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ENERGY ANALYSIS OF REAR DOOR HEAT EXCHANGERS IN DATA CENTERS WITH SPATIAL WORKLOAD DISTRIBUTION

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ABSTRACT

Data centers have complex environments that undergo constant changes due to fluctuations in IT load, commissioning and decommissioning of IT equipment, heterogeneous rack architectures and varying environmental conditions. These dynamic factors often pose challenges in effectively provisioning cooling systems, resulting in higher energy consumption. To address this issue, it is crucial to consider data center thermal heterogeneity when allocating workloads and controlling cooling, as it can impact operational efficiency. Computational Fluid Dynamics (CFD) models are used to simulate data center heterogeneity and analyze the impact of two different cooling mechanisms on operational efficiency. This research focuses on comparing the cooling based on facility water for Rear Door Heat Exchanger (RDHx) and conventional Computer Room Air Conditioning (CRAH) systems in two different data center configurations. Efficiency is measured in terms of ΔT across facility water. Higher ΔT will result in efficient operation of chillers. The actual chiller efficiency is not calculated as it would depend on local ambient conditions in which the chiller is operated.

The first data center model represents a typical enterprise-level configuration where all servers and racks have homogeneous IT power. The second model represents a colocation facility where server/rack power configurations are randomly distributed. These models predict temperature variations at different locations based on IT workload and cooling parameters. Traditionally, CRAH configurations are selected based on total IT power consumption, rack power density, and required cooling capacity for the entire data center space. On the other hand, RDHx can be scaled based on individual rack power density, offering localized cooling advantages. Multiple workload distribution scenarios were

simulated for both CRAH and RDHx-based data center models. The results showed that RDHx provides a uniform thermal profile across the data center, irrespective of server/rack power density or workload distribution. This characteristic reduces the risk of over- or under-provisioning racks when using RDHx. Operational efficiency is compared in terms of difference in supply and return temperature of facility water for CRAH and RDHx units based on spatial heat dissipation and workload distribution. RDHx demonstrated excellent cooling capabilities while maintaining a higher ΔT , resulting in reduced cooling energy consumption, operational carbon footprint (?), and water usage.

Keywords: Rear Door Heat Exchanger, hybrid cooling, high density racks, high performance computing, Air cooling

NOMENCLATURE

RDHx	Rear Door Heat Exchanger
CRAH	Computer Room Air Cooling Units
CDU	Coolant Distribution Unit
CHW	Chilled Water
PUE	Power Usage Effectiveness
DC	Data center
OU	Open Unit = 1.89 inches
CFD	Computational Fluid Dynamics
ITE	Information Technology Equipment

1. INTRODUCTION

Data centers are centralized facilities that house networking and computing equipment for remote data storage, distribution, and processing. Data Centers are particularly important for cloud service providers for backing up huge amounts of user data and

keeping critical applications up and running during nominal and peak demand periods.

Data centers are significant energy consumers, and their energy usage has been increasing rapidly in recent years. According to a report by the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE), data centers consumed approximately 2% of the electricity in the United States in 2020[1]. IT equipment, cooling systems, and power distribution infrastructure are the main contributors to energy usage in data centers. IT equipment, including servers, storage devices, and network equipment, is responsible for the largest portion of energy consumption in data centers. The US Department of Energy estimated that IT equipment consumes between 45-55% of the total energy used in data centers [2]. Cooling systems, such as air conditioners, chillers, and computer room air handlers (CRAHs), are vital for maintaining optimal temperatures and ensuring reliable IT equipment operation. The same DOE report suggests that cooling systems account for approximately 25-40% of total energy consumption in data centers. Power distribution infrastructure, such as uninterruptible power supplies (UPS) and power distribution units (PDUs), completes the energy usage picture in data centers [2]

“Air-based cooling systems lose their effectiveness when rack densities exceed 20 kW, at which point, liquid cooling becomes the viable approach.”, Vertiv [3]

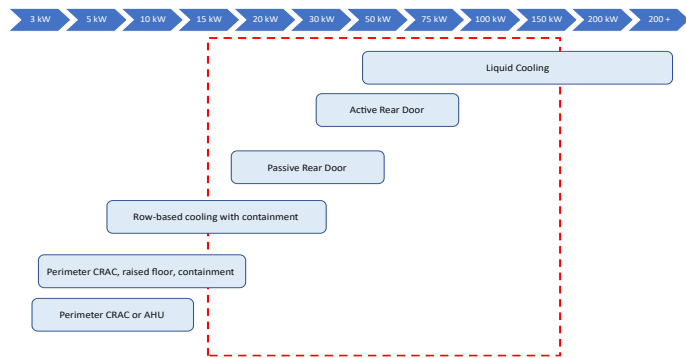


FIGURE 1: Air cooling limits: rack power density [3]

Rear Door Heat eXchangers (RDHx) have emerged as an effective solution for addressing the cooling challenges in data centers. RDHx is a type of liquid cooling system that is installed on the rear doors of server racks to remove heat directly from the IT equipment. This approach offers several advantages, including improved cooling efficiency, reduced energy consumption, and enhanced heat dissipation capabilities. Several studies have investigated the performance and benefits of RDHx in data centers. Conventional methods of air cooling have significant disadvantages in heat dissipation due to high energy consumption at the CRAH units, humidity excursions, recirculation into the cold aisle, extensive site survey effort etc. [4]. Even though there are optimization strategies for air cooling provisioning, there are limitations due to increased demand in high power consuming devices [5]. The growing rate of world-wide servers is 2.5×10^6 annually based on the industry data, and this growth is expected to continue [6]. Also, as per

ASHRAE, heat load per 42U rack shows that rack density is continuously increasing. This makes it difficult for conventional air-cooling methodologies to provision additional capacity [7]. Therefore, there are potential advancements in methods of air cooling; one such method is retrofitting existing data centers with RDHx. Simon et al. [8] studied the feasibility of deploying Rear door heat exchangers in high-capacity data centers, where it is to be noted that passive RDHx will offer significant advantage in cooling, provided, the server fans overcome the Hx pressure drop also in active mode the benefit is substantially more than the CRAH based cooling. Hybrid cooling systems are typically self-contained components like the side car, which is an air-liquid heat exchanger installed on the side of a server cabinet. IBM introduced this enclosed heat exchanger, which is designed to remove up to 35 kW [9]. A fully enclosed server cabinet, which commonly uses a V-shaped heat exchanger on the bottom of the cabinet, is another example of a hybrid cooling system [10]. The RDHx is a heat exchanger located at the back of the cabinet, where hot exhaust air leaves the servers. It was demonstrated in [11] that using an RDHx in various data center configurations can have several advantages, including 1) reducing the number of CRAH units required, 2) eliminate hot spots by removing heat closer to the source, and 3) allowing higher chilled water temperatures while still maintaining IT inlet temperatures within recommended ranges. RDHXs were used in tandem with room level air conditioning in a hybrid manner [12]. The CRAH fan speed was optimized using a control mechanism based on the heat load of the servers. They were able to save 47 kWh of energy, or around 6% of the total energy consumed by the CRAH.

OpEx (Operational Expenditure) analysis and TCO (Total Cost of Ownership) evaluation play crucial roles in understanding the financial aspects of data centers. OpEx analysis involves assessing the ongoing operational expenses associated with running and maintaining a data center, while TCO considers the overall cost incurred for owning the equipment throughout its lifespan.

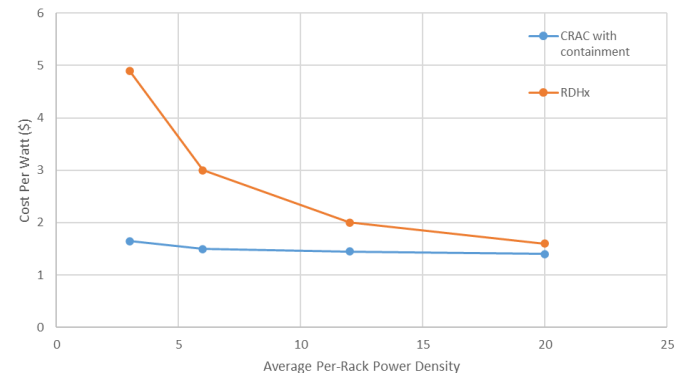


FIGURE 2: Cost of Equipment vs rack power density [13]

OpEx analysis encompasses various cost components, including energy consumption, cooling, maintenance, personnel, and equipment upgrades. It enables data center operators to identify areas of high expenditure and implement strategies for

cost reduction and operational efficiency. Additionally, OpEx analysis provides insights into the financial implications of different operational decisions, such as equipment selection, cooling system optimization, and energy management strategies. Fig. 2 from a whitepaper published by Schneider Electric shows cost per watt consumed by various air-cooling methodologies based on the rack power density. RDHx is cost effective when the rack density increases, and it reduces further beyond 20kW as room-based cooling units become ineffective.

2. COMPUTATIONAL MODEL

6SigmaRoom is a powerful computational fluid dynamics (CFD) software designed specifically for data centers. It offers numerous advantages. Firstly, it provides modeling ability to precisely define control parameters and response curves for fans, pumps, control valves etc. By monitoring airflow, temperature, and pressure distribution within data centers, the CFD tool enables data center operators to optimize energy efficiency by identifying hotspots, temperature gradients, and areas of inefficiency.

The data center model encompasses a room size of 2,447 sq ft with a height of 14.76 ft and a total power capacity of 1.28 MW. The height of the raised floor is 2 ft. It accommodates a total of 8 rows with 10 racks each, in a hot-aisle containment configuration for the CRAH-based DC model. Each rack houses 10 4U servers. A compact model of 4U servers was populated in all the racks with maximum rack power of 16 kW. All the ITEs are provided with power and temperature rise specifications of $10^{\circ}\text{C } \Delta T$. The CFD model includes 8 peripheral Computer Room Air Handling Units (CRAHs) with a net cooling capacity of 200 kW/CRAH. The data center layout is shown in Fig 3.

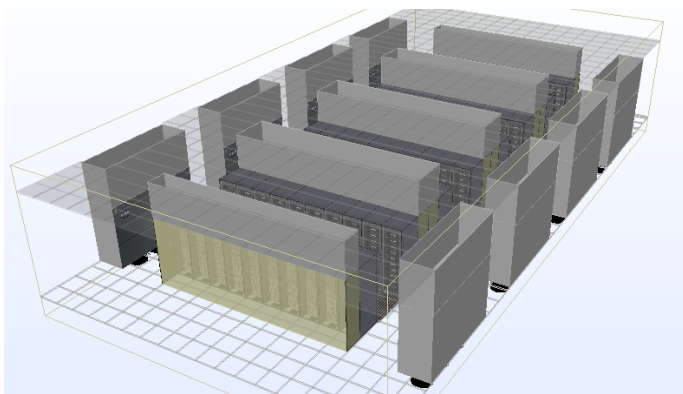


FIGURE 3: Raised floor data center with CRAH units

The CRAH based DC model has hot aisle containment as it minimizes recirculation which is typical in most of the hyperscale data centers. The CRAH units supply cold air through the underfloor plenum to the cold aisle via slotted floor grills in a raised floor configuration. After cooling the IT Equipment, the hot air is contained and ducted to the ceiling where the return air mixes and directed to the return side of the CRAH unit through a ceiling duct as shown in figure 3. Another CFD model has the same data center IT layout and specifications with RDHx attached to all the racks, and no peripheral CRAH units, raised floor or the false ceiling as shown in Fig. 4.

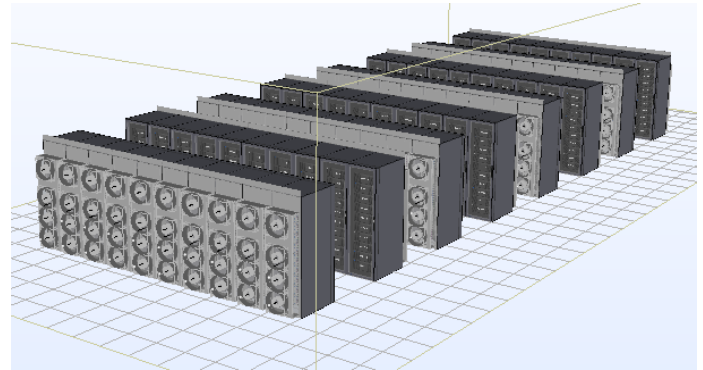


FIGURE 4: Data center with RDHx

2.1 REAR DOOR HEAT EXCHANGER

Rear door heat exchangers are typically built to fit at the rear end of the rack, which is 2 ft wide. A commercially available rear door heat exchanger (68 x 21.3 x 7 in) was chosen to fit at the back of the ORV2 rack (84.8 x 23.6 x 42 in) from the Open Compute Project (OCP). It is typical for an active RDHx to have a specification of 600W of total fan power to move 3,000 cfm of air across the assembly. For our use case, based on the required flow rate across the rack, fans usually run at approximately maximum speed of 80% of the rated speed which results in a much lower power consumption when calculated using fan laws. A typical 5% leakage is assumed to account for gaps in between the servers, mounting rails etc. In idle scenario, the server inlet air temperature would be the same as exit air temperature of the RDHx.

The RDHx typically consists of a heat exchanger unit with fans mounted on the rear side, accessible from aisle. to A control valve modulates the flow of coolant (facility water) through the coil typically depending on the leave air temperature setpoint. The position of the valves depends on the data center layout and the placement of chilled water pipes. They are either located at the top (for overhead piping) or at the bottom (raised floor configuration). The RDHx is connected to the main loop via an isolation valve, which allows for disconnecting the rack from the chilled water loop without disrupting facility operations at large. Fig. 5 shows the schematic of a traditional rack and a rack with RDHx.

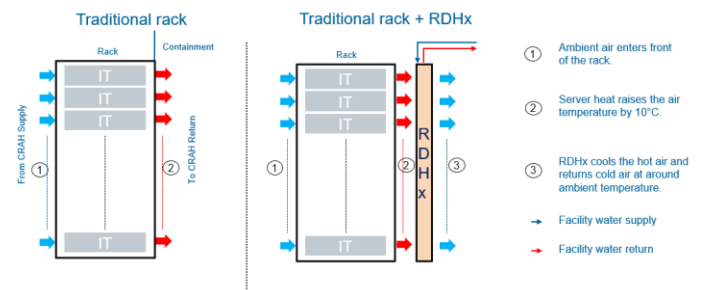


FIGURE 5: RDHx layout

The coolant flow through each of the heat exchangers is modulated by a flow control valve attached to the RDHx unit, based on the downstream air temperature at the heat exchanger.

Depending on the design of the coil, chilled water inlet direction, and variation in face velocity at the inlet of the RDHx, air may be cooled non-uniformly. To counter this, axial fans are placed at the rear of the heat exchanger unit to uniformly pull air from the cabinet. These fans can be controlled based on sensors measuring the inlet temperature at the rack or based on approach air temperature of the heat exchanger.

Although the addition of fans consumes more power, it helps to maintain a pressure-neutral data center environment for the server fans. Apart from distributing the flow uniformly over the coil, it also helps overcome the air-side pressure drop of the heat exchanger. The boundary conditions for the CRAH and RDHx units are shown in Table 1 and 2, respectively.

Table 1: CRAH unit specification and BC

CRAH Specification and Boundary conditions	
Supply CHW Temp	22 °C
Supply Air Temp	29 °C
Max. air flowrate	24,000 cfm
Max. CHW flowrate/CRAH	108 gpm
No. of EC fans	3
Fan power	3.7 kW/fan

Table 2: RDHx unit specification and BC

RDHx Specification and Boundary conditions	
Coolant flow direction	Top to Bottom
Nominal Cooling Capacity	35 kW
Reference coolant flowrate (max.)	23 gpm
Hx Effectiveness	0.8
Reference Air flowrate (max.)	3,000 cfm
Coolant Temperature	22°C
Coolant flowrate	Controlled: Hx exit air temperature (30°C)
No. of fans	4
Fan power (Full speed)	500 W

The CRAH unit air flow rate control was set to pressure-based condition so that the cold aisle is slightly over pressurized compared to hot aisle. It is a common practice to maintain a minimum ΔP of 0.05 in.H₂O across the racks to avoid hot air recirculation. CRAH supply air temperature control was set to 29°C based on the feedback from the sensors at the cold aisle. The coolant (chilled water) temperature was set to 22°C as mentioned in Table 1. CRAH units have individual flow control valves to modulate the coolant flow rate based on the return air temperature. The rest of the coolant bypasses the cooling coil and mixes with the return water from the coil. Coolant flowrate was set to modulate (using the valve) based on the cooling energy demand and maintain the set supply air temperature.

3. Uniform workload distribution (Baseline)

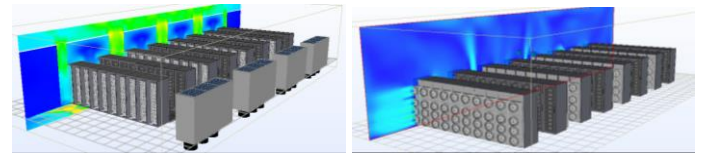
In this case, we considered a typical scenario of uniform workload distribution with similar-performance servers populated throughout the data center. Two different CFD models were created: one for CRAH-based cooling units and another for RDHx-based cooling units. All IT equipments are set to maintain a ΔT of 10-15°C across the racks, based on the rack inlet temperature. The ITE specifications are given in Table 3.

All the IT Equipment power utilization was set to a certain % utilization uniformly throughout the data center space and simulations were performed to observe the ΔT across the cooling coils in the CRAH unit as well as the CRAH unit with the bypass. This would let us know the ΔT across the chiller.

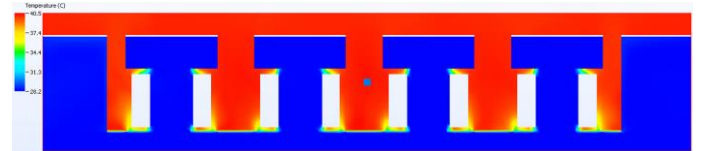
Table 3: ITE Specifications

ITE Utilization	Rack power (W)	Rack air flow required (cfm)
30%	4800	696
65%	10400	1508
100%	16000	2320

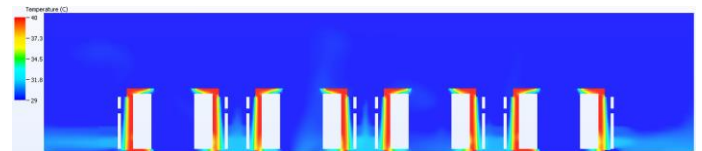
Fig. 6 (a) shows the temperature result plane for both configurations. The figure on the left shows the cold and hot aisle with raised floor and hot air return plenum. Based on the temperature contours for RDHx (right figure), it can be seen that RDHx provides a room neutral solution. The difference between the two set-ups can be prominently noted in Fig. 6 (b) and (c). It shows the temperature profile across the racks for the baseline case. The temperature profile looks similar in all three cases mentioned above since the ΔT across the racks are similar.



(a) Result plane location for CRAH based DC (left) and RDHx based DC (right)



(b) CRAH-based DC Temperature contour



(c) RDHx-based DC Temperature contour

FIGURE 6: Temperature Contours for uniform workload distribution

4. Spatial Workload Distribution

In this case, we considered a typical scenario of workload distribution with similar-performance servers populated

throughout the data center. Two different CFD models were created as mentioned in the previous case. These models were used to compare and observe the effects of spatial workload distribution on thermal profile of the room and operating energy consumption.

Out of 80 racks in the room, 20% of the fully populated racks were randomly selected and set at maximum utilization (100%) with a capacity of 16 kW per rack, while the remaining set of racks were set at idle power (30% of the total rack power). Fig. 7 shows the highlighted racks at 100% utilization with CRAH units. Similarly, another CFD model with the same racks at 100% utilization was modeled with RDHx and no peripheral CRAH units. Simulations were run based on the previously mentioned boundary conditions.

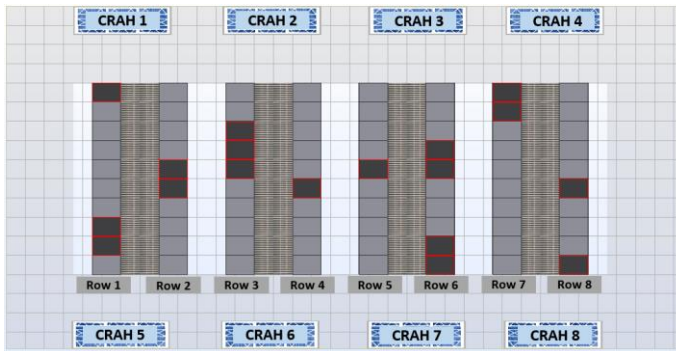
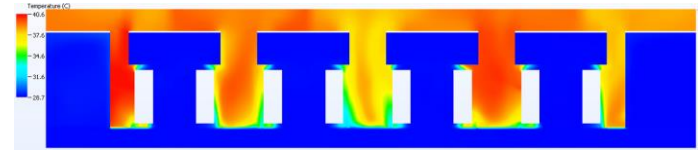


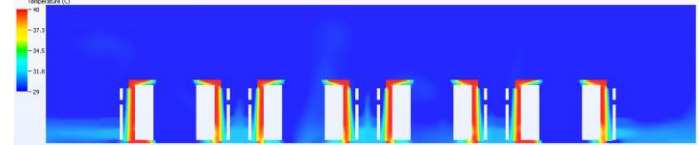
FIGURE 7: Randomly selected racks to mimic spatial workload distribution in data center

The result plane was taken at the same location as shown in previous case (Fig. 6 (a)). It was observed that RDHx delivered a uniform temperature distribution throughout the data center, irrespective of the rack utilization. The CRAH-based data center model had varying CRAH return air temperatures since the hot air from various heat sources at varying velocities mixes in the ceiling before returning to the cooling coils. This might be because of the uneven air flowrate provided by each CRAH unit that works based on sensor-based feedback while the chilled water flowrate remains constant at the facility side. Therefore, chilled water bypasses the cooling coils when there is lower energy demand leading to lower ΔT across the cooling coil and the CRAH unit while maintaining the set supply air temperature. It is a known fact that chiller units work efficiently when the ΔT across the chilled water is higher. When the difference between supply and return chilled water temperature goes below the design value (in this case equivalent to maximum data center capacity of 1.2MW) it results in cooling facility to operate at lower efficiency for majority of the time since data centers rarely operate at design capacity. For most of the data centers, maximum capacity utilized is between 65-70% of the design capacity. During off peak hours, it can lower to 30% of the design capacity. Low ΔT results in chiller consuming more energy resulting in higher Capital Expenditure (CapEx) cost. CRAH based units are observed to have much lower ΔT across the cooling coils compared to rear door heat exchangers. Under low load conditions, the coils in CRAH units can be considered

“oversized” which ultimately results in lower ΔT across facility water. In contrast, the localized cooling control provided by the RDHx results in higher ΔT . It also provides uniform temperature distribution across the data center keeping the inlet temperature of all the racks within a range of 1°C difference. Hotspots caused by high heat rejection and recirculation at the random high utilization racks were eliminated using RDHx.

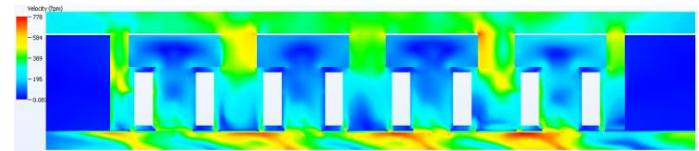


(a) CRAH-based DC

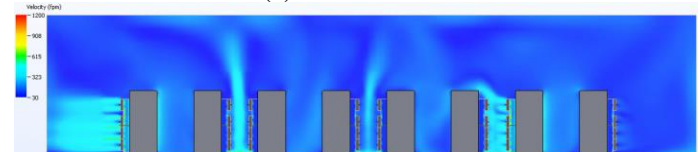


(b) RDHx-based DC

FIGURE 8: Temperature contours for spatial workload distribution



(a) CRAH-based DC



(b) RDHx-based DC

FIGURE 9: Velocity contours for spatial workload distribution

Table 4: CRAH and RDHx-based DC chilled water results

% IT Utilization			CRAH coil ΔT (°C)	Net Facility water ΔT (°C)	Total CRAH coolant flowrate (gpm)	RDHx water ΔT (°C)	RDHx flow rate (gpm)
Uniform workload distribution	30%		5.6	1.8	268.8	8.1	2.0
	65%		5.9	3.4	536.8	8.4	4.7
	100%		7.2	5.7	844.7	8.9	7.5
Spatial workload distribution	18 racks at 100%	62 racks at 30%	5.76	2.84	385.8	8.5	265.2 (Total coolant flow rate)

Based on the data from table 4, the total energy consumed by the RDHx would be lower compared to traditional style of cooling due to several reasons. The chilled water supply temperature for the RDHx is higher compared to the CRAH units, resulting in significant energy savings on the primary side. Additionally, RDHx has rack level flow control device which modulates based on the downstream temperature of the air. This level of sophistication provides localized control of coolant flow rate through the RDHx. The difference in pumping power when all the servers were at idle load compared to Case A was negligible relative to the power consumed by the CRAH units

that were provisioned by chilled water pumps from the facility. Future work would include calculating the annualized energy consumption for a specific location.

Again, similar results in terms of temperature distribution across the data center were observed. RDHx offered an even temperature distribution, and the average room temperature was maintained at or 30°C with an average difference of 1°C tolerance at the rack inlet temperature.

5. CONCLUSION

In this paper, two data center configurations were analyzed using CFD to estimate the operational efficiency of data centers under different scenarios. ΔT between facility return and supply water temperature was compared for a legacy CRAH based cooling system and RDHx based cooling system. RDHx irrespective of operating load conditions can provide consistent higher ΔT resulting in higher operational efficiency. When the ΔT on the facility side is lower than the design, chillers operate less efficiently for more than the 90 percent of the year since the peak load conditions are primarily observed during hot weather conditions (summer). Thus, it would result in chillers consuming more energy or less efficient.

In addition, for typical raised floor-based data centers with peripheral CRAH/CRAC units, it is difficult to manage airflow. As a result, CRAH units will oversupply cold air by about 10-20% of what is required by IT racks. In contrast, RDHx can provide localized thereby modulating airflow and coolant flow rates as per rack demand. In future, authors plan to calculate the annualized energy consumption for chillers based on both technologies for a particular location.

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