Experimental Characterization of an Energy Efficient Chiller-less Data Center Test Facility with Warm Water Cooled Servers

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Abstract

Typical data centers utilize approximately 50% of the total IT energy in cooling of the server racks. We present a chiller-less data center where server-level cooling is achieved through a combination of warm water cooling hardware and re-circulated air; eventual heat rejection to ambient air is achieved using a closed secondary liquid loop to ambient-air heat exchanger (dry-cooler). Several experiments were carried out to characterize the individual pieces of equipment and data center thermal performance and energy consumption. A 22+ hour experimental run was also carried out with results indicating an average cooling energy use of 3.5% of the total IT energy use, with average ambient air temperatures of 23.8°C and average IT power use of 13.14 kW.

Keywords

Liquid cooled servers, data center, energy efficiency

1. Introduction

Data center energy use and energy efficiency are key issues in today's economic and environmental backdrop and are predicted to play a growing role over the coming decades as information technology (IT) energy use begins to rival commercial, residential and industrial energy consumption [1,2]. Typical data centers utilize 25%-30% of the total data center energy (or ~50% of the IT energy) in cooling of the IT server racks with much of this energy being consumed by the computer room air conditioning (CRAC) units and the chiller plant to provide suitably cooled and conditioned air to the IT racks [1,3-5]. Heat rejection is ultimately achieved at the wet cooling tower where the heated facility water is evaporatively cooled and extra water added to replace that lost via evaporation.

A key approach to reducing the total cooling energy use is to eliminate or reduce the need for both CRAC units and chiller plants by: i) using liquid cooling at the server and/or rack level and ii) using water/air side economizers with ambient 'free-air' cooling [6]. The use of liquid cooling allows the heat generated at the servers to be more efficiently transported from the heat source to the sink as compared to air thus reducing energy waste due to the need to provide chilled and conditioned air to an entire room. The use of water or air-side economization enables the use of ambient external conditions to directly provide the necessary cooling without intermediate refrigeration steps. This is particularly attractive in regions where the weather is cool. Use of chiller-less data center cooling in hotter regions or during the hottest parts of the year would require additional evaporative cooling techniques.

Both liquid cooling and economizer based data centers have been independently investigated and presented in the literature. Ellsworth et al. recently documented the water cooling of an IBM Power 775 (P7-IH) Supercomputing system where in excess of 96% of the 180 kW of rack heat load is taken up by the water [7]. Previous work by Ellsworth and Iyengar into the water cooled IBM Power 575 (P6-IH) also determined that the power required to transfer the dissipated heat to the ambient was 45% less for a liquid cooled system [8]. Wei documents the performance of a hybrid liquid and air cooled Fujitsu high end server GS8900 where 60% of the heat dissipated is absorbed by the liquid and the remaining exhausted into the room [9]. Apart from the reduced heat dissipation into the computer room, the use of liquid cooling reduced the junction temperatures and increased performance by 10%. This cooling hardware is now implemented in the Fujitsu K-computer complex which, combined with other system improvements, results in a highly efficient 830 MFlops/W.

At the data center level, both Yahoo! and Facebook have unveiled air-side economizer based data center designs with air-cooled servers. S. Noteboom, Yahoo's VP of Global Data Centers, presented their work on a new air-side economized data center with evaporative cooling in Buffalo, NY. Results indicate a power usage effectiveness (PUE) of 1.08 and an estimated saving of 36 million gallons of water per year compared to their previous chiller based data center design [10]. Facebook's data center in Prineville, Oregon, features direct air-side economization with an evaporative cooling system. These features combined with improvements in the electrical distribution have led to a PUE ranging between 1.06 and 1.1 [11]. However the use of air cooling at the rack and servers requires the handling, filtering and conditioning of a significant quantity of air, and potentially hot/cold aisle containment.

In this study we propose a chiller-less, ambient air cooled data center where cooling at the rack is achieved through a combination of warm liquid and enclosed re-circulated air cooled servers [12]. Heat is ultimately rejected from the warm facility water to the ambient air through the use of a closed loop liquid-to-air heat exchanger. The proposed design is expected to reduce the cooling energy to less than 5% of the IT energy and eliminates the need for make-up water. Additionally, when the outlet water from the server racks exceeds 40°C there is the potential to recover some of this

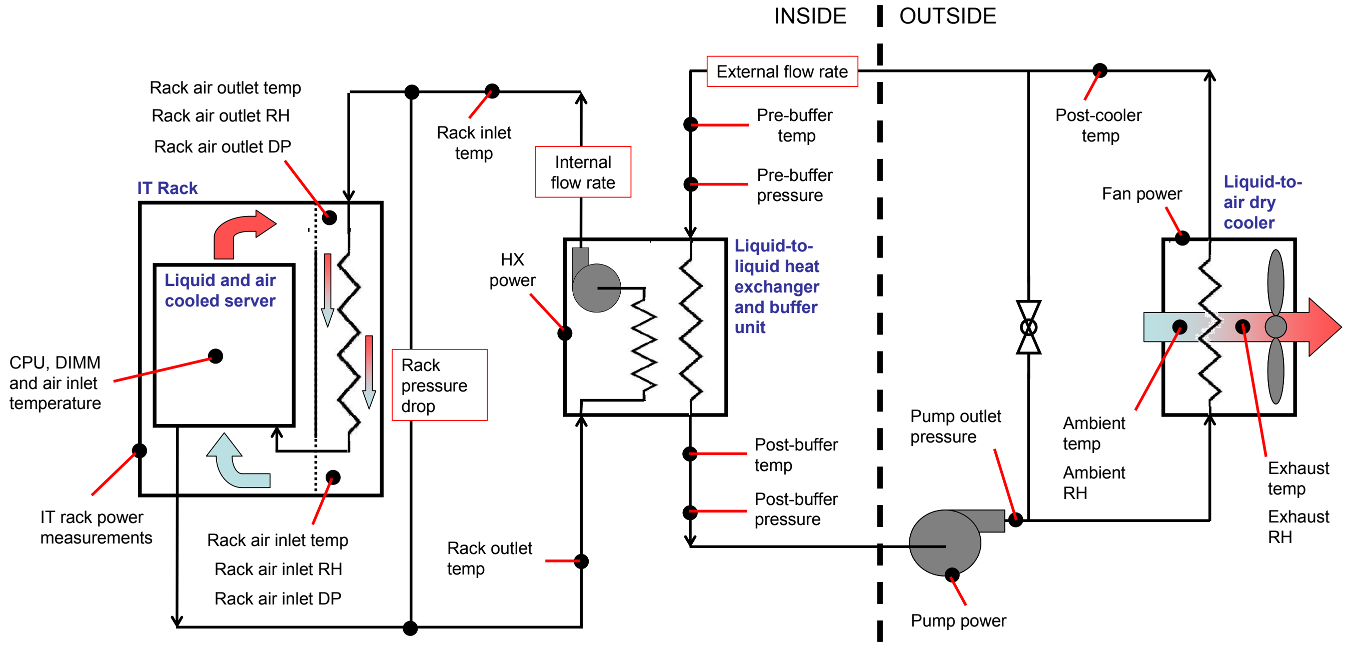

Fig. 1. Schematic representation of the energy efficient data center test facility. IT servers are warm water cooled with the heat ultimately rejected to ambient air via a liquid-to-air heat exchanger.

energy to heat water for use in low grade commercial and residential heating applications. This paper discusses the experimental characterization carried out on the designed energy efficient data center test facility and presents the hydraulic, thermal and power data for the data center at various operational conditions as well as the results obtained for a run carried out over a day with ambient temperatures ranging from 18.6°C to 32°C.

2. Description of the Dual Loop Data Center Test Facility

A dual loop data center test facility, shown above in Fig. 1, was constructed to cool a rack of warm water cooled IBM System X volume servers. The liquid cooled servers, shown in Fig. 2, contain cold plates, cold rails and heat spreaders such that the processors and memory modules are primarily water cooled and the remaining server components cooled by re-circulated air. The air is circulated within the rack and is cooled by the incoming water using an air-to-liquid heat exchanger mounted within the rack enclosure. This server and rack arrangement significantly reduces the need for specialized computer room air conditioning units since a large fraction of the heat generated at the servers is absorbed by the liquid. The liquid used in the rack is circulated in an internal loop with heat exchange to a secondary, external loop coolant such as water or water-glycol mixture. The liquid-to-liquid heat exchanger (buffer unit) allows the year-round use of thermally superior water in the internal loop as well as varying the degrees of coolant quality and chemical treatment in the internal and external loops. The external coolant is circulated through a liquid-to-ambient-air heat exchanger (dry-cooler). The closed external loop requires no additional make-up water, as would be the case in a wet cooling tower approach. The use of two coolant loops and physical isolation of the rack (or computer room) from the external air makes the local rack environment easier to control and maintain and helps ensure cleanliness and reliability of the rack and servers.

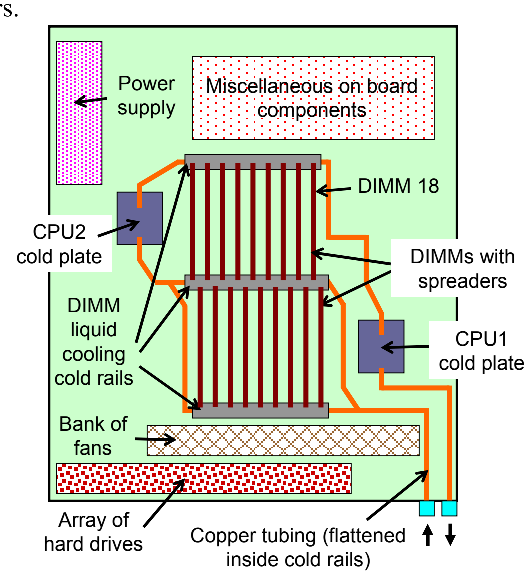

Fig. 2. Schematic representation of the liquid cooled IBM M3 X-3550 servers showing the liquid loop, two mini-channel cold plates for CPU1 and CPU2, and DIMM cold rails. Copper spreaders are attached to the DIMMs and conduct heat to the cold rails.

The described test facility is instrumented at various locations, both within the servers and in the two cooling loops. Temperature, pressure, flow-rate, humidity and power measurements are collected via a programmable logic controller (PLC) box, shown in Fig. 3, using a custom-built program running in Labview.

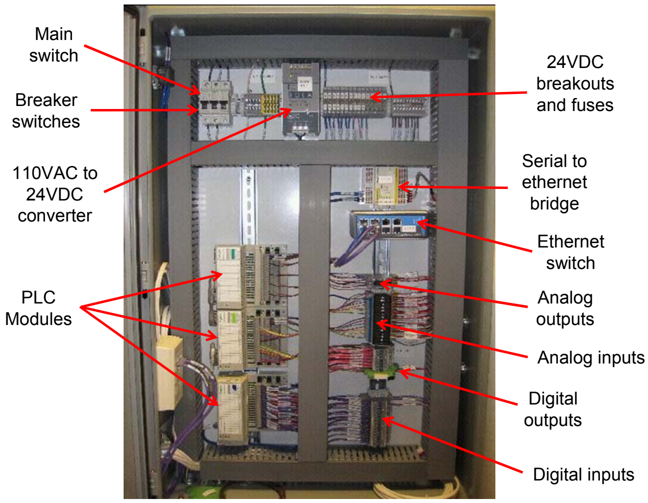

Fig. 3. Photo of PLC box used to monitor the data center test facility. The PLC is connected to a remote computer with the Labview based programs.

3. Data Center Test Facility Characterization

A key requirement to gain a more detailed understanding of the test facility behavior is characterization of the major components therein. Nine characterization tests were carried out, details of which are described in Table 1, where the internal and external pump RPM and dry cooler fan RPM were varied to study the thermal behavior of the system. The IT power during these runs varied from 13.4 to 14.5 kW.

Table 1. Test conditions used to characterize the major components of the data center test facility.

Test #	Int Pump Flow GPM (LPM)	Ext Pump Flow GPM (LPM)	Cooler RPM RPM
1	4.1 (15.5)	3.98 (15.1)	170
2	4.1 (15.5)	6.03 (22.8)	170
3	4.1 (15.5)	8.08 (30.6)	170
4	6.1 (23.2)	3.95 (15.0)	310
5	6.1 (23.0)	5.99 (22.7)	310
6	6.1 (23.1)	8.01 (30.3)	310
7	8.1 (30.7)	3.96 (15.0)	500
8	8.1 (30.5)	6.01 (22.7)	500
9	8.1 (30.7)	8.03 (30.4)	500

The key thermal data from the cooling loop obtained during the nine characterization runs is shown in Fig. 4(a). The pre-buffer liquid temperature is found to reduce significantly as the cooler fan speeds are increased from 170 to 310 RPM and less so when increasing from 310 to 500 RPM. The pre-rack liquid and pre-rack air temperatures are found to be almost 10°C and 13.5°C higher than ambient at the lowest internal flow rate of 4.1 GPM (15.5 LPM) and found to improve as the external flow rate is increased from 4 GPM (15 LPM) to 8 GPM (30 LPM) at intermediate, 6.1 GPM (23.1 LPM) and higher, 8.1 GPM (30.6 LPM), internal flow rates. At the lowest internal flow rate and dry-cooler fan speed, the lower heat capacity rate of the air flow across the dry-cooler with respect to the external liquid flow and mostly flat dry-cooler effectiveness causes the temperature of the cooling water entering the buffer unit to rise with increasing external liquid flow. This results in the temperature of water in the internal loop leaving the buffer heat exchanger to be relatively unchanged despite the increasing buffer unit effectiveness with external liquid flow rate. At the higher internal flows and fan speeds (tests 4-9), increasing the external liquid flow only results in a slight increase in the liquid temperature leaving the dry-cooler as the external liquid now has a lower heat capacity rate with respect to the air flow. This results in a more pronounced lowering of the internal loop liquid (and subsequently air) temperatures as the external liquid flow is increased.

Figure 4(b) highlights the server component temperatures with respect to the approaching liquid temperature over the nine characterization runs. Increase in the internal loop flow rate finds a significant improvement in the component temperatures when moving from 4 GPM to 6 GPM and a smaller improvement when moving to 8 GPM. CPU2 temperatures are lower than CPU1 as CPU1 sees a larger liquid preheat in the server as seen in Fig. 2.

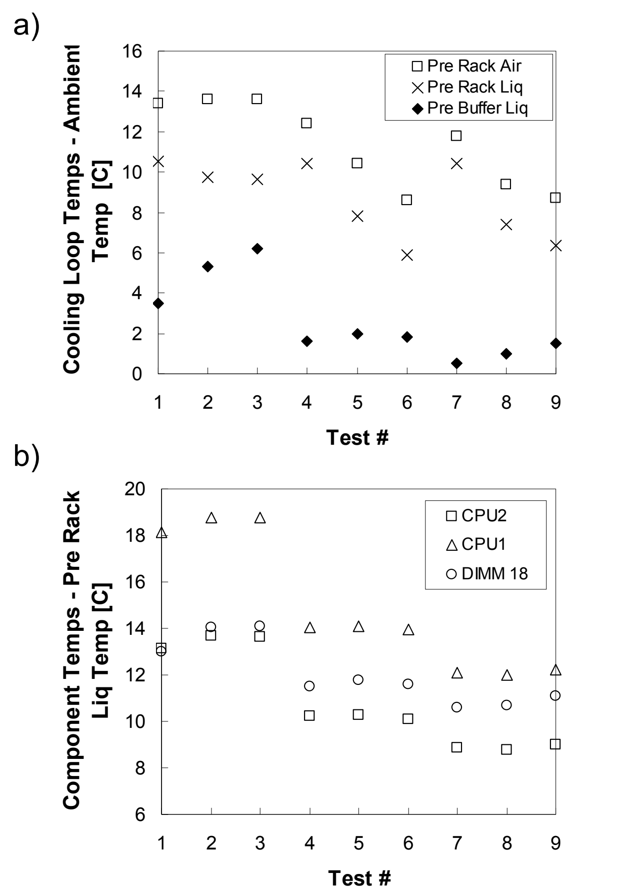

Fig. 4. Data center and server temperatures for the nine loop characterization tests: (a) Cooling loop temperatures (relative to outside ambient) (b) Server component temperatures (relative to pre-rack liquid temperatures) obtained from an instrumented server.

Using the obtained data, heat transfer effectiveness times heat capacity rate (ε-C_{min}) surfaces can be constructed (Fig. 5) as a function of the internal pump (within the buffer unit), external pump and dry cooler fan operation rates. These surfaces have value in the development of semi-empirical models of the data center and in understanding the manner in which the system reacts to changes in pumped flow rates and cooler fan speeds. Figure 5(a) shows that the buffer unit heat exchanger's ε-C_{min} increases more strongly with the increase in the internal loop pump RPM at higher external flows than at lower external flows because at higher external pump flows the internal flow is the minimum fluid. Similarly, the rise in ε-C_{min} is larger with increase in external flow rate when the internal pump flow is at the highest flow-rate. Figure 5(b) shows the ε-C_{min} surface obtained for the dry-cooler heat exchanger. In general, we found that increasing dry cooler fan RPM is less effective as compared to increasing the external pump flow rate in improving the ε-C_{min} for the heat exchanger and consequently in reducing loop temperatures (as can be seen in Fig. 4(a)). This is particularly true at the two higher cooler fan speeds of 310 and 500 RPM.

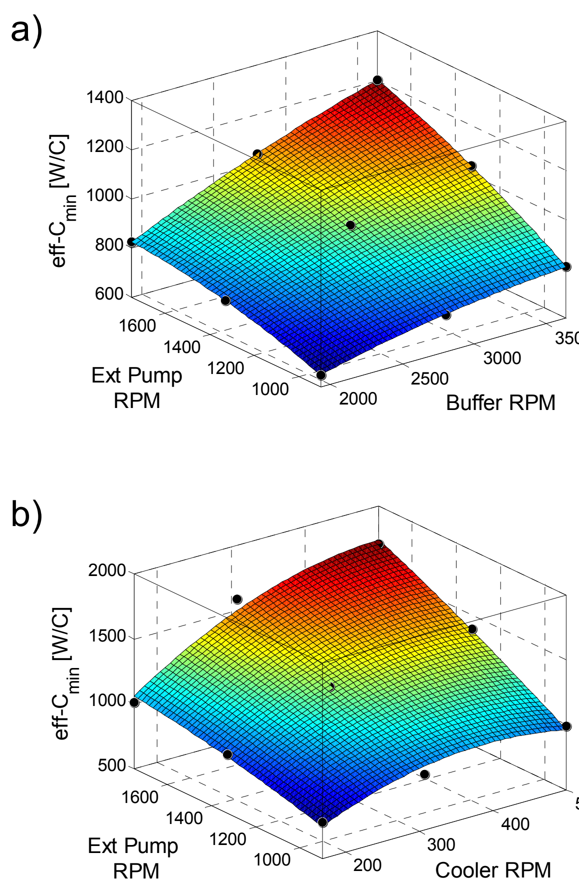

Fig. 5. ε-C_{min} surfaces obtained for the (a) buffer unit and for the (b) dry-cooler as a function of the buffer unit and external pump speed and the cooler fan and external pump speed respectively.

Additional characterization tests were carried out to obtain detailed information regarding the hydraulic and power consumption characteristics of the rack, buffer unit and dry-cooler unit. The pressure drop across the buffer unit and rack display a quadratic behavior with respect to pump speed and flow-rate. The flow-rates for the two pumps expectedly obey a linear relationship with the input RPM. Power consumption was found to follow a cubic relationship with respect to input RPM for the two pumps and the cooler fan as seen in Fig. 6. It is evident from the figure that the fans can quickly become the leading consumer of cooling energy in the data center at high operation speeds (>700 RPM). The relatively smaller improvement in loop temperatures at fan speeds higher than ~300 RPM results in a high cooling power cost for a given rack inlet liquid temperature improvement as compared to the external loop pump, emphasizing the need to limit cooler fan use. Though Fig. 6 indicates that the internal loop pump consumes less power for a given RPM, the power consumed for a given flow-rate is higher in the internal pump as compared to the external pump due to a lower flow-rate at a given RPM.

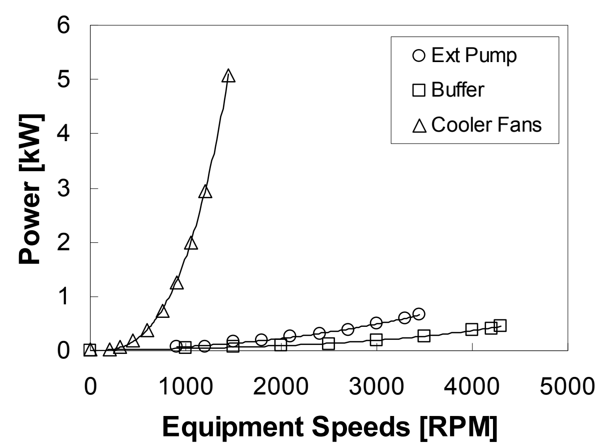

Fig. 6. Power consumption in the three pieces of cooling equipment used in the data center test facility. The cooler fans are clearly the leading power consumer at speeds greater than ~700 RPM thus motivating limited use of the fans when possible.

4. Day Long Operation of the Data Center Test Facility

The data center test facility was continuously run for a day (~ 22 hours) with varying cooler fan speeds and internal and external flow rates set to 7.2 GPM (27.2 LPM) and 7.1 GPM (27 LPM) respectively. The dry cooler fans were programmed to linearly vary in speed from 170 RPM to 500 RPM as the pre-buffer temperature varied from 30°C to 35°C. At pre-buffer temperatures below 30°C the fans run at a constant speed of 170 RPM. Figure 7 shows the pre-buffer, pre-rack liquid, pre-rack air and ambient air temperature during the course of the run. The ambient air temperature varied from 18.6°C to 32°C with an average of 23.8°C. The average pre-rack liquid and air temperature were measured to be 33.7°C and 36.4°C. The diurnal cycle can be clearly observed with temperatures dropping after sunset and reaching a low just before sunrise, after which the temperatures begin to rise rapidly. The pre-buffer, pre-rack liquid and pre-rack air temperatures generally follow the ambient temperature but the temperature difference to the ambient markedly reduces as the pre-buffer temperature rises over 30°C and the fans begin to ramp up and reduce the loop-to-ambient temperature delta.

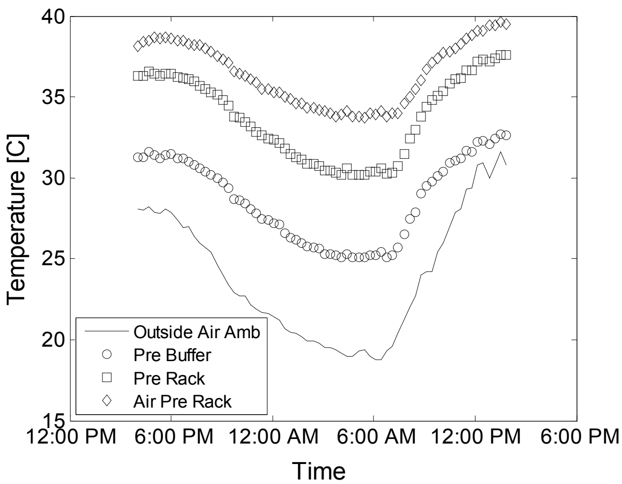

Fig. 7. Temperature data for the data center over the course of 22 consecutive hours. Cooling loop temperatures show that the loop temperatures generally follow the ambient temperature with a reduction in the delta with the ambient as the pre-buffer temperatures exceed 30°C and the dry-cooler fans are engaged.

The power consumption by the three pieces of cooling equipment is shown in Fig. 8(a). The power consumption by the internal and external pump is constant throughout the run but rises for the fans starting at around 10am. This causes the cooling power to rise during the late morning and into the afternoon. The IT power also varies during the day despite the use of a steady CPU and memory exerciser. The IT power consumption exhibits a linear relationship with the pre-rack air (and pre-rack liquid) temperature as shown in Fig. 8(b). This is due to a combination of increased leakage at higher temperatures as well as higher server fan power use. The server fan's RPMs are set by the measured server air inlet temperature. This implies that though cooling energy could be conserved by using warm water, the IT energy use may actually rise and potentially reduce the overall energy benefit. This also suggests that running IT servers as hot as allowable may not necessarily result in the best energy savings. Other factors such as the potential for energy recovery from hot water also need to be considered before the appropriate thermal operating point can be correctly identified.

Figure 9 shows a plot of the Cooling PUE, where Cooling PUE = (heat absorbed by liquid + cooling power) / (heat absorbed by liquid). The industry standard PUE number cannot be determined for our test facility due to the use of single rack situated in a mixed use lab space that is not optimized for use as a computer room. However, the Cooling PUE is a useful metric to determine the energy efficiency of the cooling solution used to cool the IT rack with values approaching unity indicating a more energy efficient cooling solution. The average Cooling PUE for this 22 hour run was calculated to be 1.035 (with an equivalent Coefficient of Performance, COP, of 29). The average IT power dissipated during the course of the run was measured to be 13.14 kW with the cooling power varying from 430 W to 490 W. The heat dissipated from the IT rack that was lost to the lab environment, and not taken up by the cooling water, was found to be a maximum of 18% of IT power with an average of just 4%. The Cooling PUE rises during the late morning and into the afternoon due to the increased power use at the external cooling fans. The power consumed by the monitoring and control enclosure is not accounted for in this calculation as it is treated as a fixed energy cost whose impact on a data center is minimal for multi-rack configurations. The power consumed by this enclosure is determined to be approximately 82 W.

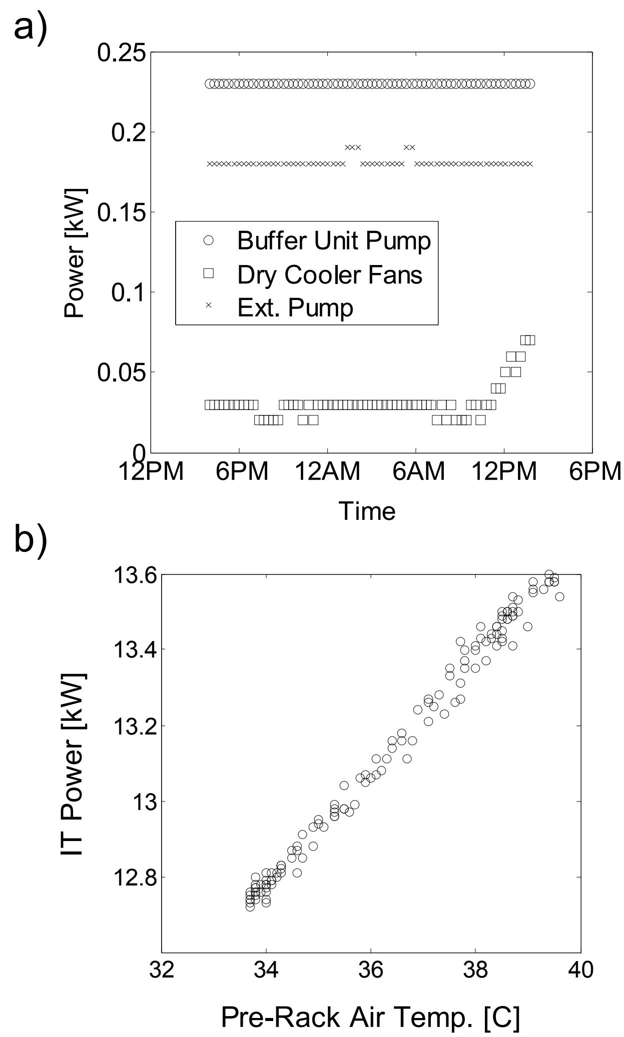

Fig. 8. (a) Cooling equipment power use over the course of the 22 hour run. Fan power increases as fans ramp up in response to increasing pre-buffer liquid temperature. (b) IT power draw as a function of rack air temperature showing increasing power use as temperature rises due to leakage and server fan speed up.

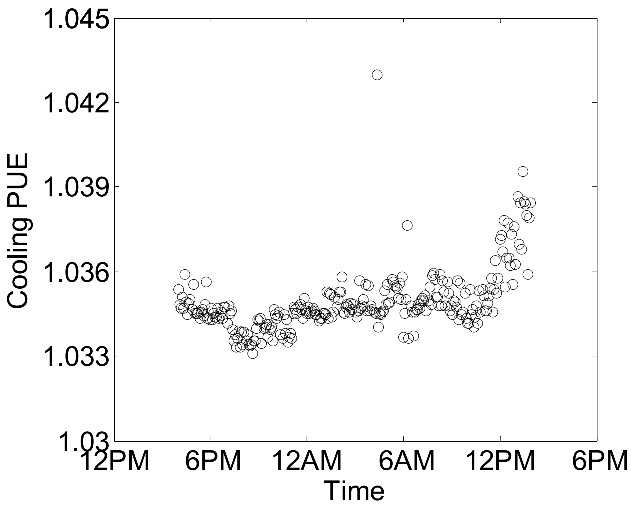

Fig. 9. Cooling PUE for the data center over the course of 22 consecutive hours. Cooling PUE can be maintained below 1.05 for most of the day with an average of 1.035 (i.e. cooling power = 3.5% of IT power absorbed by fluid). Cooling PUE rises starting late morning due to increased power use by the dry cooler fans.

5. Conclusions

An ambient air cooled, energy efficient, chiller-less data center test facility with warm water and re-circulated air cooled volume servers was designed and constructed to reduce cooling energy use below 5% of the IT energy use. This test facility has been characterized to determine the thermal, hydraulic and power consumption characteristics of the system and to determine the air-to-liquid rack heat exchanger, liquid-to-liquid buffer heat exchanger and liquid-to-ambient air dry cooler performance. This characterization is necessary for accurate modeling of the data center test facility. A one day test run was also carried out to characterize the energy efficiency of the test facility. Results from the one-day run found the cooling energy use to be on average 3.5% of the total IT energy use, with ambient air temperatures an average of 23.8°C and IT power an average of 13.14 kW. The anticipated benefits of such energy-centric configurations are significant energy savings at the data center level of approximately 25% which represents greater than 90% reduction in the cooling energy usage compared to conventional refrigeration based systems. For a typical 1 Megawatt Data Center this would represent a savings of roughly $90-$240k/year at an energy cost of $0.04 - $0.11 per kWh. The prototype dual-enclosure liquid-cooling (DELC) technology being characterized in this program will be evaluated to see how these developments may be incorporated into a portfolio of leading edge energy efficient technologies.

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