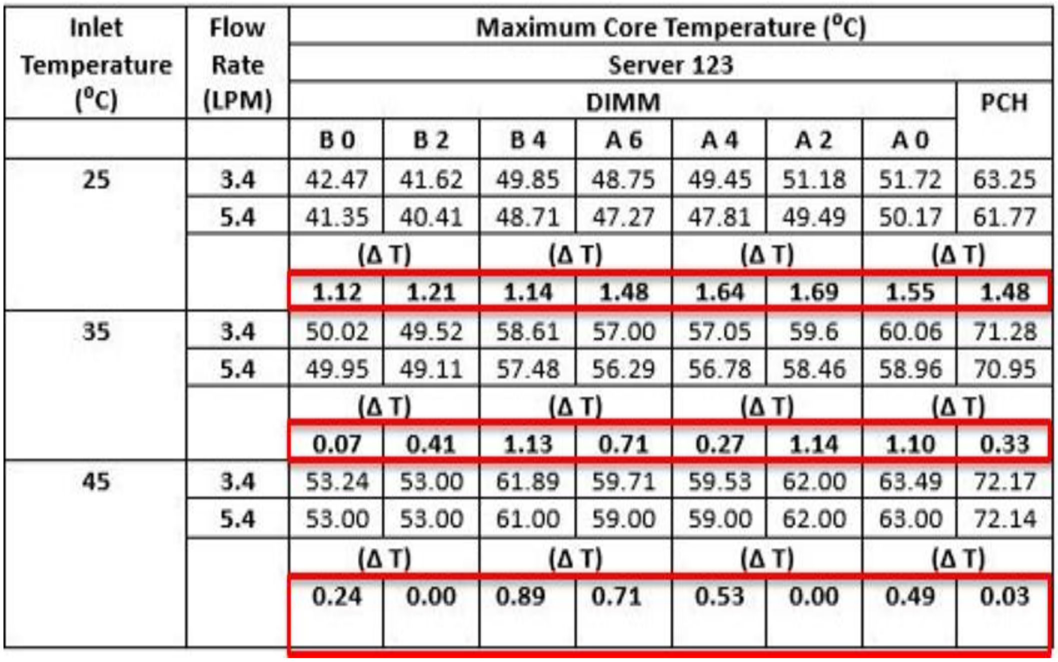


Figure 6-12 Maximum Core Temperature with Lowest Flow Rate (3.4 LPM) at an Inlet Temperature of 45ºC

- It has been observed that, the difference between the temperatures of “CPU 0” and “CPU 1” of each server (ΔT) with every increment of fluid flow rate is 5°C to 7°C at each inlet temperature

6.2 IT Performance: Air Cooled Device Components (DIMMs and PCH)

In our case of hybrid cooled servers, mainly CPUs are being liquid cooled while all other components are air cooled. Air cooled components are indirectly dependent upon the liquid cooling of the CPUs since Dead Band Control VI modulates the fans speeds based on target temperature. Thus temperatures of DIMMs and PCH are recorded with higher inlet temperature conditions with reduction in fluid flow rate.



Inlet Temperature (^oC)	Flow Rate (LPM)	Maximum Core Temperature (^oC)							
		Server 123							
		DIMM							PCH
		B 0	B 2	B 4	A 6	A 4	A 2	A 0	
25	3.4	42.47	41.62	49.85	48.75	49.45	51.18	51.72	63.25
	5.4	41.35	40.41	48.71	47.27	47.81	49.49	50.17	61.77
		(Δ T)		(Δ T)		(Δ T)		(Δ T)	
		1.12	**1.21**	**1.14**	**1.48**	**1.64**	**1.69**	**1.55**	**1.48**
35	3.4	50.02	49.52	58.61	57.00	57.05	59.6	60.06	71.28
	5.4	49.95	49.11	57.48	56.29	56.78	58.46	58.96	70.95
		(Δ T)		(Δ T)		(Δ T)		(Δ T)	
		0.07	**0.41**	**1.13**	**0.71**	**0.27**	**1.14**	**1.10**	**0.33**
45	3.4	53.24	53.00	61.89	59.71	59.53	62.00	63.49	72.17
	5.4	53.00	53.00	61.00	59.00	59.00	62.00	63.00	72.14
		(Δ T)		(Δ T)		(Δ T)		(Δ T)	
		0.24	**0.00**	**0.89**	**0.71**	**0.53**	**0.00**	**0.49**	**0.03**

Figure 6-13 The Variation in DIMMs and PCH Temperature with respect to Highest and Lowest Flow Rates at Each Inlet Temperature

- The maximum temperatures of the DIMMs and PCH are not changed drastically when the fluid flow rate is lowered from 5.4 LPM to 3.4 LPM by means of variable pumping at each inlet temperature.

6.3 Worst Case Scenario

In our case of experimental testing of centralized coolant system with using variable speed pumping, the worst case of cooling is considered as secondary coolant flows through the system with lowest flow rate and at highest inlet temperature i.e. at 45°C the secondary coolant flows with 3.4 LPM

6.3.1 IT Performance: Liquid Cooled Device Components (CPUs)

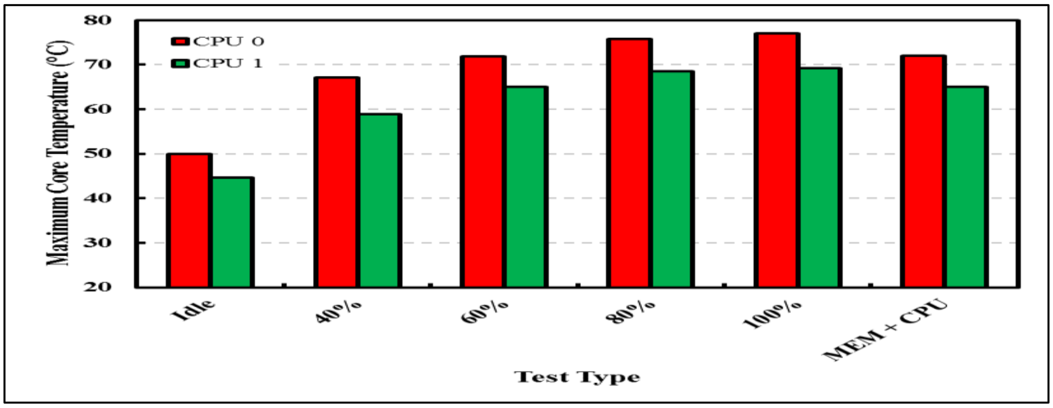


Figure 6-14 Max. Core Temperature of Server 111 at 45ºC with Fluid Flow Rate 3.4 LPM

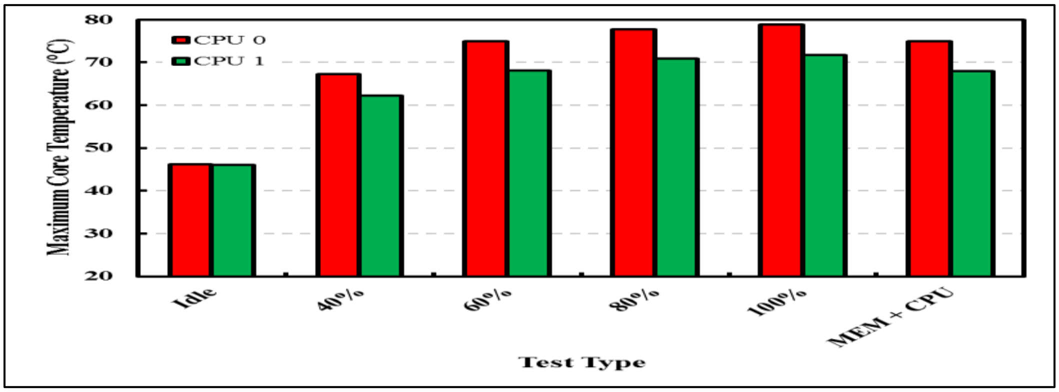


Figure 6-15 Max. Core Temperature of Server 113 at 45ºC with Fluid Flow Rate 3.4 LPM

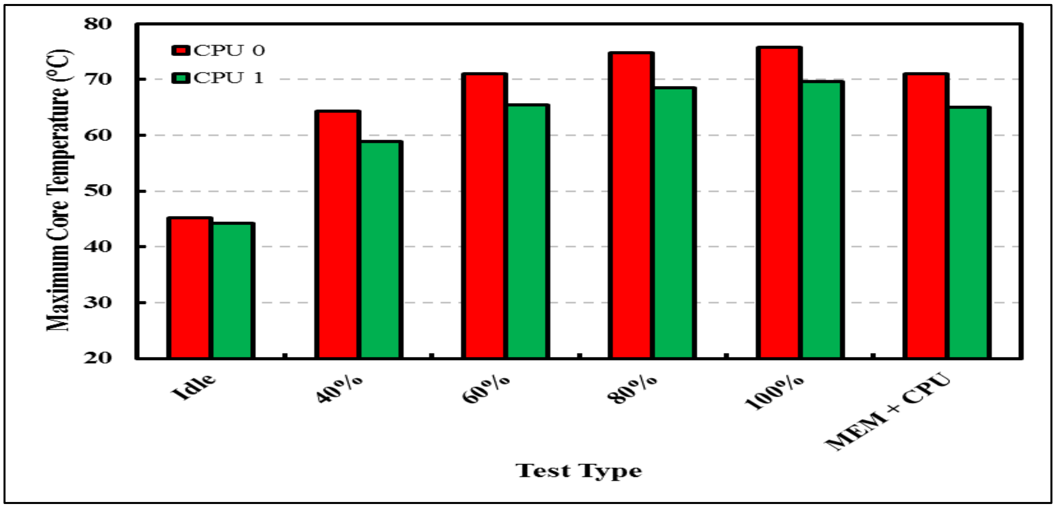


Figure 6-16 Max. Core Temperature of Server 123 at 45ºC with Fluid Flow Rate 3.4 LPM

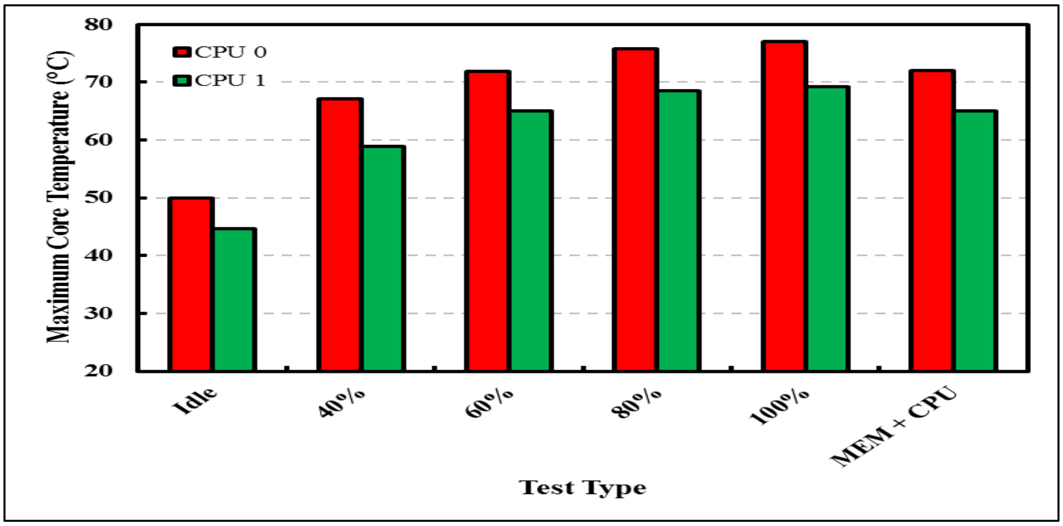


Figure 6-17 Max. Core Temperature of Server 132 at 45ºC with Fluid Flow Rate 3.4 LPM

- It has been observed that, the maximum core temperatures i.e. “CPU 0” and “CPU 1” of each server are well below the critical temperature

  (CPU T_j max= 100°C)

6.3.2 IT Performance: Air Cooled Device Components (DIMMs)

The dependence and significance of the DIMMs and PCH temperature observation is well explained in section 6.2

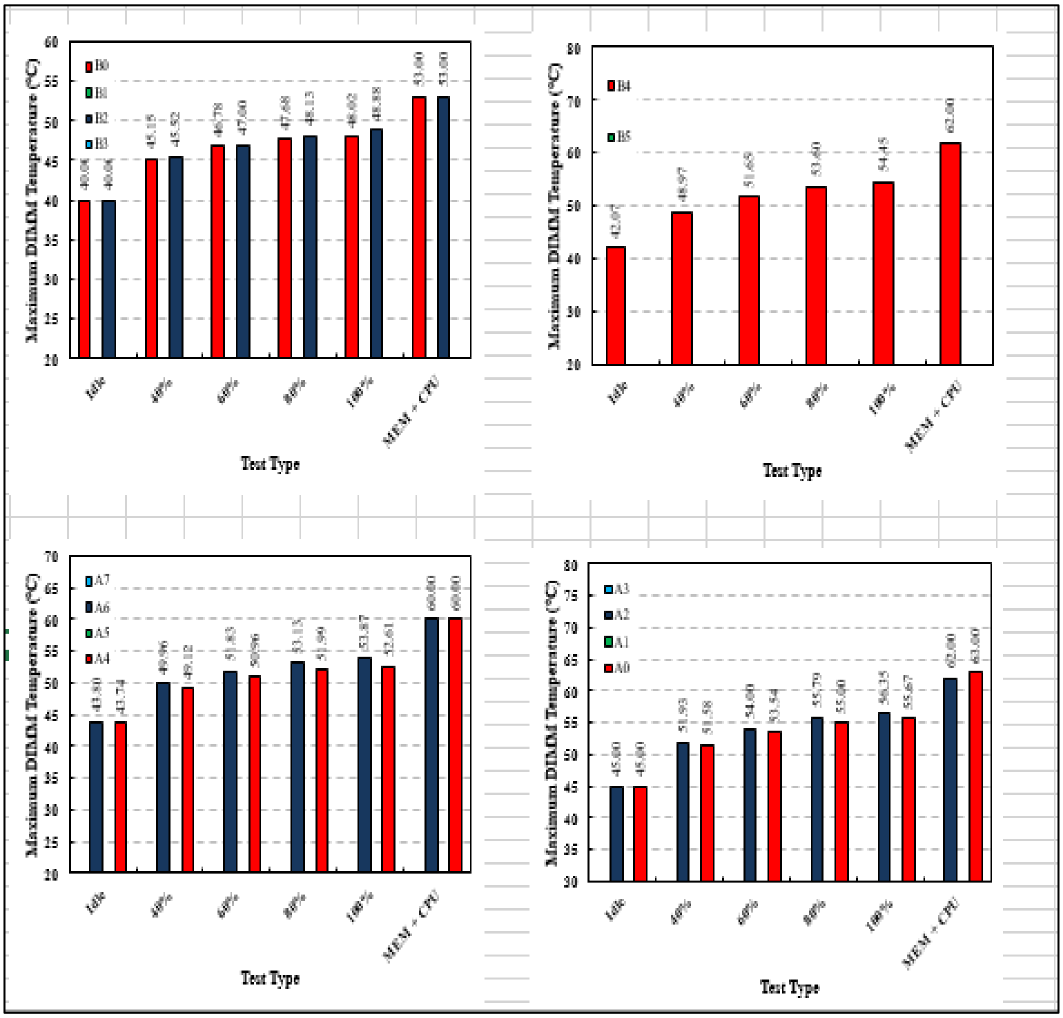


Figure 6-18 Server 111- DIMMs Temperatures at an Inlet Temperature of Secondary Coolant being 45ºC

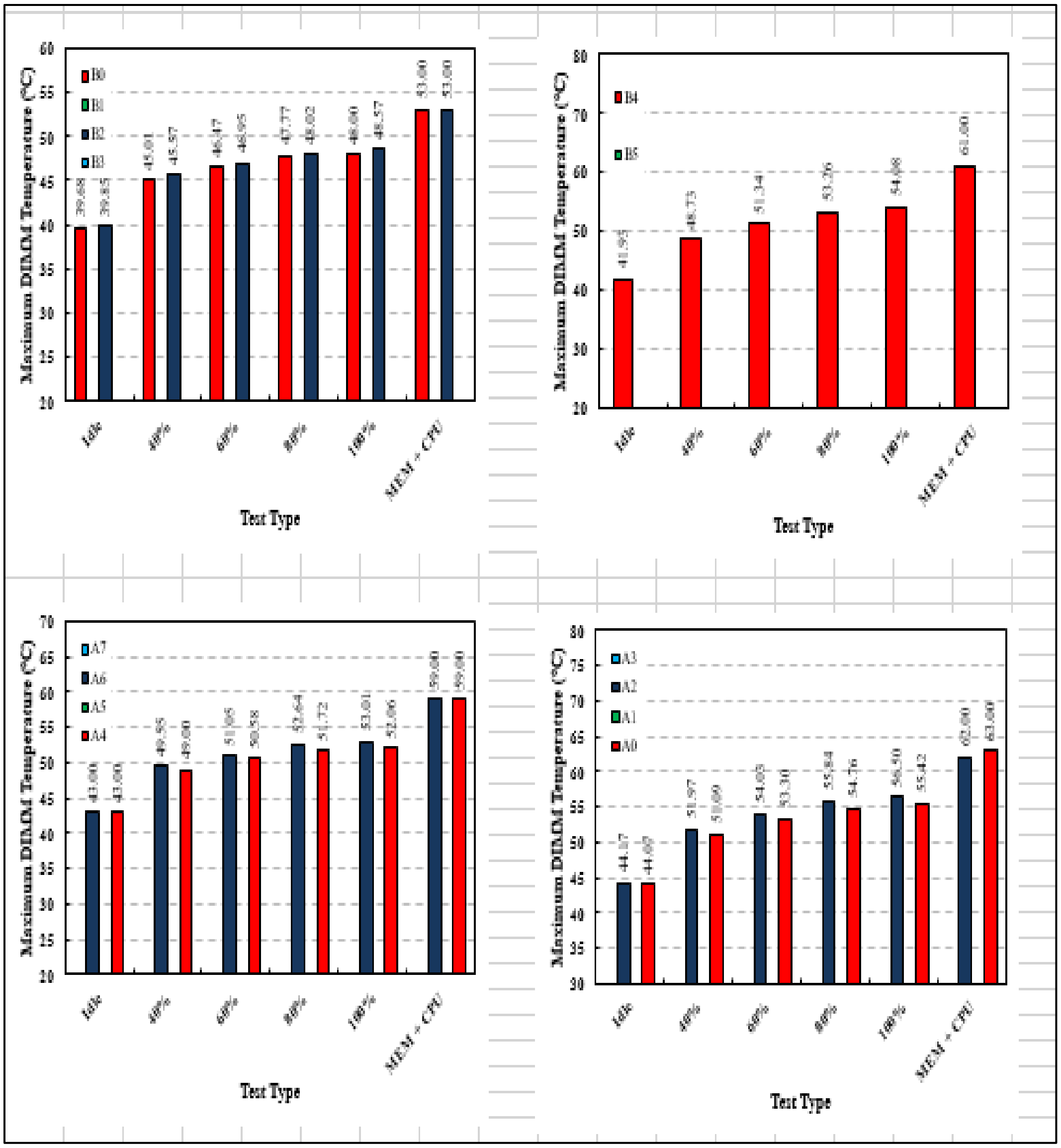


Figure 6-19 Server 113- DIMMs Temperatures at an Inlet Temperature of Secondary Coolant being 45ºC

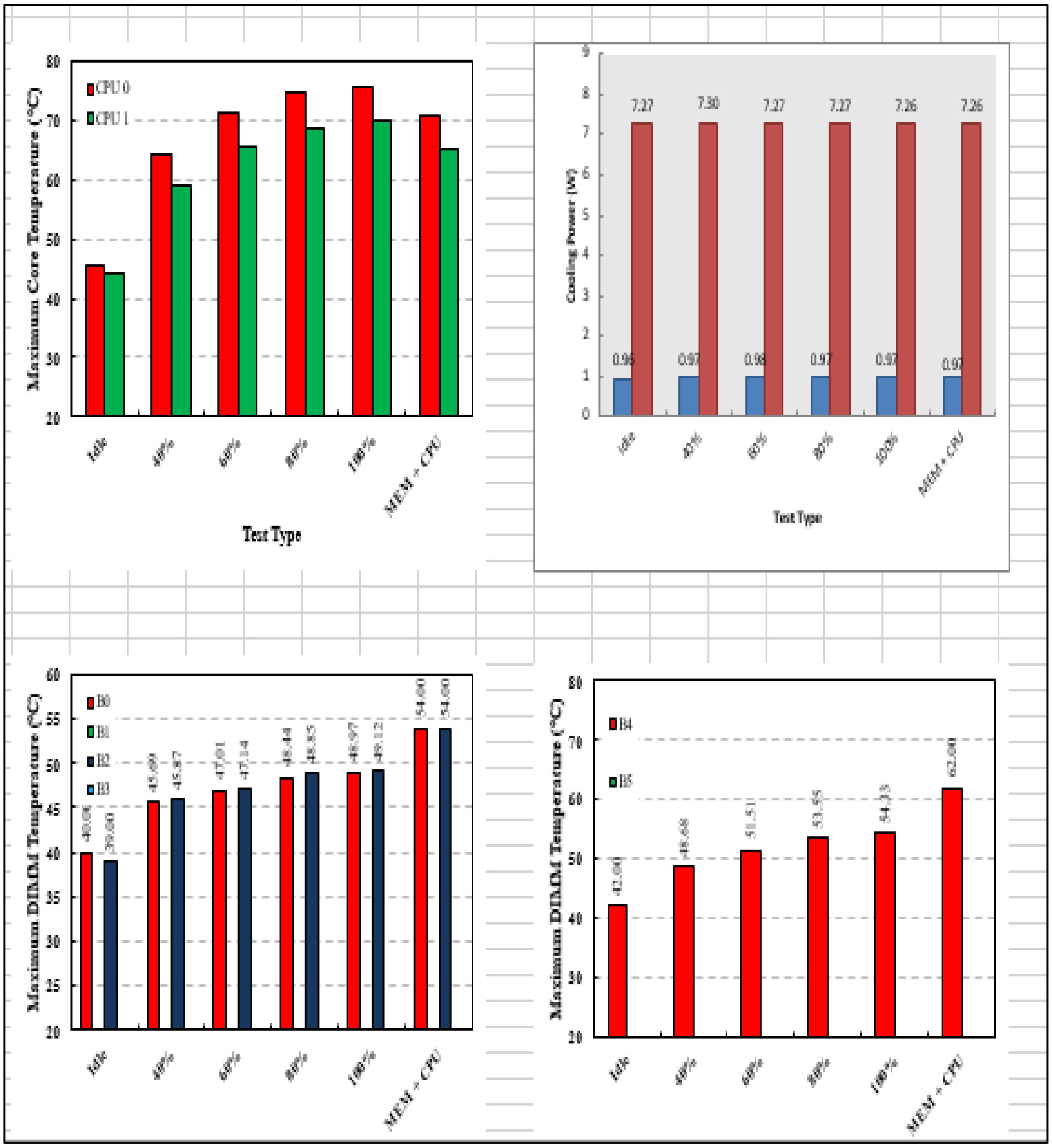


Figure 6-20 Server 123- DIMMs Temperatures at an Inlet Temperature of Secondary Coolant being 45ºC

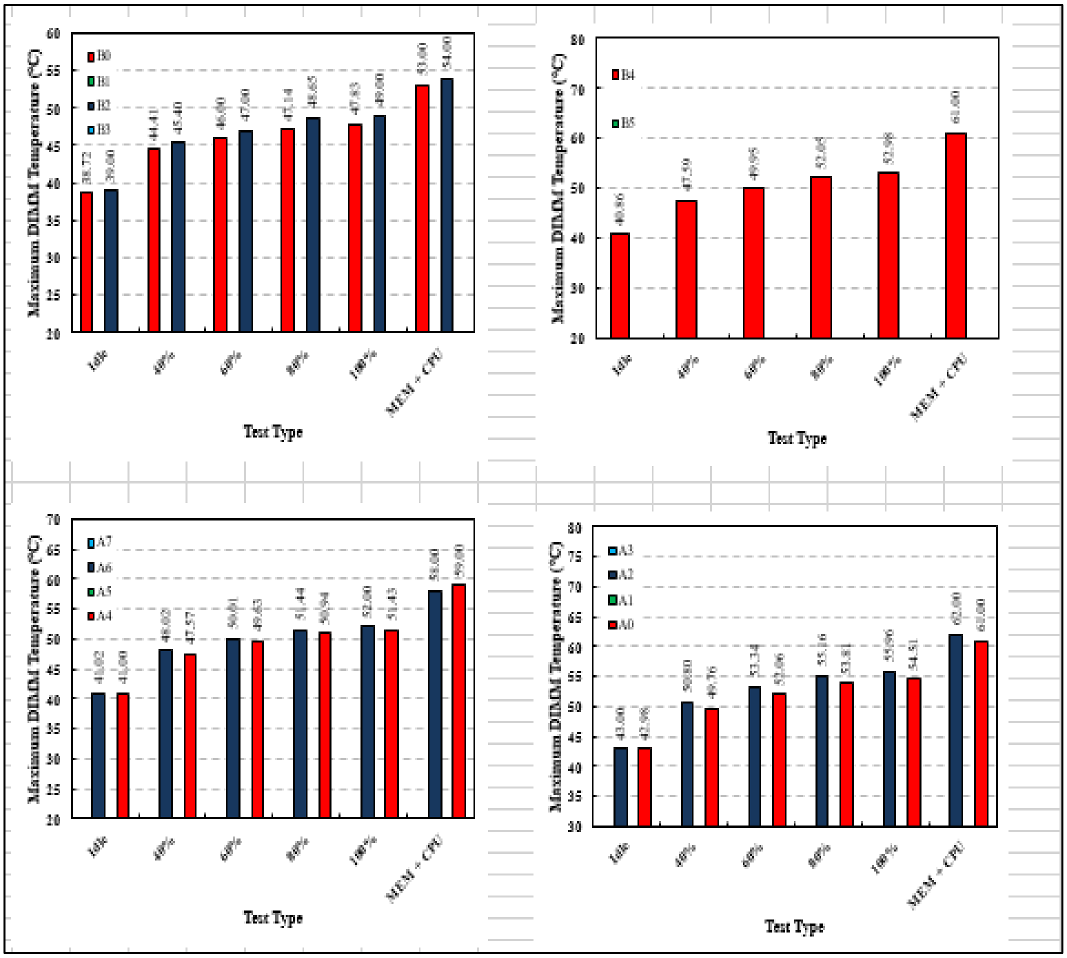


Figure 6-21 Server 132- DIMMs Temperatures at an Inlet Temperature of Secondary Coolant being 45ºC

- It has been observed that, the maximum temperatures of DIMMs of each server at an inlet temperature of coolant being 45°C are well below the critical temperature (DIMM T_(upper critical)= 82°C)

6.3.3 IT Performance: Air Cooled Device Components (PCH)

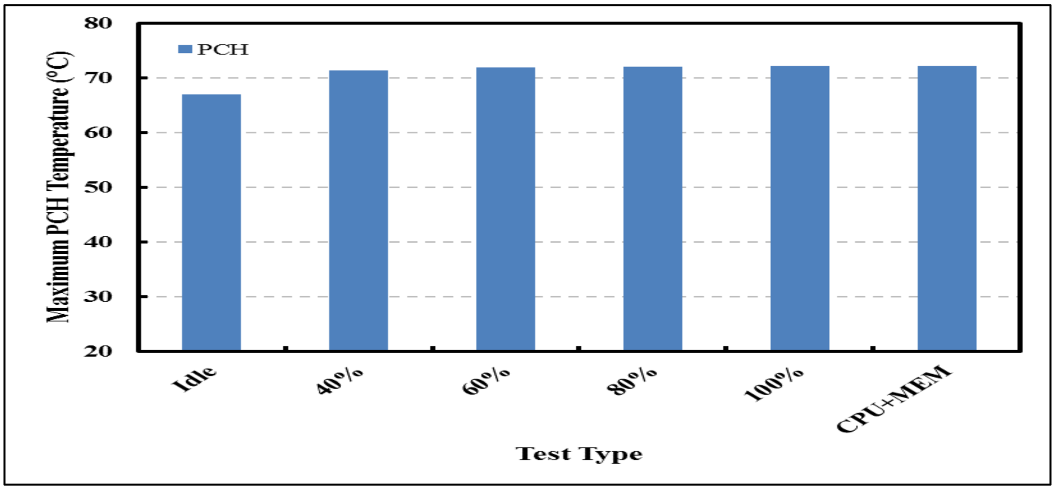


Figure 6-22 Server 111- PCH Temperatures at an Inlet Temperature of Secondary Coolant being 45ºC

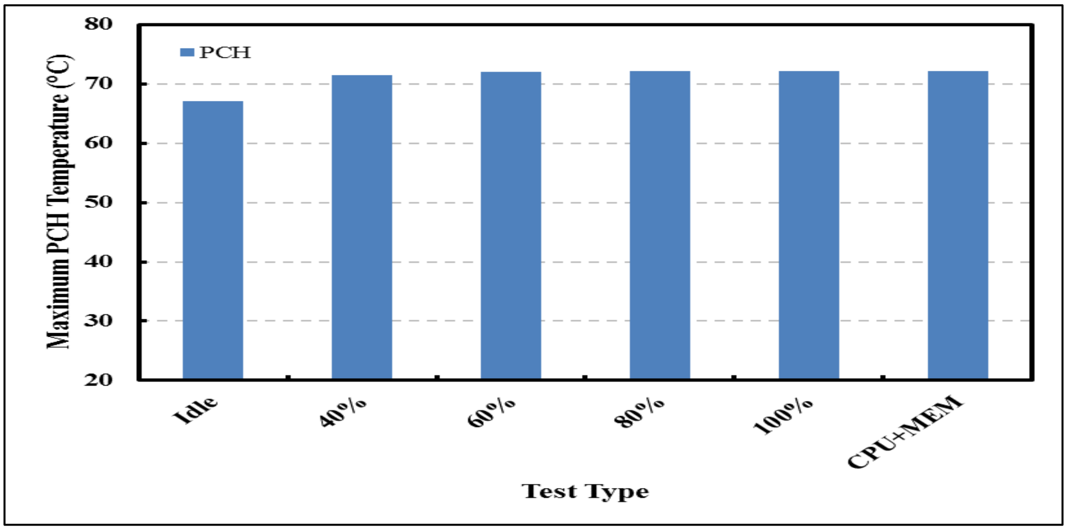


Figure 6-23 Server 113- PCH Temperatures at an Inlet Temperature of Secondary Coolant being 45ºC

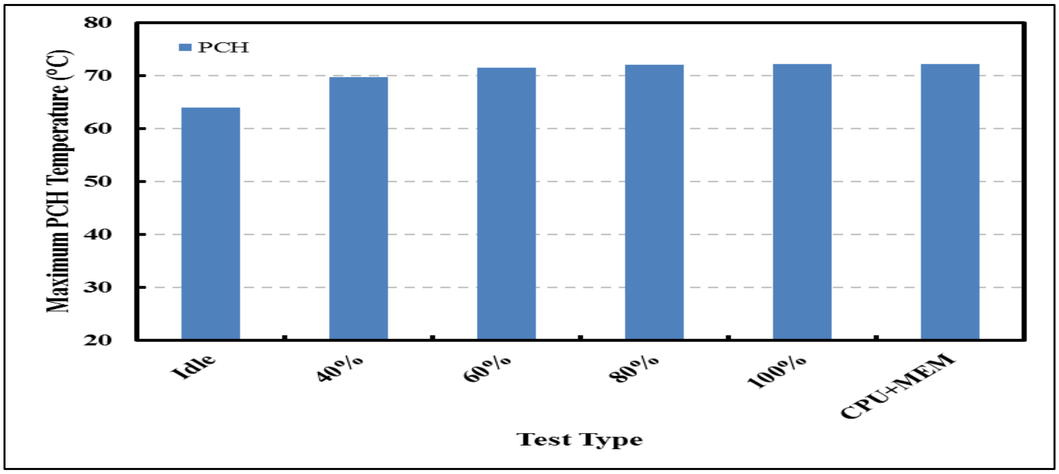


Figure 6-24 Server 123- PCH Temperatures at an Inlet Temperature of Secondary Coolant being 45ºC

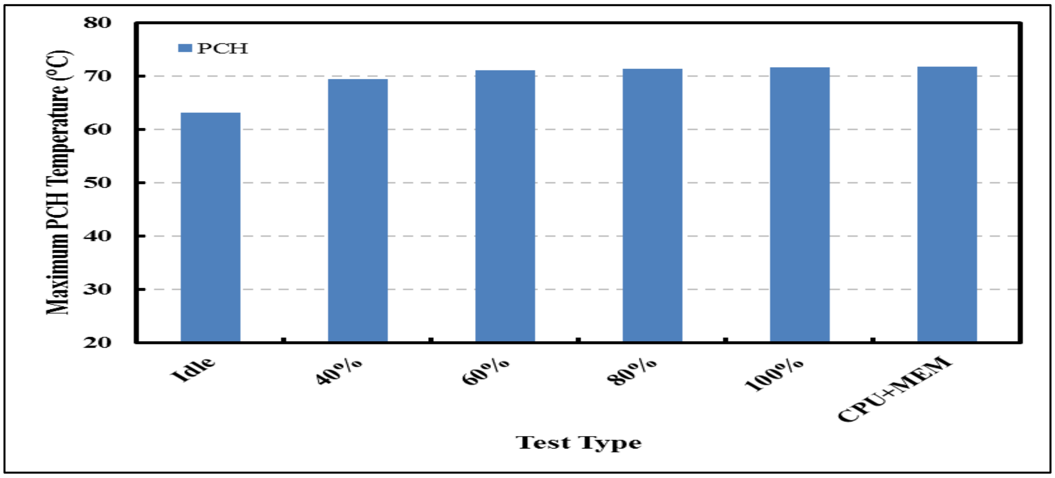


Figure 6-25 Server 132- PCH Temperatures at an Inlet Temperature of Secondary Coolant being 45ºC

- It has been observed that, the maximum temperatures of PCH of each server at an inlet temperature of coolant being 45°C are well below the critical temperature.

  (PCH T_(upper critical)= 85°C)

6.4 Reduction in Pump Power

The centralized redundant pumps are supplied with different voltages at each inlet temperature. The voltage supply to the pumps is lowered from its operational voltage of 16.5V to 11.5V to reduce the pump power consumption.

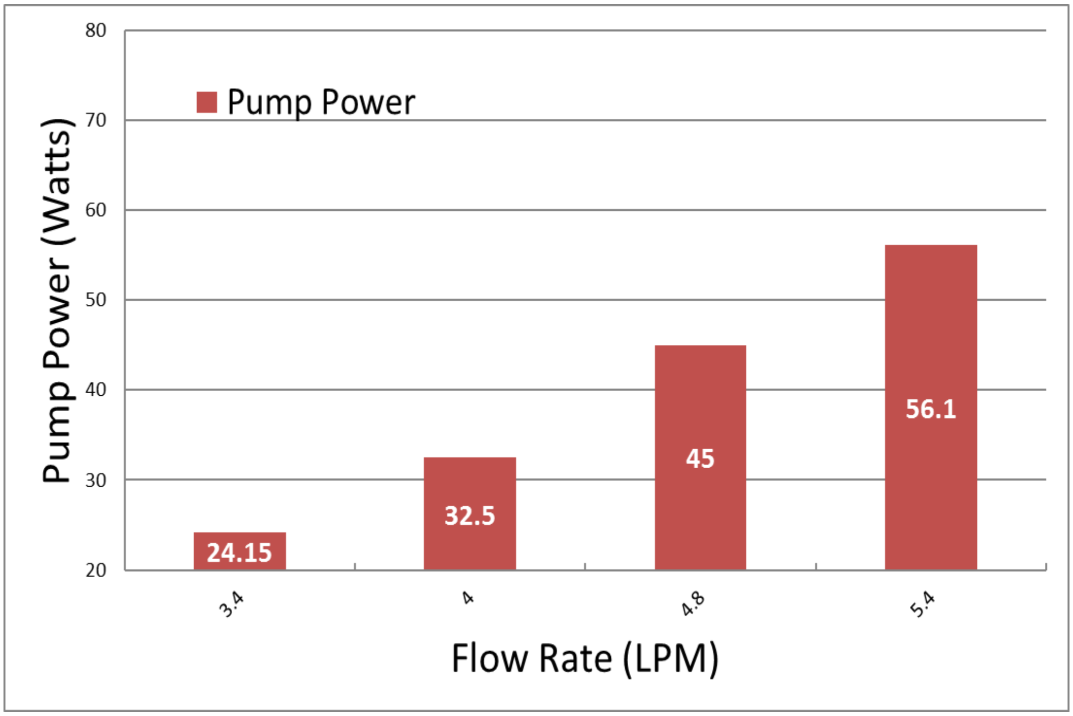


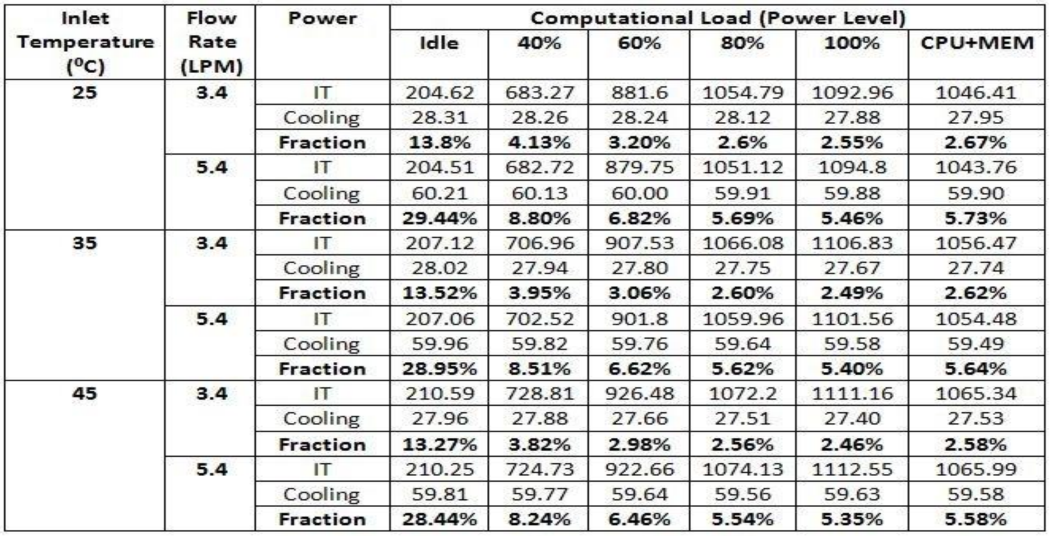
Figure 6-26 Reduction in Pump Power Along w.r.t. Deduction in Fluid Flow Rate

- It has been calculated that, around 57% of reduction in operational pump power has been achieved.

6.5 Total Cooling Power vs Total IT Power

In variable speed pumping for centralized cooling system case, the pump power has been reduced significantly from its operational power where the fan power is increased slightly but not substantial to compensate the reduction in power consumption.

The total cooling power is the summation of pump power and fan power as described in previous section, while the total power consumed by the server is called as IT power.



Inlet Temperature (°C)	Flow Rate (LPM)	Power	Computational Load (Power Level)					
			Idle	40%	60%	80%	100%	CPU+MEM
25	**3.4**	IT	204.62	683.27	881.6	1054.79	1092.96	1046.41
		Cooling	28.31	28.26	28.24	28.12	27.88	27.95
		Fraction	**13.8%**	**4.13%**	**3.20%**	**2.6%**	**2.55%**	**2.67%**
	5.4	IT	204.51	682.72	879.75	1051.12	1094.8	1043.76
		Cooling	60.21	60.13	60.00	59.91	59.88	59.90
		Fraction	**29.44%**	**8.80%**	**6.82%**	**5.69%**	**5.46%**	**5.73%**
35	**3.4**	IT	207.12	706.96	907.53	1066.08	1106.83	1056.47
		Cooling	28.02	27.94	27.80	27.75	27.67	27.74
		Fraction	**13.52%**	**3.95%**	**3.06%**	**2.60%**	**2.49%**	**2.62%**
	5.4	IT	207.06	702.52	901.8	1059.96	1101.56	1054.48
		Cooling	59.96	59.82	59.76	59.64	59.58	59.49
		Fraction	**28.95%**	**8.51%**	**6.62%**	**5.62%**	**5.40%**	**5.64%**
45	**3.4**	IT	210.59	728.81	926.48	1072.2	1111.16	1065.34
		Cooling	27.96	27.88	27.66	27.51	27.40	27.53
		Fraction	**13.27%**	**3.82%**	**2.98%**	**2.56%**	**2.46%**	**2.58%**
	5.4	IT	210.25	724.73	922.66	1074.13	1112.55	1065.99
		Cooling	59.81	59.77	59.64	59.56	59.63	59.58
		Fraction	**28.44%**	**8.24%**	**6.46%**	**5.54%**	**5.35%**	**5.58%**

Figure 6-27 The Cooling Power Consumption of the Entire Rack at Different Coolant Temperatures with Lowest and Highest Fluid Flow Rate

- Around 55% of reduction in total operational cooling power consumption has been achieved by means of variable pumping.
- It has also been observed that, centralized coolant system comprises around 5.5% of the total IT power consumption at flow rate 5.4 LPM, while 2.5% of the total IT power consumption at flow rate 3.4 LPM; both at 100% computational load.

Chapter 7

CONCLUSION

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The centralized cooling system has been evaluated at mini rack level by testing variable pumping of the centralized redundant pumps. The testing has been carried out at high ambient inlet temperature ranging from 25°C to 45°C with an increment of 10°C by lowering the flow rate of the secondary coolant by means of variable pumping.

- The temperature of all components remained below reliable operating temperature even at 100% computational load.
- The centralized liquid cooling is efficient even at the worst-case scenario i.e. at 45ºC of inlet temperature with lowest flow rate of the secondary coolant (3.4 LPM), the temperatures of all the components remained well below critical temperature.
- The temperature difference between CPUs of each server remains similar (5ºC to 7ºC) at each inlet temperature with every deduction in fluid flow rate; suggesting fluid flow rate within range (3.4 LPM to 5.4 LPM) does not have significant effect on thermal shadowing in process of cooling. Thus, the lowest fluid flow rate can be selected to achieve reduction in pump power.
- The maximum core temperatures of the servers are not increased drastically (2ºC to 4ºC) while, there is no noticeable change in temperatures of other components (DIMM and PCH) when the fluid flow rate is lowered from its operational value by means of variable pumping; but there is a significant reduction in cooling power consumption of the server where in major contribution comes from the savings in pump power.

Chapter 8

FUTURE WORK

- A flow network model of centralized cooling system can be developed to understand the effects of change in flow rate of secondary coolant on the distribution through the system
- Experimental testing can also be performed for failure scenarios by partial failing of the cooling components such as fans and pumps.
- Rack level study of hybrid cooled servers can also be done using warm water cooling with variable pumping for distributed coolant system by partially disconnecting centralized coolant system.

References

[1] Tejas Vijay Bhongale, "Computational Study and Optimization of Wet Cooling Media in Direct Evaporative Heat Exchangers", Master's Thesis, UT Arlington, December 2016.

Available online at:

https://uta-ir.tdl.org/uta-ir/bitstream/handle/10106/26454/BHONGALE-THESIS-2016.pdf?sequence=1

[2] Yevgeniy Sverdlik, "Here's How Much Energy All US Data Center Consume", an Article in Data Center Knowledge, June 27, 2016.

Available online at:

http://www.datacenterknowledge.com/archives/2016/06/27/heres-how-much-energy-all-us-data-centers-consume/

[3] Jimil Shah, "Reliability challenges in air side economization and oil immersion cooling", Master's Thesis, UT Arlington, May 2016.

Available online at:

https://www.researchgate.net/publication/315726572_Reliability_challenges_in_airside_economization_and_oil_immersion_cooling

[4] Alekhya Addagatla, "Effect of Warm Water Cooling for an Isolated Hybrid Liquid Cooled Server", Master's Thesis, UT Arlington, December 2014.

Available online at:

https://uta-ir.tdl.org/uta-ir/bitstream/handle/10106/24951/Addagatla_uta_2502M_12940.pdf?sequence=1

[5] Adam Trujillo, "Data center liquid cooling vs. forced air cooling", February 19, 2007.

Available online at:

http://searchdatacenter.techtarget.com/news/1244279/Data-center-liquid-cooling-vs-forced-air-cooling

[6] M. Iyengar, M. David, P. Parida, V. Kamath, B. Kochuparambil, D. Graybill, M. Schultz, M. Gaynes, R. Simons, R. Schmidt and T. Chainer, "Server liquid cooling with chiller-less Data Center Design", Semiconductor Thermal Measurement and Management Symposium (SEMI-THERM), 2012 28th Annual IEEE.

Available online at:

http://ieeexplore.ieee.org/document/6188851/

[7] H. Coles and S. Greenberg, "Direct Liquid Cooling for Electronic Equipment", Ernest Orlando Lawrence Berkeley National Laboratory, March 2014.

Available online at:

https://eta.lbl.gov/sites/all/files/publications/direct_liquid_cooling.pdf

[8] M.J. Ellsworth Jr. , "New ASHRAE Thermal Guidelines for Air and Liquid Cooling, High Performance Computing, Networking Storage and Analysis, SC Companion", Salt Lake City, Utah, USA, June 2012.

Available online at:

https://www.computer.org/csdl/proceedings/sccompanion/2012/4956/00/4956a942-abs.html

[9] Chinmay Kshirsagar, Mathan Kumar Kaliappan, Manasa Sahini, Pat McGinn, Dereje Agonafer, "Rack Level Study of Hybrid Cooled Servers Using Warm Water Cooling with Variable Pumping for Centralized Coolant System", ASME InterPACK 2017, August 2017

[10] H. Li and A. Michael, "Intel Motherboard Hardware v2.0", April 11, 2012.

Available online at:

http://www.opencompute.org/assets/download/Open-Compute-Project-Intel-Motherboard-v2.0.pdf

[11] Wikipedia, "Thermal Design Power"

Available online at: https://en.wikipedia.org/wiki/Thermal_design_power

[12] “Product Specification: R3 Passive CPU Cold Plate 820-00570”, CoolIT Systems, December 2012.

[13] Intel Corporation, “4-Wire Pulse Width Modulation (PWM) Controlled Fans”, September 2005.

Available online at:

http://www.formfactors.org/developer/specs/4_wire_pwm_spec.pdf

[14] “Computer Room Air Handler (CRAH)”, TechTarget – SearchDataCenter.

Available online at:

http://searchdatacenter.techtarget.com/definition/computer-room-air-handler-CRAH

[15] J. Ning, “Intel Server in Open Rack Hardware v0.3”, January 16, 2013.

Available online at:

http://www.opencompute.org/wp/wp-content/uploads/2013/02/Open_Compute_Project_Intel_Server_Open_Rack_v0.3.pdf

[16] CoolIT Systems, “Operational and Maintenance Manual, Rack DCLC CHx40 Module”, May 28, 2015.

[17] CoolIT Systems, “Operational and Maintenance Manual, Rack DCLC AHx Module”

[18] Romtec Utilities, An article on redundant pumps.

Available online at:

http://romtecutilities.com/faq/what-are-the-advantages-of-having-redundant-pumps-in-a-lift-station/

[19] National Instruments, “DC Motor Calculations, Part 1”, White Paper, March 07, 2017.

Available online at:

http://www.ni.com/white-paper/14921/en/

[20] National Instruments, “LabVIEW System Design Software”

Available online at: http://www.ni.com/labview/

[21] Ametherm – Circuit Protection Thermistors, “Product Description NTC Thermistor”.

Available online at:

https://www.ametherm.com/thermistor/what-is-an-ntc-thermistor

[22] Intel corporation, “Power budget and thermal configuration tool”.

Available online at:

https://downloadcenter.intel.com/download/21174/Power-budget-and-thermal-configuration-tool

[23] “Vision and Roadmap-Routing Telecom and Data Centers Toward Efficient Energy Use”, May 13, 2009.

Available online at:

https://www1.eere.energy.gov/manufacturing/datacenters/pdfs/vision_and_roadmap.pdf

[24] sourceforge, “IPMItool, open source software”

Available online at https://sourceforge.net/projects/ipmitool/

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