Performance Evaluation for Modular, Scalable Cooling Systems with Hot Aisle Containment in Data Centers

Final Report

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Disclaimer

Contents

Evaluation for Modular, Scalable Cooling Systems with Hot Aisle Containment in Data Centers

1 Problem Statement

Scientific and enterprise data centers, IT equipment product development, and research data center laboratories typically require continuous cooling to control inlet air temperatures within recommended operating levels for the IT equipment. The consolidation and higher density aggregation of slim computing, storage and networking hardware has resulted in higher power density than what the raised–floor system design, coupled with commonly used computer rack air conditioning (CRAC) units, was originally conceived to handle.

Many existing data centers and newly constructed data centers adopt CRAC units, which inherently handle heat transfer within data centers via air as the heat transfer media. This results in energy performance of the ventilation and cooling systems being less than optimal. Understanding the current trends toward higher power density in IT computing, more and more IT equipment manufacturers are designing their equipment to operate in "conventional" data center environments, while considering provisions of alternative cooling solutions to either their equipment or supplemental cooling in rack or row systems.

Naturally, the trend toward higher power density resulting from current and future generations of servers has, in the meanwhile, created significant opportunities for precision cooling suppliers to engineer and manufacture packaged modular and scalable systems. The modular and scalable cooling systems aim at significantly improving efficiency while addressing the thermal challenges, improving reliability, and allowing for future needs and growth. Such pre-engineered and manufactured systems may be a significant improvement over current design; however, without an energy efficiency focus, their applications could also lead to even lower energy efficiencies in the overall data center infrastructure.

The overall goal of the project supported by California Energy Commission was to characterize four commercially available, modular cooling systems installed in a data center. Such modular cooling systems are all scalable localized units, and will be evaluated in terms of their operating energy efficiency in a real data center, respectively, as compared to the energy efficiency of traditional legacy data center cooling systems.

2 Technical objectives

The technical objective of this project was to evaluate the energy performance of one of the four commercially available modular cooling systems installed in a data center in Sun Microsystems, Inc. This report is the result of a test plan that was developed with the industrial participants' input, including specific design and operating characteristics of the selected modular localized cooling solution provided by vendor 2.

The technical evaluation included monitoring and measurement of selected parameters, and establishing and calculating energy efficiency metrics for the selected cooling product, which is a modular, scalable pair of chilled water cooling modules that were tested in a hot/cold aisle environment with hot aisle containment. The scope of this report is to quantify energy performance of the modular cooling unit in operation as it corresponds to a combination of varied server loads and inlet air temperatures.

The information generated from this testing when combined with a concurrent research study to document the energy efficiency of the host data center's central chilled water cooling plant can be used to estimate potential energy savings from implementing modular cooling compared to conventional cooling in data centers.

3 Technical information on the characteristics of cooling systems and servers

The evaluation tests were performed in a data center space located in Santa Clara, California. The datacenter area is approximately 12,800 square feet, with a ceiling height of 13 ft 6 inches and no raised floor. All server racks and support equipment are installed directly on the slab floor. There were various types of servers, rack sizes and shapes from various vendors. The data center was specifically designed to support racks with any type of IT equipment.

Power, chilled water, and communication cables to the server racks were provided through overhead cable trays. 700 tons of cooling is provided to the space from the central chilled water plant for cooling the IT equipment. The chilled water is supplied by a 2,000 ton central chilled water plant.

Power for thirty six 150kW PDUs was provided through a 480v AC bus way system. The 150kW power distribution units (PDUs) were located throughout the space. The PDUs transform the power from 480v AC to 208v AC for distribution to the server racks. The data center currently can support 190 watts/ft^2 of floor area. The design load per rack footprint was 5kW/rack with growth to 9kW/rack.

3.1 Modular, scalable cooling system with hot-aisle containment

The modular, scalable cooling system in this study was a chilled-water-based cooling solution combined with a hot aisle containment system. The cooling system consists of two parallel rows of IT Racks (sizing 42"x29x78") sharing a common hot aisle with a width of 36", with each row containing a chilled-water modular cooling module (42"x23"x78"). The common hot aisle was contained with modular clear ceiling panel along with access doors at the end of the aisle.

Each chilled-water cooling module contains a chilled water coil, chilled water flow control valve, multiple variable speed fans, DC power supply, instrumentation and controls needed to assure continuous automatic operation. The fans in the cooling module pull hot air from the hot aisle through the chilled water coil and transport the cooler supply air into the cold aisle.

The controls automatically regulate the airflow and chilled water flow rates as needed to achieve the desired operating conditions driven by specific set points. The primary control loop regulates chilled water to maintain the user selected supply air temperature. Additional controls regulate the fan speed as needed to provide airflow necessary to maintain the selected temperature differential across the servers (heat load). Figure 1 show a cooling module used within the hot aisle containment system

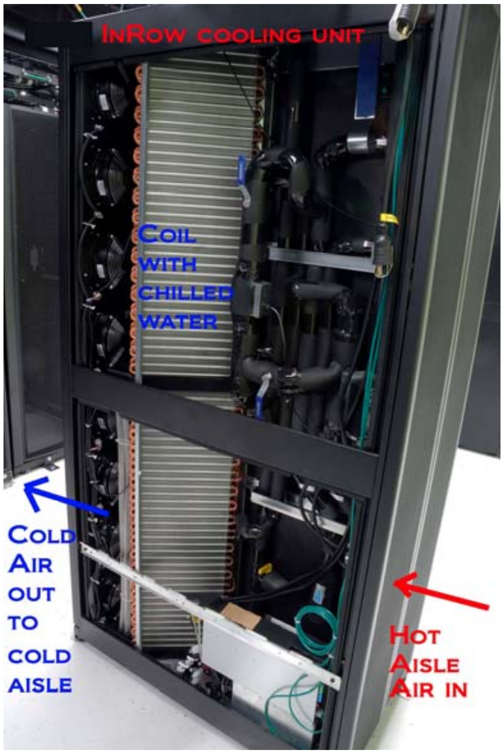

Figure 1. Modular cooling unit

3.2 Server equipment

The IT or heat load in each server rack was provided by 40 standard Sun V20 1U servers, each with a size of 28”x17”x1.75”. Due to data center space availability constraints for the study, and the high capital cost for servers, 240 servers were selected to be stacked in six server racks. As a result, the maximum nominal load per server rack was designed to be 10 kW. The maximum load per server rack tested ranged from 5kW to 10kW based upon the preset inlet air temperature of the cooling modules. Details of the servers provided in this study are publicly available [1].

3.3 Server power management

Using a commercially available software program as the “control program,” the load within each rack was effectively controlled at desired levels by dynamically turning on and off servers and running the program [2] at various CPU loads to achieve the desired power consumption and resulting heat load to test the energy efficiency of the modular cooling system. Prior to the test, reference measurements on each type of server that was being used in the racks were performed to measure idle and loaded power consumption.

To achieve the desired partial or full power load level (kW/rack) to be tested, the number of servers needed to run at 100% load was calculated beforehand using the control program, which turned the rest of the servers off. For example, the number of servers running at full load per rack corresponding to each server load level was calculated as: 10 kW - 33 servers on; 7.5 kW - 25 servers on; 5kW - 17 servers on; 2.5 kW - 9 servers on. A combination of these was used to achieve the desired heat load levels pre-defined in the test plan. Although all of the servers used in the test configuration were the same, the initial reference measurements identified that they had significantly different power consumption due to different memory or computing configurations installed.

In order to achieve and maintain the desired full or partial power load per rack during each test sequence, the monitoring system collected real-time measurements of server power from the rack power strips. At the same time, the control program used this information to turn on or off additional servers as necessary to maintain the desired power load levels throughout the tests.

In order to monitor the inlet air temperature being delivered to the test racks by the modular cooling system, air temperature sensors (probes) were installed at the top, middle and bottom of each rack. To improve the response time of these sensors, the power to the servers installed at these rack elevations were maintained to be constant during each testing sequence. Prior to starting a specific modular cooling system test sequence, the total power consumption at each rack was verified against the readings of the power strip and adjusted as needed until the power consumption was stable.

3.4 Equipment location

Two rows of server racks were positioned at the southwest corner of the data center for this study. They were separated from the rest of the data center by an array of curtains surrounding the six server racks and the two cooling modules. The space within the curtain has a floor area of 110” x 178” and a height of 86”. The in-row cooling modules are designed to draw air from the hot aisle, passing it through the chilled water heat exchanger and directing cold air into the cold aisle, from which cold air is then drawn into the inlet of the servers and passes through the warmer rack before exiting toward the contained hot aisle. The air from the hot aisle then repeats the movement powered by the modular cooling unit.

Figure 2 and Figure 3 show the equipment layout in this study.

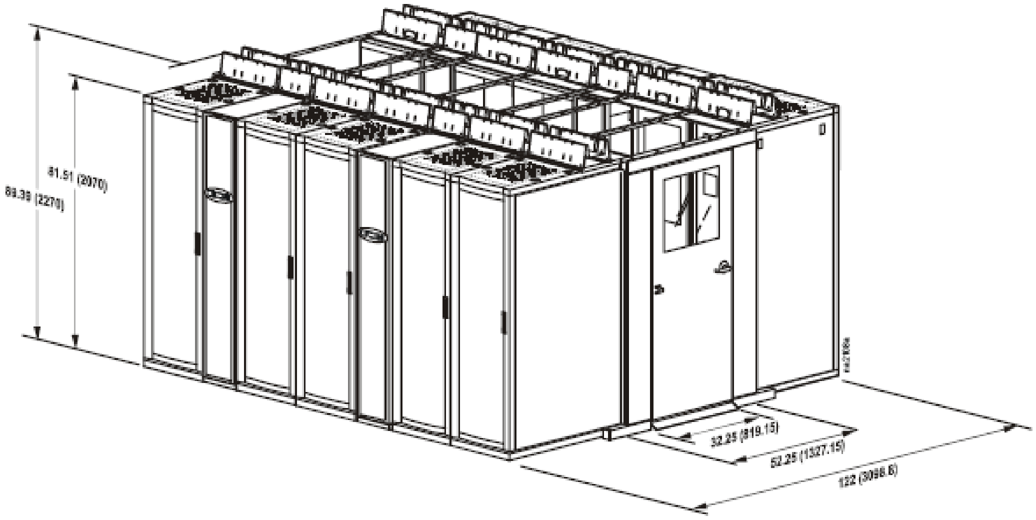

Figure 2 Generic Layout of Equipment

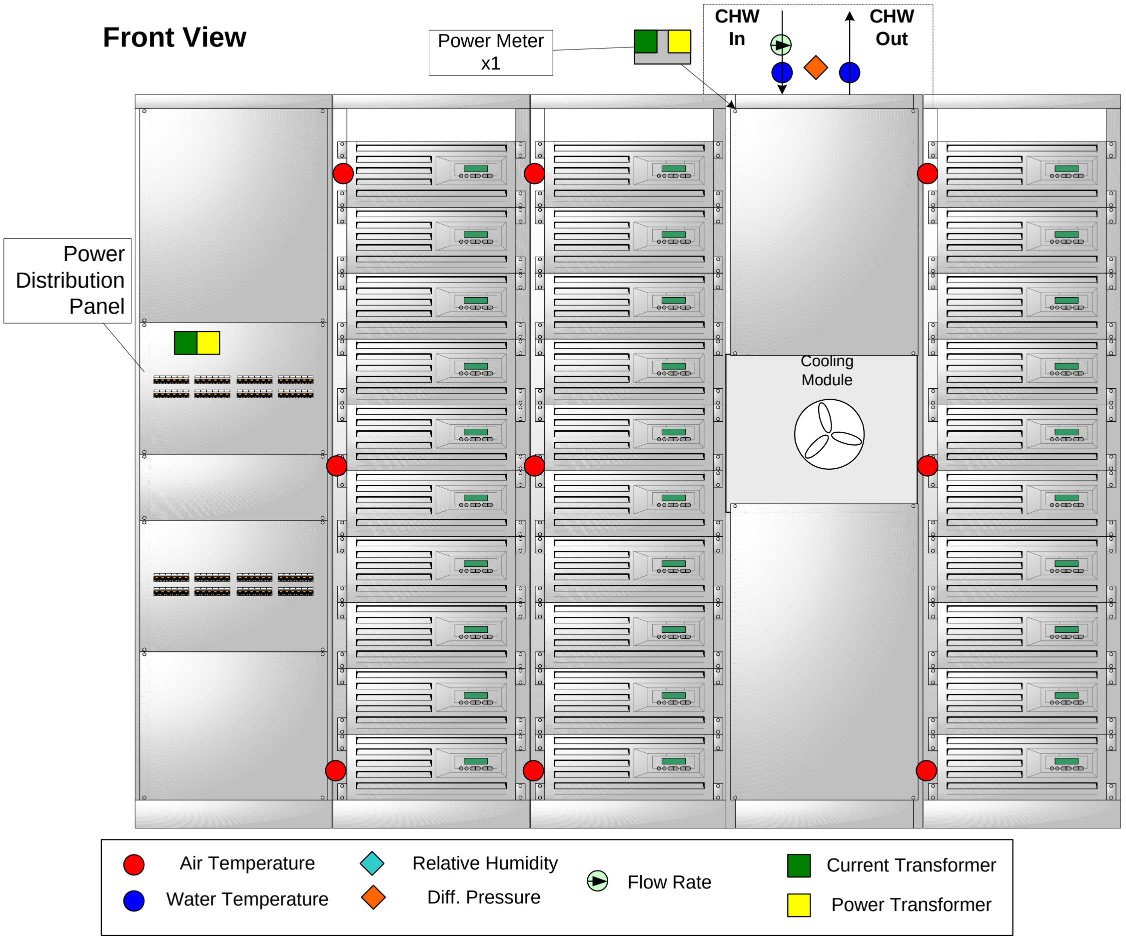

Figure 3 Layout of Equipment – Front View

4 Measured parameters

The following parameters were monitored or measured during the evaluation

- Power demand of servers and cooling modules
    - Actual power demand for servers used in this study.
    - Actual power demand for the cooling modules

      Electric power demand for the pump unit and eight cooling modules was monitored separately.
- Air temperature
    - Cold inlet air temperature to the front of server racks

      There were three temperature sensors (RTDs) installed at the bottom, middle, and top positions (0.65", 37.5", and 69", respectively) at the front inlet of each of the server racks. These heights corresponded to servers 2U, 20U, and 38U, respectively.
    - Hot outlet air temperature from the back of server racks

      There were three temperature sensors (RTDs) installed at the bottom, middle, and top positions (0.65.", 37.5", and 69", respectively) at the rear outlet of for each of the server racks.
    - Data center air temperatures (outside the enclosed test area): from building energy management system
    - Outdoor air temperatures (dry-bulb & relative humidity).
- Cooling module entering and leaving chilled water temperatures

  Chilled water temperatures in the supply and return pipes were measured by installing two temperature sensors on the surface of the water pipes, with insulation material wrapped around.
- Cooling module chilled water flow rates
- Cooling module entering and leaving chilled water pressure differential.

In addition to the real-time measurements taken of the test environment, the following parameters were recorded manually to quantify the power demand in the data center and the energy use of the central chilled water plant: total IT equipment power; total central chilled water plant power; primary chilled water flow and chilled water temperatures (supply and return); chilled water supply/return differential pressure. This data was used to perform an engineering analysis to determine the central chilled water plant energy efficiency to estimate the potential energy savings versus using a conventional raised, CRAH cooling system and the modular, scalable cooling system in this study.

5 Data acquisition system

Data collection for the test environment was performed using a commercially available data acquisition system [3]. Data collection for the central chilled water plant was collected from both the site energy management system and from field measurements taken were continuous monitoring data points were not available. Data points were measured over the duration of the study, gathered from the manufacturer's modular cooling equipment (where available), the Sun servers, the rack power strips, and an array of power meters, flow meters, pressure transducers, and RTD temperature sensors.

Data was gathered by local network appliances via a variety of network and serial communication protocols from the meters, the servers, and various analog sensors through I/O modules. After initial local processing and alarm checking, data was reported to a remote server and stored in a relational database. Similar data points were measured for each rack cooling technology, and stored in a shared relational database at a remote server. The real-time data was available through a web application, allowing users to monitor and manage the study remotely in real time. Access controls ensured that each manufacturer could see only its own data, while the designated host had access to all data.

Two power meters measured the energy use of the entire system and the in-row cooling modules alone. Smart power strips reported current for each rack. RTDs were placed at three heights on each rack, front and back, as well as at the inlet and outlet of the fan units. Ambient temperature and humidity were measured on the cold-aisle. Various internal server temperatures were gathered from selected servers, as reported by the servers themselves. Supply and return chilled water conditions were measured using a flow meter, pressure transducers, and RTDs. The cooling modules themselves also reported water conditions, fan speed, air temperatures, and cooling output power.

6 Test procedures and operating conditions

The supply water temperature to the cooling modules used in this evaluation was the data centers 45°F design chilled water temperature from the central cooling system which was maintained constantly and was continuously monitored.

Selected operating conditions were designed by combining various server loads (25% to 100%) with the full load level indentified by vendor input and are presented in the following table.

Table 1 Set Points for Test Conditions

Inlet air temperature set point (F)	Targeted total server load (kW) for 6 servers racks	Various server loads (kW) per rack			
		100%	75%	50%	25%
68	40	6.7	5.0	3.3	1.7
72	56	9.3	7.0	4.7	2.3
76	60	10.0	7.5	5.0	2.5
80	60	10.0	7.5	5.0	2.5

During the testing, we controlled the server load at a specific load (e.g., full level at100%) for at least an hour or often longer. We then adjusted the air temperatures from cold aisle (i.e., server inlet air temperature) at discrete set points from 80°F down to 68°F, in 4°F steps. Per the vendor's recommendation, we used a 30-minnute duration for the system to reach steady-state operation at each desired inlet air temperature level. In fact, a minimum of 30 minutes up to several hours of operation was observed after adjusting each temperature set point before the actual test conditions and operating performance data were recoded for the evaluation.

Same test procedures and preparation were followed for testing the system performance when the system operated at partial rack power loads, i.e., 75%, 50%, and 25% of the 10 kW/rack capacity, respectively, with each server load level corresponding to various inlet air temperature set points (ranging from 68°F to 80°F).

7 Performance metrics for modular cooling

In order to characterize thermal performance of the module, we used the ratio of cooling provided from the cooling module to the total power demand for the operation of the module (water pump and fan), defined as the "coefficient of performance (COP)." Normally COP of a cooling module is the ratio of the heat removed by the module to the work supplied to the module. The COP is unit less, with a higher value representing higher efficiency for the cooling module. The COP can be calculated under applicable operating conditions (a range determined by inlet air temperature and server load).

In this evaluation, the work supplied is the pump and fan power required to produce the required water and air flow from the cooling module, while the heat removed is equivalent to the cooling provided by the module.

$$COP = \frac{Cooling}{P_{total}}$$

Where Cooling is the cooling provided by the cooling module and P_{total} is defined as the total power demand for all components (e.g., fan, pump) in the two cooling modules in this evaluation. Because there are fans and water pumps in the cooling modules, the total power demand was for the pumping and air-circulation. The cooling module fans and pumps used in this study were 115 VAC, single-phase power.

Total power demand for the cooling modules can be calculated as follows:

$P_{total} = P_{module1} + P_{module2}$

The actual cooling provided by the water-cooling module can be calculated from the secondary-loop chilled water temperature rise and chilled water flow rate, using the following formula:

Where

$$Cooling = \frac{60 \rho Q C_p \Delta T_w}{3412.1}$$

Cooling is the cooling transported by the cooling module, in kW.

ρ: Water density in lb/gal, assuming water density ρ of 8.34 lbm/gal (or 62.4 lbm/ft^3)

Q: Averaged water flow rate measured in gallon per minute

Cp: Specific thermal conductivity of water, 1 BTU/F-lbm

ΔT_w : Measured water temperatures rise, in °F

Therefore, for each cooling module, the cooling can be calculated by the following formula.

$$Cooling = 0.1467 Q\,\Delta T_w$$

Because there were two cooling modules operating at the same time for the six server racks, the total cooling from the modules can be calculated by the following formula:

$$\sum Cooling = 0.1467 \sum_{i=1}^{2} Q_i \Delta T_{w,i}$$

$$COP = \frac{\sum Cooling}{P_{total}} = \frac{0.1467 \sum_{i=1}^{2} Q_i \Delta T_{w,i}}{P_{total}}$$

The portion of chiller pumping power required to deliver the chilled water volume in the primary-loop was ignored for this evaluation.

Another performance metric we calculated is the ratio of total power for the modular cooling units divided by the cooling provided. This is similar to chiller efficiency defined as power demand per cooling produced. Represented in kW per cooling ton, a lower value of this ratio indicates a higher cooling energy efficiency at which the cooling system is performing in terms of delivering cooling needed for rack cooling.

$$MSE = \frac{12000 \mathrm{P_{total}}}{\sum Cooling} = \frac{12000 \mathrm{P_{total}}}{\sum_{i=1}^{2} 60 \rho Q_i C_p \Delta T_{w,i}} = 24 \frac{\mathrm{P_{total}}}{\sum_{i=1}^{2} Q_i \Delta T_{w,i}}$$

where

Module System Efficiency (MSE): ratio of total cooling power to cooling provided, in kW/ton

Q: Averaged water flow rate measured in gallon per minute

ΔT_w : Measured water temperatures rise, in °F

An alternative metric, defined as the module's power utilization index, *PI*, is the ratio of power demand for the cooling system to computer load under selected operating conditions. A higher value of the power index indicates higher cooling energy demand for the cooling system at a given server load.

$$PI = \frac{P_{total}}{P_{server}}$$

Total server load was measured at the PDU supporting the server racks. The three-phase real power demand of the PDU was monitored and was considered to be the total server power load in this evaluation.

8 Summary of findings and conclusions

The measurement and data collection system deployed in this study was reliable and accurate, and provided continuous monitoring of a wide range of critical parameters. It also provided real-time data display during the course of the experimental study. Data analysis was further enabled by writing custom database queries to parse the raw data collected to provide the ability for effective analysis of the large amount of data collected during the testing.

The software program used in the study to measure and monitor the power to the test environment effectively created various load/power consumption scenarios (based on the reference measures) to make sure the necessary power draw was generated and maintained required for all the tests in this study. Each rack was capable of consuming approximately 10 kW and depending on the server load set points, the program was used to set load levels (e.g., 2.5 kW, 5 kW, 7.5 kW, 10 kW or maximum) by turning on/off the necessary amount of servers and by running the server power benchmarking tool at full load.

The overall coverage of operating conditions ranged from 65°F to 80°F for inlet air temperatures, with the server loads ranging from 1.7 kW/rack up to 10.4 kW/rack. The difference between maximum and minimum inlet temperatures ranged from less than 3°F up to 6°F, with the standard deviation ranging from less than 1°F to 2.5°F.

Table 2 also shows the actual results from the tests performed at the facility, including server load, average inlet/outlet air temperatures monitored at three different heights for all six server racks, cooling delivered by the modules, power demand of the cooling modules, and three performance metrics in this study: COP, module system efficiency, and power index.

Table 2 Actual Test Conditions and Results

Server Load per Rack (kW/rack)	Average Inlet Air Temperature (F)	Average Outlet Air Temperature (F)	Cooling from Module 1 (kW)	Cooling from Module 2 (kW)	Total Cooling (kW)	Total Power for Cooling Module (kW)	Total Power for Server (kW)	COP	Modular System Efficiency (kW/ton)	Power Index
10.4	80	113	27.3	26.9	54.2	2.3	62.4	23.1	0.15	0.04
10.4	79	112	28.1	26.3	54.4	2.3	62.4	23.2	0.15	0.04
10.4	77	110	28.3	27.8	56.1	2.3	62.2	24.1	0.15	0.04
9.6	74	105	28.1	26.6	54.7	2.3	57.7	23.5	0.15	0.04
9.6	74	105	27.1	25.2	52.3	2.3	57.4	22.3	0.16	0.04
7.8	76	101	23.5	22.9	46.4	2.3	46.8	19.8	0.18	0.05
7.3	72	94	22.9	22.3	45.2	2.3	43.8	19.4	0.18	0.05
6.9	68	91	23.0	21.9	44.9	2.3	41.3	19.2	0.18	0.06
5.1	74	98	16.5	14.4	30.9	1.1	30.7	28.2	0.13	0.04
4.7	72	95	14.4	12.8	27.2	0.8	28.4	32.2	0.11	0.03
4.5	66	88	17.8	16.4	34.2	1.2	27.0	29.1	0.12	0.04
3.4	67	87	9.8	1.1	10.9	0.5	20.4	22.5	0.16	0.02
2.6	75	98	9.7	7.4	17.1	0.5	15.7	34.5	0.10	0.03
2.6	73	97	10.4	8.0	18.4	0.5	15.6	37.5	0.09	0.03
2.4	69	91	8.6	6.8	15.4	0.5	14.3	31.4	0.11	0.03
1.7	65	87	9.0	6.9	15.9	0.5	10.4	32.5	0.11	0.05

It is clear that different IT equipment operation and environmental operating conditions affected the cooling delivery efficiency of the modular cooling unit. Specifically, variations in server power load and inlet air temperature have resulted in different COP, module cooling efficiency (kW/ton), and power index for modular Cooling System 2.

Generally, total modular cooling power demand was somewhat stable (mostly around 2.3 kW) at higher server loads. The cooling power demand decreased when lower server loads were in operation which is a good characteristic. This is the intended behavior to reduce cooling power with reduced IT power to maintain better PI under lower load conditions.

Under a similar server load, the COP of cooling module 2 tended to be constant at various inlet supply air temperatures, as was the cooling module's cooling kW/ton value. In addition, the PI values seemed to change little under a similar server load with various inlet air temperatures. The COP values of the modular cooling increased with the decrease in server loads – indicating a higher energy efficiency of cooling module's performance in transporting cooling when coping with lower server loads in this study.

Overall, the COP values ranged from 19 up to 38, MSE (kW/ton) values from 0.09 kW/ton up to 0.18 kW/ton, and PI from 0.03 to 0.06. Cooling System 2 exhibited an energy efficiency level better than traditional CRAH units under the selected operating and environmental conditions (combinations of rack power density and inlet air temperature) used in this study.

The dynamic nature of the fan control algorithms within this particular modular cooling system allowed the MSE (kW/ton) values to decrease in response to reductions of IT server loads, with a range from 0.09 kW/ton to 0.18 kW/ton. This power consumption compares favorably against conventional CRAH units that typically have higher kW/Ton values (lower efficiency).

The findings from this study indicate that by implementing in-row modular cooling in lieu of traditional CRAH units, the overall kW/Ton in the data center could be reduced. This type of modular cooling system also provides increased flexibility in data center configuration and layout. Overall, the test results show that this cooling system was generally capable of providing cooling needed to achieve various inlet air temperatures under various server loads pre-defined in the study. Therefore, integration of such modular, scalable cooling systems within the "traditional" data center infrastructures should be to be carefully planned and considered for successful implementation of modular cooling in data centers.

The overall energy demand for cooling server racks in a data center is largely affected by the efficiency of the central cooling system, such as chilled water plant or cooling tower plant. In addition, the overall energy demand will be also be affected, to some extent, by the individual CRAH units or other modular cooling units installed within the data center. In this evaluation, the cooling system was operating at the chilled water temperature of approximately 45°F provided by the central chilled water plant.

It would be useful to understand the cooling effectiveness by coupling modular cooling units with the chilled water plant supplying cooled water of various temperatures. It is recommended the cooling performance and energy efficiency of Cooling System 2 be evaluated when operating with higher supply water temperature up to the vendor's recommended maximum level.

In addition, due to testing constraints, evaluation of cooling performance was not performed for Cooling System 2 at its maximal cooling capacity or operation with elevated chilled water temperatures (i.e., higher than 45F).

This evaluation does not include the assessment of the potential energy savings possible if this cooling system technology was used for the entire data center. Based on the magnitudes of the performance metrics developed and evaluated in this study, it is clear that this modular cooling system can be more efficient than the typical CRAH units widely used in traditional data centers. This being said, however, it would be premature to directly compare this modular cooling system with those of other similar modular, scalable cooling systems because of their differences in actual operation conditions and optimal design loads that could impact actual efficiency outcomes from the tested operation.

In addition, it is recommended that the reader consider not only the energy efficiency performance of the modular scalable cooling system, but also the system's design capability, its effectiveness to control and maintain server inlet air temperature (e.g., within ASHRAE recommended levels), and its potential dependence on other cooling or humidification in the data center.

Finally, in order to quantify or estimate the impact of modular, scalable cooling systems on overall data center energy efficiency, one must also assess their integration with the rest of the data center eco-system, the temperature range of chilled water available from the plant, the local weather conditions where the datacenter is located, and the power density characteristics of the data center.

9 Acknowledgements

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