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

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ABSTRACT

As global demand for data centers grows, so does the size and load placed on data centers, leading constraints on power and space available to the operator. Cooling power consumption is a major part of the data center energy usage. Liquid cooling technology has emerged as a viable solution in the process of optimization of the energy consumed per performance unit. In this data center rack level evaluation, 2OU (Open U) hybrid (liquid+air) cooled web servers are tested to observe the effects of warm water cooling on the server component temperatures, IT power and cooling power. The study discusses the importance of variable speed pumping in a centralized coolant configuration system.

The cooling setup includes a mini rack capable of housing up to eleven hybrid cooled web servers and two heat exchangers that exhaust the heat dissipated from the servers to the environment (the test rig data center room). The centralized configuration has two redundant pumps placed in series with heat exchanger at the rack. Each server is equipped with two passive (i.e. no active pump) cold plates for cooling the CPUs while rests of the components are air cooled. Synthetic stress load has been generated on each server using stress-testing tools. Pumps in the servers are separately powered using an external power supply. The pump speed is proportional to the voltage across the armature [1]. The pump rpm has been recorded with input voltages ranging from 11V to 17V. The servers are tested for higher inlet temperatures ranging from 25°C to 45°C which falls within the ASHRAE liquid cooled envelope W4 [2]. Variable pumping has been achieved by using different input voltages at respective inlet temperatures.

INTRODUCTION

Data centers in USA consume around 91 billion kilowatt-hours of energy each year which is more than 2% of country's energy consumption [3]. There is a significant increase in last few years. High heat dissipating devices are the cause of increase in energy consumption. Cooling of the data centers contribute more than 50% of total IT power [4]. Conventionally most data centers are air cooled. The conventional method of cooling has its own disadvantages like less heat carrying capacity of air due to lower heat transfer coefficient of air, high energy consumption by the chillers and compressors, formation of hot spots, contamination etc. Liquid cooling provides solution to most of these critical issues associated with conventional cooling because of higher heat transfer coefficients of water based coolants. The formation of hot spots at room level can be minimized by moving the liquid cooling source closer to the heat dissipating devices, thereby improving the effectiveness of the cooling. Immersion cooling with mineral oil has also been explored as a new effective option to cooling electronics [5]. However, the cost and maintaining serviceability for oil immersed electronics along with fire hazard protection codes are not yet explored deeply. Hence, liquid cooling does still continues to the emerging technology in data center industry. Encouraging extensive use of "warm water cooling" in data center industry gives flexibility in operating liquid cooling within wider range of temperatures which leads to the partial or complete elimination of Computer Room Air Conditioning (CRAC) units reducing cooling power consumption significantly [6]. Liquid economizers play an important role in eliminating refrigeration chiller compressor which consumes half of the cooling energy. In an addition, liquid cooled system can also help in heat recycling to improve energy efficiency. Due to the advantages discussed above, current study is aimed to quantifying the effect of warm coolant temperatures on the thermal performance of the IT rack along with exploring the advantages of varying flow rates.

KEYWORDS:
Liquid cooling, data center, centralized cooling system, hybrid cooling, redundant pumps, variable speed pumping, Fluid flow rate, Pump power, higher inlet temperatures

EXPERIMENTAL SETUP:

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 [7], hard disk drive (HDD) and bus bar clip shown in Figure1. The chassis dimensions are 804x171x88 mm³. The cover has internal ducting.

The motherboard has two CPUs and up to 16 DIMMs of installable memory. Each CPU has a thermal design power (TDP) rated up to 115 W. Each server has CPUs that are mainly being liquid cooled with two passive micro-channel cold plates while rests of the components are being air cooled. The cold plates are integrated with brushless motor liquid coolant pumps shown in Figure2 [8]. The coolant enters the chassis through cold channel passes through the radiator and two cold plates in series before exiting through hot channel. 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 as shown in figure 3. 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. The baffled air flow from the fans cools DIMMs present on left hand side (LHS) by forced convection as shown in Figure3.

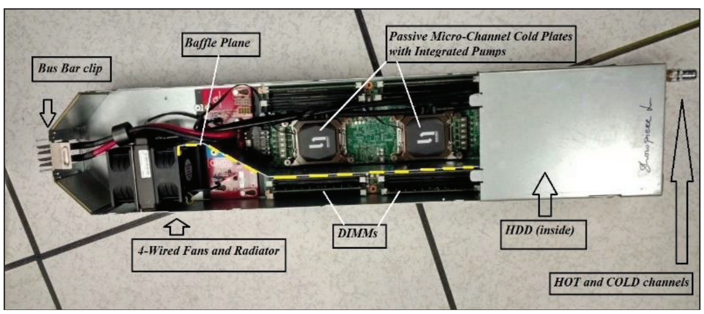

Figure 1: Hybrid-Cooled Winterfell Serv

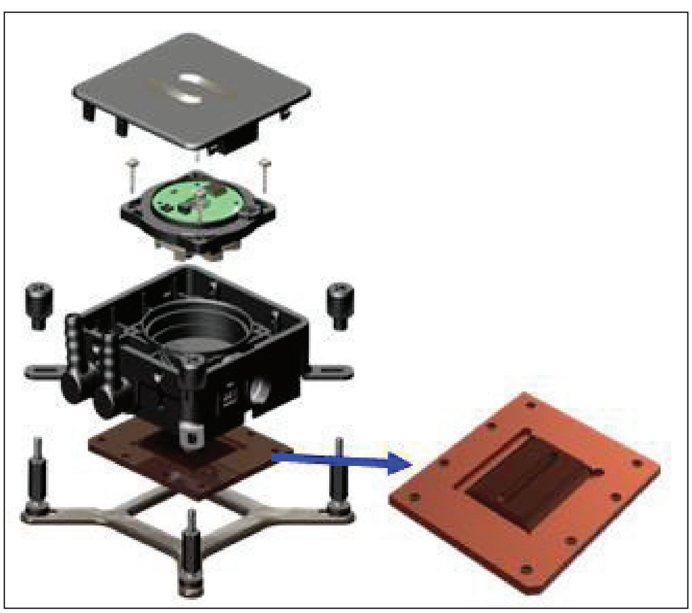

Figure 2: V-groove microchannel cold plate with pump

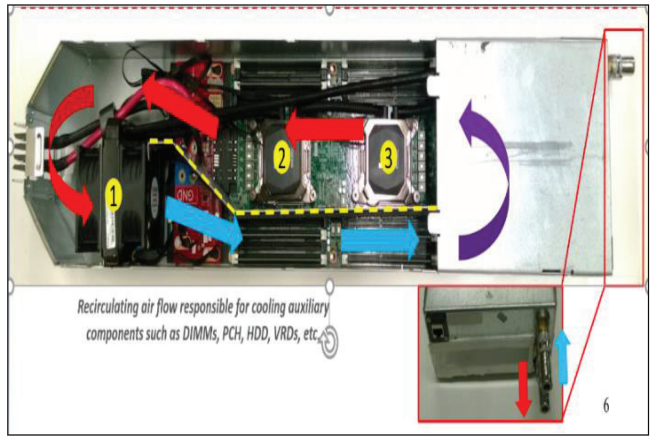

Figure 3: Flow of Secondary Coolant and Air within the Server

Rack Configuration:

The test bed data center room is equipped with CRAH Unit and 3 Open compute 45U racks filled with 1U resistive heaters for maintaining desired temperature of inlet air. The testing rack is placed in the test bed data center. The experimental setup includes one-third size of an Open Rack V1.0 with a network switch, power shelf and four 2 OU slots as shown in Figure 4.

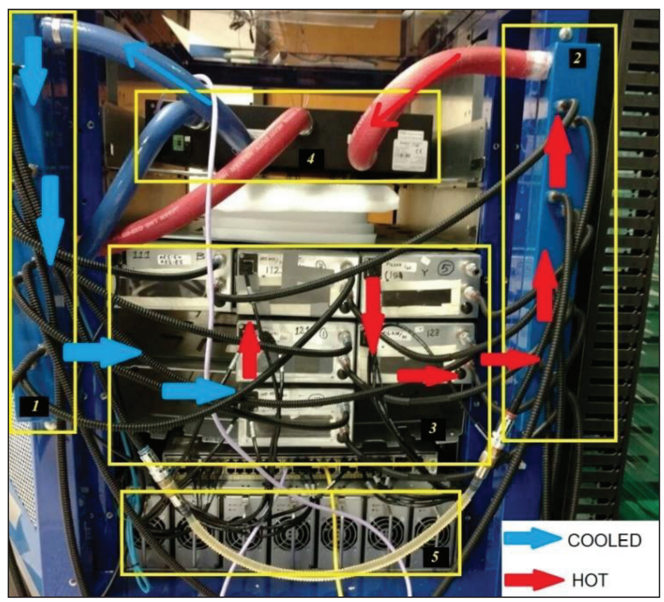

Figure: 4: Front View of the Open Rack V1.0 Showing 1) Inlet Manifold 2) Outlet Manifold 3) 2 OU Servers 4) CHx40 (Liquid-to-Liquid Plate Heat Exchanger) 5) Power Shelf and Inlet-Outlet Manifolds Showing Path of Hot and Cooled Secondary Coolant Through the System

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). 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 Figure 5. It has an ability to operate with ASHRAE W3-W5 (2^0C-45^0C) warm water cooling [9]. AHx unit consists of twenty 4-wire fans with 1200 rpm andtwo HFD5 pumps. 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. The rack has inlet manifold for distribution of already cooled liquid into each server and outlet manifold for collecting hot coolant from each server. 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.

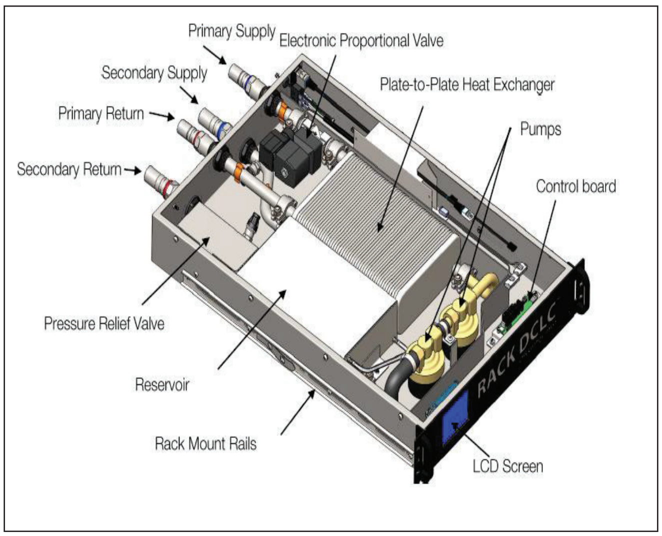

Figure 5: CHx40 Unit (2U Centralized Pumping Module Integrated with Liquid-to-Liquid Plate Heat Exchanger)

COOLING PROCESS:

The secondary coolant distributed from inlet manifold enters each server through cold channel. Within the server tray, it firstly enters the radiator and then into the cold plates in series. Hot secondary coolant from each server is then collected in an outlet manifold. The hot secondary coolant collected from all the servers then enters liquid-to-liquid plate heat exchanger (CHx40) where it exhausts heat to the already cooled primary coolant. On the other hand, hot primary coolant enters liquid-to-air heat exchanger (AHx) and exhaust heat to the colder air by means of the fans cooling the AHx coil.

EXPERIMENTAL PROCEDURE:

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 25^0C to 45^0C and repeat the tests for different flow rates. The cooling power consumption of the servers is the summation of fan power and pump power; thereby both are measured separately. In our case, the centralized pumps are redundant (in series) and the variation in pump power consumption is observed by varying the supply voltage. The fans are variable speed control; we observe the variation in fan power consumption is triggered by PCH temperatures [10].

Variable Pumping:

The centralized pumps are supposed to be constant flow pumps by default design. However, these pumps are over-sized for the given rack heat load, hence, could be over-cooling the system. The effect of reduced flow rate on the component temperatures while warm water cooling is of main interest. The centralized pumps are powered externally by DC supply unit as shown in Figure 6. 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 flow rates varies with supply voltage. The supply voltage is not recommended to be reduced below 11.5V, hence, the minimum flow rate is limited to 3.4 LPM. The pump power has been calculated for respective voltage supply and current readings from DC power supply.

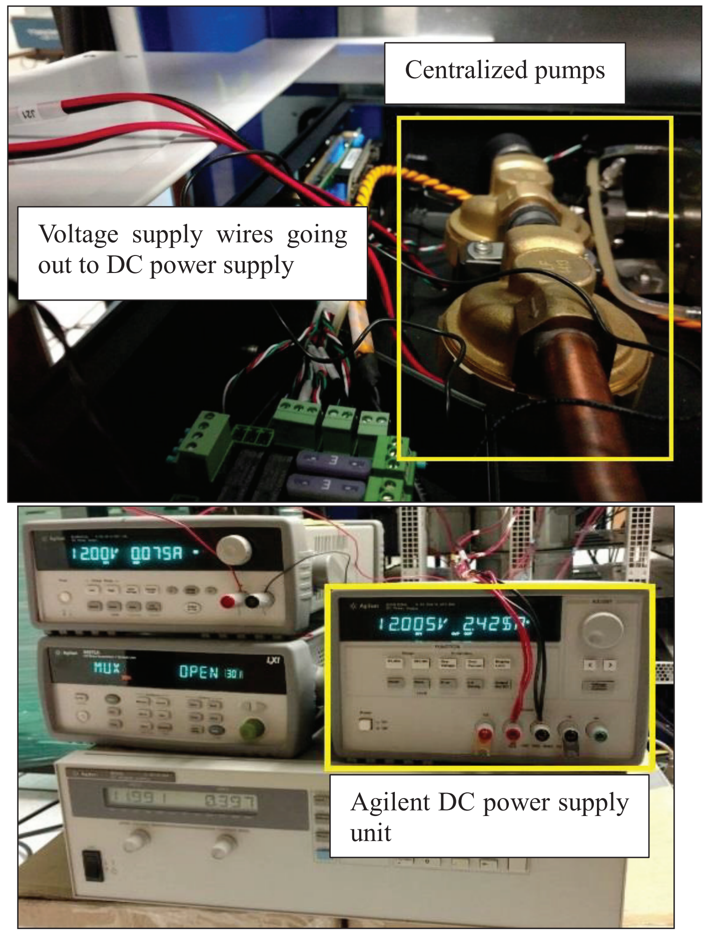

Figure 6: Externally Powered Centralized Redundant Pumps

Desired Secondary Coolant Inlet Temperature Set point:

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 the 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 to regulate the coolant inlet temperature. 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 and by means of an Arduino UNO interfaced with CHx40 control circuit, the labview code adjusts AHx fans speed. The desired set point of inlet temperature; e.g. 25°C, is therefore achieved by controlling the AHx PWM of 4-wire fans. The rack flow rates are measured using the LCD display that reports the fluid velocity sensor information.

Synthetic Load Generation:

A total of 4 hybrid-cooled servers are tested simultaneously in the rack as shown in Figure 7. A communication to each server is established through software WinSCP by means of the static IP address allocated to each server. The servers are referred and positioned in the rack as shown in Figure 7.
The operating system of the servers for communication is Linux. 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 [11]. 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.

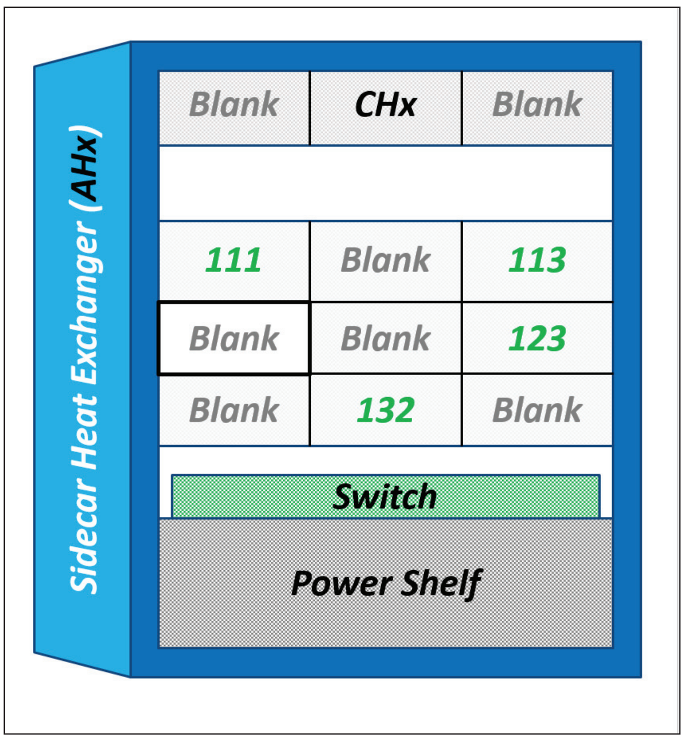

Figure 7**:** Four Servers Tested in the Rack

TESTING PROCESS:

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. 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 from Intelligent Platform Management Interface (IPMI) tool [12]. The data collection in last 30 minutes of each test is to be accounted, since steady state is expected to reach during that period. Hence, the average steady state values obtained from all the repeated tests have been used for analysis.

RESULTS:

Worst Case Scenario:

It has been observed that server 123 showed higher component temperatures compared to other servers. Hence, this server with lowest flow rate (3.4 LPM) and highest coolant inlet temperature(45ºC) is considered as worst-case scenario.
In each server, over 75% of heat load comes from CPUs. Figure 8 shows the maximum core temperatures of the two CPUs i.e. "CPU 0" and "CPU 1" of server 123. These temperatures are well below the critical temperature limit i.e. 100ºC.

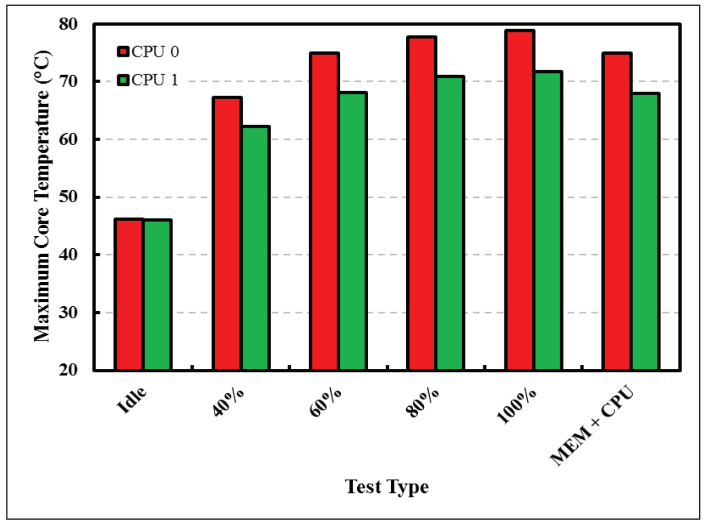

Figure 8: Maximum Core Temperature of Server 123 at 45ºC with Fluid Flow Rate 3.4 LPM

The difference between the maximum core temperatures of each server (ΔT) with lowest and highest flow rates at each inlet temperature as tabulated in Table1.

Inlet Temperature(ºC)	CPU0			CPU 1		
	3.4 LPM	5.4 LPM	ΔT	3.4 LPM	5.4 LPM	ΔT
25	61.76	55.19	6.57	58.32	52.88	5.44
35	71.4	68.08	3.32	64.56	62.38	2.18
45	78.9	76.01	2.89	71.77	70.99	0.78

Table 1: Flow Rate vs Maximum Core Temperature

With the increase in inlet temperature, we see that the difference in CPU temperatures for 3.4 LPM case vs. 5.4 LPM case decreases. This means at higher inlet temperatures, the lower flow rates do not significantly affect the junction temperatures i.e., to junction-to-case thermal resistances of the components. The thermal margin available at 45ºC inlet in server 123 is 21ºC.

Flow Rate vs DIMM and PCH Temperature:

The other critical board component temperatures like, memory modules and PCH are air-cooled. The maximum temperatures of the DIMMs and PCH are not changed drastically (no more than 1.7ºC-highlighted in table 2) when the fluid flow rate is lowered from 5.4 LPM to 3.4 LPM by means of variable pumping and with changing inlet temperature.

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

Table 2: The Variation in DIMMs and PCH Temperature with respect to Highest and Lowest Flow Rates at Each Inlet Temperature

The DIMM and PCH temperatures differences for 3.4LPM vs. 5.4 LPM are negligible with increasing inlet temperature. This agrees to what we saw in the case of CPUs.

For server 123 which is the worst case scenario, the maximum temperatures of DIMMs and PCH at an inlet temperature of coolant being 45ºC are well below the critical temperatures of each component (DIMM T_(upper critical)= 82ºC) and (PCH T_(upper critical)= 85ºC) respectively. The minimum thermal margin available for DIMMs is 18ºC and for PCH it is 13ºC.

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. Around 57% of reduction in pump power has been achieved as shown in and Figure 9.

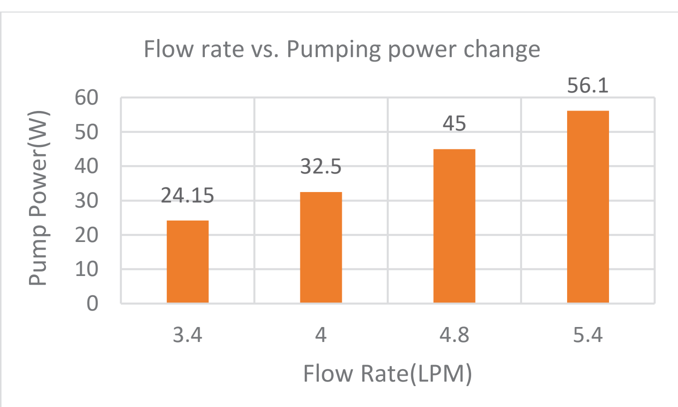

Figure 9: Plot Representing Reduction in Pump Power Along with Respective Deduction in Fluid Flow Rate

Total Cooling Power vs Total IT Power

In variable 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. Table 3 below shows the IT and cooling power consumption and 'fraction' represents how much cooling power is a percentage of IT power for each case.

Inlet Temperature (ºC)	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%**

Table 3: 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 cooling power consumption has been achieved between 3.4 LPM vs. 5.4 LPM case.

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 as shown in Table3 (highlighted part). For lower computational loads, cooling is inefficient as it contributes to higher percentage of IT load.

CONCLUSION:

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 25ºC up to 45ºC with an increment of 10ºC by lowering the flow rate of the secondary coolant by means of variable pumping. There are two factors affecting the component temperatures, flow rate of the coolant and the inlet temperature of the coolant.

- The temperature of all components remained below reliable operating temperature even at 100% computational load.
- The centralized liquid cooling is effective 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 temperatures with reasonable thermal margins.

- The temperature difference between CPUs of each server remains similar (up to 7ºC) at each inlet temperature with reducing 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 CPUs are increased by ~3ºC at 45ºC and for 3.4 LPM vs. 5.4 LPM case, 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 to lowest flow rate; but there is a significant reduction in cooling power consumption of the server where in major contribution comes from the savings in pump power.
- The total cooling power consumption can be reduced to 55% when changed from 5.4 LPM to 3.4 LPM case without effecting the IT thermal performance significantly even when using the warm water cooling.
- The next step is to develop a flow network model of centralized cooling system to understand the effects of change in flow rate of secondary coolant on the distribution through the system and from there we can estimate how much perturbation exists due to this non-uniform in individual server coolant flow rates.

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