

Thermal Considerations in Cooling Large Scale High Compute Density Data Centers

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ABSTRACT

A high compute density data center of today is characterized as one consisting of thousands of racks each with multiple computing units. The computing units include multiple microprocessors, each dissipating approximately 250 W of power. The heat dissipation from a rack containing such computing units exceeds 10 KW. Today's data center, with 1000 racks, over 30,000 square feet, requires 10 MW of power for the computing infrastructure. A 100,000 square foot data center of tomorrow will require 50 MW of power for the computing infrastructure. Energy required to dissipate this heat will be an additional 20 MW. A hundred thousand square foot planetary scale data center, with five thousand 10 KW racks, would cost ~\$44 million per year (@ \$100/MWh) just to power the servers & \$18 million per year to power the cooling infrastructure for the data center.

Cooling design considerations by virtue of proper layout of racks can yield substantial savings in energy. This paper shows an overview of a data center cooling design and presents the results of a case study where layout change was made by virtue of numerical modeling to avail efficient use of air conditioning resources.

Key Words: data center, provisioning, modeling, thermal management

NOMENCLATURE

\dot{m} = mass flow rate (kg/s)
 C_p = specific heat (kJ/kg.K)
 Q = Air Conditioning unit cooling load (kW)
 T = temperature (K)

Subscripts

in = inlet
out = outlet
v = vapor/air

MOTIVATION

The cooling design in a high power density data center is quite complex. Today's modus operandi, one of energy balance in sizing the air conditioning and intuitive distribution of air, does not suffice. It is necessary to model the air flow and temperature distribution in the data center. Initial studies in computational fluid dynamics (CFD) modeling of data centers have been reported by Patel *et al.* [1] and Schmidt [2]. In the former report [1], engineers at Hewlett Packard and Emerson Energy Systems developed a three-dimensional model of a 7.5mx5.5m (450ft²) data center and experimentally verified the numerical results to ensure specified inlet air temperature to the computer systems. This paper expands the original work by exploring the energy extraction distribution in the air conditioning resources in the data center i.e determining the terminal temperatures of the air circulating through an air conditioning coil through numerical modeling and determining the energy extraction. The cooling load on a computer room air conditioning (CRAC) unit compared to its conventionally sized capacity will be referred to as provisioning of the unit in a data center environment. An under-provisioned CRAC unit would indicate that the cooling load is higher than the capacity of the unit, while an over-provisioned CRAC unit would signify that the load is well within its capacity. The hypothesis is that mal provisioning will lead to waste of energy and a properly provisioned environment will lead to efficient use of energy resources. The authors believe that this assessment of provisioning is a key measure of data center thermal design.

The air conditioning units used in today's data centers do not vary their capacity based on the distributed needs of the data center. The state of the art in capacity variation is one based on sensing the inlet air temperature to the air conditioner (AC) unit. The authors believe that a variation in capacity, within an energy efficient range of AC provisioning, will save significant power used for cooling. The authors believe that approximately 25% savings in power required for cooling can be achieved based on current technologies.

DATA CENTER COOLING TECHNIQUES

Patel *et al.* [1] showed two types of cooling options. As shown in Fig. 1, and covered in references [1] and [2], the computer room air conditioning (CRAC) units cool the recirculated exhaust hot air from the computer racks. Generally, the racks adhere to a geometric standard [1]. A refrigerated or chilled water cooling coil in the AC unit extracts the heat from the air and cools it within a range of 10 °C to 17 °C. A typical 3 m by 0.9 m by 1.8 m CRAC unit has a sensible heat removal capacity of 95 kW. The cool air is recirculated back to the racks through vented tiles in the raised under-floor plenum. The air movers in the CRAC unit have a volumetric delivery of approximately 5.7 m³/sec. The air handlers pressurize the plenum with cool air. The cool air enters the data center through vented tiles near the inlet of the racks. The vent tile opening has to be devised to allow the air to be delivered through the tiles with enough momentum to reach the inlet of the targeted systems in a rack. The racks are laid out in rows separated with hot and cold aisles [3] as shown in Fig.1. While the cold aisles supply cold air to the systems, hot aisles are designated to remove hot air from the systems.

In addition to the raised floor approach, there exists a ceiling based approach [4]. Furthermore, there could be other office type air distribution techniques in data center. In this paper the raised floor approach will be used for modeling. A percentage opening in the plenum and the tiles will be assumed.

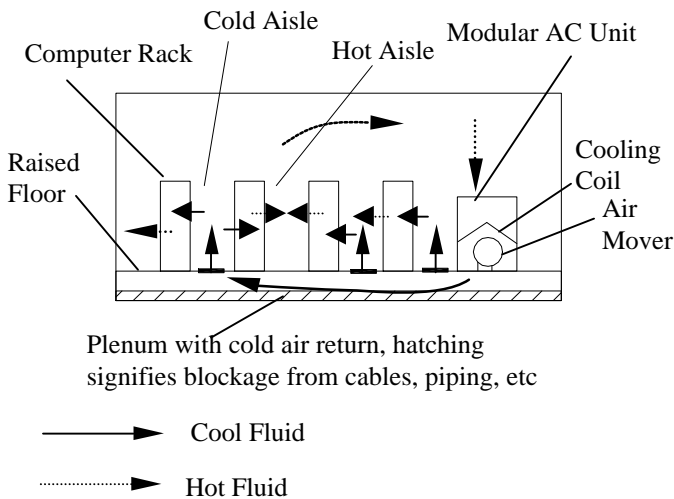


Figure 1. Under Floor Cooling of Data Center

DATA CENTER RACK LAYOUT

Although racks come in standard sizes, improper layout can radically change the fluid mechanics inside a data center leading to inefficient utilization of CRAC units. Preliminary modeling studies of a 55.7 sq. m (600 sq. ft) data center (see Fig. 2) reveals that minor layout changes in rack placement can lead to imbalance in cooling loads on computer room air conditioning (CRAC) units by as much as 25%. In the present

study, four rows each consisting of seven 12kW racks were placed in cold-aisle and hot-aisle formation [3] in a 9.14mx6.09mx3.05m data center. Numerical experiments were carried out on two models using the Computation Fluid Dynamics (CFD) tool Flovent [7], which uses finite volume techniques to solve the conservation equations:

- Symmetric Model
- Perturbed Model

Racks A and B were placed 0.85m (2.8ft) apart separated by a row of 2ftx1ft vent tiles. An identical row of vent tiles separated rows C and D by 0.85m (2.8ft). For perturbation case study, the rack spacing between A and B was increased to 0.9m (3ft), maintaining a 0.85m clearance from the CRAC units and reducing the spacing between B and C to 0.8m (2.6ft). Figure 2 shows the layout of the data center. The CRAC units were modeled based on constant air supply of 6 m³/sec with an outlet temperature of 15°C. Each rack was modeled as a 12kW heat source with flow rate of 0.85 m³/sec.

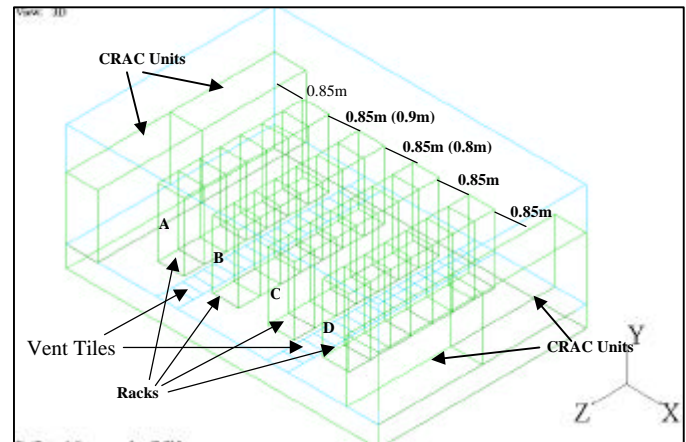


Figure 2. Rack Layout (*dimensions for perturbed case shown in parenthesis*)

The plenum depth was 0.6m. The data center was discretized into 71,000 grid cells.

Effect of Minor Geometric Asymmetry

The objective of the perturbation study was to determine the effect on heat extraction by air conditioning units. The heat extraction of each CRAC unit was determined using Eq. (1) and average air inlet temperatures from the CFD modeling. The hypothesis was that even a minor perturbation would dramatically effect the provisioning of AC resources compared to the geometrically symmetric distribution of racks with respect to the AC units in the room.

Figures 3 and 4 show the temperature contour plots at an elevation of 0.9m from the data center floor for the symmetric case and perturbed case. The symmetric temperature distribution in Fig. 3 can be attributed to the uniform airflow pattern in the data center. Perturbation of the rack layout disturbs the airflow pattern by changing pressure drop in the aisles and creating positive pressure gradients at end of aisles.

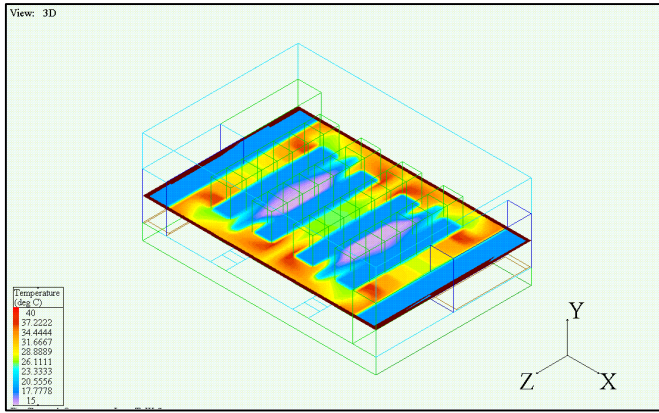


Figure 3. Temperature Contour plot for the symmetric case at height of 0.9m.

Positive pressure gradients force the air to recirculate in the room, interfering with the overall airflow pattern and creating regions of high temperature in the data center. Presence of such re-circulation zones can aggravate the problem by forcing hot air back into the servers. As a result, cooling of data centers can be very inefficient if proper measures are not taken to ensure an optimal layout.

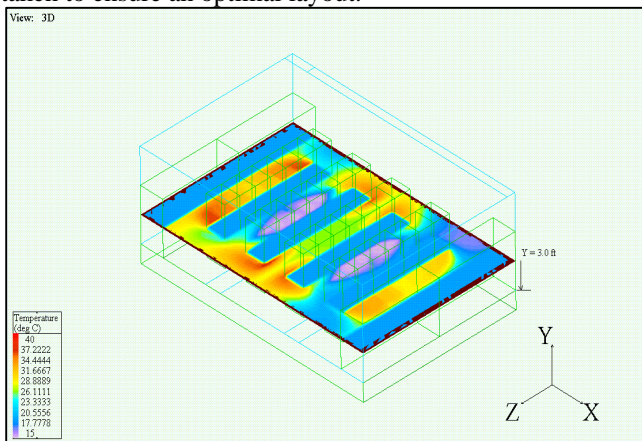


Figure 4. Temperature Contour plot for perturbed case at height of 0.9m

Table 1 compares the cooling loads on four CRAC units for the symmetric case and the perturbed case.

CRAC Units	1	2	3	4	Total
Actual Load (kW) (Symmetric Case)	87.9	81.2	85.3	81.8	336.2
Actual Load (kW) (Perturbed Case)	104.2	66.6	85.8	79.9	336.5
Deviation (%)	18.5	17.9	0.5	2.3	0.1

Table 1 Comparison of cooling loads among CRAC units between symmetric case and perturbed case

The analysis of the perturbed layout with uniform heat load showed the adverse impact on air conditioning utilization. Aided by an optimized airflow pattern, data center

performance depends on how heat is extracted, maintaining suitable room level air temperatures at all times. From practical construction considerations, a symmetric layout with reference to air conditioning units is not achievable in most cases. Therefore, exact flow optimization with uniformly balanced cooling load based on layout can be difficult to implement in practice. As a result, in an actual data center, the cooling loads on CRAC units are always non-uniform. The purpose of this paper is to understand this variation through modeling and provide motivation for a properly provisioned cooling infrastructure.

NON-UNIFORM HEAT LOAD DISTRIBUTION

Apart from asymmetry in layout, the heat load of the devices in a data center is also non-uniform, based on the heterogeneous mix of hardware types and models e.g. storage, networking, compute racks. Heat loads in data center can also vary with time due to addition or removal of racks and changing compute workloads. In this section the effect of non-uniform loading in the data center is analyzed.

To understand the effect of non-uniform heat load distribution, a new data center model was created based on service core specifications defined in HP Utility Data Center Solutions [5]. As before, the CFD model was created in Flovent [6]. The test data center was considered to be in a raised floor configuration with four modular CRAC units as shown in Fig. 5. The computer racks were constructed with machine models representing different types of servers, storage and networking devices. The data center was populated with 52 such racks arranged in four rows with heat loads of 41kW, 182kW, 101kW and 152kW, respectively. The rack dimensions are based on EIA (Electronic Industries Association) standards. The data center room was modeled as a 10mx9.75mx3m enclosure located over a 600mm deep plenum. The data center was modeled as an isolated system with insulated walls. Mesh sensitivity runs were carried out at different grid sizes to obtain grid-independent results with respect to CRAC provisioning. The complete basic service core model was discretized into 73400 grid cells. When run on a Hewlett-Packard J-Class workstation, the model took 45 minutes to converge.

Modeling the Service Core

The model was constructed by using the following salient heat load and flow attributes:

- Each server was defined as heat source with its characteristic fixed heat load and flow rate.
- Server heat loads and flow rates were based on the respective server specifications.
- Each CRAC unit model was based on fixed flow rate of 5.7m³/s and outlet temperature of 15°C [7]. It consisted of a constant flow air circulation device [6] with a constant outlet temperature condition.

- Each vent tile was modeled as a 450mm square perforated plate with 40% open area. Standard loss coefficients based on device velocity were used [6].

RESULTS

Three-dimensional CFD analysis of the fundamental service core model revealed the effect of heterogeneous cooling loads in a data center. The CRAC unit air inlet temperatures obtained from the CFD analysis are used to calculate the sensible cooling load on each unit.

$$Q = \dot{m}_v C_{p,v} (T_{in} - T_{out}) \quad \text{where } T_{out} = 15^\circ C \quad (1)$$

In our series of numerical experiments, the mean load for each unit is the arithmetic average of CRAC unit loads for comparison purposes. Conventionally, CRAC units are sized for mean heat load. Mean heat load on CRAC unit is given by:

$$\bar{Q} = \sum Q/n \quad (2)$$

where n denotes number of CRAC units. The load (Q) on each unit is compared with the mean load and expressed as a percentage deviation (d)

$$d = \left[\frac{(Q - \bar{Q})}{\bar{Q}} \right] \times 100 \quad (3)$$

Figure 5 shows the temperature contours across visualization planes located perpendicular to the CRAC units. The percent figures associated with each CRAC unit denote the mal-provisioning of the CRAC units from the sized capacity. Since CRAC units are modeled as constant outlet temperature devices and not as constant capacity heat exchangers, the temperature contours do not reflect the actual temperature values in a conventionally designed data center. Rather, the visualization planes show the relative temperature distribution in the data center for CRAC units that are able to vary their capacities. (Variable capacity units are discussed subsequently in greater detail.) As shown in Fig. 5 CRAC units B, C and D are well provisioned to meet the data center cooling loads.

In a data center with conventionally sized infrastructure, CRAC unit A would not be able to meet its outlet air temperature specifications due to higher cooling load beyond its capacity. But it may be argued that the above over-provisioning of the CRAC unit is still well within the limits of redundancies of the infrastructure.

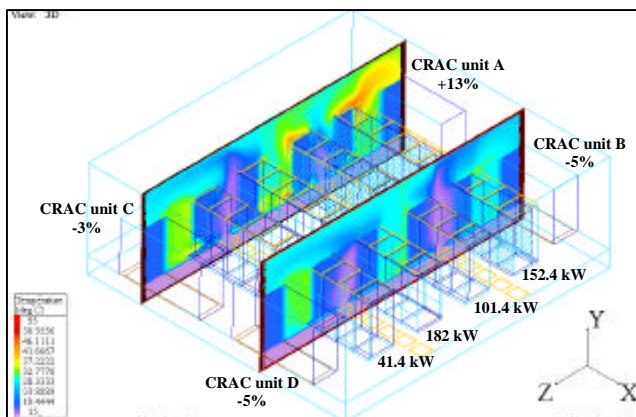


Figure 5. Cooling load variation between CRAC units in a typical service core layout

To further understand the issue of mal-provisioning, the two rows in the center of the data center were swapped to create a modified service core model. For purposes of comparison, the identical flow directions were maintained in different rows. Figure 6 shows the results in a modified data center with the swapped racks. The cooling loads on CRAC units A and B have gone up by a third of the sized capacity. CRAC unit C is operating close to half its capacity. Results indicate that providing cooling and maintaining inlet temperature specifications at different locations in a data center with skewed heat load distribution can be difficult with conventionally sized CRAC units. Since heat load distribution in data centers can change both in time and space, in ways that are difficult to predict at times, capacity provisioning of

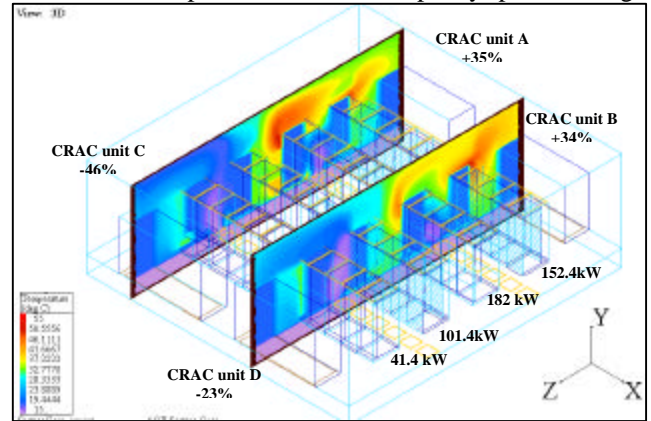


Figure 6. Cooling load variation between CRAC units in a modified service core layout

CRAC units is crucial. Moreover, heat load distribution in data centers can be complicated by air distribution limitations in the data center infrastructure.

Results of Larger Scale Data Center Configurations

Figure 7 shows the results for a pair of modified service core models housed in a large data center. Identical vent tile and rack layout was maintained.

The visualization planes indicate the relative temperature distribution close to the CRAC units. Cooling load distribution

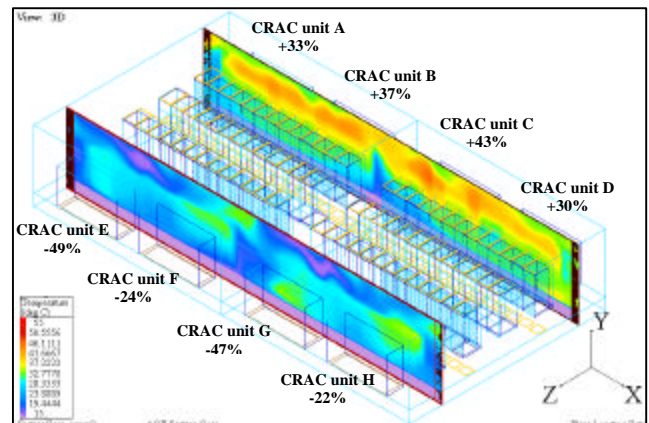


Figure 7. Cooling load variation between CRAC units in a combined data center with two service cores.

results are similar to those for the single modified service core shown in Fig. 6. The CRAC units close to the high heat load racks are operating at cooling loads more than a third above their sized capacity. CRAC units close to low heat load racks have a low capacity utilization. Depending on hot air flow pattern, cooling loads close to the center of the data center can be higher than that near the walls.

Changes in hot air flow pattern can affect the cooling loads on CRAC units. Hot air flow can be manipulated by changes in rack heat load layouts. The modified service core model shown in Fig. 6 was combined with its mirror image to create a composite data center with two modified service core models in Fig. 8. Compared to combined data center in Fig. 7, the composite data center in Fig. 8 has identical heat loads and identical vent tile layout with laterally inverted (rotated by 180°) rack heat layouts among the two service cores. Figure 8 shows that there is a significant improvement in provisioning of CRAC units close to the center of the data center. However, CRAC units close to the walls, normal to X-axis, remain widely mal-provisioned as before. In this case, proximity of high and low heat load rows in the center of the room aided by a favorable hot air flow pattern, tends to reduce the mal-provisioning of CRAC units. However, effectiveness of an approach such as this – one that moves services cores rather individual racks and components - to improve provisioning needs to be investigated from energy efficiency and practical considerations standpoint. Mixing of hot and cold air streams to improve provisioning has a potential to increase energy consumption in air handlers by increasing pressure drop in the system. Nonetheless, results from similar numerical experiments can help us to develop static rack layout patterns that enable efficient utilization of air-conditioning resources for data center cooling.

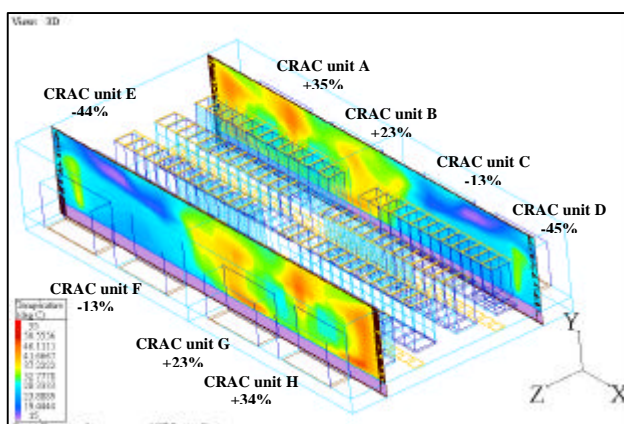


Figure 8. Cooling load variation between CRAC units in a composite data center with two mirrored service cores

When the rack heat loads exceed the adjacent CRAC unit cooling capacity, outlet air temperature to the racks rises. Increase in supply air temperatures raises the mean temperatures, by mixing with the cold supply air from other CRAC units, in the data center. A case study (not included in

this paper) of the modified data center (see Fig. 6) showed that the maximum temperature in the room increased by 4°C when the CRAC units were modeled as constant capacity heat exchangers. Therefore, mal-provisioned CRAC units can also adversely affect energy management by increasing the mean temperature in data centers.

In the following section, we discuss the opportunities and challenges in achieving provisioning through modeling methods

Opportunity to Improve Provisioning through Modeling

An opportunity exists to use modeling to help balance CRAC loading. Based on the results discussed above, doing so will provide two primary benefits:

- Elimination of under-provisioned CRAC units resulting in acceptable rack inlet air temperatures;
- Elimination of over-provisioned CRAC units resulting in more efficient AC operation and installation costs.

Under-provisioned CRAC units will provide supply air to the room at an unacceptably high temperature, which will result, ultimately, in elevated component inlet temperatures and hot spots. Alternatively, over-provisioned units may operate significantly below their capability and, if unable to vary their energy consumption commensurate with their load, will waste energy as will be discussed subsequently.

In order, therefore, to maximize energy savings, and to operate the data center with adequate inlet air temperatures, the following need to be considered in any model:

- Rack layout iteration – sensitivity analysis;
- CRAC layout optimization;
- Appropriate local CRAC sizing.

The potential benefits of rack layout studies have been discussed elsewhere in this paper. There are, however, compute environments in which the physical deployment of racked components is restricted due to rack location and interconnect constraints. The appropriate placement of CRAC units in locations where they can be more fully utilized must be considered in concert with any rack layout scheme to affect the best deployment of resources for the satisfaction of any given deployment constraints under static layout conditions. Indeed, the constraints may be such that significant temperature variations exist after optimizing rack and CRAC deployment. Figure 8 could represent one such example where large thermal variations continue to exist after completion of the service core layout modification. Modeling clearly helps to identify these temperature variations and allows room architects the ability to size CRAC units in a manner appropriate to their location in the room, thus avoiding mal provisioning and unnecessary construction costs.

Proper provisioning has been shown to be critical within data centers operating at very high power densities - the service

core model of Fig. 5 has a power density of 4895 W/m^2 (455 W/ft^2). Nevertheless, future work is required on understanding at what power density a careful consideration of provisioning, and therefore, 3-D numerical modeling, becomes necessary. Additionally, as shown in Figs. 5 and 7, the size of the data center affects the allocation of resources within the three-dimensional space.

Apart from modeling, thermal management challenges in data centers can also be addressed, to some extent, by variable capacity air conditioning resources, as discussed in the next section.

Energy Savings from Air Conditioning Resources

While, static layout optimization can be achieved through modeling, flow optimization with uniformly balanced cooling load based on layout alone, can be difficult to achieve in practice. Besides, working data centers of tomorrow are envisaged to be dynamic environments where layouts may change as new racks are added. Based on the dynamic scenario and practical considerations, there is a need for cooling capabilities that are variable. Cooling enabled by variable capacity CRAC units can maintain the right air temperatures by efficiently managing the cooling load in different areas of the data center. Such systems can complement the existing infrastructure by providing the right proportion of cooling based on the overall energy flow in the data center.

The state of art CRAC units have the ability to vary capacity based on a local temperature measurement e.g. return hot air temperature. It is critical to have such automatic ranging in capacity to utilize energy efficiently. In the introduction, the authors claimed that proper provisioning can save, approximately, 25% in energy costs. The saving is postulated based on using the variable capacity units in certain areas over the fixed capacity types. Indeed, it is the judicious use of these variable capacity CRAC units, upon completion of requisite modeling, that will maintain the required proportion of cooling based on the overall energy flow in the data center.

Inability of CRAC units to reject heat beyond the designed capacity leads to increase in mean temperature in the room and regional increase in temperature. Such an instance in a large data center would require addition of CRAC units in areas where required cooling exceeds capacity. Addition of fixed capacity units in these areas, with factors of safety and redundancies in mind, would lead to waste of energy. The authors, upon examining models, such as the symmetry studies shown in Fig.4 and Fig. 5 conclude that the net savings would be approximately 25% in a properly provisioned layout with judicious use of variable capacity air conditioning resources. Indeed, when the layout results in mal provisioning of the order shown in Fig. 6 and Fig. 7, the savings would be larger.

Based on the numerical models presented (Figs. 5,6,7 and 8) in the paper, an analysis of energy savings was carried out (see Appendix A). To establish the current scenario, the case study data centers were assumed to be conventionally designed without CFD analysis. Initially, each CRAC unit was sized conventionally for mean heat load. Each CRAC unit was assumed to be a direct expansion (DX) refrigerant-based unit with hot gas bypass for cooling capacity variation. In course of data center operation, due to higher air temperatures near high heat load racks, additional capacity, as reflected in the Figs. 5, 6, 7 and 8, was added to adjacent CRAC units. As a result, the power consumption of these CRAC units increased. Meanwhile, other CRAC units, which were operating at lower capacities with hot-gas bypass, still consumed the full-rated power.

Our research proposes to provide energy saving by removing the need for this additional capacity in CRAC units, by CFD modeling and variable capacity air conditioning infrastructure. The magnitude of energy savings will depend on the rack heat load layout and the severity of mal-provisioning in the specified number of CRAC units. In the modified service core data center with two over capacity CRAC units (Fig. 6), an average energy savings up to 35% can be obtained in each unit by elimination of additional capacity. Energy saving in the basic service core data center of Fig. 5, however, is only 12% per under-provisioned unit due to a favorable rack heat load layout. For the large-scale data center configurations in Figs. 7 and 8, energy savings are 35% and 29% per under-provisioned CRAC unit, respectively. The overall energy savings from the data center will also depend on the overheads in power consumption and the standard capacity of each CRAC units.

Variable Capacity Air Conditioning Resources

The achievement of variable capacity cooling depends on the type of air conditioning. The CRAC units in the data center are typically:

- Chilled water cooling coils
- Direct cooled compressor based refrigerated units.

In the former, appropriate variation of the flow rate and bypass valves leading to a variable capacity chiller can achieve the purpose. In the latter, in the compressor capacity in the CRAC units is varied. There are several options [8,9,10] as outlined below.

On/Off

This method, used with constant capacity compressors (CCC), makes the compressor works either zero or full as the demand requires.

Cylinders Unloading

Multi-cylinder compressors allow for their capacity to be varied by the loading and unloading of cylinders. This

technique changes the compressor capacity with the reduced load by deactivating cylinders.

Hot Gas Bypass

Hot gas bypass is currently used in many industrial applications. It adds heat load to the system by recirculating the hot gas back to the suction thereby stabilizing suction pressure. The compressor in this case operates at full discharge pressure and capacity all the time. The returned gas has to be cooled to the normal suction temperature and pressure in order to avoid high discharge pressure. The hot gas bypass technique does not provide any energy savings but helps the cycle run smoothly when loads are varied.

Variable Speed Drive Compressors

Variable speed drives, a well-established energy saving technology in motor systems, is an available option with compressors today. With a variable speed motor, a variable capacity compressor (VCC) can vary its capacity according to the required cooling load. Most VCCs can efficiently run between 100% to 50% capacity (2:1) ratio and for larger variations, a multi-compressor unit can be used.

Multicompressor Unit

Multicompressor units are a combination of one variable capacity compressor (VCC) and one or more constant capacity compressor (CCC) with the same maximum capacity. In a two in one compressor, as shown in Fig. 9, the VCC comes on first while the load is increasing from its minimum capacity to its maximum capacity (region I). Once the maximum capacity of the VCC is reached, the CCC is turned on while the VCC is turned off (region II). If the load increases above the maximum capacity of the CCC, the VCC is brought back on (region III). This will allow the air conditioning unit to operate below its maximum capacity and as low as 25% of its maximum capacity thereby saving a significant portion of its operating cost.

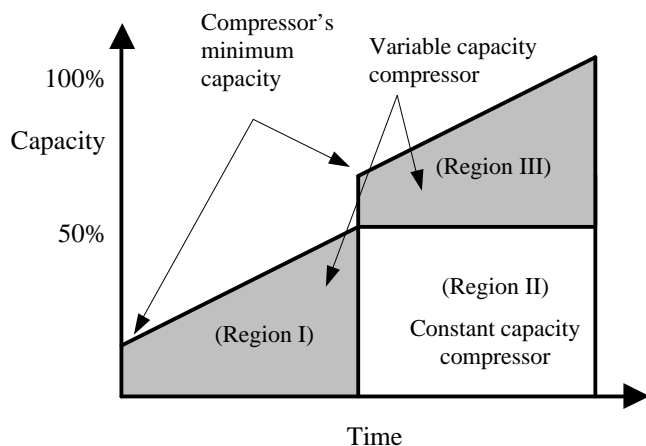


Figure 9. Two in One Compressor Unit

Energy costs account for a significant component of a compressor operating cost. Therefore, it is important to limit the use to only the energy required for the process and use it efficiently. The most practical variable capacity compressors are scroll and screw compressors since they give much better performance than the other rotary or reciprocating compressors. Scroll compressors are best for systems with capacity of 5 ton (17.6 KW) to 100 tons (351 KW) and screw compressors are best for systems with capacity of 50 tons to several hundreds tons. Today's scroll compressors are available in 2:1 ratio and approaching 3 or 4:1 ratio in the near future.

SUMMARY AND CONCLUSIONS

High power density computer rooms require numerical modeling to design airflow and temperature distribution. Intuitive distribution of racks and air conditioning resources does not suffice. Citing previous work on use of computational fluid dynamics modeling [1], and one validated by metrology, the authors expand on the use of numerical modeling. Using an example data center called a service core, based on Hewlett Packard's Utility Data Center Solutions [5], the authors have shown the modeling is necessary for appropriate provisioning of air conditioning resources. Based on fixed heat loads from computer racks, modeling allows one to attain an optimal layout, with reference to provisioning of air conditioning resources. Such a step leads to statically optimized layout. While static optimization of layout based on fixed heat load can be achieved by modeling, there remains the need to vary the capacity of air conditioning resources to account for the dynamically changing heat loads due to physical rearrangement of hardware in the room, and run time variation of power dissipation. In order to provide a data center cooling solution with the dynamic capability of matching the current cooling requirement, certain specifications have to be added to the CRAC unit to make its capacity variable and controllable.

By way of examples, the paper covers these issues, and lays the groundwork for further work in data center design. Very large data centers may prove more difficult to model, and therefore properly provision, than small ones due to the sheer magnitude of the problem. Further investigation in this area is required to understand how best to apply the concepts discussed in this paper to large-scale problems. Having introduced that data center modeling and variable capacity air-conditioning resources allow one to achieve energy efficiency, there is also a need for research into methods for incorporating these capabilities into a common data center environment.

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APPENDIX A

FIGURE 5								
						Sized	Additional	
CRAC Units	MassFlow	T _{inlet}	T _{outlet}	Cooling Load		Capacity	Capacity	
							(approx.)	
	kg/s	°C	°C	kW	tons	tons	tons	
A	6.7394	34.821	15	134.52	38.11	34	12.54%	4
B	6.7394	31.711	15	113.41	32.13	34	-5.12%	0
C	6.7394	32.095	15	116.02	32.87	34	-2.94%	0
D	6.7394	31.825	15	114.18	32.35	34	-4.47%	0
Total				478.13				12%
25% of CRAC Units are Under-Provisioned								
Required Additional Capacity Per Under-Provisioned CRAC Unit = 12%								

FIGURE 6								
						Sized	Additional	
CRAC Units	MassFlow	T _{inlet}	T _{outlet}	Cooling Load		Capacity	Capacity	
							(approx.)	
	kg/s	°C	°C	kW	tons	tons	tons	
A	6.7394	38.846	15	161.83	45.84	34	35.39%	12
B	6.7394	38.424	15	158.97	45.03	34	32.99%	12
C	6.7394	24.569	15	64.94	18.40	34	-45.67%	0
D	6.7394	28.613	15	92.39	26.17	34	-22.71%	0
Total				478.13				35%
50% of CRAC Units are Under-Provisioned								
Required Additional Capacity Per Under-Provisioned CRAC Unit = 35%								

FIGURE 7								
						Sized	Additional	
CRAC Units	MassFlow	T _{inlet}	T _{outlet}	Cooling Load		Capacity	Capacity	
							(approx.)	
	kg/s	°C	°C	kW	tons	tons	tons	
A	6.7394	38.398	15	158.79	44.98	34	32.85%	11
B	6.7394	39.08	15	163.42	46.29	34	36.72%	12
C	6.7394	40.15	15	170.68	48.35	34	42.80%	14
D	6.7394	37.91	15	155.48	44.05	34	30.08%	10
E	6.7394	23.991	15	61.02	17.29	34	-48.95%	0
F	6.7394	28.362	15	90.68	25.69	34	-24.13%	0
G	6.7394	24.277	15	62.96	17.84	34	-47.33%	0
H	6.7394	28.728	15	93.17	26.39	34	-22.05%	0
Total				956.20				35%
50% of CRAC Units are Under-Provisioned								
Required Additional Capacity Per Under-Provisioned CRAC Unit = 35%								

FIGURE 8								
						Sized		Additional
CRAC Units	MassFlow	T_{inlet}	T_{outlet}	Cooling Load		Capacity		Capacity
								(approx.)
	kg/s	°C	°C	kW	tons	tons		tons
A	6.7394	38.706	15	160.88	45.58	34	34.58%	12
B	6.7394	36.711	15	147.34	41.74	34	23.25%	8
C	6.7394	38.652	15	160.52	45.47	34	34.27%	11
D	6.7394	36.619	15	146.72	41.56	34	22.73%	8
E	6.7394	24.728	15	66.02	18.70	34	-44.78%	0
F	6.7394	30.407	15	104.56	29.62	34	-12.54%	0
G	6.7394	24.837	15	66.76	18.91	34	-44.16%	0
H	6.7394	30.262	15	103.58	29.34	34	-13.36%	0
Total				956.38				29%
50% of CRAC Units are Under-Provisioned								
Required Additional Capacity Per Under-Provisioned CRAC Unit = 29%								