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DIMENSIONLESS PARAMETERS FOR EVALUATION OF THERMAL DESIGN AND PERFORMANCE OF LARGE-SCALE DATA CENTERS

Ratnesh K. Sharma, Cullen E. Bash, Chandrakant D. Patel
Hewlett-Packard Laboratories
1501 Page Mill Road, ms 1183
Palo Alto, CA 94304

Abstract

Large-scale data centers (~20,000m^2) will be the major energy consumers of the next generation. The trend towards deployment of computer systems in large numbers, in very dense configurations in racks in a data center, has resulted in very high power densities at room level. Due to high heat loads (~3MWs) in an interconnected environment, data center design based on simple energy balance with zones, is inadequate. Energy consumption of data centers can be severely increased by inadequate air handling systems and rack layouts that allow the hot and cold air streams to mix. In this paper, for the first time, we formulate non-dimensional parameters to evaluate the thermal design and performance of large-scale data centers. The parameters, based on temperature and flow data, reflect the convective heat transfer and fluid flow inside the data center. These parameters have been formulated as indices that are scalable from rack level to data center level. To provide a proof of concept, computational fluid dynamic models of data centers are used to validate and demonstrate these indices. A first level design of experiment study is carried out to understand the effect of geometry and data center workload on the parameters. Different data center configurations are also investigated to understand the effectiveness of these parameters in specific cases. These parameters will not only provide an invaluable tool to understand convective heat transfer in large data centers but also suggest means to improve energy efficiency in data centers.

Motivation

The miniaturization of semiconductor devices and integration of several functionalities on a single microprocessor chip has resulted in very high power densities at chip level[1]. These high power density microprocessors, support chips, mass storage and power supply are mounted in ultathin server enclosures. In turn, the deployment of large number of these ultrathin servers, in very high densities in computer racks, has resulted in 10 to 15 KW racks[2,3]. To enable pervasive computing, thousands of racks are expected to reside in future data centers[4]. A data center, thus characterized by high-density deployment of computer racks, can itself be viewed as a computer. Over the years, tremendous research and development has occurred in computer system cooling design. One now has to view the *data center as the computer*, where the walls are the enclosures and the racks are akin to electronic devices dissipating heat. Therefore, the due diligence traditionally applied to system cooling design has to be applied to a data center.

The use of numerical techniques to model the airflow behavior has been presented by Patel *et al*.[2]. The authors argued that the current modus operandi, that of summing the heat load, and intuitively distributing the airflow will not suffice. Numerical modeling to optimize the layout of the racks (heat loads) and the airflow vents was proposed. Validation of the modeling was presented by virtue of measurements and modeling undertaken in a specially designed data center[2]. In a subsequent paper, modeling to ensure proper provisioning of air conditioning resources was presented[5]. While all these studies highlighted the need to model a data center, they all had to rely on complex fluid dynamics models to create layout "guidelines" that could be used to design the data center. The study presented herein is an attempt to develop dimensionless, scalable parameters for design and performance evaluation of data centers. Based on these parameters, we propose an approach to evaluate a figure of merit for data centers.

Nomenclature

a	Dimensionless cold-aisle width
b	Dimensionless hot-aisle width
c	Dimensionless ceiling height above rack
C_p	Specific heat of air at constant pressure
d	Dimensionless lateral rack to wall spacing
l	Rack depth
m	Mass flow rate of air through a rack
M	Mass flow rate of air through a CRAC unit
Q	total dissipation from data center components
T	Temperature
x	Geometric parameter

Superscripts

c	CRAC unit
r	Rack

Subscripts

in	inlet
out	outlet
ref	CRAC supply

Data Center Cooling Infrastructure

Figure 1 is a simplified representation of a traditional data center with under floor cool air distribution. The hot exhaust air from the EIA (Electronics Industries Association) racks is cooled by recirculating the air through modular computer room air conditioning units (CRAC). Multiple CRAC units, sized to extract the total heat load in the data center, are located within the data center or in close proximity. A refrigerated or chilled water cooling coil in the CRAC unit cools the air to a temperature of approximately 10^oC to 17^oC. 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 typical volumetric delivery of approximately 5.7 m^3/sec (~12,000 CFM). Conventionally, the racks are laid out in hot aisle and cold aisle format as shown in Figure 1 with supply air inlet vents in cold aisles.

Figure 2 shows a ceiling return infrastructure and is similar to Fig. 1. The primary difference is that the hot air from the racks is pulled up into the ceiling plenum where it is less likely to mix with the cooler room air. Additionally, a duct connects the CRAC unit to the ceiling plenum. Studies by Stahl and Belady[6], Patel *et al*.[2,5] and Schmidt[7] provide review of other data center infrastructures. The present study is focused on understanding raised-floor plenum data centers with room-return and ceiling-return based infrastructures.

Hypothesis based on Non-Dimensional Parameters

We hypothesize that there exist key non-dimensional parameters that can be used to determine a scalable "index of performance" for the data center configuration of the type shown in Fig. 1 In the subsequent sections, we will define the set of non-dimensional parameters and develop the indices based on computational fluid dynamics (CFD) modeling of example data centers. The key measure of data center cooling arrangement is temperature. Any element – computer rack, vent tile, CRAC – can be characterized by inlet and outlet temperature. Thus, we will base the index of performance, on inlet and outlet temperature and a reference fixed temperature (typically CRAC supply temperature). The key temperature measure, at the inlet of the rack, is a function of the geometrical layout of the data center. Ideally the temperature at the inlet of the racks should be equivalent to the vent tile inlet temperature or CRAC outlet temperature, henceforth referred to as T_{ref}. However, due to infiltration of hot air from the hot aisles and recirculation of exhaust air from the racks, the rack inlet air temperature is typically higher than the vent tile inlet temperature (see Fig.1). Similarly, the hot exhaust air temperature from the racks, and the hot aisles, would be equal to the CRAC return air temperature e.g. if a duct was provided that picked up all the hot air from the hot aisle and returned it back to the CRAC inlet. However, due to infiltration of cool air from the vent tiles and the cold aisles the return air temperature to the CRAC is not equal to the exhaust air temperature from the rack. Yet another phenomenon is the "short circuiting" of the vent tile airflow back to the CRAC return. Thus, we based this study on examining the flow and thermal behavior of the return air to the CRAC and the rack inlet air. We hypothesized that key to maximizing the performance in the data center would be to:

- Minimize the infiltration of hot air into the cold aisles
- Minimize the mixing of hot return air with cold air streams, prior to return to the CRAC units
- Minimize the short-circuiting of cold air to the CRAC inlet.

Based on numerous computational fluid dynamics studies of example data centers of the type shown in Figure 1 and 2, we propose two key indices: Supply Heat Index (SHI) and Return Heat Index (RHI).

Consider Q as the total heat dissipation from all the racks in the data center and δQ as the rise in enthalpy of the cold air before entering the racks. Then:

$$Q = \sum_j \sum_i m^r_{i,j} C_p \left(\left(T^r_{out}\right)_{i,j} - \left(T^r_{in}\right)_{i,j} \right) \qquad (1)$$

where $m^r_{i,j}$ is the mass flow of air through i^{th} rack in the j^{th} row of racks, $(T^r_{in})_{i,j}$ and $(T^r_{out})_{i,j}$ are average inlet and outlet temperature from the i^{th} rack in the j^{th} row of racks. Similarly:

$$dQ = \sum_j \sum_i m^r_{i,j} C_p \left(\left(T^r_{in}\right)_{i,j} - T_{ref} \right) \qquad (2)$$

where T_{ref} denotes the vent tile inlet air temperature, assumed to be identical for all rows. Assuming no heat transfer in the plenum, the vent tile air temperature and CRAC supply air temperature are considered to be equal and referred to as reference temperature for enthalpy calculations.

The Supply Heat Index (SHI) for the data center is given by:

$$SHI = \frac{dQ}{Q + dQ} = \frac{\text{Enthalpy rise due to infiltration in cold aisle}}{\text{Total Enthalpy rise at the rack exhaust}} \qquad (3)$$

The numerator denotes the sensible heat gained by the air in the cold aisle before entering the racks while the denominator represents the total sensible heat gain by the air leaving the rack exhausts. Since the mass flow rates at the inlet and outlet of each rack are equal, *SHI* can be rewritten as a function of rack inlet, rack outlet and CRAC outlet temperatures. For the data center, this gives:

$$SHI = \left(\frac{\sum_j \sum_i \left(\left(T^r_{in} \right)_{i,j} - T_{ref} \right)}{\sum_j \sum_i \left(\left(T^r_{out} \right)_{i,j} - T_{ref} \right)} \right) \qquad (4)$$

Supply Heat Index can be additionally calculated for a cluster of racks in an aisle to evaluate the infiltration of heat into specific cold aisles. Individual rack SHI can be calculated to isolate areas susceptible to hot spots. Equations 2 and 3 indicate that higher δQ leads to higher T^r_{in} and hence, a higher *SHI*. When the inlet temperature (T^r_{in}) to the rack rises, systems become more vulnerable to failure and reliability problems. Increased T^r_{in} also signifies increased entropy generation due to mixing and reduced energy efficiency for the data center. Therefore, *SHI* can be an indicator of thermal management and energy efficiency in a row or data center.

The hot air from the rack exhausts is drawn up into the ceiling space and flows into the CRAC units, subsequently. During this flow process the hot air mixes with partly cooler air from cold aisles and loses heat. The quantity of heat lost in this process is equal to the secondary heat acquired by the air in the cold aisle (see Eq. (2)). From overall heat balance in the data center, total heat dissipation (*Q*) from all racks should be equal to the total cooling load of the CRAC units. Therefore, the heat balance in the data center between the rack exhausts and the CRAC unit inlets can be written as:

$$\sum_j \sum_i m^r_{i,j} C_p \left(\left(T^r_{out} \right)_{i,j} - T_{ref} \right) - \sum_k M_k C_p \left(\left(T^c_{in} \right)_k - T_{ref} \right) = dQ \qquad (5)$$

where, on the left-hand side, the first term denotes total enthalpy ($Q+dQ$) of the hot air leaving all the row exhausts (see Eq. (1,2)) and the second term denotes total enthalpy at the inlet to all the CRAC units. The right hand side represents decrease in enthalpy due to mixing of hot and cold air streams. T^c_{in} and M are the individual CRAC inlet temperature and mass flow rates respectively. Normalizing Eq. (5) with respect to the total exhaust air enthalpy and rearranging, we have:

$$SHI + RHI = 1 \qquad (6)$$

where RHI is the Return Heat Index and is defined by:

$$RHI = \left(\frac{Q}{Q+dQ} \right) = \frac{\sum_k M_k C_p \left(\left(T^c_{in} \right)_k - T_{ref} \right)}{\sum_j \sum_i m^r_{i,j} C_p \left(\left(T^r_{out} \right)_{i,j} - T_{ref} \right)} = \frac{\text{Total heat extraction by the CRAC units}}{\text{Total Enthalpy rise at the rack exhaust}} \qquad (7)$$

Since the heat extracted by the CRAC units is also equal to the heat dissipation from the racks, the numerator represents the effective heat dissipation in the data center. Increase in T^r_{in} leads to rise in T^r_{out} on the return-side of racks, provided the heat load in racks is constant. From Eq. (7), its apparent that this change in temperature would reduce RHI, indicating that the air undergoes a higher degree of mixing before reaching the CRAC unit. Hot air from the rack exhaust can mix with cold air inside the hot aisle, in the ceiling space, or in the space between the rack and the walls. To investigate local mixing in each row, RHI can be evaluated in an aisle-based control volume between the aisle exhaust and the rack exhaust or it can be inferred from calculation of SHI through known temperature data and Eq. 6. Higher values of RHI would indicate a better aisle design with low mixing levels.

Methodology

Modeling studies were carried out on a representative raised-floor data center with, both room-return and ceiling-return infrastructures, to understand the effect of geometric parameters on the Return and Supply heat index. A 100m^2 (38.3ftx28ftx10ft) data center model was created with 600mm deep plenum. Four rows, each with seven racks, were arranged back-to-back to create cold aisles and hot aisles. Each rack contained twenty A-Class HP servers[8] dissipating a total of 12kW. Each server had a rated flow of 0.034m^3/s (71cfm) and heat dissipation of 600W. Cold air flows uniformly into the data center through the vent tiles located on the floor in the cold aisles. In the room-return infrastructure, the hot air rises from the hot aisle, into the ceiling space and flows back to the CRAC units. In the ceiling-return infrastructure, the hot air rises through the ceiling tiles into a ceiling plenum before flowing back to the CRAC unit. Each CRAC unit supplied 4.72m^3/s (10000cfm) of cold air at 15^{o}C to the raised floor plenum.

The data center model was created with commercial CFD software[9] as an isolated system with insulated walls. Mesh sensitivity runs were carried out at different grid sizes to obtain grid-independent temperature and flow distributions. Base models were constructed for each infrastructure and were discretized into ~450000 grid cells. When run on a Hewlett-Packard J-Class workstation, the models took 3 hours to converge.

Figures 3 and 4 show the isometrics of the data center rack layout for both infrastructures, indicating the geometric parameters investigated in the study and their corresponding initial values. The parameters are cold aisle width (x_1), hot aisle width (x_2) and the ceiling space above the rack top (x_3) and the lateral spacing between rack and wall (x_4). The geometric variables were non-dimensionalized with respect to rack depth *(l)*. Based on the EIA standard each rack was 940mm (37 in.) deep.

$$a = x_1/l\ ;\ b = x_2/l\ ;\ c = x_3/l\ ;\ d = x_4/l \qquad (8)$$

Minimum and maximum settings were calculated for each geometric parameter. Table 1 shows the values of geometric variables and the dimensionless parameters, in parenthesis.

SETTINGS	-1	0	+1
x_1 (*a*)	0.91m(.97)	1.22m(1.3)	1.52m(1.62)
x_2 (*b*)	0.91m(.97)	1.22m(1.3)	1.52m(1.62)
x_3 (*c*) room	0.81m(.86)	1.12m(1.2)	1.42m(1.52)
x_3 (*c*) ceiling	0.54m(.54)	0.82m(.87)	1.12m(1.2)
x_4 (*d*)	0.91m(.97)	1.22m(1.3)	1.52m(1.62)

Table 1: Input variables and dimensionless parameters (in parenthesis)

A benchmarking run was carried out at average setting (0) for all the variables. Extensive post processing was carried out to extract the average T^r_{in}, T^r_{out} and T^c_{in} values for individual rows of racks and CRAC units, respectively. SHI and RHI values were calculated to get base case performance data for each infrastructure. The geometry considered for this run is shown in Figs 3 and 4. The power density in the data center was 3.37kW/m^2 (313W/ft^2). The maximum temperatures obtained from the base case runs for room return and ceiling return infrastructures were 44.2^{o}C and 45.9^{o}C respectively.

For the ceiling return infrastructure, the SHI and RHI values were 0.2 and 0.83, respectively. The SHI and RHI values for the room return case was 0.21 and 0.81, respectively. Figure 5 shows the stacked column chart with SHI and RHI for room-return and ceiling return infrastructures. In both cases, the indices add up to unity within an error of less than 2% (see Eq. (6)). This variation was well within uncertainty limits obtained during prior verification studies on Flovent[9] by Patel *et al*.[2].

Having established and verified the theoretical foundation of the heat indices, CFD simulations were conducted with new data center layouts to understand the performance variation with geometry. New data center layouts were created by modifying geometric parameters (see Table 1) one at a time. These models were run to obtain the SHI and RHI values. Parameters yielding significant variation in indices have been included in this study. Variation of lateral spacing (x_4) did not have a significant impact on the temperature distribution of either infrastructure and was, therefore, not considered in the present study. Other parameters, namely, the cold aisle width (x_1), hot aisle width (x_2) and the ceiling space (x_3) were considered to be significant. The next section discusses the results for the variation of these parameters.

Results and Discussion

Room Return Infrastructure

Figure 6 shows the variation of SHI with geometry parameters a, b and c. SHI appears to decrease with increase in "*a*". In case of variation in cold aisle width (or "*a*"), the tile sizes are varied accordingly to fit into the aisle space. An increase in cold aisle width increases the tile flow area and, hence, reduces the velocity of cold air stream, entering into the aisle through the vent tiles. This reduction in cold air velocity increases the static pressure within the cold aisle. Higher static pressure prevents hot air from flowing into the aisle, thus reducing the heat infiltration. Increase in hot aisle width, on the other hand, reduces static pressure in the hot aisle. Airflow in the hot aisle is determined by the induced draft created by the CRAC units and pressure gradients within the data center. Unlike cold aisles, the air velocity in the hot aisle is low. So an increase in hot aisle width decreases the static pressure. In the range of variation, change in ceiling height (*c*) did not alter airflow in the cold aisle. No significant impact on the average SHI was observed with variation in ceiling height.

Return heat index captures the mixing process between the rack exhaust and the inlet to the CRAC unit. Hot air from the rack exhausts mix with air from other racks and cold air from cold aisles before entering the CRAC unit. In some cases, hot air streams may get cooled within the data center space by mixing with cooler air streams and reenter racks. Such a flow pattern is difficult to avoid in the absence of ducted flow, and especially, when the return path to the CRAC units are longer. Since room return infrastructures are more prone to this flow pattern, changes in cold aisle width and ceiling space have little impact on the RHI. As a result of directed flow from the vent tiles, changes in cold aisle width do not affect the mixing in other regions of the room. Ceiling space variation, on the other hand, was not significant enough to cause any perceptible variation in the return index. However, as shown in Fig. 7, changes in hot aisle width affects the

RHI. Hot aisle flows are driven by suction created by the CRAC units. Reduction in hot aisle width increases the static pressure in hot aisle and enhances mixing of the hot air, thus, reducing CRAC inlet temperatures.

Although some geometric parameters on a data center level do not have a significant effect on the average RHI for room-return infrastructures, this is not necessarily true for local row-based return indices. Decreasing cold aisle width reduces the inlet temperature to racks, thereby reducing δQ and increasing RHI (see Eq. (2)). Figure 8 indicates that all rows of racks show this effect in various degrees. Racks located at the center of the data center or away from walls are more susceptible to this effect than others, after a certain reduction in cold aisle width.

Variation of row-wise RHI with ceiling parameter "*c*" is plotted in Fig. 9. Increase in ceiling space improves the RHI for the central rows of racks more than others. This reduces the mixing of hot and cold streams in the hot aisle by providing a low resistance flow path for the hot air towards the CRAC units.

Ceiling Return Infrastructure

Figures 10 and 11 show the variation of SHI and RHI with geometry parameters for the ceiling return infrastructure. Variation of SHI over the data center with respect to cold aisle width follows the same trend exhibited in the room return case. The effect being even more pronounced than the room-return case. The presence of the ceiling plenum causes a marked change in room airflow patterns resulting in a greater sensitivity to the static pressure variation in the cold aisle that occurs from a change in aisle spacing. The RHI variance reflects this trend as well indicating a greater degree of room-level mixing at smaller aisle widths.

Conversely, a change in hot aisle spacing produces a result that is the inverse of that found for the room return infrastructure. A decrease in hot aisle spacing combined with the select placement of ceiling vent tiles results in increased static pressure in the hot aisle. Since low pressure areas exist above the hot aisles near the return vents, the increased pressure gradient forces more of the hot air directly up and into the ceiling plenum resulting in a lower SHI. Alternatively, a large hot aisle reduces this beneficial gradient causing more mixing to occur in the room, indicated by the reduction in RHI, and added hot air recirculation into the cold aisles, indicated by an elevated SHI.

The ceiling height follows the same trend as the hot aisle. As the ceiling is lowered, the pressure gradient between the hot aisle and ceiling increases, forcing more hot air directly into the ceiling plenum and out of the room and reducing SHI while increasing RHI.

The Supply Heat Index is a measure of the amount of heat that infiltrates the cold aisle and subsequently gets pulled into heat-producing equipment. Heat infiltration into cold aisles is ultimately a result of recirculation patterns in the room. Air moving devices like fans and blowers contained in the components of the racks greatly affect these circulation patterns. Intuitively, air that flows through racks at the end of aisles should be more prone to recirculation around the sides of the row than racks in the middle. Figure 12 illustrates this by displaying SHI against Workload for the ceiling return infrastructure. The bar representing uniform workload of 12 kW/rack is representative of the base case model described previously and exhibits an SHI of 0.194. Heat was removed from the three racks in the middle of each row to gauge the effect of workload placement, and consequently heat load distribution, on SHI. A numerically insignificant increase in SHI of 1% to 0.196 was noted despite a 43% reduction in heat load to the data center. Subsequently, heat was removed from the two racks at the ends of each row such that only the middle three racks in each row were powered. In contrast to the middle racks being off, a 22% decrease in SHI 0.151 was observed with a 57% reduction in power from the uniform loading case. The marked change in SHI is clearly a result of the location of the heat load, not the magnitude of the power decrease indicating that outer racks contribute more towards unwanted recirculation than inner racks and that the placement of racks with highest power dissipation should be biased towards the center of each row for this infrastructure.

To study the effect of overall heat generation on SHI, the power level in the room was uniformly increased from 6 kW/rack to 12 kW/rack to 24 kW/rack for the ceiling return infrastructure. The mass flow rate through the racks was held constant across the cases. The effect, shown in Fig. 12, is a steady reduction in SHI with increased uniform heat load from a maximum of 0.237 at 6 kW/rack to a minimum of 0.138 at 24 kW/rack. The increase in power in the data center positively effects circulation patterns and results in a decrease in $\delta Q/Q$, or the fraction of heat generated in the data center that contributes to increasing the enthalpy of the equipment supply air. This is shown graphically in Figure 13. Since the mass flow rate was kept constant, the change in rack power results in a change in T^r_{out} from an average of 25°C at 6kW/rack to 46°C at 24 kW/rack. This change in temperature produces a change in the buoyant force, which becomes larger at higher exhaust temperatures and aids in the direct return of hot exhaust air to the ceiling vent tiles. Note that this increased buoyant force is beneficial for the ceiling return infrastructure, but may prove problematic for other infrastructures with hot air returns located farther from the rack exhausts.

Summary and Future Work

In this paper, we have proposed and verified dimensionless parameters for design and performance of data centers for the first time. Based on energy balance and fluid flow patterns, these heat indices can be used from rack level to data center level design and analysis. Proof of concept for applicability of parameters was verified using CFD models for two different infrastructures. Supply Heat Index and Return Heat Index, based on temperatures, can be measured in a simple and efficient manner to evaluate the performance of functioning data centers

It was observed that geometric parameters could affect the performance of data centers in different ways, depending on the infrastructure. In the present study, effects of cold aisle and hot aisle widths and ceiling space were observed to be significant. Heat load studies on a ceiling infrastructure model indicate that data centers can be optimized not only based on geometric parameters, but also on heat loads.

A detailed analysis is required to develop the composite functional relationship between the geometry parameters, heat load and the indices. Experiments are underway at Hewlett-Packard Laboratories to validate the preliminary findings. Further investigation may be needed to correlate the heat indices to energy efficiency and measure effects on other infrastructures.

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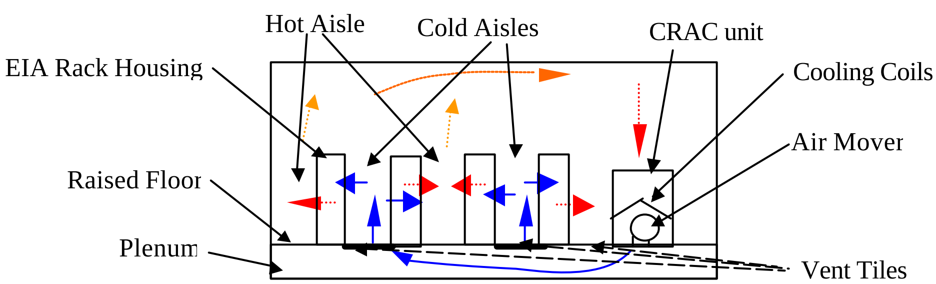

Figure 1. Typical Under Floor Air Cooling Data Center Configuration with Room Return

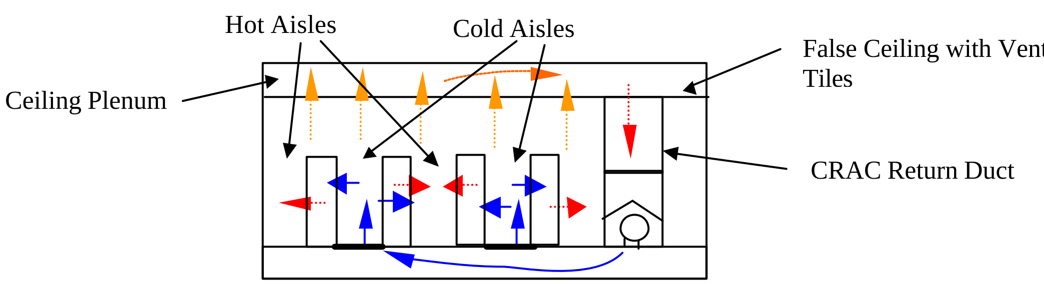

Figure 2. Typical Under Floor Air Cooling Data Center Configuration with Ceiling Return

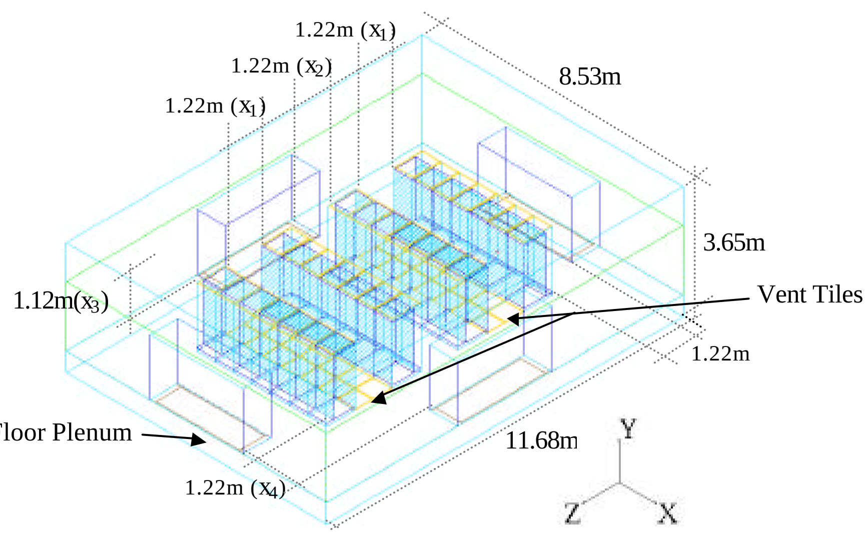

Figure 3: Base Case layout for room return infrastructure

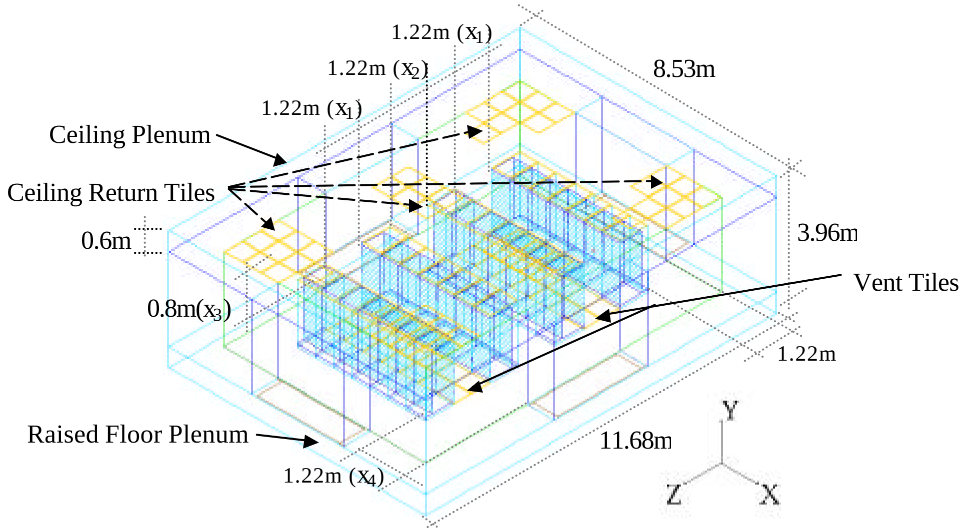

Figure 4: Base Case layout for ceiling return infrastructure

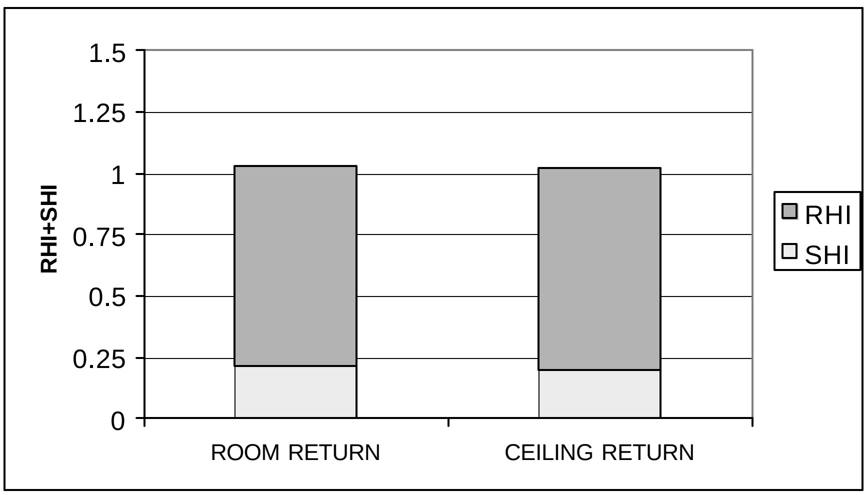

Figure 5: Sum of Heat Indices for different infrastructures

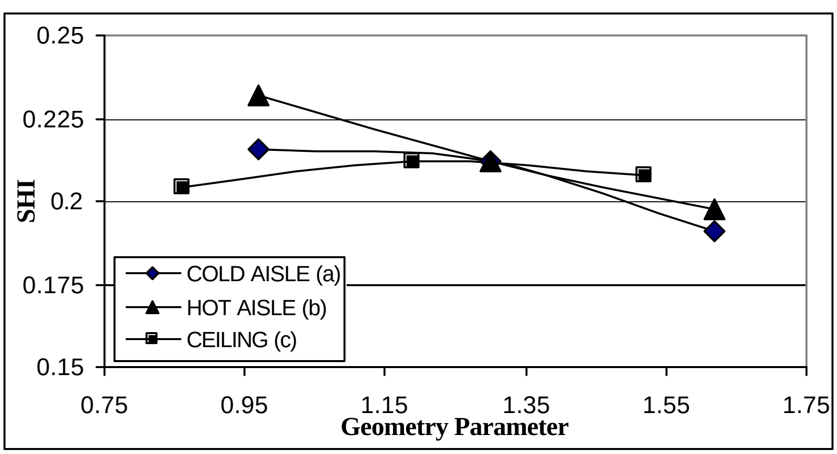

Figure 6: Variation of SHI with Geometry Parameters for Room Return

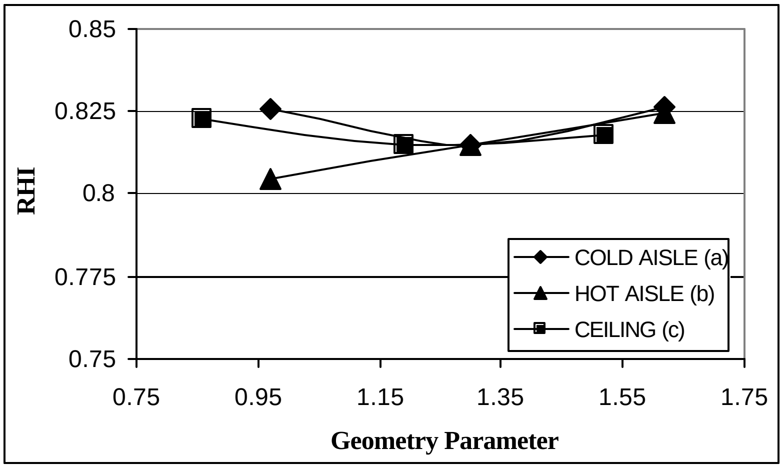

Figure 7: Variation of RHI with Geometry Parameters

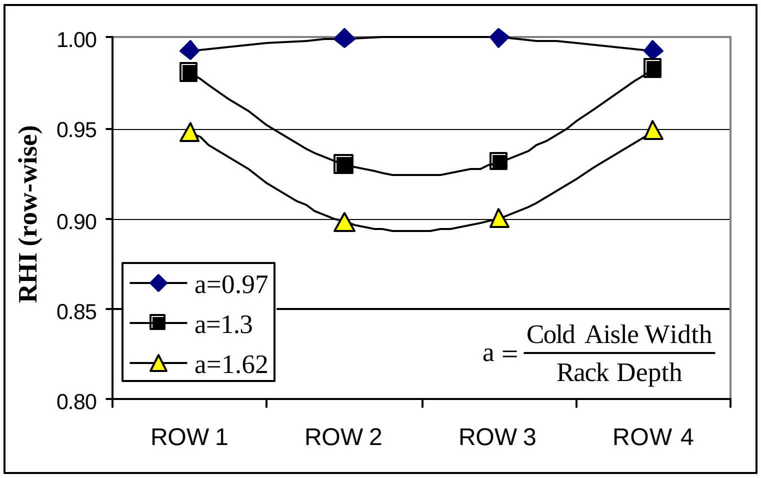

Figure 8: Variation of row-wise RI with cold aisle geometry parameter "*a*"

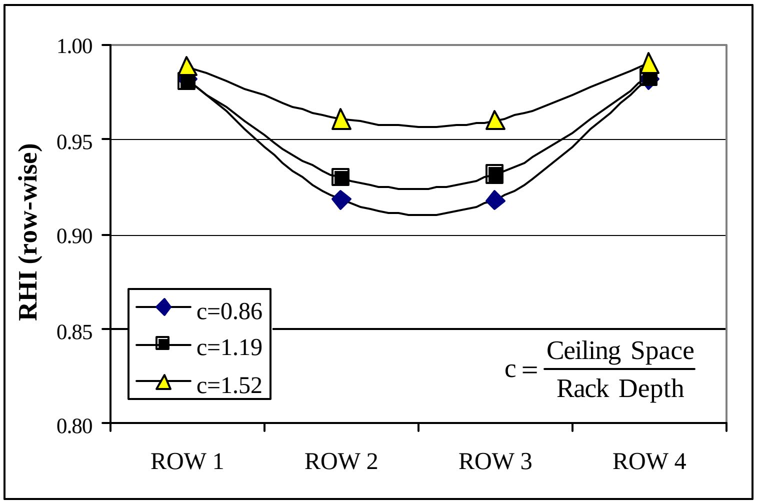

Figure 9: Variation of row-wise RI with ceiling space geometry parameter "*c*"

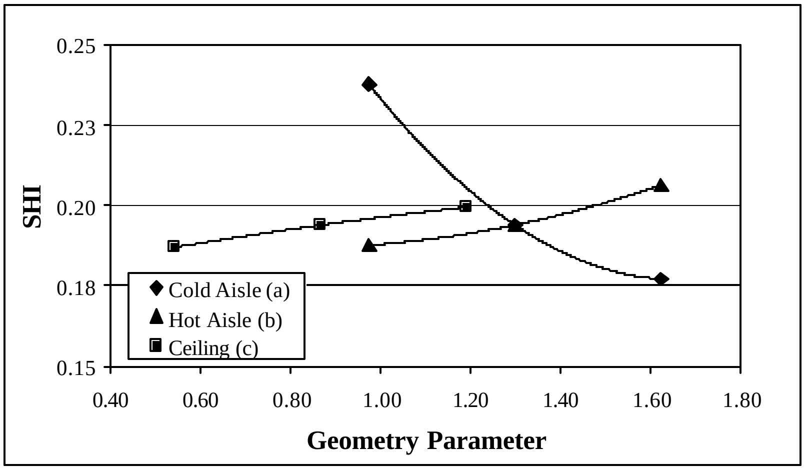

Figure 10: Variation of SHI with Geometry Parameters for Ceiling Return

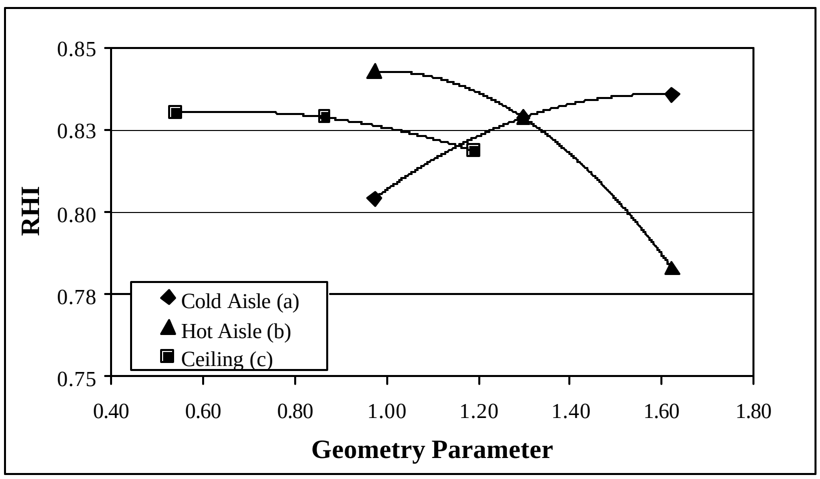

Figure 11: Variation of RHI with Geometry Parameters for Ceiling Return

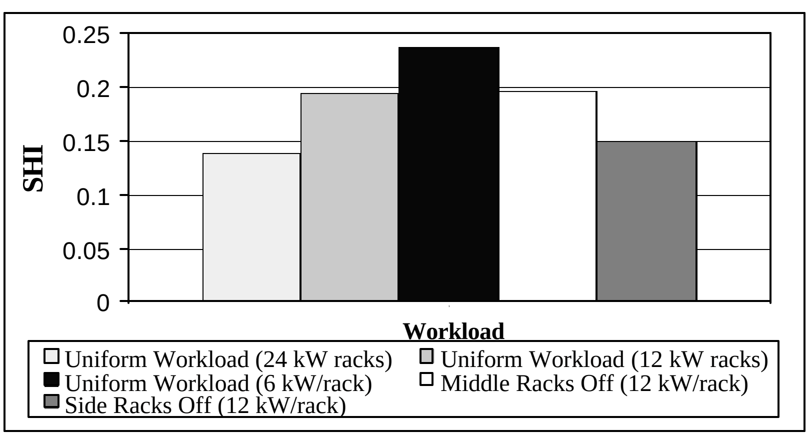

Figure 12: Variation of SHI with Data Center Equipment Workload

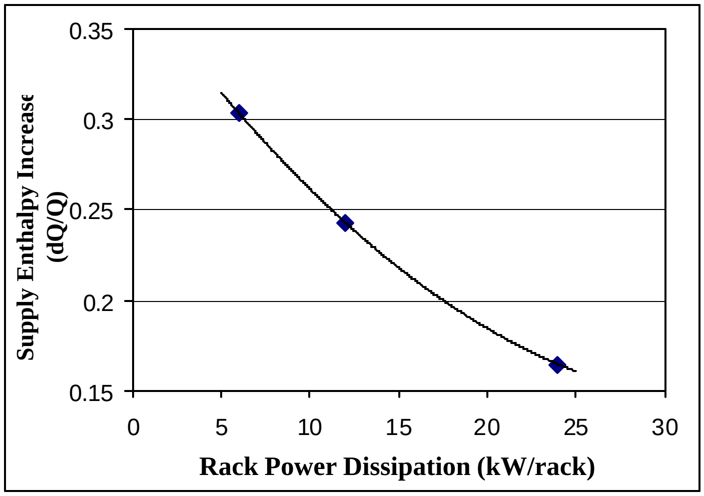

Figure 13: Supply Air Enthalpy Increase vs. Data Center Power Dissipation