REDUCING ENERGY USAGE IN DATA CENTERS THROUGH CONTROL OF ROOM AIR CONDITIONING UNITS

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ABSTRACT

Information Technology data centers consume a large amount of electricity in the US and world-wide. Cooling has been found to contribute about one third of this energy use. The two primary contributors to the data center cooling energy use are the refrigeration chiller and the Computer Room Air Conditioning units (CRACs). There have been recent changes in specifications for the data center environmental envelopes as mandated by ASHRAE (American Society for Heating Refrigeration and Air Conditioning Engineers), one of which specifically pertains to the upper and lower bound of air temperatures at the inlet to servers that are housed in data center rooms. These changes have been put in place in part to address the desire for greater cooling energy efficiency of these facilities. This paper primarily focuses on the methodologies to reduce the energy usage of room air conditioning devices by exploiting these recent changes in standards for the equipment environmental envelope.

A 22000 square foot (6706 m^2) data center with 739 kilo Watt of IT load is used as a representative example for numerical CFD analyses using a commercial software package to demonstrate methodologies to reduce the cooling energy use of Information Technology data centers. Several test case simulations are used to enable the calculation of room level air temperature fields for varying design conditions such as different numbers of operational CRACs or the volumetric air flow rate setting of the CRACs. Computation of cooling energy is carried out using available vendor equipment information. The relationship between the reduction in energy usage in CRAC units and the server inlet air temperatures are quantified and a systematic methodology for CRAC shut off is proposed. The relative magnitude of reduction in data center cooling energy use from shutting off CRACs or reducing CRAC motor speeds is also compared with scenarios involving increases in refrigeration chiller plant water temperature set point.

KEY WORDS: data center, cooling, thermal management, raised floor, energy efficiency.

INTRODUCTION

The expanding nature of computer and internet usage in our society, has driven advances in semiconductor technology, server packaging, and cluster level optimization in Information Technology (IT) products. Not surprisingly, this has an impact on our societal infrastructure with respect to providing the requisite energy to fuel these power hungry machines. A recent report issued by the US Environmental Protection Agency (EPA) entitled "Report to Congress on Server and Data Center Energy Efficiency" [1] emphasized the need to reduce energy usage by IT equipment and supporting infrastructure. Figure 1(a) illustrates the EPA projections regarding IT data center energy usage for the future assuming several different scenarios ranging from “business and usual” to using aggressive measures.

As discussed in [2], these different scenarios represented in figure 1(a) via historical data and projections, were divided into categories according to energy savings: improved operation (20% overall energy savings and 30% savings in infrastructure), best practices (45% overall energy savings and 70% savings in infrastructure) and state-of-the-art (55% overall energy savings and 80% savings in infrastructure). Only the best practices or state-of-the-art scenarios show a reduction in energy use. The improved operation scenario may be a more realistic achievement, which would project the energy usage going up by 36% based on 2006 energy levels. Contrast this to the overall US increase in IT energy use for the same period (2006 to 2011) by a factor of about 1.5 to 2 [3]. Clearly the IT industry will garner increased scrutiny if increases of this magnitude continue.

In addition to the total energy used by IT data centers, as can be clearly seen, the IT data center energy usage can be projected to be rising much faster than the other industrial sectors also tracked in figure 1(b) [4]. Figure 1(b) shows past historic data and forward looking projections for the delivered energy consumption by sector for 1980-2030 in Billion kWh. If the EPA historical trend of IT data center electricity usage continues in the future (doubling ever 5 years) as projected in figure 1(b) through 2030, comparisons will continue to be made on an annual basis to other industries also shown in figure 1(b), and the sense of urgency on what needs to be done will only grow.

DATA CENTER ENERGY USE BREAK DOWN

In a typical data center, sub-ambient refrigerated water leaving the chiller plant evaporator is circulated through the Computer Room Air Conditioning (CRAC) units using building chilled water pumps. This water carries heat away from the raised floor room (that houses the IT equipment) and rejects the heat into the refrigeration chiller evaporator

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via a heat exchanger. The refrigeration chiller operates on a vapor compression cycle and consumes compression work via a compressor. The refrigerant loop rejects the heat into a condenser water loop via another chiller heat exchanger (condenser). A condenser pump circulates water between the chiller condenser and an air cooled cooling tower. The air cooled cooling tower uses forced air movement and water evaporation to extract heat from the condenser water loop and transfer it into the ambient environment. Thus, in this "standard" facility cooling design, the primary energy consumption components are: the server fans, the computer room air conditioning unit (CRAC) blowers, the building chilled water (BCW) pumps, the refrigeration chiller compressors, the condenser water pumps, and the cooling tower blowers.

Figure 2(a) shows the overall electricity usage hierarchy of a data center, figure 2(b) displays the energy consumption breakdown for a typical data center, and figure 2(c) presents a detailed break down of the cooling energy components [5]. In a typical data center, electrical energy is drawn from the main grid (utility lines) to power an Uninterruptible Power Supply (UPS) system, which then provides power to the IT equipment. Electrical power from the main grid is also used to supply power to offices, as well as to power the cooling infrastructure, i.e. for the Computer Room Air-Conditioning units (CRACs), building chilled water pumps, and the refrigeration chiller plant.

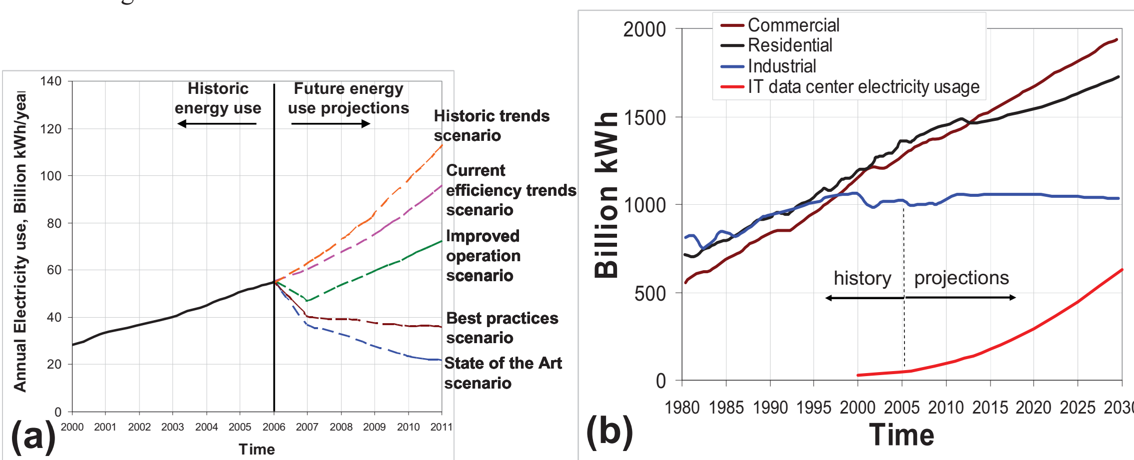
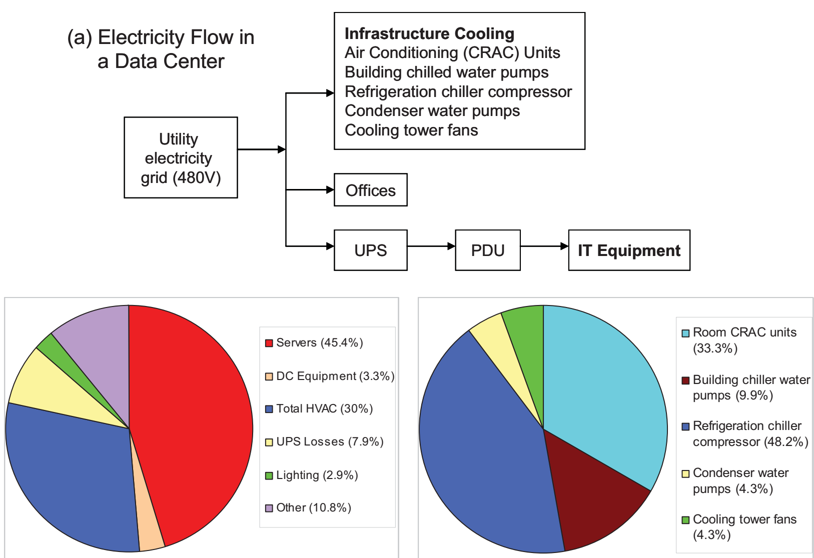


Figure 1: Historical trends and projections in data center energy usage, (a) Environmental Protection Agency projection on IT data center energy usage [1] (b) Data/projections for US delivered electricity consumption by sector (1980-2030 (BkWh) [4]



(b) Typical total data center energy breakdown (c) Typical data center cooling energy breakdown

Figure 2: Typical breakdown of data center energy usage, (a) Electricity usage hierarchy in a data center, (b) Overall break up of energy use components, (c) Detailed break up of the cooling energy components

The IT equipment usually consumes about 45-55% of the total electricity, and total cooling energy consumption is roughly 30-40% of the total energy use. The cooling infrastructure is made up of three elements, the refrigeration chiller plant (including the cooling tower fans and condenser water pumps, in the case of water-cooled condensers), the building chilled water pumps, and the data center floor air-conditioning units (CRACs).

About half the cooling energy used is consumed at the refrigeration chiller plant and about a third is used by the room level air-conditioning units for air movement, making them the two primary contributors to the data center cooling energy use. This paper primarily focuses on the methodologies to reduction of energy usage of room air conditioning devices by exploiting recent changes in standards for the equipment environmental envelope.

RECENT CASE STUDIES BY LAWRENCE BERKELEY NATIONAL LABS

In 2006, Lawrence Berkeley National Labs (LBNL) reported benchmark data collected from more than 20 IT data centers [6]. The study covered a wide range of facility designs and IT equipment. This work led to a subsequent white paper [7] and has been widely cited as a seminal benchmarking study for IT data center energy efficiency. The data collected [6] for values for the ratio of IT power to the total data center power is shown in figure 3(a) with an average reported value of 0.56. The data [6] for the ratio of IT power to the facility Heating Ventilation Air Conditioning (HVAC) cooling power is shown in figure 3(b) with an average value of 1.9 which means that on average, for every 1.9 kW of IT power being used, 1 kW of facility HVAC cooling power was required to cool the IT equipment, i.e. a facility level cooling COP of 1.9. This total HVAC cooling quantity includes the Computer Room Air Conditioning cooling component as well as the refrigeration chiller plant component, the latter being comprised of the refrigeration chiller plant (pumps, compressor, and fans). The same study [6] also reported an average value for the chiller plant energy efficiency performance metric of 0.94 kW/ton, which translates to an average reported [6] chiller plant COP of 3.74. On subtracting the average chiller plant cooling power usage from the average total facility HVAC cooling value from the LBNL data [6], the apparent CRAC cooling component COP can be calculated to be 3.9, which can be assumed to include some degree of CRAC unit over provisioning.

Over provisioning of CRAC units in data center room designs relates to the prevalent practice of providing more CRAC units for a given IT floor that would be necessary purely based on a heat load driven sizing of cooling. An examination of vendor literature [8] for CRAC units reveals COP values to be in the 15.9-22.1 range based on manufacturer data for rated sensible cooling capability and blower motor power rating for nominal fluid conditions. Thus, using the average value from [8] for the CRAC device COP of 18.9, and dividing this value by the observed average CRAC COP value from [6] of 3.9, one can estimate a CRAC over provisioning factor of 4.9 to be embedded in the LBNL data [6]. Thus, in order to improve the cooling energy efficiency of IT data centers, it is extremely important to address the substantial prevalent inefficiencies that exist in the use of the Computer Room Air Conditioning (CRAC) units.

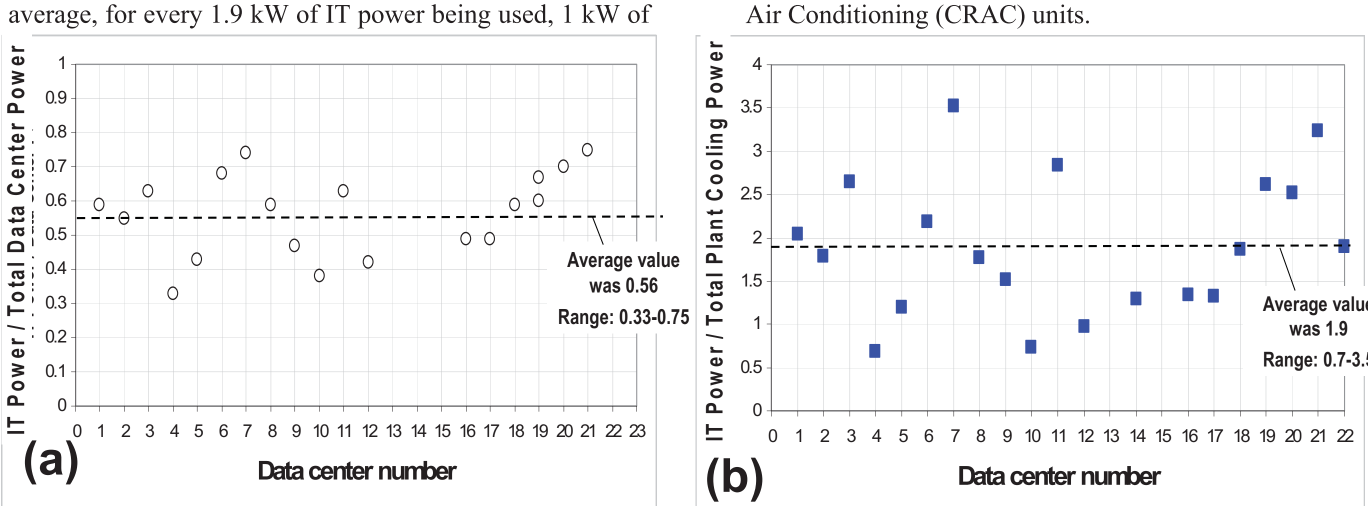


Figure 3: Data from 2007 Lawrence Berkeley National Lab white paper,
(a) Energy Data from LBNL Study [6, 7] - Ratio of IT power to total data center power,
(b) Energy Data from LBNL Study [6, 7] - Ratio of IT power to total cooling power

RECENT CHANGES IN ASHRAE DATA CENTER ENVIRONMENTAL SPECS

Before any case studies can be outlined it is important to state the criteria one would use to establish the operational health of a data center both in normal mode and in a failure mode. The two criteria are stated explicitly in the ASHRAE thermal guideline book [9] and both of these criteria refer to the inlet air conditions to the IT equipment:

1) For ASHRAE class 1 environment the allowable temperature specification is 59 to 90 ^{o}F (15 - 32 ^{o}C). The allowable envelope represents the boundaries where IT manufacturers test their equipment in order to verify that the equipment will function within those limits. This is not a statement of reliability but one of functionality of the IT equipment. For short periods of time it is acceptable to operate at or near the extremes of the allowable envelope.

2) For ASHRAE classes 1 and 2 the recommended temperature specification is 64 to 81 ^{o}F (18 - 27 ^{o}C). This is a new guideline developed by the ASHRAE TC9.9 committee) during normal operation (see Table 1 below).

Table 1: ASHRAE Recommended Environmental Envelope for Class 1 Environments

	2004 Version	2008 Version
Low End Temperature	20 C(68 F)	18 C(64,4 F)
High End Temperature	25 C(77 F)	27 C(80.6 F)
Low End Moisture	40 % RH	5.5 C DP(41.9 F)
High End Moisture	55 % RH	60% RH & 15 C DP(59 F)

The recommended envelope is a statement on reliability. For extended periods of time, the IT manufacturers recommend that data center operators maintain their environment within the recommended envelope.

DATA CENTER MODELING CASE STUDY

Figure 4 shows a numerical model of a 22000 square foot (6706 m^2) data center with a total IT equipment load of 739 kW (thus yielding a heat flux of about 34 W/ft^2) which is used in this paper as a representative example to demonstrate various methodologies. The model shown in Fig. 4 has been constructed using a commercially available software package called Tileflow [10]. The commercial code employs the standard k-ε turbulence model which has been the model of choice by a large number of data center operators, designers and researchers.

The raised floor region is 140' by 160' (42.7 m x 48.8 m) with a ceiling height of 10' (3.048 m) and an under floor plenum that is 18" (0.457 m) deep. This room is organized on a grid made up of 2' x 2' square tiles which can be seen Fig. 4. This IBM data center located in Poughkeepsie, New York, houses 213 IT racks as well as other equipment such as Uninterruptible Power Supplies UPS). The cooling is provided by 23 CRAC units located along the periphery of the room as seen in figure 4, supplying a total volumetric air flow rate of 248400 cfm (117.23 m^3/s). These CRAC units draw in heated air from the IT equipment with powerful blowers and then force this air first through an air-to-liquid heat exchanger coil and then into a under floor plenum which acts as the chilled air supply plenum that exists under the raised floor on which the rack reside. The CRAC discharge temperature for all the modeling discussed in this study is set at 55 ^{o}F (12.8 ^{o}C). In reality there will be a small variation in the discharge temperature of a specific CRAC based on its' suction air temperature and its air flow rate. However, the impact of these parameters on the discharge temperature is very small and is not directly relevant to the methodologies discussed herein. This raised floor shown in figure 4 has 256 perforated tiles which vent the cool air into the room as specific locations that are desirably in front of racks. In the image shown in figure 4, two sides of the data center floor are denoted as sides A and B, respectively. This has been done to allow the reader to related subsequent plan view air temperature contours to this perspective view shown in figure 4.

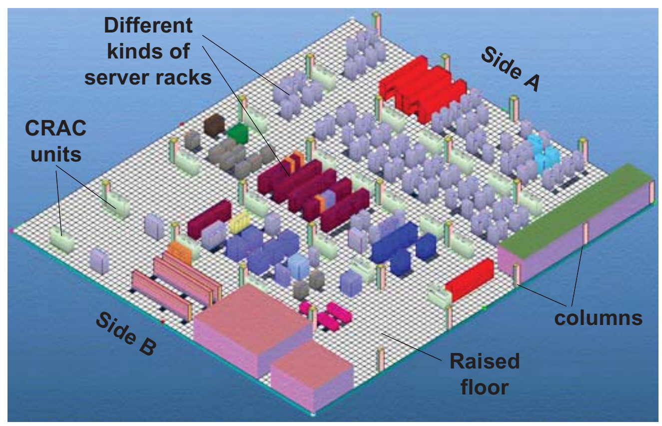


Figure 4: Model of IBM data center utilized for modeling study in this paper

The layout of the IT equipment is anything but an idealized hot aisle – cold aisle arrangement which is so widely studied in the literature. While there are some instances of a hot aisle – cold aisle layout in the data center illustrated in figure 4 there are also a large number of exceptions to such a "best practice". Such exceptions are in fact very common in data centers which often have racks housed in a variety of arrangements with the resulting floor layout being one which constantly evolves with the influx and removal of IT equipment and with temporary changes enforced by data center managers. Thus, the resulting layout often looks like the one shown in figure 4 where in some cases there are no perforated tiles in front of racks, gaps exist on either sides of racks which can yield complex air flow patterns, and large regions of white space where no IT equipment are being housed.

METHODOLOGY TO SYSTEMATICALLY TURN OFF CRAC UNITS

Obviously the simplest way to reduce CRAC energy usage is to turn off the ones that might not be needed, as indicated by the prevalence of over provisioning exposed by the LBNL case studies [6, 7] that have been previously discussed in detail via Figs. 3(a) and 3(b). This action of turning off CRAC units can also be used to exploit the increase in the ASHRAE recommended [9] server inlet air temperature specification of 27 °C that is shown in Table 1. However, the turning off of CRAC units must be done in a way so as to ensure cooling of IT equipment. This section proposes a systematic methodology to perform such actions and demonstrates the process by means of a modeling study.

Thermal Characterization of the Baseline Case (all CRACs are on)

Figure 5 shows air temperature contours for the model depicted in figure 4. Also shown in figure 5 are the CRAC numbers for the 23 CRACs which are the focus of this study. The average flow for the 256 perforated tiles was 897 cfm (0.423 m^3/s) with maximum and minimum values of 1331 cfm (0.628 m^3/s) and 94 cfm (0.044 m^3/s), respectively. The average under floor plenum pressure was 0.0314" of water (7.8 Pa).

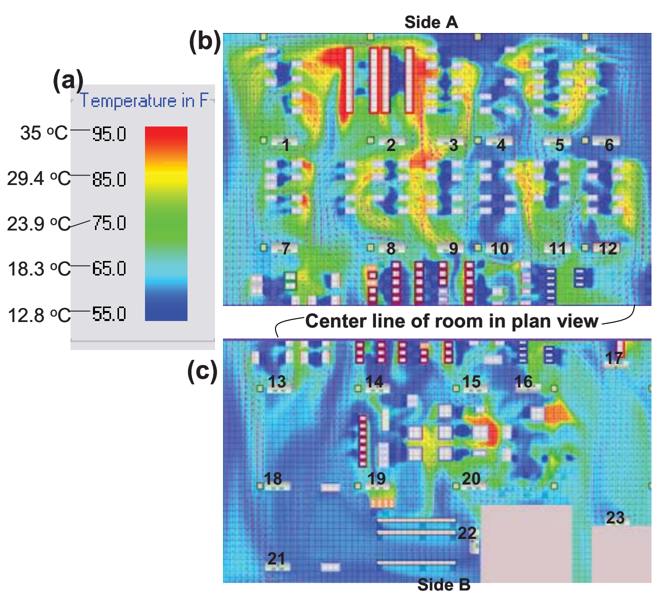


Figure 5: Model temperature contours for IBM data center utilized for study in this paper, (a) Temperature legend, (b) Top half of plan view, (c) Bottom half of plan view

As seen in figure 5, there are hot and cold regions in the data center. Firstly, there are floor areas around specific CRAC units or between CRACs that are either hot or cold. For example the regions near CRACs 1-3 and 7-9 contain hot spots and are relatively warm. Similarly, the regions near CRACs 13, 14, 18, 19, and 21 are relatively cool. The second level of visually discernable thermal gradients are those between the fronts and rears of racks with the inlet being relatively cool and the exhaust regions warm. For example in the regions between CRACs 2-4 and 8-9 the racks are arranged in a hot aisle – cold aisle layout as are the racks in the regions between CRACs 8-10 and 14-16. While images such as those seen in figure 5 help guide a data center engineer in identifying regions of high and low heat load there is a need for a simple systematic methodology to help turn off the underutilized CRAC units.

Maximum Rack Inlet Temperatures (baseline case)

Table 2 provide detailed thermal information relating to the server racks. The distribution of the air temperature at the inlet to the racks is reported in Table 2 for all the 213 racks. The data is collected at the center of the top third of the rack. While this rack inlet air temperature data used in this study is numerical, such information can be readily collected by a person walking around the data center with a handheld temperature meter and recording the temperatures measured.. The objective of the methodology described and demonstrated in this section is to use the easily collected rack inlet air temperature information in conjunction with CRAC manufacturer catalogue data to systematically shut off CRAC units.

As can be seen from Table 2, a disproportionate number of racks (58%) have extremely cool air at their inlets and only 1 rack has an inlet air temperature that is marginally greater than the new ASHRAE recommended limit of 27 °C (for long term operation) that is discussed earlier in this paper. The focus of this paper is to numerically demonstrate simple methodologies that can shift the distribution of rack air inlet temperatures closer to the new ASHRAE limit of 27 °C through either turning off CRAC units (this section) or through reducing the volumetric air flow rate of all the CRACs using motor speed control (next section).

Table 2: Model results for server inlet air temperature at the top of the rack

Temps, C	Frequency
27.1-30	1
24.1-27	0
21.1-24	4
18.1-21	21
15.1-18	64
12.1-15	123

Average = 15.2°C
Maximum = 27.6 °C

CRAC Cooling Performance Calculations (baseline case)

Table 3 shows several input and calculated parameters with the ultimate objective of evaluating how close a specific CRAC unit is performing relative to its manufacturer rated cooling capability [8]. The first column in Table 3 lists the CRAC number (as seen in figure 4 while the second and third columns report the inlet (warm) and discharge (cool) air temperatures using the numerical results. As discussed previously in the context of rack air inlet temperature data, the CRAC air inlet and discharge temperature could also have just as easily have been collected using a person using a hand held temperature meter.

Table 3 Model results for CRAC utilization for IBM data center

CRAC No.	CRAC Return, C	CRAC Supply, C	Manufacturer Rated CRAC Flow, cfm	Calculated CRAC Cooling, kW	Manufacturer Rated CRAC Cooling	CRAC Utilization Metric
1	18.9	12.8	12400.0	42.8	81.8	0.5
2	17.5	12.8	12400.0	32.8	81.8	0.4
3	18.3	12.8	12400.0	38.2	81.8	0.5
4	16.9	12.8	12400.0	28.5	81.8	0.3
5	17.7	12.8	12400.0	34.3	81.8	0.4
6	15.1	12.8	12400.0	15.8	81.8	0.2
7	16.8	12.8	12400.0	28.2	81.8	0.3
8	16.1	12.8	12400.0	23.1	81.8	0.3
9	16.1	12.8	12400.0	22.8	81.8	0.3
10	15.4	12.8	12400.0	18.5	81.8	0.2
11	17.2	12.8	12400.0	30.5	81.8	0.4
12	17.9	12.8	12400.0	35.5	81.8	0.4
13	21.3	12.8	12400.0	59.4	81.8	0.7
14	19.4	12.8	12400.0	46.3	81.8	0.6
15	22.8	12.8	12400.0	69.8	81.8	0.9
16	20.3	12.8	12400.0	52.5	81.8	0.6
17	19.3	12.8	12400.0	45.1	81.8	0.6
18	15.4	12.8	12400.0	18.5	81.8	0.2
19	20.7	12.8	12400.0	55.2	81.8	0.7
20	16.1	12.8	12400.0	22.8	81.8	0.3
21	18.6	12.8	12400.0	40.1	81.8	0.5
22	16.3	12.8	12400.0	24.7	81.8	0.3
23	18.2	12.8	12400.0	37.4	81.8	0.5

These CRAC inlet and exit air temperatures are used in conjunction with the manufacturer rated maximum air flow rate shown in the fourth column used to calculate the CRAC cooling performance in kW (column 5). While the CRAC cooling is calculated using the vendor rated information the actual model input for the CRAC flow rate is actually less, i.e. 87% of the maximum value from vendor data. The reason for this is that in reality due to the additional resistance posed by the air travel through the under floor plenum and the perforated tiles, the actual CRAC flow will always be slightly less than the rated flow. The rated CRAC flow provided by the vendor only considers the device flow impedance i.e. that from the air filters, the heat exchanger coil, and the various expansion and contraction losses within the CRAC. Thus, the 10800 cfm used as an input in the CFD model is assumed to be a conservative estimate for the "true" CRAC flow while for the simple calculations, the user of this methodology would use available information via vendor data. The reason for this approximation is that it is very difficult to get good measurements of the CRAC air flow rate inside data centers. The CRAC units are often about 6' tall with the ceiling being at 9-10', thus leaving only 3' to insert an air measurement device. Often a commercially available air flow hood (balometer) designed for air flow measurement through a perforated tile is used for this measurement with some modification to allow it to fit inside the 3-4' space. Since this flow hood is typically 2'x2' in cross-section (same as a tile), to collect data for air flow rate over a larger surface area (typically ~ 30 ft^2 for a CRAC) several flow measurements are required to arrive at some estimate for CRAC air flow rate. This results in a tedious time consuming and labor intensive process. One drawback with such measurements is that they force the air flow to be normal inside the flow measurement device thus possibly altering the air flow patterns over CRACs. Thus, the use of a CRAC air flow rate provided by the vendor would greatly expedite the process. It should be noted that the use of a higher vendor value for CRAC flow results in a total CRAC cooling value that is larger (822.9 kW) than the actual true value (739 kW). This artifact yields a conservative element to the methodology discussed herein.

CRAC Utilization Metric Calculations (baseline case)

Once the cooling performance of all the CRAC units have been estimated using air temperature information and CRAC vendor data [8] for rated flow, the calculated cooling is compared to the vendor rated value (column 6). This vendor rated value [8] used is for a conservative operating condition and can be user defined. For this paper this vendor rated CRAC cooling value is used for 72 ^{o}F (22.22 ^{o}C) and 45% RH. The ratio of the calculated CRAC cooling to the vendor rated value is shown in column 7 of Table 3 and is denoted at the "CRAC Utilization Metric". Values for this metric close to 1.0 are of course desirable since that means that the CRAC is performing commensurate to the original data center floor design. A low value means that the CRAC is under utilized and could be considered for possibly be turned off.

The ratio of the total rated CRAC cooling (1881.4 kW for air inlet of 72 ^{o}F/45% RH) and the total calculated CRAC cooling (822.9 kW) is also the Over Provisioning Factor (OPF) that was discussed in great detail previously in this paper in the context of the LBNL case studies [6, 7]. For the data center case described via figure 5 and Tables 2-3, this OPF was 2.29. Since a value that is much greater than 1 indicates an inefficient data center, the goal of this methodology is to reduce the OPF via CRAC shut off, thus realizing energy savings from elimination of some CRAC blower power. For this study the target OPF is assumed to be 1.35 which is another input to the methodology that can be user defined. Thus, a certain number of CRAC units are desirably shut off in order to change the OPF from the existing value of 2.29 to a target value of 1.35. The difference in the OPF between the existing (2.29) and the target value (1.35) can be multiplied by the total calculated CRAC cooling to yield the total amount of rated CRAC cooling capacity that needs to be shut off. In this case, this operation results from the product of 0.94 (= 2.29 - 1.35) and 822.9 kW (sum of column 5 in Table 3) and yields a value of 770.5 kW. Thus, CRACs need to be shut off until the sum of the rated cooling capacity of all those shut off equal 770.5 kW.

Identification CRACs To Be Shut Off

Table 4 shows a part of the same information also provided in Table 3, but with the CRACs reordered in an ascending order of CRAC Utilization Metric values. Thus, the first few CRACs in Table 4 have low utilization values and vice versa. As seen in Table 4, the top 9 CRAC units numbered 6, 10, 18, 9, 20, 8, 22, 7, and 4 are identified as those underperforming units that can be shut off to reduce the OVP from an inefficient existing value of 2.29 to an efficient target value of 1.35. Returning to air temperature contour plot shown in figure 5, while these CRACs are in relatively cool regions, they could not have been easily identified visually as the underperforming CRAC units. It should be reemphasized that the user inputs for CRAC rated cooling (by choosing a specific condition) and the target OPF will determine how many CRAC units are chosen for shut off.

Tables 4: Tabulation of CRAC information after reordering of CRACs in ascending order of utilization metric

CRAC No.	Utilization	Cooling, kW	Rated, kW	
6	0.18	15.8	81.8	
10	0.21	18.5	81.8	163.6
18	0.21	18.5	81.8	245.4
9	0.25	22.8	81.8	327.2
20	0.25	22.8	81.8	409
8	0.26	23.1	81.8	490.8
22	0.28	24.7	81.8	572.6
7	0.31	28.2	81.8	654.4
4	0.32	28.5	81.8	736.2
11	0.34	30.5	81.8	818
2	0.37	32.8	81.8	
5	0.38	34.3	81.8	
12	0.40	35.5	81.8	
23	0.42	37.4	81.8	
3	0.43	38.2	81.8	
21	0.45	40.1	81.8	
1	0.48	42.8	81.8	
17	0.50	45.1	81.8	
14	0.52	46.3	81.8	
16	0.59	52.5	81.8	
19	0.62	55.2	81.8	
13	0.66	59.4	81.8	
15	0.78	69.8	81.8	

CRACs that should be shut off to achieve target Over Provisioning Factor

Figure 6 shows the perspective view of the data center model with the selected CRAC units highlighted using colored circles that are green, pink, or blue. There are of course a total of 9 CRAC units that were identified in Table 4, but they are grouped in three distinctly colored sub-groups of three CRACs each. The rationale for the three sub-groups is that one might not want to shut off all the CRACs in a single step and that one would want choose sub-groups such that the CRACs in each sub-group are spatially remote. The grouping depicted in figure 6 demonstrates this methodology.

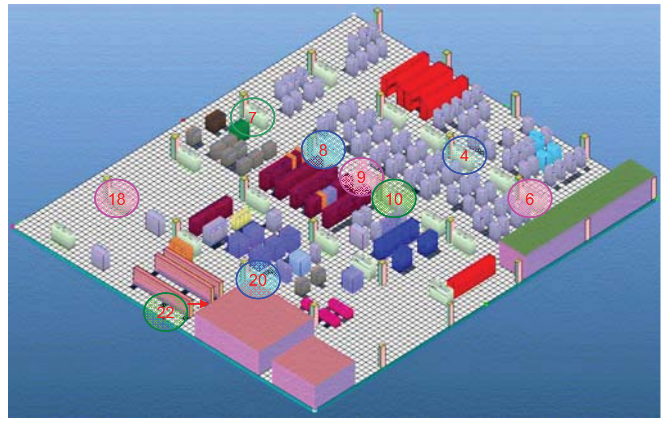


Figure 6: Identification and grouping of poorly utilized CRAC units on layout

Thermal Characterization and Energy Savings After CRACs Are Shut Off

Table 5 provides model results for the rack air inlet temperatures for the base line case described previously as well as for three additional CRACs shut off cases. The three additional cases relate to the three CRAC sub-groups identified in figure 5: (i) the green CRAC are turned off, (ii) the green and pink CRACs are turned off, and (iii) the green, pink, and blue CRACs are turned off.

Tables 5(b), 5(c) and 5(d) display model results for the top of rack inlet temperature for the three cases of CRAC shut off, namely, 3, 6, and 9 CRACs shut off, which correspond to energy savings of 13% (16.8 kW), 26% (33.5 kW), and 39% (50.3 kW), respectively. The CRAC power use at the maximum air flow setting which is typical in data centers is assumed to be 5.59 kW per the vendor data [8]. While the average of the top of rack air inlet temperatures was 15.2 ^{o}C for the base line case with all the CRACs operational, the shut off of 3, 6, and 9 CRACs resulted in an increase in the average top of rack air inlet temperatures of 0.4 ^{o}C, 1.3 ^{o}C, and 3 ^{o}C for CRAC energy usage reductions of 13%, 26%, and 39%, respectively.

While the increase in the average of the top of rack air inlet temperatures was rather small, the maximum of top of rack inlet temperature did increase from 27.6 ^{o}C to 35.1 ^{o}C when all the 9 CRACs were shut off. While 35.1 ^{o}C is indeed unacceptable, very minor changes to the positioning of the perforated tiles reduced this value to 31.2 ^{o}C. In real world data centers, there always exist some racks even in significantly over provisioned data centers which are much hotter at their inlets than the average rack. This is due to some of the observations discussed earlier in this paper related to the sub-optimal nature of actual data center layouts (divergence from hot-aisle cold aisle layout, gaps between and inside racks, prevalence of leakage flow).

Table 5: Model results after progressive CRAC shut down by sub-group - Rack inlet air temperatures at the top of the rack

(a) Rack temperatures after Initial Step 0

Temps, C	Frequency
27.1-30	1
24.1-27	0
21.1-24	4
18.1-21	21
15.1-18	64
12.1-15	123

Average = 15.2°C
Maximum = 27.6 °C

No CRAC power savings
Total CRAC power = 128.6 kW
{23 x 5.59 = 128.6 kW}

(b) Rack temperatures after sub-group 1 CRACs are turned off

Temps, C	Frequency
27.1-30	1
24.1-27	4
21.1-24	4
18.1-21	32
15.1-18	59
12.1-15	113

Average = 15.6 °C
Maximum = 27.8°C

13% CRAC power savings
Total CRAC power = 111.7 kW
Savings = 3 x 5.59 = 16.8 kW

(b) Rack temperatures after sub-groups 1 & 2 CRACs are turned off

Temps, C	Frequency
27.1-30	1
24.1-27	3
21.1-24	22
18.1-21	33
15.1-18	57
12.1-15	97

Average = 16.5 °C
Maximum = 29.5 °C

26% CRAC savings
Total CRAC power = 95.1 kW
Savings = 6 x 5.59 = 33.5 kW

(c) Rack temperatures after sub-groups 1,2, & 3 CRACs are turned off

Temps, C	Frequency
33-36.1	1
30.1-33	0
27.1-30	6
24.1-27	25
21.1-24	29
18.1-21	29
15.1-18	51
12.1-15	72

Average = 18.2 °C
Maximum = 35.1 °C

39% CRAC savings
Total CRAC power = 78.3 kW
Savings = 9 x 5.59 = 50.3 kW

It is anticipated that use of the methodology described in this paper will always be supplemented by additional best practices measures such as the use of blanking panels between and inside racks to mitigate hot air recirculation, increase in the number of perforated tiles in front of high power racks, and the reduction of leakage flow through undesirable openings including cable cut outs.

USE OF VARIABLE CRAC AIR FLOW USING MOTOR SPEED CONTROL

While shutting off a CRAC is certainly one simple and straightforward approach to reducing the data center room cooling energy usage, there are other options. One such method is the use of CRAC blower motor speed control using Variable Frequency Drive technology to vary the CRAC volumetric air flow rate and also their motor power consumption. This underlying concept is not new to fluid moving devices such as fans, blowers, and pumps. This approach is used extensively in server nodes to increase or decrease the revolutions per minute (rpm) of fans or blowers that provide air cooling for heat sinks attached to processor chips. However, the technology has not been widely adopted in existing data centers with CRAC units. One reason for this is cost and effort to retrofit the large number of existing CRAC units in legacy facilities. Another reason is the perception that changing CRAC speeds will result in undesirable and unforeseen flow interaction in the under floor plenum and lead to unpredictable air flow rates through the perforated tiles. This section aims to quantify the energy reduction from ramping down the CRAC flow in over provisioned data centers in the context of rack air inlet air temperatures.

Literature Review

There have been some recent papers in the literature that discuss the manipulation of CRAC air flow rates using motor speed control. Boucher et al. [11] and Bash et al. [12] both describe real time dynamic motor speed control of CRAC units using a distributed sensor network for real time temperature measurement at the inlet to the server racks. These methodologies [11, 12] result in manipulation of individual CRAC air flow based on the air temperatures of the IT equipment that have been determined via some form of calibration process influenced by performance parameters of specific CRAC units. Both papers [11, 12] focus primarily on the control architecture and the algorithms. Boucher et al. [11] gathered experimental data on a 19 rack data center cell with 2 CRAC units that was visually estimated by the authors to be about 728 ft^2 (67.6 m^2) by examining the layout figure in [11]. Bash et al. [12] performed experiments on a 2500 ft^2 (230 m^2) data center with 76 racks arranged in a hot aisle-cold aisle layout with 6 CRAC units providing the cooling. They [12] reported a 58% savings through individual CRAC flow control and 49% savings using uniform control of all CRAC units. Patterson et al. [13] use a modeling study to propose a control scheme to manipulate both the CRAC flow and the chilled air temperature discharged from the CRAC units. Their analyses [13] highlighted the difficulties in implementing a control scheme for CRAC flow control using server inlet temperatures due to the wide distribution of rack inlet air temperatures.

This current analyses pertaining to CRAC flow control adds to the existing literature in two ways: (i) it relates the increases in rack inlet temperatures from the reduction in

CRAC air flow back to the energy savings realized in the context of the ASHRAE temperature specification, and (ii) it compares this motor speed control approach with the simpler CRAC shut off method, and both these analyses are performed for a relatively disorganized real world data center layout that is based on an existing facility and with vendor obtained CRAC data.

Relationship Between CRAC Flow and CRAC Power Use

Figure 7 shows a typical curve for a commercially available CRAC unit manufactured by the same vendor as the devices shown in figure 4 [14]. The data was derived using two obvious known operating conditions, namely, no (0%) power savings for no (0%) flow reduction and 100% power savings for 100% flow reduction (CRAC shut off). In addition to these data, two operating points on the CRAC flow impedance curve were chosen for two different blower rpm settings and the blower power data for these two operating points were identified using the blower data sheet. The cubic relationship apparent in figure 7 is nothing new to those familiar with fan theory. However, figure 7 does highlight the dramatic power savings realizable through even modest reductions in the CRAC flow using motor speed control to ramp down the blower rpm. CRAC flow reductions of 10%, 20%, 30%, and 40% yield CRAC power reductions of 23.1%, 42.7%, 59.1%, and 72.4%, respectively. For the data center studied in this paper and depicted in figure 4 and when CRAC flow control is implemented across all CRACs, energy savings of 29.6 kW, 54.9 kW, 75.9 kW, and 93.1 kW are achieved for the four conditions mentioned above.

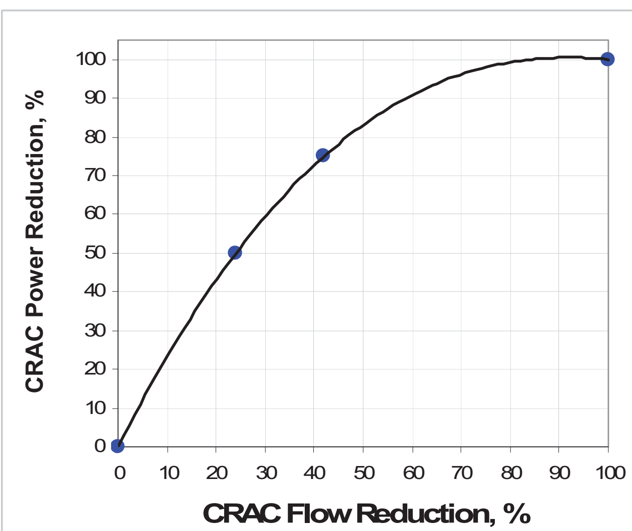


Figure 7: Typical CRAC blower power use for different air flow rate set via motor speed

Rack Inlet Air Temperatures for Different CRAC Flows

Calculations were carried out using the model depicted in figure 4 for 4 reduced CRAC flow settings defined as a percentage of the maximum flow settings used for the base line case previously discussed. The fours additional analyses were performed for 90%, 80%, 70%, and 60% of the maximum CRAC flow that was specified in the base line case. These four setting correspond to the 10%, 20%, 30%, and 40% CRAC flow reductions discussed in the previous section in the context of CRAC power use reductions.

Figure 8 shows 5 histograms for maximum rack inlet air temperatures for the base line case and the 4 additional reduced CRAC flow cases. As may be expected the distribution shifts from being dominantly cool for the base line case with 123 racks (58%) in the 12.1-15 ^{o}C range to significantly warmer with only 34 racks (16%) in this range for the 60% of maximum flow case. For the baseline case there are only 5 racks (2%) with maximum inlet air temperatures greater than 21.1 ^{o}C while for the 60% flow case there are 57 racks (28%). It should be noted that for the 60% CRAC flow reduction case, there are 3 racks with maximum inlet air temperatures that are in the 30.1-33 ^{o}C range and 11 racks with the maximum air inlet temperatures between 27.1-33 ^{o}C. These 11 racks would also need the necessary best practices based remedial treatment that has been discussed previously in this paper (more perforated tiles, blanking panels, etc).

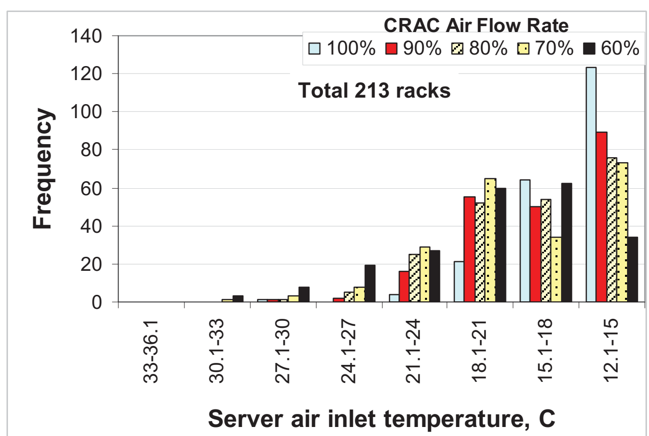


Figure 8: Model results for different CRAC flow settings – Histograms for maximum server inlet temperatures

Relationship Between CRAC Power Use Reduction and Rack Air Inlet Temperatures

Figure 9 provides further summarized information on the maximum rack inlet air temperatures using average, maximum, and minimum values of the distribution for all the CRAC flow cases and relates them to the estimated

CRAC power use savings using the two variable plot shown below.

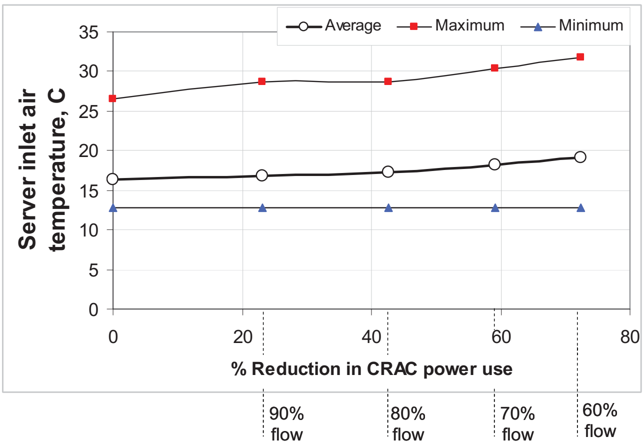


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Figure 9: Relationship between maximum server air inlet temperature and CRAC flow and CRAC blower power use

As seen in figure 9, minor increases in the average of the maximum rack inlet temperatures of 2.9 ^{o}C results from a substantial 40% reduction in CRAC air flow rate and an even bigger 72% decrease in CRAC power use, while for these conditions the maximum rack inlet air temperature increases from 27.6 ^{o}C to 31.8 ^{o}C. It should be noted while the 31.8 ^{o}C air temperature is higher than the long term recommended ASHRAE guideline [9] it is still lower than the allowable maximum (for short term operation). Thus, the data center engineer would have the option to go back to higher CRAC air flow rate or to enforce appropriate best practices measures to lower the temperature. Also shown in figure 9 as an x axis variable, are the CRAC flow settings as a percentage of the maximum flow rates.

CHILLER POWER REDUCTION VIA SET POINT TEMPERATURE INCREASE

Returning to the energy break down presented in figure 2, one might expect that targeting savings at the chiller plant would always be the optimal strategy for data center cooling energy savings. A detailed characterization of the chiller plant that supplied cold water to the data center CRACs modeled in this study has been presented in [15] which reported a reduction of 17% in chiller energy usage for a 10 ^{o}C rise in chilled water set point temperature. This increase in chiller energy efficiency is a thermodynamic result of doing less refrigeration work. The energy usage of the chiller when the set point was increased from 0^{o} C to 10 ^{o}C changed from 0.63 kW/ton to 0.52 kW/ton where 1 ton = 3.516 kW of cooling load. For the data center consider in this paper which has a total IT load of 739 kW, the cooling tonnage based on the IT load is 210.2 tons. Thus, using this tonnage value, the chiller based energy reduction for a 10 ^{o}C increase in set point temperature translates to a 22.9 kW savings at the chiller plant. Even if the total CRAC power of 128.6 kW usage when all 23 CRACs are operational is added to the IT load to thereby increase the total load on the chiller for such a comparison, the chiller savings increase modestly to be 26.9 kW.

This is a smaller number compared to the CRAC blower based energy savings that have been estimated in the preceding two sections, i.e. 50.3 kW savings shutting off 9 CRAC units and 93 kW savings from a 40% reduction in CRAC flow using motor speed control. A decision to raise the chiller set point by 10 ^{o}C would shift the entire maximum rack inlet temperature distribution that is displayed in Table 2 to be higher by 10 ^{o}C, thus requiring many racks (77) to need some sort of remedial best practices based actions. Thus, for this particular data center, and starting at the existing configuration shown in figure 4, the optimal route to save cooling energy is to turn off CRACs or use CRACs with speed control rather than increasing the chiller set point.

It should be noted that factors and parameters such as the nominal efficiency of the chiller, the chiller loading, the type of chiller, the chiller condenser design, the extent of prevalent CRAC over provisioning, and the availability of CRAC motor speed control are all factors that could change these CRAC versus chiller comparisons with respect to what the optimal approach to reducing the cooling energy usage of a data center. Zhang et al [16] presented a tool which could be used to model the energy usage of a data center for different operating conditions such as chilled water set point temperature and airflow within the data center room. Their model [16] was based in part on a regression analyses based model to characterize the air flow behavior within the data center room.

CONCLUSIONS

This paper primarily focuses on the methodologies to reduction of IT data center energy usage through control of room air conditioning devices and by exploiting recent changes in standards for the equipment environmental envelope. A 22000 square foot (6706 m^2) data center with 739 kW of IT load is used as a representative example to demonstrate methodologies to reduce the cooling energy in data centers. The relative magnitude of reduction in data center cooling energy use from CRAC shut off or CRAC motor speed ramp down is also compared with comparable scenarios involving refrigeration chiller plant temperature set point increases. For the data center considered in this study, increasing the refrigeration chiller plant water set point temperature is the least successful strategy for data center cooling energy reduction (up to 3.6% of IT load). The use of motor speed control to ramp down the CRAC air flow rate was found to be the most effective method (up to 12.6% of IT load). The simple and straightforward approach of systematically shutting off underperforming CRAC units provided a reduction of 8.1% of IT load.

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