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A HYBRID METHODOLOGY FOR THE OPTIMIZATION OF DATA CENTER ROOM LAYOUT

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ABSTRACT

Today's data centers are designed for handling heat densities of 1000W/m^2 at the room level. Trends indicate that these heat densities will exceed 3000W/m^2 in the near future. As a result, cooling of data centers has emerged as an area of increasing importance in electronics thermal management. With these high heat loads, data center layout and design cannot rely on intuitive design of air distribution and requires analytical tools to provide the necessary insight to the problem. These tools can also be used to optimize the layout of the room to improve energy efficiency in the data center. In this paper, first an under floor analysis is done to find an optimized layout based on flow distribution through perforated tiles, then a complete Computational Fluid Dynamics (CFD) model of the data center facility is done to check for desired cooling and air flow distribution throughout the room. A robust methodology is proposed which helps for fast, easy, efficient modeling and analysis of data center design. Results are displayed to provide some guidance on the layout and design of data center. The resulting design approach is very simple and well suited for the energy efficient design of complex data centers and server farms.

KEY WORDS

Computational Fluid Dynamics (CFD), Data centers, Under floor analysis, TileFlow, Raised floor data center, Flovent, CRAC (Computer Room Air Conditioning)

INTRODUCTION

Continued advances in microprocessor technology and demand for higher performance density have together increased the power density of computers significantly. For example, 1U servers are now exceeding 300W and are pushing rack powers to unprecedented levels. Manufacturers are all indicating that rack powers of over 20kW will be the norm in not too distant future. Fig 1. shows the projections published by the Uptime Institute in 2000 for IT products. Industry experts are already arguing that the Uptime projections may not be aggressive enough.

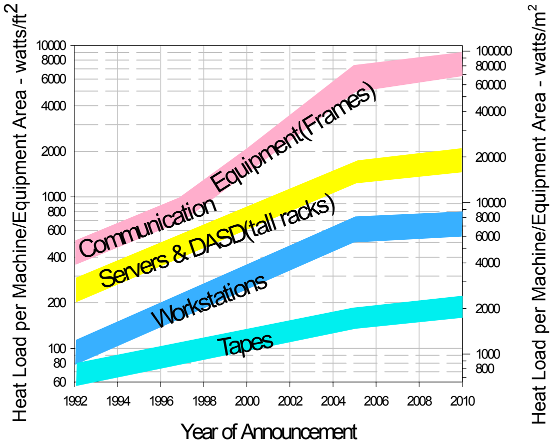

Figure 1. Heat Density Trends and Projections for IT Products. Uptime Institute white paper [1]

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In a typical data center these racks are placed on a raised floor area, which serves as plenum allowing cooled air to move below the racks then up through perforated floor tiles to cool the racks and ultimately being drawn back to the CRAC units. These racks are typically 0.6m wide, 2m high and as much as 1m deep.

Today's data centers are usually designed to handle heat densities of up to 1000W/m^2 at the room level. Trends indicate that power densities will exceed 3000W/m^2 in the near future. As a result of these high heat loads, data center layout and design cannot rely on intuitive design of air distribution. Since data centers are measured on their ability to generate revenue per square meter, the effective use of the room is extremely important. The customer wants to squeeze as much as possible into the data center.

In the past three years there has been a significant increase in effort to the study of data center architecture through modeling and simulation. References [1, 2] describe the increase in heat load of data centers. Techniques such as creation of "hot aisles" and "cold aisles" have been proposed and implemented [3]. Design and implementation of a new technology for future data center cooling is discussed in [4]. CFD modeling and analysis of data center is presented in reference [5] for the verification of the technology presented in [4]. The importance of under floor analysis for a raised floor data center design is discussed in [6]. Measurements and predictions of flow distribution through perforated tiles was undertaken in [7]

Although there has been an effort to study the air flow distribution in the floor decoupled from the data center room, as well as data center simulation covering the entire room, there has little study that integrates both under floor and room [8]. In this paper a robust methodology is proposed to design an energy efficient data center for any given computer and physical infrastructure.

NOMENCLATURE

C_p = specific heat capacity
G = volumetric air flow rate
K = loss factor based on approach velocity
Q = heat load
T = temperature
ΔP = pressure drop
ΔT = temperature change
ρ = air density

Subscripts

in = inlet of rack
out = exit of rack

MOTIVATION

Data centers are the "nerve centers" of new digital economy. Today traditional data centers are often cooled by chilled air distributed in a raised floor and exhausted up through the perforated tiles located in front of the rack footprint. With ever increasing heat loads on the data center, the reliability of its operation is becoming an issue of great concern. So investigating the data center architecture to improve the reliability, efficiency, and flexibility is of great value to enterprises hosting their compute infrastructure.

It is the Fluid mechanics of space below the raised floor (plenum) that determines the distribution of chilled air coming out of the perforated tiles [6-7] and [9]. For this reason, it is important to do the under floor analysis with modest effort in order to see if the required air flow is supplied to the tile at each rack. It is, however, also equally important to make sure how this flow gets distributed after coming out of the perforated tile by performing complete CFD analysis of full scale model later to see whether the proper cooling is assured or not.

This paper will discuss a robust methodology that encompasses both under floor analysis and above floor analysis to arrive at the best layout possible. The modeling results of both analyses will also be compared. Finally, the modeling also covers how flow gets distributed through the racks in order to ensure that rack inlet temperature is within prescribed.

PHYSICAL SYSTEM CONSIDERED

A data center having four rows with six racks in each row is considered to illustrate the proposed methodology (see Fig 2). Racks in row A and row B are assumed to have a maximum heat load of 4kW and racks in row C and row D have maximum heat loads of 6kW. For this facility, an energy balance calculation was done to decide on airflow rate required and the number of CRAC units needed.

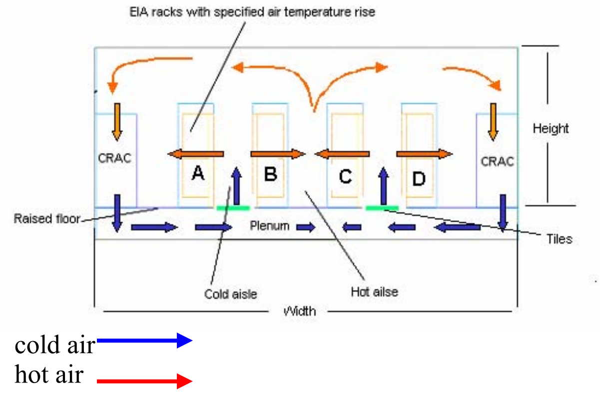

Figure 2. A simple raised floor data center configuration considered for study

Room	Variable width and depth with fixed height of 3.05m (10ft)
Plenum	Variable depth 0.305m- 0.762m (12 in – 30 in)
Perforated Tile	Fixed size of 0.61m x 0.61m (2ft x 2ft) and variable % opening area
CRAC	Width 0.914m (3ft), height 1.82m (6ft) depth 1.82m (6ft)

Table 1.Some details of room considered for study

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METHODOLOGY PROPOSED

The proposed methodology comprises of 3 steps to arrive at the best possible layout and design of an energy efficient data center for a given infrastructure. This simple method can be extended for optimizing layouts of much larger and more complex facilities. The 3 steps are as follows:

Step 1: Calculations

For a given data center, using the maximum heat load, a simple energy balance is done to arrive at the minimum CRAC flow rate required and minimum number of CRAC's needed to cool the load.

Step 2: Under floor Analysis

Different possible layouts are considered and for each layout an under floor analysis is performed to see the variation of velocity and pressure fields under the plenum. Assuming that proper cooling can be achieved by providing the correct amount of chilled airflow through perforated tiles at the footprint of each rack [9], extensive under floor analysis is done by varying the floor size, plenum depth, CRAC location, CRAC and percentage tile opening. The layout that provides the flow distribution closest to the need is chosen as the best possible layout for further analysis as in step 3.

Step 3: Complete CFD analysis of data center

With this best possible layout from Step 2, a detailed CFD model of the entire data center is developed and solved for air flow and air temperature. Post processing is done to study the airflow distribution through the racks as well as rack inlet air temperature. Proper cooling of data center is assured by making sure that this rack inlet air temperature is within optimum limits (typically less than 30^0 C.)

Application of methodology using data center in Figure 2.

Step 1.Calculations

a). Flow rate

The cooling air is normally supplied at 13^0C (55^0F) with an acceptable temperature rise (ΔT) of 11^0C(20^0F) through the rack (see Fig 3).

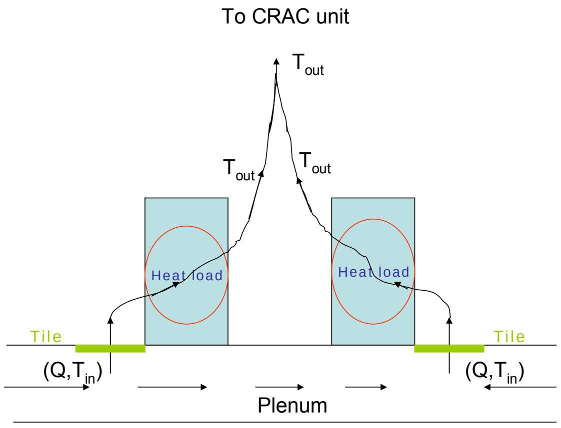

Figure 3.Schematic showing the energy balance calculation

Therefore for the given heat load Q per rack, the correct minimum amount of airflow rate G needed is calculated by using Eq. 1

$$Q = \rho\, G C_p \Delta T \qquad \text{(in kW)} \qquad (1)$$

where $\Delta T = T_{out} - T_{in} = 11^0C$

If we consider properties of air at an altitude of 3050 m, at a temperature of 13^0C this leads to Eq. 2

$$G = 6.456 \times Q \qquad (\text{in } m^3/\text{min}) \qquad (2)$$

So total flow rate required for cooling the entire data center with total heat load of 120kW under ideal conditions is calculated,

Total cooling airflow rate =774.7 m^3/min (27,380 CFM)

Four CRAC units are used to supply cool air as shown in Fig 4. CRAC units are located in such a way that hot air exhausted from the racks will easily enter the extract side of CRAC. The CRAC 1 and CRAC 2 units have flow rate of 155 m^3/min (5500 CFM) and CRAC 3 and CRAC 4 units have flow rate of 233.6 m^3/min (8250 CFM) in all cases. Note that slightly higher airflow was used in order insure adequate airflow.

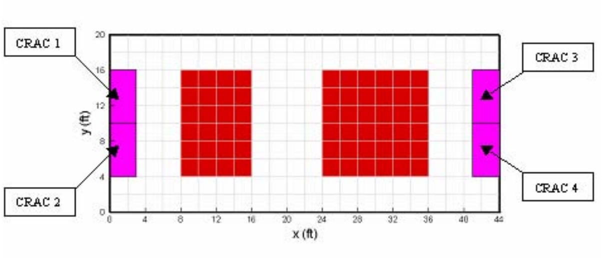

Fig 4.Layout of perforated tiles on the floor

b) Tile resistance

As the air is passed through the perforated tile from the pressurized plenum, it's velocity decreases and pressure increases. The resulting pressure drop [10] (TileFlow user manual) is given by Eq. 3

$$\Delta P = K (1/2 \rho V^2) \qquad (3)$$

ΔP – pressure drop across tile
ρ – air density
V- approach velocity
K - non-dimensional constant

Under ideal conditions, K for a perforated tile depends only on the fractional area as shown in Eq. 4

$$K = 2.8/(\text{percentage open area})^2 \qquad (4)$$

Step 2. Under floor analysis using TileFlow

The numerical modeling was done using a commercially available CFD code called TileFlow [9,10]. The modeling reveals the velocity and pressure fields of air space below the raised floor and the amount of flow rates through the perforated

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tiles. Each layout took 6-8 seconds for the solution to converge and yield tile flow rates.

Various layouts were tried out until an optimized layout is obtained on the premise that proper cooling of rack is assured if desired chilled air is delivered through perforated tiles at each rack foot print.

Constraints

1.All CRAC units are assumed to be fixed flow devices within permissible pressure developed in the plenum.

2.For all practical purposes it is considered that the pressure under the perforated tile should be less than 0.05 in wg, with this limitation the maximum flow rates possible out of each particular tile is tabulated below.

Perforated tile type	Max available Airflow
25% open	14.2 m^3/min (500 CFM)
30% open	18.4 m^3/min (650 CFM)
40% open	28.31 m^3/min (1000 CFM)

Table 2.Tabulation of maximum possible flow rates for different types of tiles.

3.As data centers are now measured on their ability to generate revenue per square meter, minimum floor size is preferred at the best interest of real estate.

Layout 1

For a layout with 25% perforated tiles, an under floor analysis was completed by varying plenum depth. For one case, the tile flow rate distribution is shown in Fig 5., and the pressure and velocity distribution plot is shown in Fig 6. These distributions are summarized in Table 3.

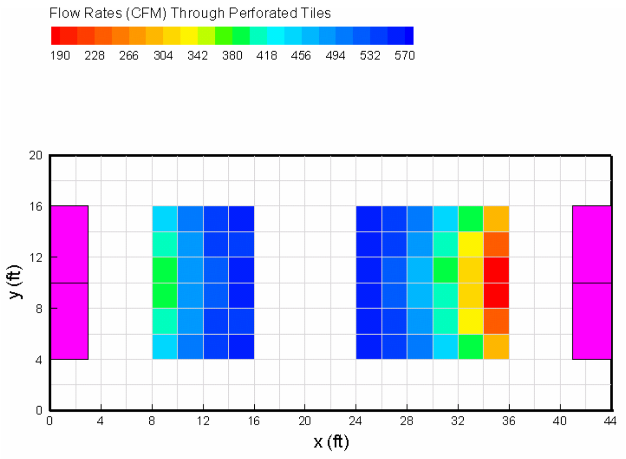

Figure 5.Tile flow rate plot for plenum depth of 12 in

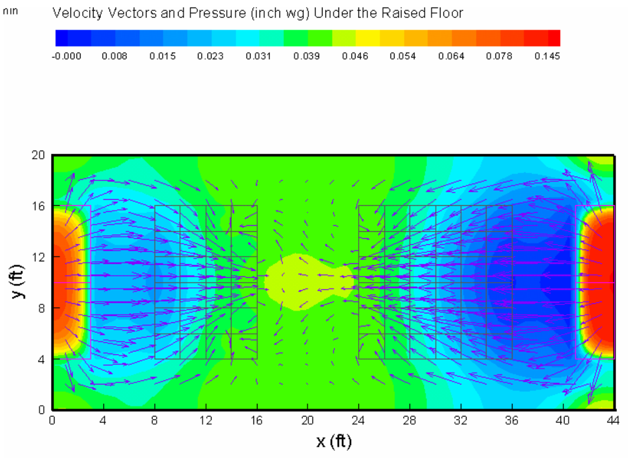

Figure 6. Pressure and velocity plot for plenum depth of 12 in

Plenum Depth (in)	Tile Flow variation (CFM)	Pressure variation (in wg)	Comment
12	190 - 570	0.000 - 0.145	High pressure
18	330 - 510	0.013 - 0.078	High pressure
24	370 - 500	0.017 - 0.055	High pressure
30	390 - 490	0.020 - 0.045	Okay

Table 3. Summary of under floor analysis for layout 1
(1in = 0.0254 m, 1CFM = 0.0283 m^3/min, 1in wg = 248.8 Pa)

Floor size for this type of layout is 81.75 m^2 (44 ft X 20 ft).

Layout 2

For a layout with 30% perforated tiles, an under floor analysis was completed by varying plenum depth. For one case, the tile flow rate distribution is shown in Fig 7., and the pressure and velocity distribution plot is shown in Fig 8. These distributions are summarized in Table 4.

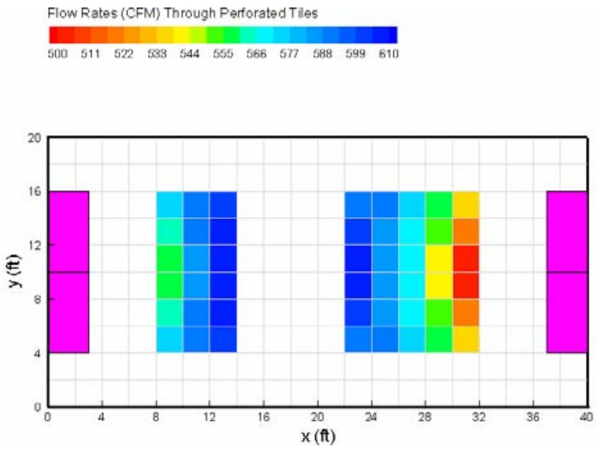

Figure 7.Tile flow rate plot for plenum depth of 30 in

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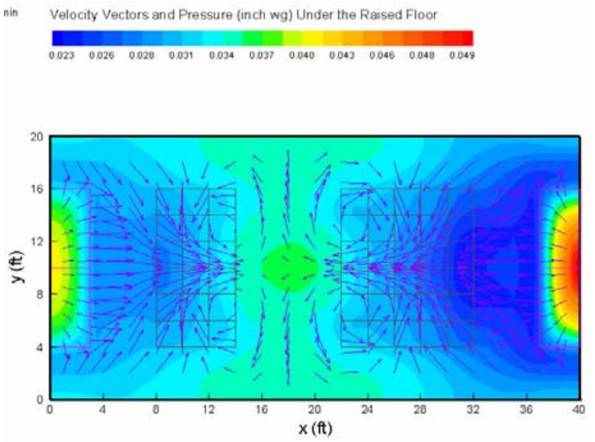

Figure 8. Pressure and velocity plot for plenum depth of 30 in

Plenum depth (in)	TileFlow variation (CFM)	Pressure variation (in wg)	Comment
12	250 - 700	0.003 - 0.149	High pressure
18	420 - 640	0.016 - 0.082	High pressure
24	470 - 620	0.021 - 0.059	High pressure
30	500 - 610	0.023 – 0.049	Good

Table 4. Summary of under floor analysis for layout 2
(1in = 0.0254,1CFM = 0.0283 m^3/min, 1in wg = 248.8 Pa)

Floor size for this type of layout is 74.32 m^2 (40ft X 20ft). For this layout when plenum depth is 30in, the pressure under the tile looks nearly uniform and good airflow distribution is observed as well.

Layout 3

For a layout with 40% perforated tiles, an under floor analysis was completed by varying plenum depth. For one case, the tile flow rate distribution is shown in Fig 9., and the pressure and velocity distribution plot is shown in Fig 10. These distributions are summarized in Table 5.

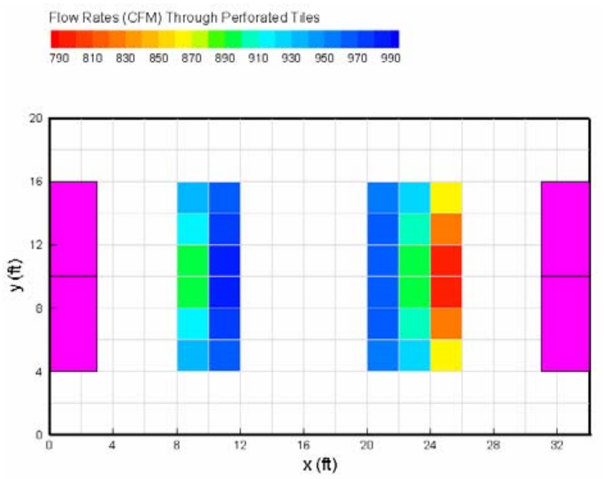

Figure 9.Tile flow rate plot for plenum depth of 24 in

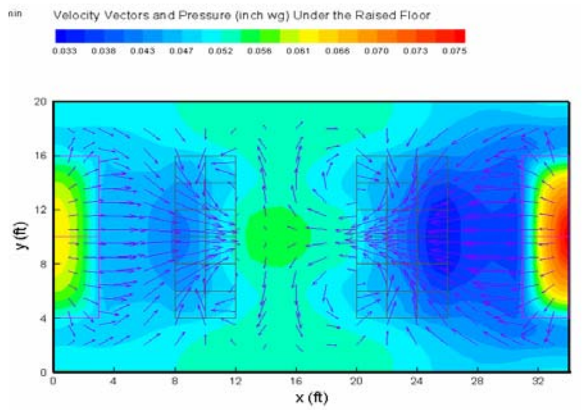

Figure 10. Pressure and velocity plot for plenum depth of 24 in

Plenum depth (in)	Tile Flow variation (CFM)	Pressure variation (in wg)	Comment
12	530 - 1100	0.014 - 0.165	High pressure
18	720 - 1010	0.028- 0.098	High pressure
24	790 - 990	0.033 - 0.075	High pressure
30	820 - 980	0.036 - 0.064	High pressure

Table 5. Summary of under floor analysis for layout 3
(1in = 0.0254,1CFM = 0.0283 m^3/min, 1in wg = 248.8 Pa)

Floor size for this type of layout is 63.17 m^2 (34ft X 20ft). The main problem with this layout is higher plenum pressure because once the plenum pressure reaches a certain it will start impacting the CRAC flow rate; and flow rate will decrease as the plenum pressure increases.

From Layout 2, it is very clear that variation in pressure beneath the perforated tiles is much less, which is favorable for providing uniform flow distribution. Ideal flow balancing is near impossible but the best layout appears to be layout 2 since it is within 12% of the goal.

Step 3. Complete CFD analysis using Flovent

Using layout 2 from the previous step, a complete CFD analysis using Flovent [11] was completed to gain understanding of airflow patterns and examine the value of inlet air temperature to the racks (see Fig 10).

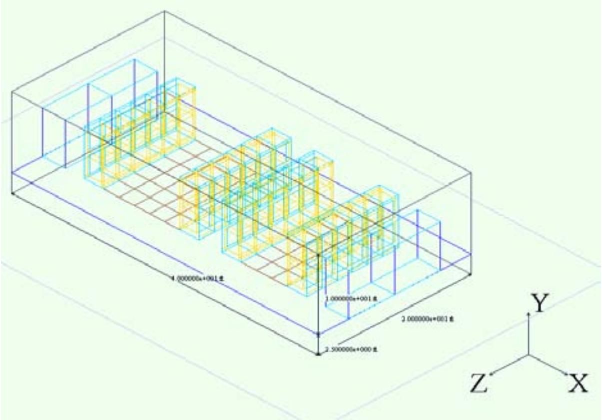

Figure 10.Complete 3-D model for the best possible layout

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BRIEF DESCRIPTION OF THE MODEL

In the Flovent model, the numerical computational domain was entire data center room. Because of high flow rates and large domain size, the flow rate was expected to be turbulent. As a result, the k-ε model turbulent mixing algorithm was used in Flovent [11].

The model was constructed using following assumptions and boundary conditions.

- Data center room was modeled as adiabatic “enclosure” made of concrete walls.
- Raised floor was modeled as collapsed “cuboid” made of chipboard.
- Each perforated tile was represented as “collapsed “resistance” with % opening area and loss coefficient based on the approach velocity.
- CRAC unit was modeled as a fixed flow device with supply temperature of 13^0C(55^0F). A “cuboid” with “fixed flow device” at both extract and supply side was used with a constant outlet temp condition on supply side.
- Each rack was modeled as an “e*nclosure*” that contains shelves with airflow from front to back (See Fig.11).

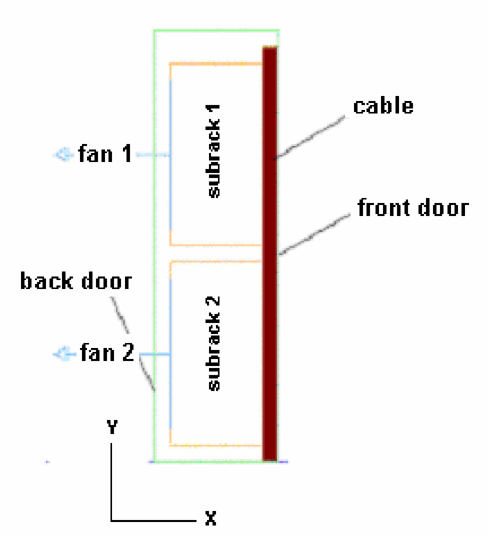

Figure 11.Simplified definition of rack in the model

The rack had ventilated doors on both front and backside, with 2 groups of sub-racks that were perforated on the front face with “fan” on their rear face. Inside the shelf, the electronics was represented by a “source” producing the heat and preventing vertical velocities. A “resistance” was used to produce the appropriate pressure drop through the shelf. Cables are connected to the front of the shelves and a “resistance” was used to represent their presence in the shelf.

In this fashion, the racks, CRAC units and perforated tiles were used to form the full-scale model of data center room. The revised k-ε model was used to account for large-scale turbulence within the room. The complete data center model was 266,684 grid cells and was solved for flow and temperature across the solution domain. Using a Pentium- 4, 2 GHz, 1.0 GB RAM computer, the problem took 55 minutes to converge to a solution.

RESULTS FROM FLOVENT

The simulation results of data center CFD model are reported to show the temperature contours at various locations.

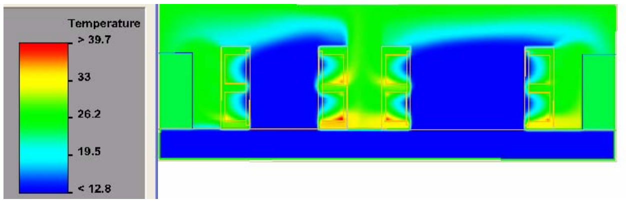

Figure 12.Temperature plot on Z-plane

Fig 12 shows the location of maximum temperature on a Z= 2.49 m (8.16 ft) plane.

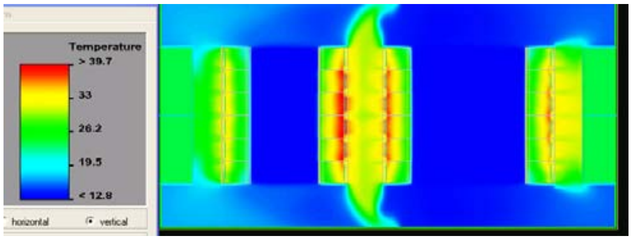

Figure 13. Temperature plot on Y-plane

Fig 13 shows the location of maximum temperature on a Y= 1.01m (3.32 ft) plane.

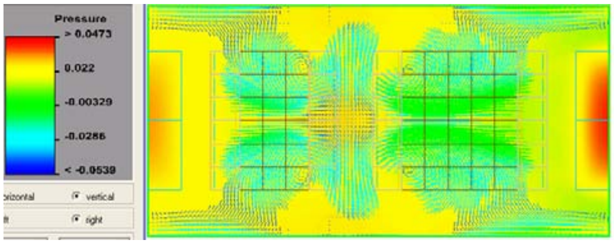

Figure 14.Pressure plot on at Y-plane

Fig 14 shows the pressure and velocity contour plots within the plenum on a Y= 0.46 m (1.5 ft) plane.

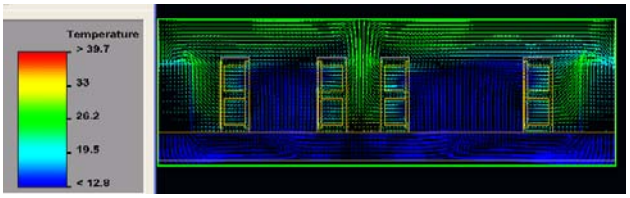

Figure 15.Velocity contour plot with temperature scale

Fig 15 clearly shows the airflow distribution from CRAC units to the plenum and then through perforated tiles into the room and passing through the racks from front to back. It can also been seen that the hot air leaving the racks in the hot aisles

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and re-entering into the CRAC units where it is subjected to cooling and re-circulation.

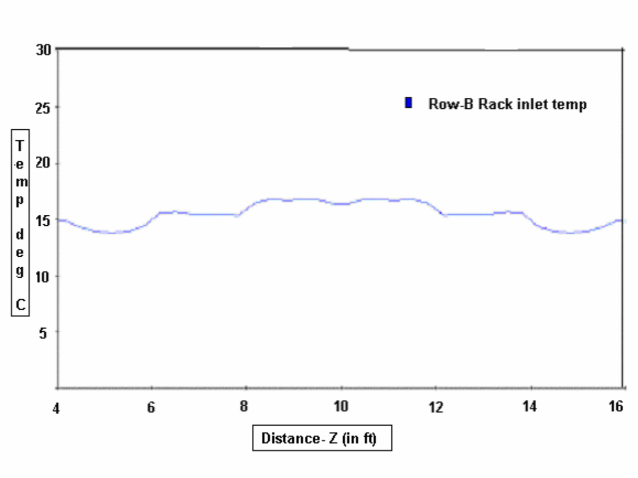

Figure 16.Rack inlet air temperatures for Row-B

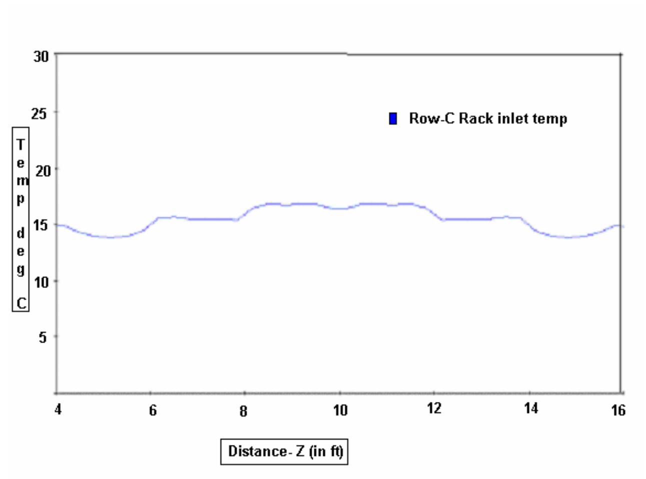

Figure 17.Rack inlet air temperatures for Row-C

Fig 16 and Fig 17 show the variation of rack inlet air temperatures in Z- direction for Row-B and Row-C respectively at 0.6m (2ft) rack height i.e. Y=1.4m (4.5 ft). Similar examination of these temperatures at various heights for different rows revealed that the rack inlet air temperatures did not cross 30^0C. Thus maximum rack inlet temperature was found to be within acceptable limits. So our assumption in step 2 of the proposed methodology works well.

COMPARISION OF TILEFLOW AND FLOVENT RESULTS

A layout shown in Fig 18. was chosen to compare the results of TileFlow and Flovent for identical layout and boundary conditions. Because of space restrictions only few tiles were chosen to compare flow rates.

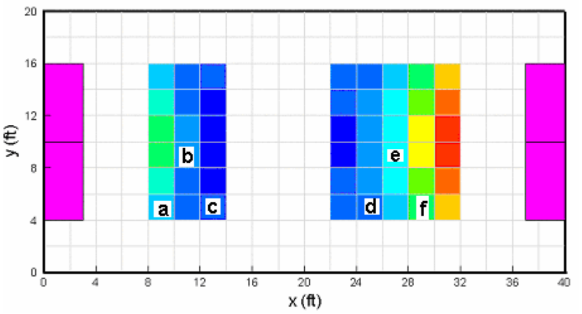

Figure 18.Schematic of layout chosen for comparison

The amount of airflow rates coming out of these tiles and pressure variation within the plenum are shown in Table 6.

Parameter	TileFlow results	Flovent results
Flow rate (in CFM)		
Tile a	574	585
Tile b	586	593
Tile c	600	592
Tile d	589	576
Tile e	567	559
Tile f	558	560
Pressure (in wg)		
Plenum pressure	0.023 – 0.049	0.022-0.047

Table 6.Comparison of results from each tool.
(1CFM = 0.0283 m^3/min and 1in wg = 248.8 Pa)

The comparison done above clearly shows that airflow rates for each perforated tile and pressure variations within the plenum predicted by TileFlow and Flovent analysis exhibit the same trend and are very close in their airflow predictions. .

DISCUSSION

Data centers are evolving systems because. equipment is frequently moved around, new computer systems are installed, and new CRAC units are commissioned. Before any actual change is implemented, it is very helpful to do the under floor analysis to check the airflow distribution to simulate the behavior of the new layouts. Under floor analysis will also help to see whether all CRAC units are used to maximum benefit and also to quickly check what happens with failed CRAC units, by analyzing failure scenarios.

So this robust methodology can be successfully employed for complex layouts to ensure that the proposed layout gives the desired airflow for the immediate and future needs and helps to build an energy efficient data center.

The allowable plenum pressure limits the maximum airflow rate obtainable from a commonly used 25 % perforated tile. Using 25% tiles, in achieving adequate cooling would require several tiles in front of each rack. This would increase the aisle space drastically, which would not economical from

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the real estate perspective. Of course, as rack power continue to rise, this problem will only get worse.

The use of perforated tiles with higher percentage opening area is still an option. Unfortunately, this will cause large variation in plenum pressure which will result in mal-distribution of chilled air and hence, flow balancing will become a daunting task.

Increasing the plenum depth reduces the plenum pressure variation and helps to achieve more uniform plenum pressures, which is desirable to avoid mal distribution of chilled air.

SUMMARY/CONCLUSIONS

This paper highlights a proposed methodology for data center analysis using a three-step method.

1. A simple energy balance
2. An under floor only flow analysis
3. A complete CFD analysis for flow and temperature.

The importance of under floor analysis has been emphasized [9] and proven to be an excellent component of this new robust methodology for the optimization of the data center. This is then followed by complete CFD analysis of the room to determine if adequate cooling is provided for the racks. The methodology has been demonstrated for better design of a simple raised floor data center configuration.

Finally, this paper also compared the results of TileFlow and Flovent and showed that results are consistent.

FUTURE WORK

As the rack heat loads are fast approaching 20kW in not so distant future, cooling of such high heat density facilities will be a great challenge. At these high heat loads traditional raised floor data center design may not be sufficient to meet these cooling requirements. As a result, it is expected that new technologies, innovations and methodologies will emerge. Our future work will explore some of these future solutions.

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