EFFECT OF CRAC LOCATION ON A FIXED RACK LAYOUT OF A DATA CENTER

by

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ABSTRACT

EFFECT OF CRAC LOCATION ON A FIXED RACK LAYOUT OF A DATA CENTER

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Microprocessor driven escalation of thermal management needs has resulted in significant cooling challenges at the data center facility level, which can house thousands and tens of thousands of heat producing processors. Raised floor air ducting is the most common configuration, where chilled air from the air conditioning units is forced into the room via a under floor plenum and through perforated tiles on the floor. The hot air from the racks finds its way to the top of the air conditioning units and is then cooled and blown into the under floor plenum. The temperature at inlet of the racks is the key performance metric in evaluating the cooling performance data center facility. This rack inlet temperature is influenced by the air flow patterns within the room, which in turn is a function of several different factors such as the rack flow rates, the

perforated tile location, the CRAC location, the room dimensions and geometry. In this project the effect of the CRAC location of a fixed rack layout is studied. A representative raised floor data center was numerically modeled using commercially available software. The results of the simulations are utilized to gain insight into the flow patterns and the data from the parametric analysis is used to quantify the effect of CRAC (chilled air conditioning unit) location with respect to the computer racks.

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CHAPTER 1

INTRODUCTION TO DATA CENTERS

1.1 Background

Data centers are the buildings with high concentrations of computers and digital electronic equipment dedicated to hosting websites, supporting e-commerce and providing an essential service for the new digital economy.[1] Data centers centralize and consolidate Information Technology (IT) resources, enabling the organizations to conduct business around the clock and around the world. [2]

Data centers house a high density of digital electronics and computer technology requiring higher quality and more reliable electric power than most commercial buildings. They are essentially building shells packed with computers, power conditioning equipment, control electronics, and back up power systems along with air conditioning systems to keep the equipment cooled to optimum operating temperatures, generally 68-70°F. The computes used in data centers are generally known as servers. Multiple servers are secured in racks that typically have 2 foot by 21/2 foot footprint and 70 to 87 inches high. These racks are placed on a raised floor, which serve as a plenum allowing cooled air to move below the racks, then up through perforated floor tiles to cool the racks. This cool air is sucked in the racks aided by fans and the heated air thus rejected by these server racks is drawn back by the A/C systems.

Power supplies, conditioning equipment, and back up generators are placed separate from raised floor area. [3]

Figure 1.1 shows a typical raised floor data center

Fig 1.1 Raised floor data center showing racks and perforated tiles

1.2 Types of Data Centers

Data centers fall into two major categories,

1) Private Data Centers (PDC)

2) Internet Data Centers (IDC)

Private data centers are owned and operated by private corporations, institutions or government agencies for the prime purpose of supporting data processing and web oriented services for their own organizations.

Internet data centers are owned and operated by traditional telecoms, and regulated competitive service providers or other types of commercial operators to provide outsourced IT services, access through internet connectivity.

There are functions common to any data center, for the most part, all data centers provide,

- Internet access and wide area communication
- Application hosting
- Content distribution
- File storage and back up
- Database management
- Fail safe power supply
- Adequate HVAC and fire suppression
- High performance cabling infrastructure
- Security

1.3 ASHRAE Power Trends & Heat Density Issues

- Thermal Management Consortium / Uptime Institute

- Based on equipment footprint
- Confusion in calculating area
    - Blade
    - Cabinet
    - Support Equipment
    - Interior Facility
    - Exterior facility
- Different Scenarios yield variation in watts/sq.ft. (16:1)

Fig below illustrates the power trends for various electronic systems

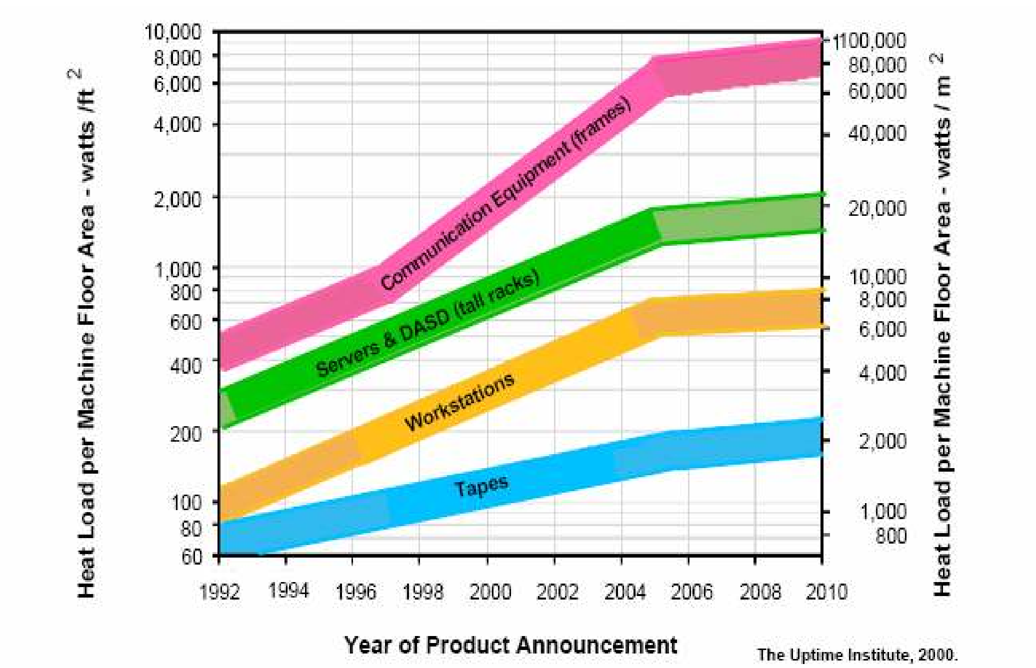


Fig 1.2 Heat Density Trends, The Uptime Institute, 2000

ASHRAE Modified Power Trends extended up to 2014 is given as below:

- All trends projected out to 2014

- The Servers & Disk Storage Systems trend was split into two distinct categories with different trend projections:
  - Compute Servers
  - Storage Servers
- The Compute Servers trend was further split into two categories to indicate another trend projection split:
  - Compute Servers 1U, Blade and Custom
  - Compute Servers 2U and Greater
- The Communication Equipment trend was split into two categories with different trend projections:
  - Communication Equipment – High Density
  - Communication Equipment – Extreme Density

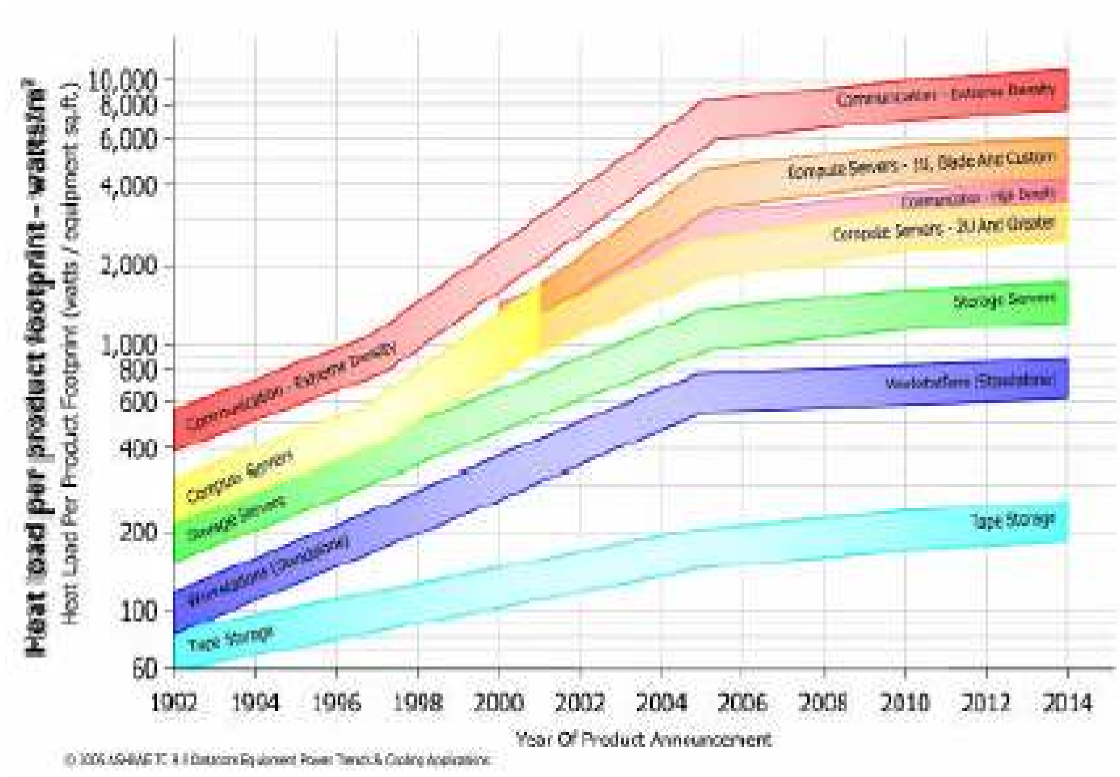


Fig. 1.3 Power Trends in Compute servers, ASHRAE TC 9.9, 2006
Courtesy by Dr. Schmidt, IBM Corporation & ASHRAE TC 9.9 2006

1.4 Efficient Allocation of Space

Proper allocation of floor space is a major issue in good data center design. Table 1.1 provides information on the raised floor area usage. A good design must take care of all variables to deliver high density and availability, with adequate cooling and cabling infrastructure flexibility.

Table 1.1: Approximate usage of raised floor space area. Source: Uptime Institute

Area	Usage
Computer hardware footprint (servers, rack-mounted equipment, and telecommunication frames)	25-30%
Service clearance around products (allows for movements of cooling air and personnel)	30-35%
Main aisles, support columns, other non electrified areas	20%
Infrastructure support equipment (in room UPS's, PDU's, Cooling systems, Air handling equipment and other support electronics)	20%

Racks, Cables and Support Infrastructure: Data centers employ a wide variety of racks, enclosures, electrical and communication path connectivity products like cable tray and ladder racking. They must in all ways, individually and together, support four key areas of need: (i) Climate control, (ii) Power management, (iii) Cable management and (iv) Security and monitoring.

Redundancy and Path Diversity: These are the issues concerning cabling, power, internet access and carrier services. Tolerance for downtime measured against equipment costs and floor usage must be closely examined and matched against success criteria. Data centers must carefully weigh the cost of downtime with respect to their revenue model.

Security: Data centers are the nerve centers of new digital economy. Company and customer data should be treated like money in the bank vault. PDC and IDC's must take very definitive measures to limit access only to authorized personnel, ensure use of proper fire prevention and life safety systems while minimizing the potential equipment damage.

Storage: As the volume of stored data escalates and management of content becomes more challenging, additional or complimentary connectivity concerns must be addressed in data center design to accommodate for more flexibility and most efficient and effective use of space.

Flexibility and Adequate Connectivity: This is the key in bringing users online quickly and effectively, whether in PDC or IDC environment. Time is very critical whether provisioning new data center customer, upgrading their bandwidth, or leased services, or providing a quick, coordinated and efficient move/add/change services to a corporate user base. Therefore performance, flexibility, headroom, patching and error-resistance are all the variables in the same crucial design formula.

1.5 Different Room Layouts of Data Centers

Data centers are typically arranged into hot and cold aisles as shown in Figure 1.5.1. This arrangement accommodates most rack designs which typically employ front to back cooling and somewhat separates the cold air exiting the perforated tiles (for raised floor designs) and overhead chilled air flow (for non-raised floor designs) from the hot air exhausting at the rear of the racks. The racks are positioned on the cold aisle such that the fronts of the racks face the cold aisle. Similarly the rear of the racks face each other and provide a hot air exhaust region. This layout allows the chilled air to wash the fronts of the data processing (DP) equipment while the hot air from the racks exit into the hot aisle as it returns to the inlet of the air conditioning (A/C) units. [5] Fig 1.5.1 Alternate Hot & Cold aisles Arrangement in Data Centers [5]

With the arrangement of DP equipment in rows within a data center there may be zones where all the equipment within that zone dissipates very high heat loads. This arrangement of equipment may be required in order to achieve the performance desired by the customer. These high performance zones (shown in Figure 1.5.1) can provide significant challenges in maintaining an environment within the manufacturer's specifications.

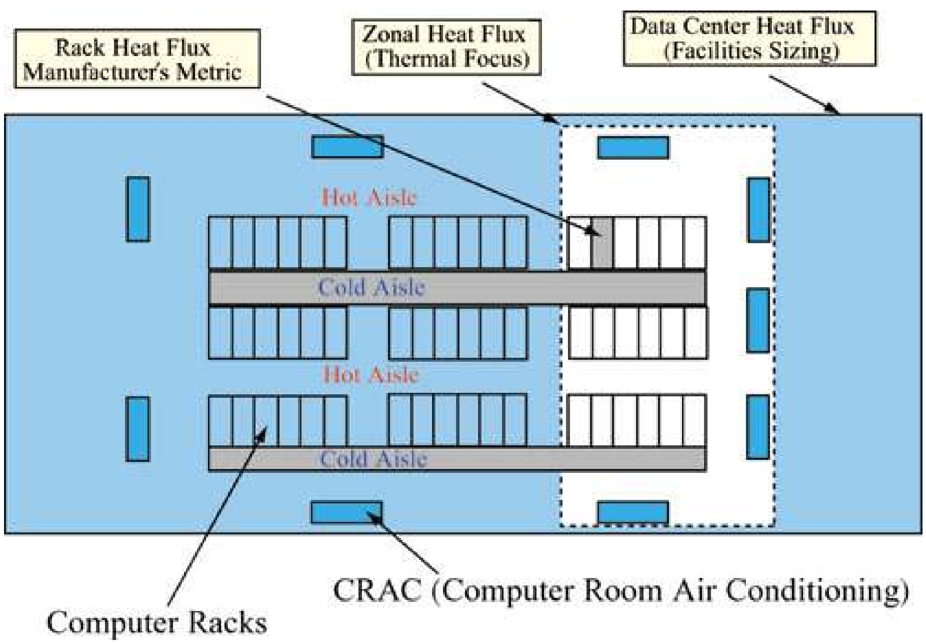


Fig 1.4 Alternate Hot & Cold Aisle Arrangement in Data Centers [5]

Figure 1.5 shows trends for these high heat flux zones using the equipment power trends of Figure 1.4.

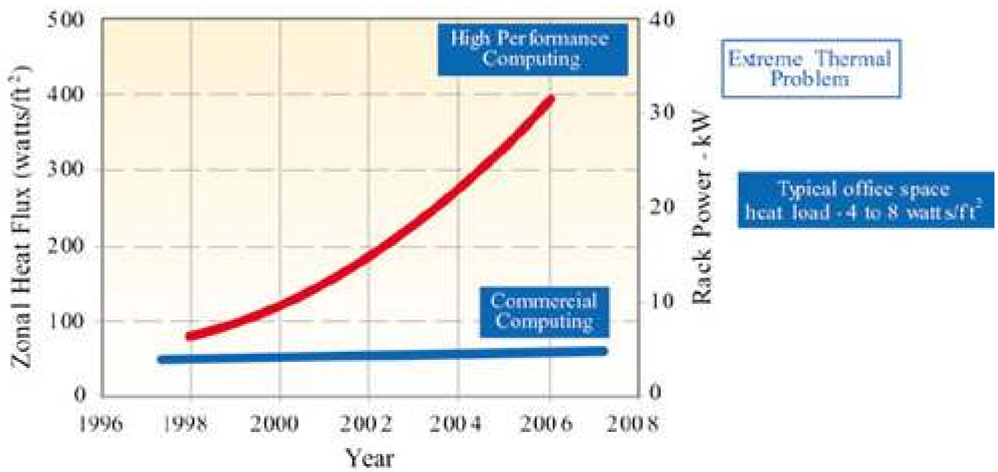


Fig 1.5 Zonal heat fluxes (watts/ft^2)

Room Air Flow Designs [5]

Air flow distribution within a data center has a major affect on the thermal environment of the DP equipment located within these rooms. A key requirement of manufacturers is that the inlet temperature and humidity to the electronic equipment be maintained within the specifications. To provide this environment, customers of such equipment typically employ two types of air distribution systems. These are briefly described below.

Non-Raised Floor Room Cooling [5]

Cooling air can be supplied from the ceiling in the center of the room, where computers are located, with exhausts located near the walls. Short partitions are installed around the supply opening to minimize short-circuiting of supply air to returns. Similarly cool air from a more distributed area of the ceiling can be supplied with exhaust located around the perimeter or a return in the floor. Alternatively a design employed by the Telecom industry and more recently employed in the computer industry utilizes heat exchangers located above the racks near the ceiling. The racks are arranged using the hot and cold aisle concept where hot air from hot aisles enter the heat exchangers and, once cooled by the heat exchangers, is forced down into the cold aisles using fans mounted to the bottom of heat exchangers.

Raised Floor Room Cooling [5]

Computers typically have many cables connecting the components within a rack and between racks. To maintain a neat layout, a raised floor (also known as false floor or double floor) is used and all interconnect cabling is accomplished under the raised floor. In many cases this space under the raised floor can be used as an air supply plenum with the use of perforated tiles exhausting chilled air. Similarly, it is possible to have a false ceiling (also called a dropped ceiling) in the room with the space above the false ceiling used as the air supply or the return plenum. The air flow can be from floor to ceiling, ceiling to floor, floor to exhausts located in the walls or other locations in the room.

1.6 Most Common Issues Faced in Data Center Design

Energy efficient technologies, smart design and proper preventive maintenance procedures can significantly decrease data center energy demands. During the time of rapid data center expansion for many people in the internet hosting industry, getting a new data center online as fast as possible was the overriding factor in designing and building data centers. However haste to install data centers, lack of accepted and standardized design guidelines, and lack of financial incentives to save energy has led to inefficient design, poor design implementation, and use of energy-inefficient technologies in data center.

Due to multidisciplinary work involved in the design and construction of data center, various issues need to be addressed beforehand. These issues are critical because once data centers are up and running, they have zero tolerance for downtime and other problems caused by poor design or flawed installations. Following is the list of issues that needs to be addressed by the scientific community,

- **Professional Engineering:** With many electrical, mechanical and communication variables involved, successful data center design and constructions needs professional engineering. Data centers are unique environments, so developers can benefit from the architect, engineering and consulting community, along with construction firms with experience in designing and building data centers.

- **Power Requirements:** Packing as many servers as possible into a rack or cabinet means more revenue generated per square foot. Data centers today often specify 100 W per square foot and many are provisioning for double of that. Servers are supplied with dual power supplies, each having own power cord. So racks and cabinets must be designed must be designed to provide plentiful power strips and cable routing. Environmental monitoring (fan control, incoming voltage and UPS) and access control can provide additional and management.

CHAPTER 2

CFD MODELING OF DATA CENTERS

2.1 Introduction to CFD Modeling Technique [12]

The solution procedures in FLOTHERM are based on CFD techniques. CFD is concerned with the numerical simulation of fluid flow, heat transfer and related processes such as radiation.

The objective of CFD is to provide the engineer with a computer-based predictive tool that enables the analysis of the air-flow processes occurring within and around electronics equipment, with the aim of improving and optimizing the design of new or existing equipment.

The CFD techniques that are in use today evolved from techniques developed in response to the stimuli of the `high-technology' aerospace and nuclear power industries. Today CFD applications are to be found in many industries, research institutes and universities.

2.2 Mathematical Representation [12]

The mathematical simulation of fluid flow and heat transfer phenomena involves the solution of a set of coupled, non-linear, second order, partial differential equations.

FLOTHERM uses what is known as the primitive variable treatment in that the field variables that it solves are:

u, v and w, the velocity resolutes in cartesian coordinate directions x, y and z,

p the pressure,

T the temperature of the fluid and/or solid materials.

These variables are functions of x, y, z and time.

The differential equations that these field variables satisfy are referred to as conservation equations. For example u, v and w satisfy the momentum conservation equations in the three coordinate directions. Temperature satisfies the conservation equation of thermal energy. The pressure does not itself satisfy a conservation equation, but is derived from the equation of continuity which is a statement in differential form of the conservation of mass.

2.3 Domain of integration [12]

The domain of integration (or solution domain) is the region of space within which the differential equations are to be solved. In addition to setting the extent of the domain, problem specification involves the provision of boundary conditions, viz. a specification of the values (or fluxes) of the variables at these boundaries. Problem specification also requires the properties of the fluid to be described, viz. its conductivity, density, viscosity, specific heat, expansivity and diffusivity.

2.4 The Solution Method [12]

The conservation equations and their associated boundary conditions do not have a general analytical solution. There are particular solutions of the equations for simple situations (e.g. laminar flow in a channel). But for the vast majority of cases of practical interest, the equations can only be solved by means of numerical integration. CFD provides the means of numerical integration.

In the CFD technique used in FLOTHERM, the conservation equations are discretized by sub-division of the domain of integration into a set of non-overlapping, contiguous finite volumes over each of which the conservation equations are expressed in algebraic form. These finite volumes are referred to as `grid cells', `control cells' or quite simply as `cells'. The layout for the grid and velocities for a grid having a total of 224(7*8*4) cells is shown below.

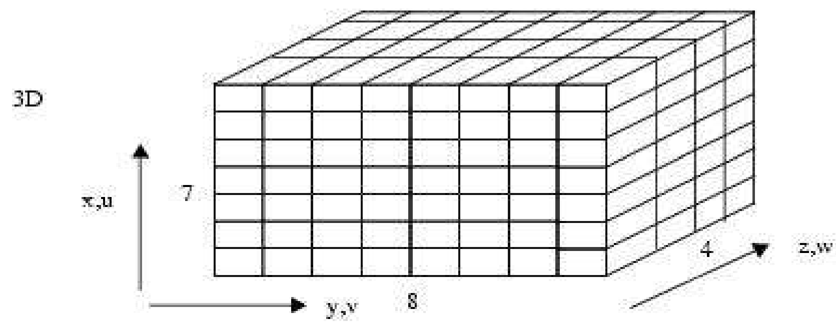


Fig 2.1 System Grid [12]

The discretization results in a set of algebraic equations, each of which relates the value of a variable in a cell to its value in the nearest-neighbor cells.

For example letting T denote the temperature, the algebraic equation connecting T in a cell to its value in its six neighboring cells (denoted $T1$,$T2$,$T3$,$T4$,$T5$,$T6$) and its value at the old time step (denoted $T0$) is written:

$$T = \frac{(C_0T_0 + C_1T_1 + C_2T_2 + C_3T_3 + C_4T_4 + C_5T_5 + C_6T_6 + S)}{(C_0 + C_1 + C_2 + C_3 + C_4 + C_5 + C_6)}$$

where the Cs denote the coefficients that link the in-cell value to each of its neighbor-cell values. S denotes the terms that represent the influences of the boundary conditions (if any), e.g. a source of heat.

If there are a total of n cells in the integration domain, there are n algebraic equations to solve for each of the field variables $T, u, v, w, p,$ i.e. there are 5n equations to solve. Thus, for example, for a grid of 50000 cells there are 250000 equations to be solved, or more if the KE turbulence model is in use.

Expressed in the above form the equations appear to be linear, but they are not really so because the coefficients (i.e. the Cs) are themselves functions of T, u, v, w and p. This appearance of linearity, however, is exploited as follows: at each **outer iteration** the coefficients are calculated once only and then taken as constant while the resulting algebraic equations are solved by means of **inner iteration.**

Localised Grid [12]

For localized grids, a section of the base grid is subdivided as shown in the figure below.

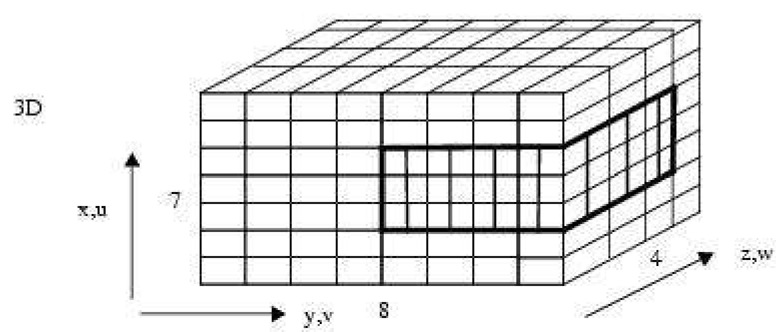


Fig. 2.2 Localised Grid [12]

The cell values for a localized grid are solved in exactly the same way as for the base grid, with the following exceptions.

Cells in the base grid which are overlapped by the localized grid are not solved for. Cells in the base grid adjacent to the localized grid feel the effect of the localized grid through extra terms and coefficients: any of the terms C_i, T_i (i = 1, 6) are replaced by a sum over coefficients and temperatures from the adjacent localized grid cells in the above equation for T.

Cells in the localized grid on its boundary with the base grid are affected by adjacent cells in the base grid through *halo cells* which have the same boundary cross-section as the localized grid cells, and the normal width of the adjacent base grid cell. These cells provide the neighbor T_i values required, which are interpolated from the base grid values.

These extra relationships are all included in the inner iteration algebraic solution. The same relationships exist between a localized grid nested in another localized grid, and its parent.

Summery of Algorithm used:

The algorithm is summarized by the following example for a 3D simulation of flow and heat transfer:

a. initialise the fields of pressure, temperature and velocities,

b. increase outer iteration count by 1,

c. set up coefficients (i.e. the Cs) for temperature field, T,

d. solve linearized algebraic equations for the value of T in each cell by performing a number of inner iterations,

e. repeat c) and d) for field variables u, v and w,

f. solve the continuity equations in a similar manner and make any associated adjustments to pressure and velocities,

g. check for convergence and return to b) if required.

2.5 Grid Definition [12]

The finer the grid used (i.e. the greater the number of grid cells) the closer the algebraic equations approximate to the differential equations from which they originated.

Normally more grid is used in regions of the domain where gradients of the variables are expected to be greatest. However, grid-independence of the solution alone is not enough to ensure that the solution obtained simulates what in reality occurs because other modeling assumptions (e.g. the accuracy of the boundary condition information supplied, the adequacy of the turbulence model) may be determining factors in the agreement of the simulation with physical reality.

Consequently, the outcome of a CFD simulation must be inspected carefully with a view to assessing the physical realism of the results obtained.

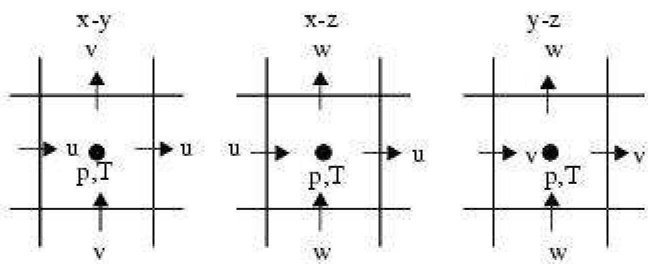
2.6 Interpretation of Results [12]

Scalars

The discretized values of scalar field variables like temperature and pressure are located at the centers of the grid cells.

Staggered Vectors

However, the discretized values of the components *u, v* and *w* of the velocity vector field are located at the faces of the grid cells. This arrangement is depicted schematically in the X-Y, X-Z and Y-Z planes for a single cell:



This displacement from the cell centers of the locations of the values of the velocity components is known as staggering and is a recurrent theme in CFD methodologies employing the finite-volume representation described above.

When displaying results in FLOTHERM, you have the option of viewing the velocity values either at the cell faces or interpolated to the cell center.

2.7 Solving the Project [12]

The FLOTHERM solution activates the CFD algorithms which provide an integration of the fluid flow and heat transfer equations within the solution domain.

The solution may be monitored in profile plots of the convergence of residual errors and/or variable values at monitored points.

2.8 Controlling the Solution [12]

Normally, the default settings are sufficient to achieve convergence. However, if convergence problems are encountered, there are solution controls available to help.

This following sections provide an overview of the FLOTHERM solution process and describes the dialogs supplying the solution controls.

2.8.1 Solution Process

2.8.1.1 Overview

The FLOTHERM solution activates the CFD algorithms which provide an integration of the fluid flow and heat transfer equations within the solution domain. These calculations are of an iterative nature for each grid cell in the solution domain and continue until:

a. A prescribed maximum number of iterations have been performed, or

b. A predetermined level of residual error is attained, at which time the solution is said to be converged. In this case convergence applies to the complete system and can be verified using defined monitor points.

As the solution proceeds, you can monitor its progress in the plot of the residual errors against iteration number for each variable using the Profiles application window as shown:

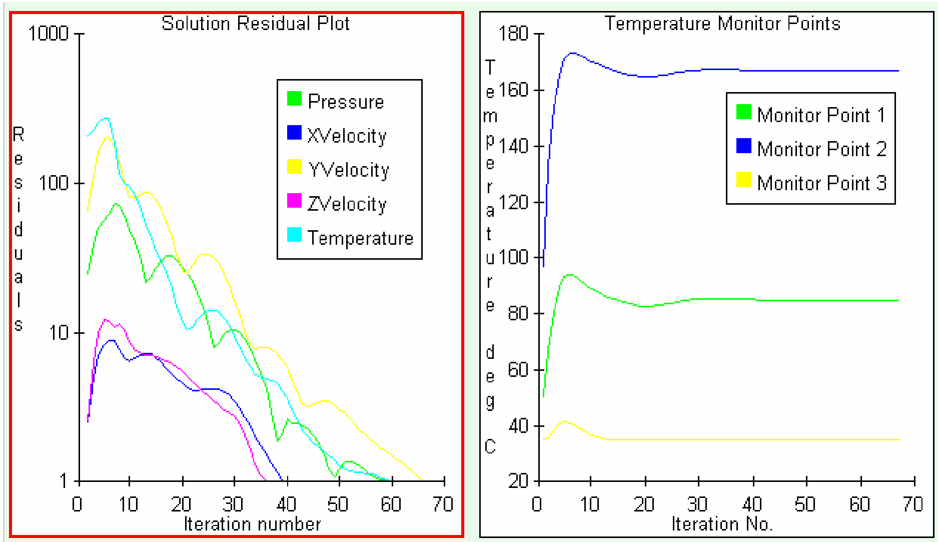


Fig. 2.3 Residual Curve & Monitor Points, Flotherm 6.1, Flomerics, U.K. [12]

2.8.1.2 Residual Errors

Residual errors represent a measure of:

a. the mass imbalance in the system (associated with pressure, P)

b. the momentum imbalance in the system (associated with the velocities U,V and W)

c. the energy imbalance in the system (associated with temperature T).

For a full description of the residual error in terms of the system equations, see "Finite Volume Equations" in "Background Theory".

Termination Residual

As the solution progresses, the residual errors should fall for each variable. The termination residual is set automatically by FLOTHERM to provide a safe margin for the majority of systems analyzed and is based on mass, momentum and energy inputs into the system as follows:

2.8.1.3 Mass Continuity

The termination residual for mass continuity, E_p, is taken as one half of one per cent of a characteristic flow rate, $\dot{M}$, within the enclosure:

$$E_p = 0.005\dot{M}$$

For an enclosure with forced inflow or outflow, $\dot{M}$ is taken as the total inlet flow rate or the total outlet flow rate, whichever is the largest. In the absence of forced flow (i.e. the pure free convection case) $\dot{M}$ is calculated as the product of the density, the Estimated Free Convection Velocity and the area of the enclosure normal to the vertical.

2.8.1.4 Velocity Components

The termination residual for the velocity components, E_{vel}, is taken as one half of a per cent of the characteristic flow rate, $\dot{M}$, multiplied by the associated characteristic velocity, V:

$$E_{vel} = 0.005\dot{M}V$$

2.8.1.5 Temperature

The termination residual for the temperature E_T, is calculated as one-half of a per cent of a characteristic heat source, Q:

$$E_T = 0.005\ Q$$

If heat sources are specified within the enclosure, Q is taken as the sum of the total heat sources or the total heat sinks. If no heat sources are present, Q is taken as:

$$E_T = 0.005\dot{M}C_p\Delta T_{typ}$$

where:

C_p = the specific heat of the fluid, and

DT_{typ} = 20°C.

2.8.1.6 Turbulence Parameters (k and epsilon)

In most calculations the production of turbulence within the solution domain is greater than that in the incoming flows. In order to compensate for this the termination criteria are less stringently set to prevent unnecessary calculation as follows:

$$E_k = 0.05k\dot{M}$$

$$E_\varepsilon = 0.5\varepsilon\dot{M}$$

Conservative Estimates

These termination residuals work extremely well in guaranteeing convergence for the majority of problems. However, they should be considered as conservative estimates, and for certain cases of problem can be too restrictive a criteria to base convergence on as discussed below.

2.8.1.7 Controlling the Solution

If your solution fails to converge or converges extremely slowly, then you can reset the solution control panels, but first consider the following rules for assessing a solution convergence problem as the problem may well lie in the project set-up.

2.8.1.8 Rules for Assessing Convergence Problems

If a solution diverges, it is almost guaranteed to be a problem definition problem. Be immediately suspicious of the set up and check all defined objects and attributes before proceeding to alter any solution control parameters.

If a solution fails to converge successfully, then it is important to check the grid. If there are poor aspect ratio grid cells and large jumps in grid size between adjacent grid cells, then this is the likely cause of the problem.

If you are happy with the set up and the grid, then and only then should the solution control parameters be adjusted.

Do not waste time forcing low-level stable or low-level oscillation convergence profiles down to a residual error level of 1. Use the monitor points and error field to sensibly assess whether the solution is converged to a defined level of accuracy, and then stop the solution.

If you do need to change the control parameters, then the following section provides an overview of how to resolve and manage the solution process.

Techniques for Controlling the Solution [12]

FLOTHERM contains a number of techniques, both automatic and manual, which can be used to optimize the solution process. In discussing their use, it is important to note that it is only possible to give general guidelines rather than hard and fast rules on how they should be altered for particular situations.

In FLOTHERM, extremely complex and highly non-linear systems involving multiple modes of heat transfer are being modeled and it is impossible to automatically generate appropriate solution control parameters that will guarantee convergence under all circumstances. The automatic settings have been designed to give a reasonable convergence profile for the majority of applications, but may need to be adjusted in more complex situations.

CHAPTER 3

FACTORS AFFECTING COOLING OF DATA CENTER

3.1 Introduction

The primary thermal management focus for data centers is that the temperature and humidity requirements for the electronic equipment housed within the data center are being met. For example, one large computer manufacturer has a 42U rack configured for front to back air cooling and requires that the inlet air temperature into the front of the rack be maintained between 10 and 32°C for elevations up to 1287 m (4250 feet). Higher elevations require a derating of the maximum dry bulb temperature of 1°C for every 218 m (720 feet) above 1287 m (4250 feet) up to 3028 m (10000 feet). These temperature requirements are to be maintained over the entire front of the 2 m height of the rack where air is drawn into the system. Since air enters the front of the each rack over the entire height of the rack, it is a challenge to maintain the temperature within the requirements as stated for all the racks within the data center. Although the inlet air temperatures for all the racks met the requirements, some modifications were still required after the installation. And herein lies the challenge to data center facility operators, especially with the increased equipment heat loads as shown in Figure 1.3. How do operators maintain these environmental requirements for all the racks situated within the data center and in a data center where the equipment is constantly changing?

Without proper attention to the design of the facilities in providing proper airflow and rack inlet air temperatures, hot spots within the data center can occur.[5]

3.2 Different Factors Affecting the Rack Inlet Air Temperature [5]

Chilled Air Distribution: Non-Raised Floor (overhead) vs. Raised Floor [6, 11] Once the lower portion of the rack is satisfied with chilled air drawn into the rack from the raised floor, the upper portions of the rack do not receive any chilled air from the perforated tile in front of the rack and, in order to satisfy conservation of mass needs, to draw air from other portions of the room.

Ceiling Height [6]

The formation of recirculation cells within the rack is highly undesirable. Ceiling height is a very important factor to be considered because it has the control on mixing of hot & cold air & it can avoid formation of recirculation cells within the rack.

Rack Powers [6]

Racks of higher power (which have higher rack flow rates to maintain the same temperature difference across the rack) had lower rack air inlet temperatures. The higher tile and rack air flow rates aid in moderating the rack inlet air temperatures.

Raised Floor Chilled Air Exiting Hot Aisles [7] Chilled air exiting the cold aisle is more effective in lowering rack inlet temperatures than bleeding some of the chilled air into the hot aisle. It mixes the hot & cold air & affects the uniform distribution of flow. It also reduces the flow rate coming from cold aisles resulting in violating the purpose of cooling of data center.

Rack Flow Rates [8]

Decreasing rack flow rates for the same perforated tile flow rate may result in decreased rack inlet temperatures for a cluster of uniformly powered racks. It is a very important parameter to be considered. It has been studied in detail in this project.

High Powered Racks amongst Low Powered Racks [9]

Much less perforated tile chilled air flow is required for single high-powered racks situated amongst a cluster of low-powered racks. High-powered racks requiring high rack flows pull chilled air from surrounding perforated tiles thereby requiring much less flow from the tile immediately in front of the high-powered rack. However, some inlet air temperatures of nearby low powered racks increased.

Perforated Tile Flow Rate [10]

Perforated tile openings are important because they are the resistances to the flow of chilled air. The opening of the perforated tiles actually moderates the air flow rate & the velocity with which air is thrown in upward direction. It is very important aspect for regulating Rack Inlet Air Temperature.

Under Floor Plenum Height [10]

Plenum height is very important design variable for optimization because it determines the velocity & the pressure drop & ultimately governs the flow pattern of the chilled air which is getting supplied to the racks.

Effect of CRAC Location [14]

A/C units placed parallel to rows of racks improved rack inlet air temperatures compared to A/C units placed perpendicular to the rows. The reduction was a result of the recirculation cell above the racks decreasing in strength thereby reducing rack inlet air temperatures.

Effect of CRAC Flow Rate [14]

CRAC flow rate determines the velocity of the cold air coming out of the perforated tiles & ultimately affects the cooling effect of the racks. It also has a major impact on the temperature difference across the different heights of the racks.

CHAPTER 4

DESIGN OPTIMIZATION FOR OPTIMUM COOLING

4.1 Introduction

The data center is a server room, which has all the data servers stacked up in huge racks. Data centers are typically arranged in hot aisles and cold aisles as shown in Figure 2. This arrangement accommodates most rack designs which typically employ front to back cooling and somewhat separates the cold air exiting the perforated tiles from the hot air exhausting from the rear of the racks and returning to the A/C units. The racks are positioned on the cold aisle such that the fronts of the racks face the cold aisle. Similarly the rears of the racks face each other and provide a hot air exhaust region. Although the cold aisle/hot aisle arrangement is desired for data center thermal management viewpoint but it is not easily achieved [1]. The primary thermal management focus for data centers is that the temperature and humidity requirements for the electronic equipment housed within the data center are being met.

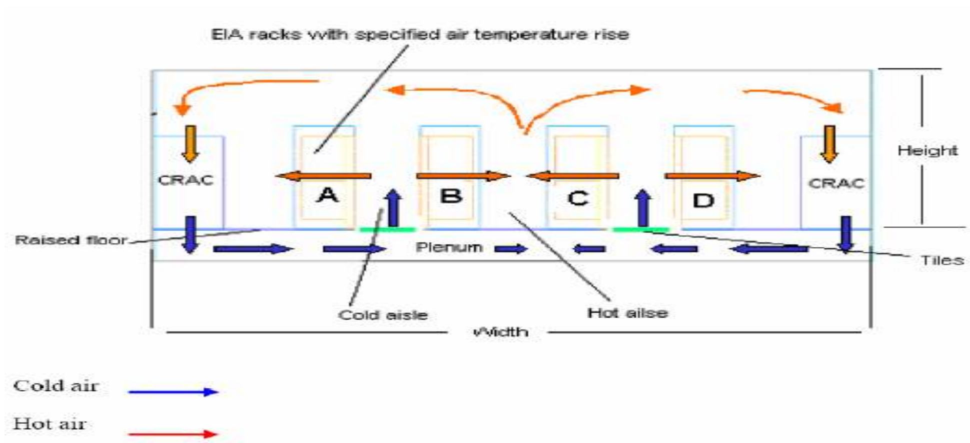


Figure 4.1 Typical Raised Floor Data Center with Alternating Hot and Cold Aisles (Room Return Infrastructure) [4]

The heat load per rack is increasing at a very rapid rate, which makes it necessary to develop better techniques for data center cooling [4]. With reference to fig. 2 we can see that by 2010, average heat load would be around 1000 W/ft2. Cooling of such high heat load racks in a data center is a big issue currently faced.

Majority of the data centers today employ raised floor structure to supply cooling air to server racks. For better thermal management it is necessary to supply the required amount of airflow through the perforated tiles situated in front of every rack. Thus to achieve desired thermal management it is absolutely must to study the air flow pattern and hence to ensure that necessary air is been supplied to server. This will not only ensure proper functioning but will also increase the reliability of data centers. Air flow distribution in raised floor datacenter is been addressed in this paper.

The key point here is the chilled air coming from the perforated tiles is not getting uniformly distributed at the different heights. The lower servers get more chilled air compared to the servers on higher level. This in turn resulted into the rise in the average rack inlet temperature of the chilled air. Also, the Maximum RIT increased. The typical data centers have alternate hot & cold aisles. Front to back cooling approach is used here as well in the test model. Also, the air coming out from the back of the Racks is getting recirculated through the CRAC units. An optimization approach must be adopted for such a purpose so that various design parameters are thoroughly studied & understood before running them in optimization. This particular study involves the variation of the location of the Computer Room Air Conditioning (CRAC) unit all over the floor of the data center to have optimum cooling. Also the location of the CRAC unit is varied considering 3 different airflow rates for the CRAC unit. For this case study different scenarios were studied. This paper primarily focuses on the improved performance due to change in the location of the CRAC unit.

4.2 Data Center Model Details

For this study, a full model of (32ft x 32ft) is considered as shown below. There are four CRAC units. There are four groups of Racks. As mentioned earlier, a data center with fixed cold air flow is considered for analysis. Owing to the symmetric nature of the system, room layout considered is of 256 (16x16) ft^2. The symmetric cutout is seen in the figure shown below. The model is shown in figure 3 below. We are saving nearly half of the time for simulation & hence, this symmetrical consideration helps in the visualization of the results as well as behavior of the data center as a whole. The following figure would clarify more about the different locations of the CRAC unit under different scenarios based on their performance as a whole.

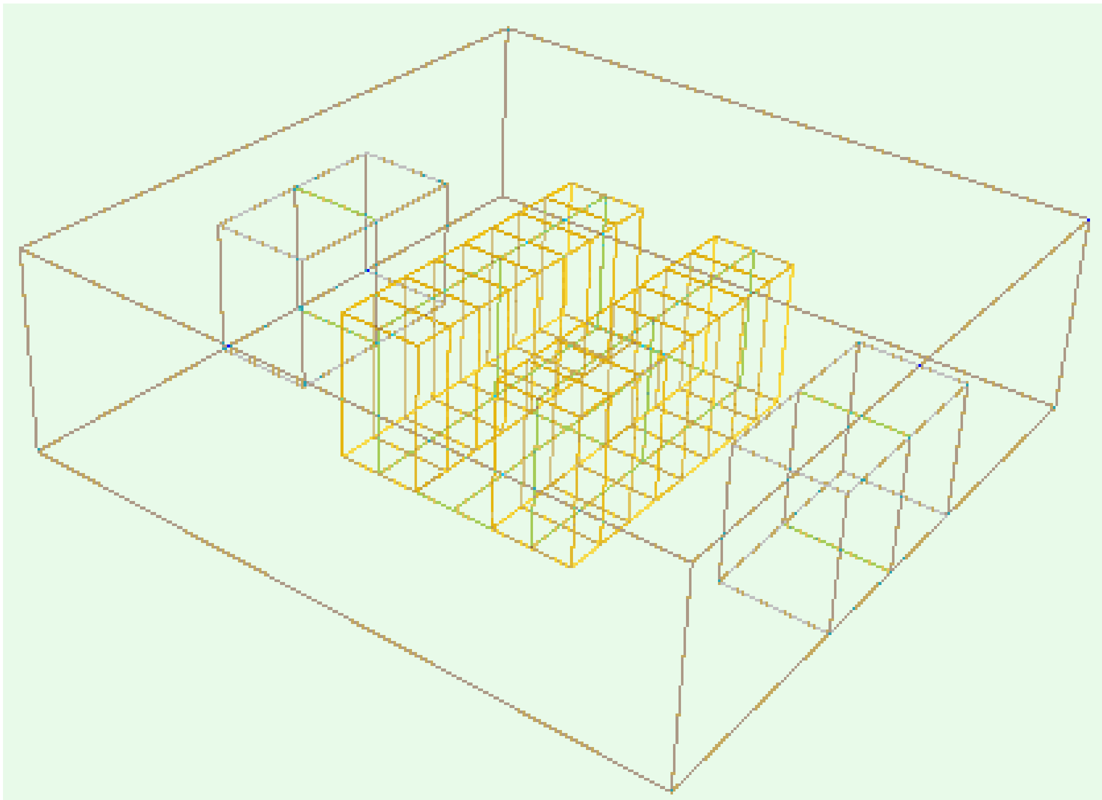


Fig 4.2 Data Center Layout before Symmetry

4.3 Consideration of Symmetry

Symmetrical Quarter model is considered as shown in a Fig below. It shows the cutout of the full model. It shows row of racks with tile through which the cold air at 15 deg C is coming out to cool the racks. CRAC unit is located as shown for the Benchmark case.

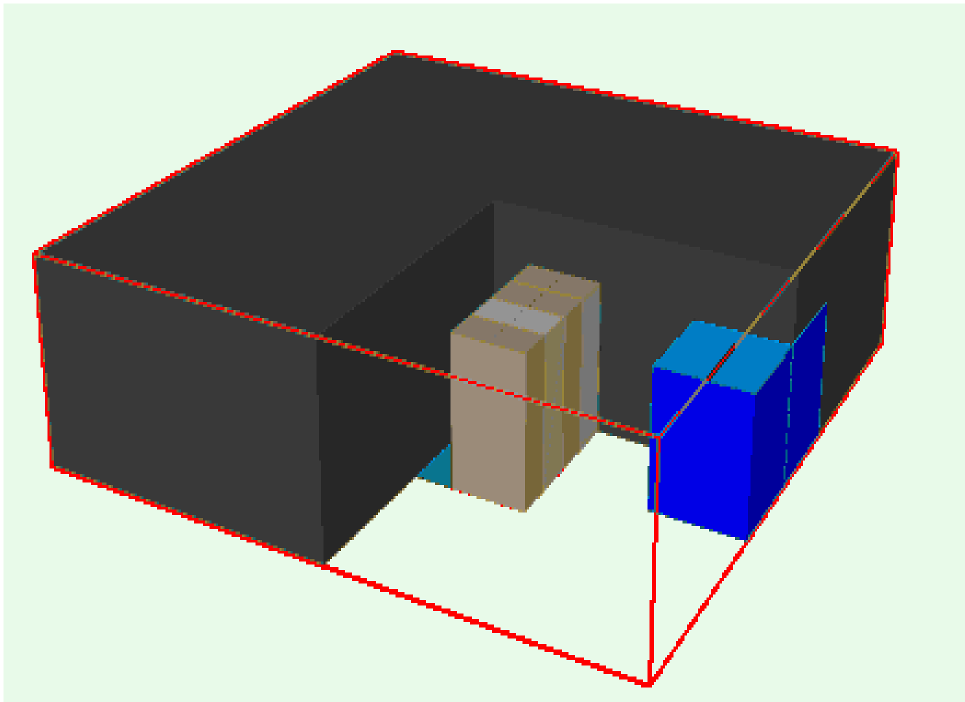


Fig 4.3 Symmetric Cutout of full model showing quarter symmetry

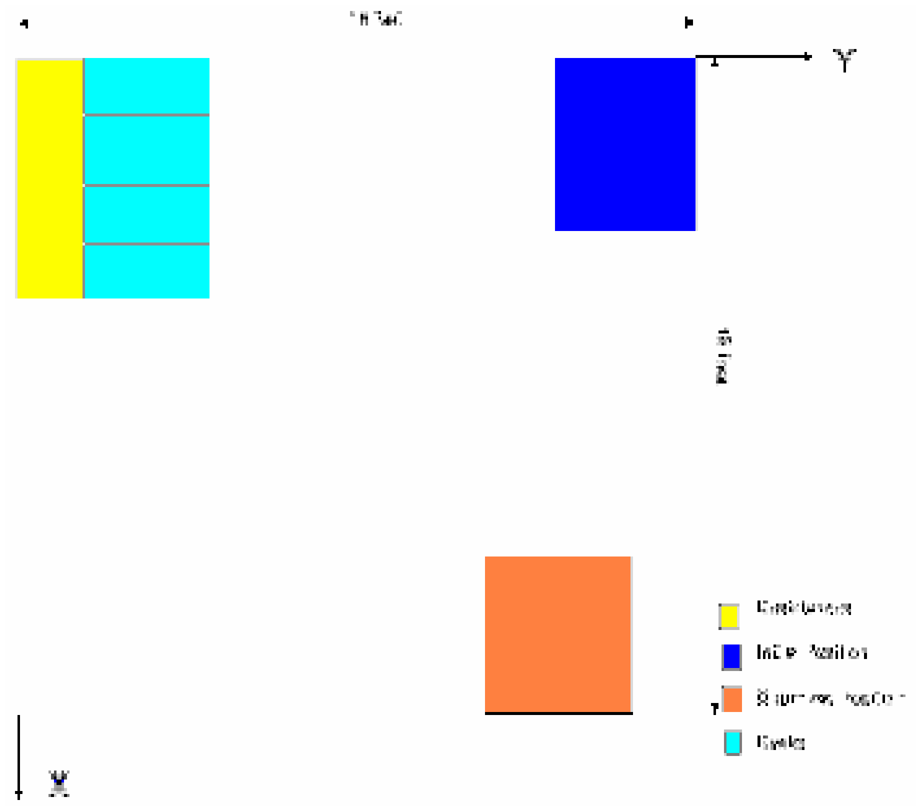


Fig 4.4Data Center Layout Considered for Analysis

Four racks were considered each having a foot print area of 8 (2x4) ft2. Each rack has a power of 25 KW. To supply cold air, perforated tiles (2x2 feet) are placed immediately in front of each rack. CRAC is initially located at X=0 and Y=10.971 feet. This is the starting condition for all three CRAC flow rates. Then CRAC location is changed circumferentially as well as inside the quarter room layout and its effect on rack inlet air temperature is considered. Effect of CRAC location is studied for 3 different flow rates 6000cfm, 8000cfm and 10000cfm. For each case a sequential optimization for CRAC location is performed. For each rack 9 monitor points are considered at different heights in order to note the rack inlet temperature. All the dimensional details are shown in the figure above for the symmetrical model.

For each scenario, cost function is defined. Here, cost function is a linear function of temperature. It is defined with regards to the temperature at the monitor points. In this paper, an effort is made to study the effect of CRAC location unit on the rack inlet air temperature and ultimately the performance of data center. Also CRAC flow rate was increased and its effect on CRAC location was observed. A comparative chart is made right from the initial performance of the Benchmark model with CRAC flow rate of 6000 cfm to the performance of the optimized model with CRAC flow rate of 10000 cfm.

4.4 Grid Independence Analysis

Following is the curve for the Grid Sensitivity analysis. It shows that for different system grid taken into consideration, the difference of Maximum temperature for the scenarios is marginal. Scenario 1 is considered for the optimization which has about 40000 cells into consideration.

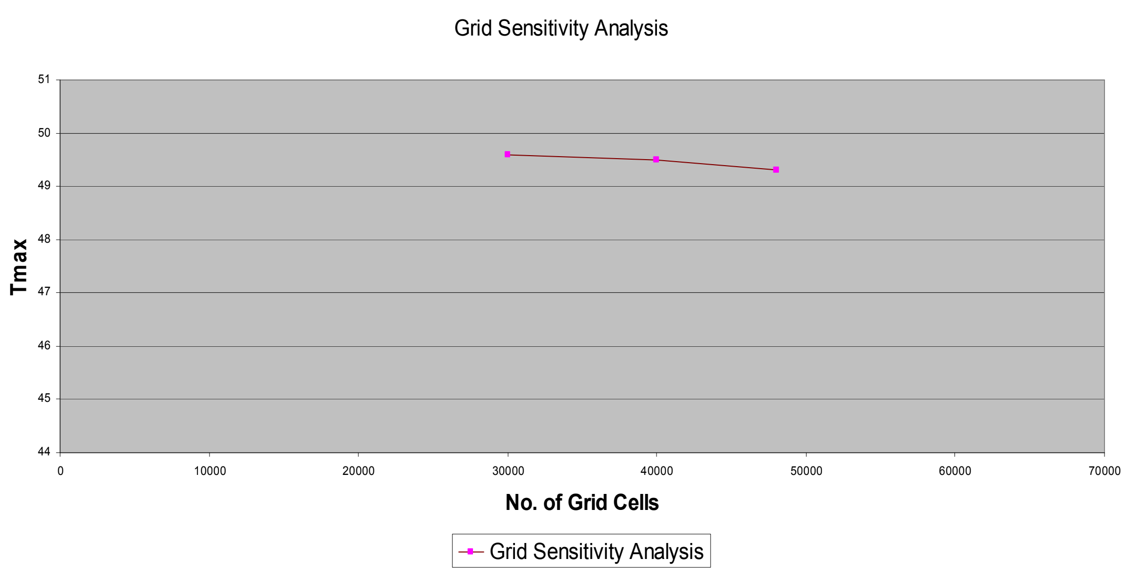


Fig 4.5 Grid Independence Analysis

4.5 Design Optimization

Analysis is performed using commercial code [13] available. In the method adopted, it creates number of Design of Experiments (DoE) or scenario projects where the selected input variables are varied within the defined maximum and minimum range, which can then be solved. Monitor points are uniformly scattered outside each server to monitor the rack inlet air temperature. These monitor points are defined as the output variables, and are included in *cost function*, to evaluate the best design. In design optimization, *cost function,* is the weighted sum of the number of output variables [12].

$$\text{Cost Function} = W1R1 + W2R2 + \ldots + WNRN$$

The multi-variable approach to optimization of data center room layout uses more than one design parameter which has a significant effect on rack inlet air temperature, as the input variables. Monitor points, to measure the rack inlet air temperatures, are defined as output variables (Rs). The weighted factor (Ws) is fixed at 1. Finally an optimization code, with all the combination of selected input variables is run to obtain the least cost function and hence the most optimal solution. Following are the optimization methodologies for the 2 and 3 design variable optimization codes.

4.6 Consideration of Different Flow Rates

In this project 3 different flow rates are considered for optimization. The total Rack flow rate equals 10000 cfm. The CRAC flow rates are 60%, 80% & 100% of the Rack flow rate. Optimizations are run for these 3 different flow rates & a comparative study is made to find out the optimum location of the CRAC unit as with respect to all 3 flow rates. In this study, about 80 different scenarios were run for each of the CRAC flow rate & comparative study has been made between the various temperatures in front of the racks.

4.7 Performance of the Benchmark Model

In the present study, effect of CRAC location is studied for three different flow rates as mentioned before. In each case, the CRAC is initially located at the same position (X=0ft and Y= 10.971ft) and then its position is changed circumferentially. Figure 4.7.3 shows the temperature distribution for the first case i.e. for 6000 cfm flow rate and CRAC located at the initial position mentioned above. Maximum rack inlet temperature observed in this case is around 55ºC. This temperature is very high when compared to the designed inlet air temperature (15ºC). From the plot we can see that, the high inlet air temperature is observed at the top of the rack. This is mainly because of formation of recirculation cells. These recirculation cells drastically affects the inlet air temperature [17], and in the present study an effort is made so that these recirculation cells are decreased and hence the rack inlet temperature

Location of CRAC unit for the benchmark model as shown in fig. below. The location for the first simulation is the same for all the three flow rates.

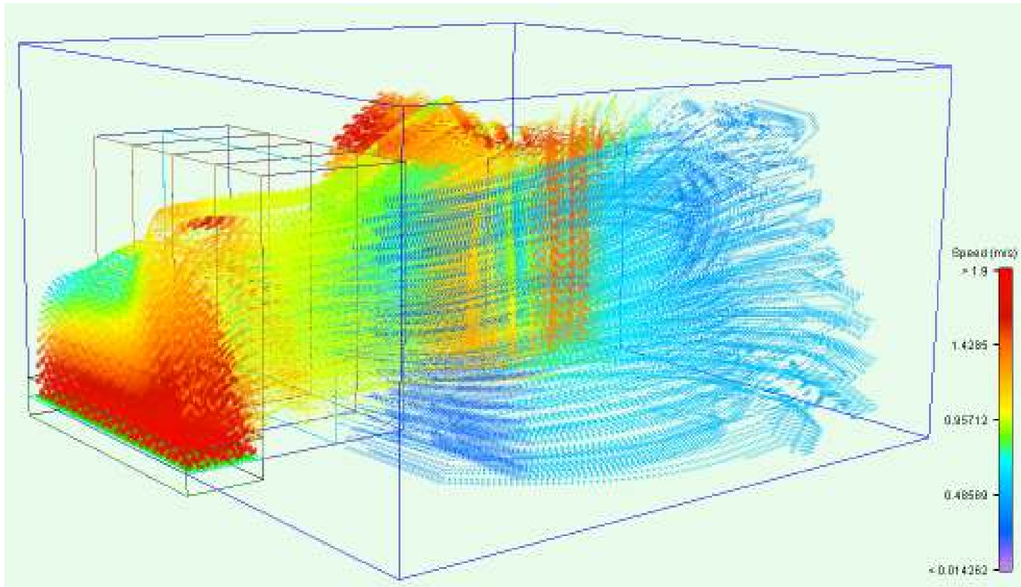


Fig 4.6 Flow Pattern of the Benchmark Model

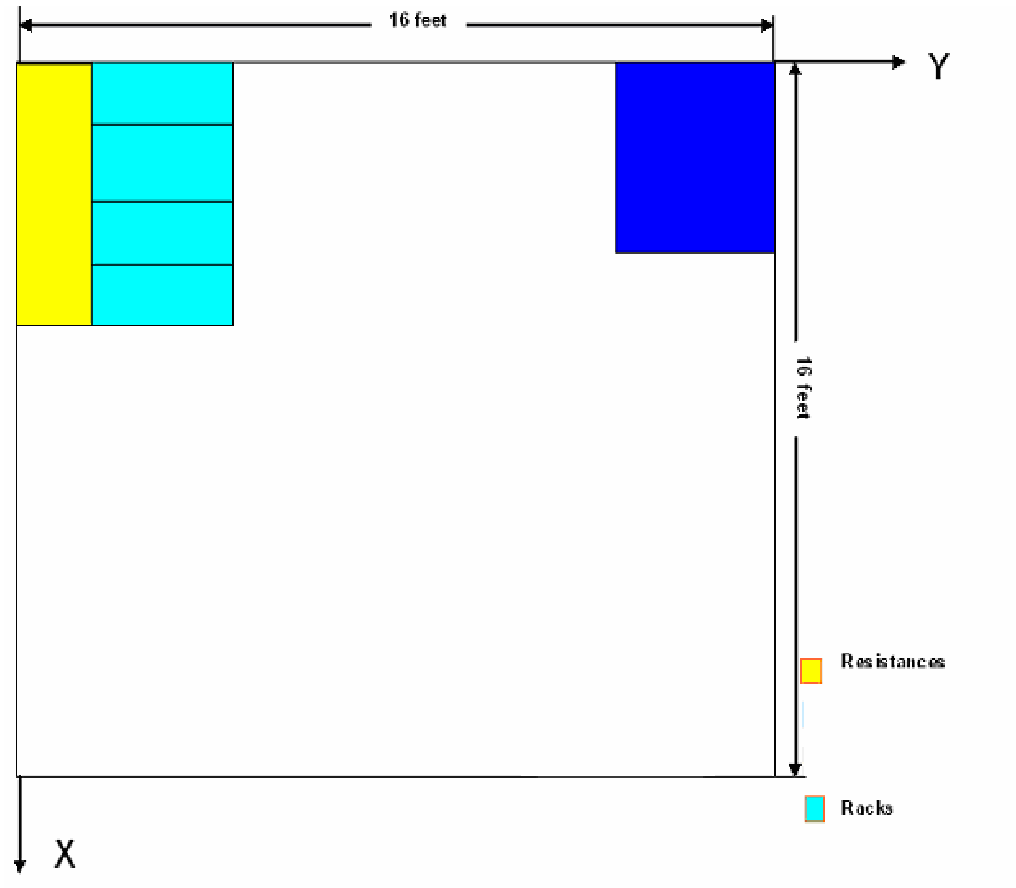


Fig 4.7 Location of the Benchmark Model

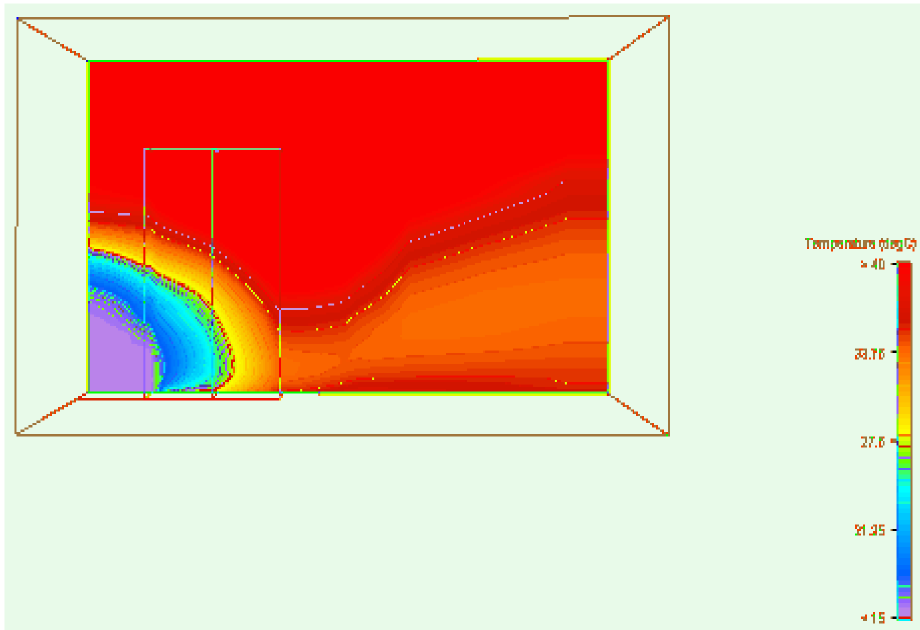


Fig 4.8 Temperature Contour of the Benchmark Model

As we can see the temperature distribution is not uniform & the cold air supply is not sufficient for the racks located at higher locations. As we can see, barely up to half of the Rack height cold air flow is getting supplied. Also, the average Rack inlet temperature is 25 ºC which is higher than the acceptable range. Also, we can see that the temperature for the upper portion of the Racks is greater than 40 ºC which is again not acceptable for the performance of those servers.

Later, simulation results were obtained for around 80 different CRAC locations, and rack inlet temperature for each case was noted. Figure 4.7.4 below shows the plot of different scenario against the cost function. From the plot we can see that the scenario 29 shows the best optimized performance. CRAC location at this point is X=4.124 ft and Y=8.72ft.

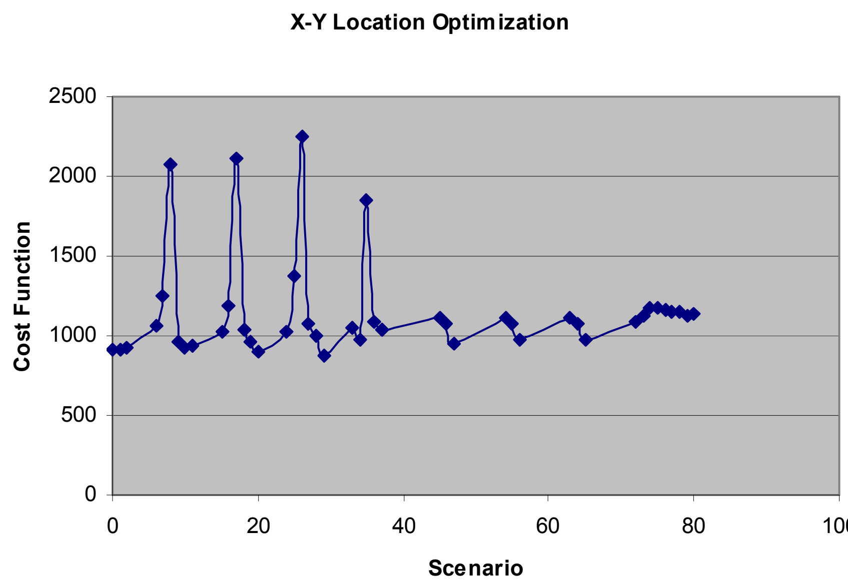


Figure 4.9 Optimization plot for 6000 cfm CRAC flow rate

Temperature distribution of air across the data center for the optimized CRAC location is shown below in figure.

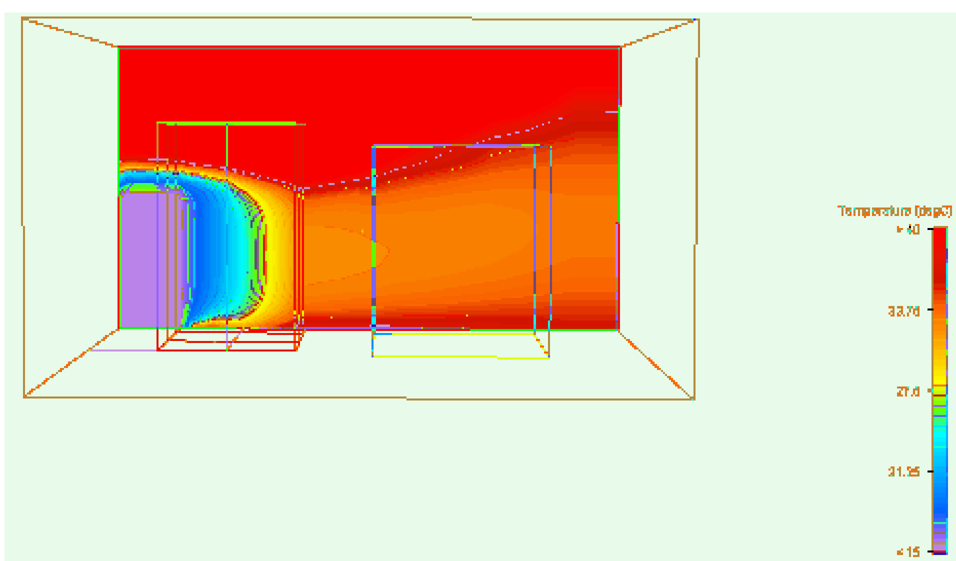


Figure 4.10 Temperature Contour for Optimized Location

Similar kind of analysis was performed for 8000cfm and 10000cfm flow rate.

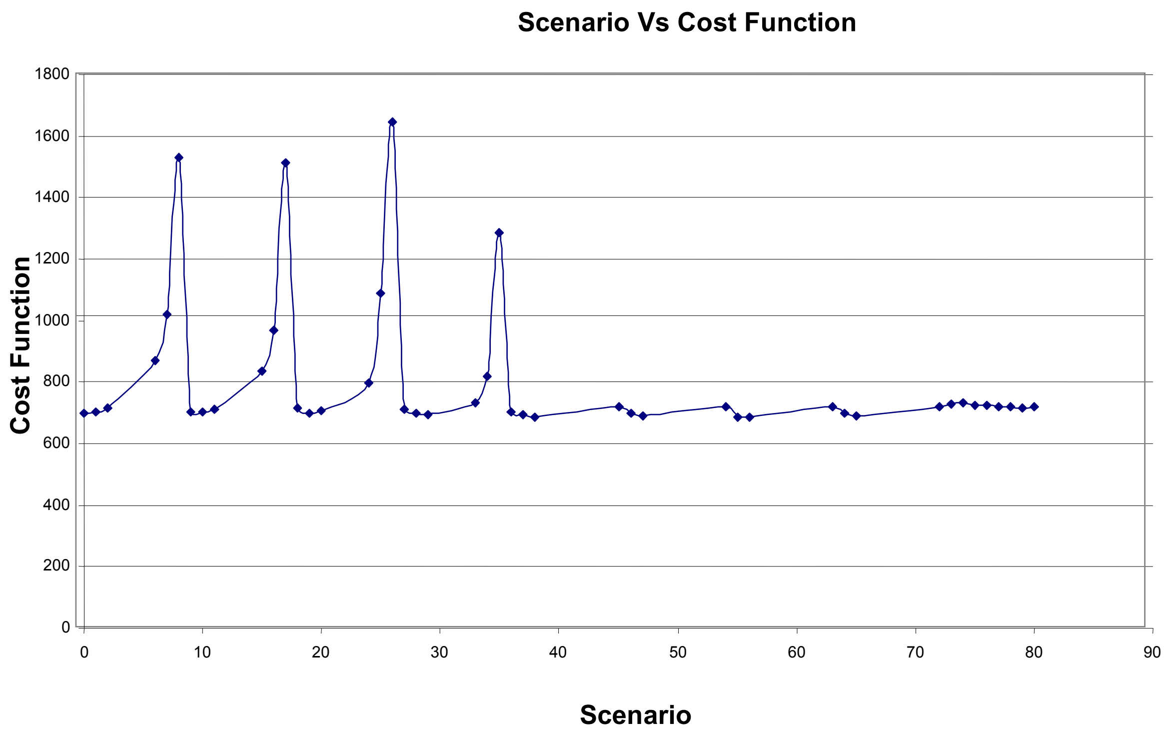


Fig 4.11 Optimization plot for 8000 cfm CRAC flow rate

Temperature distribution of the optimized case with 8000 cfm flow rate was obtained as follows.

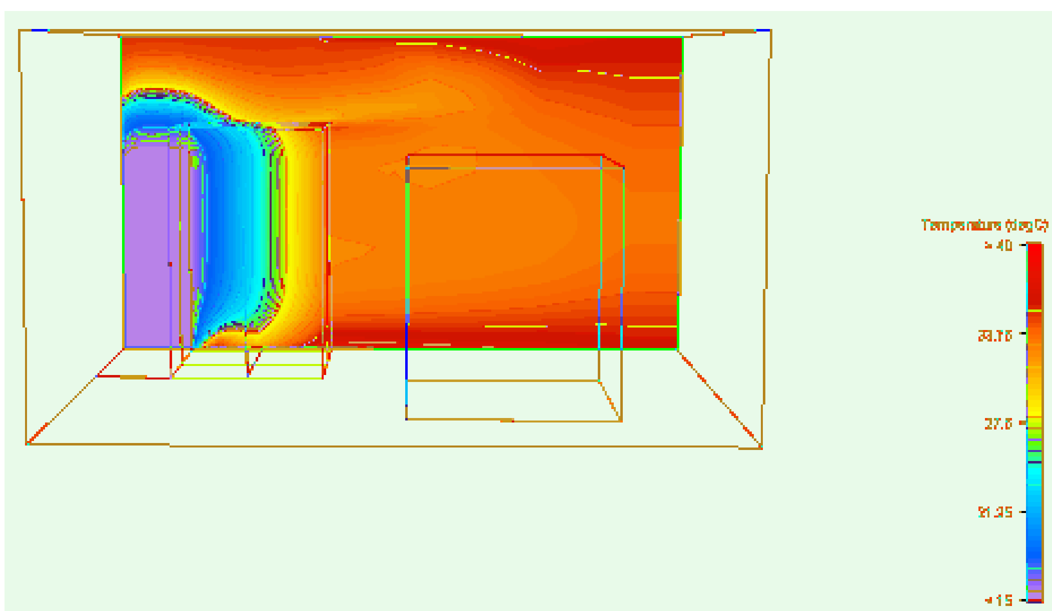


Fig 4.12 Temperature Contour for Optimized Location

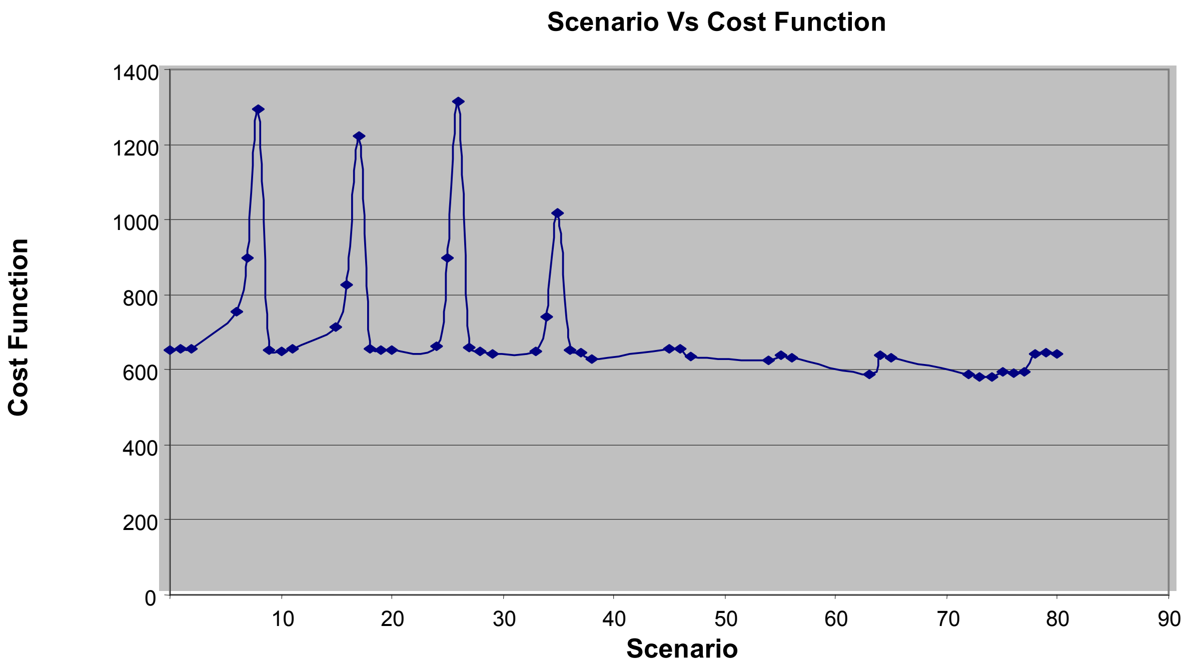


Fig 4.13 Optimization plot for 10000 cfm CRAC flow rate

Similarly the temperature distribution & Velocity contour for the 10000 cfm CRAC flow rate are as follows.

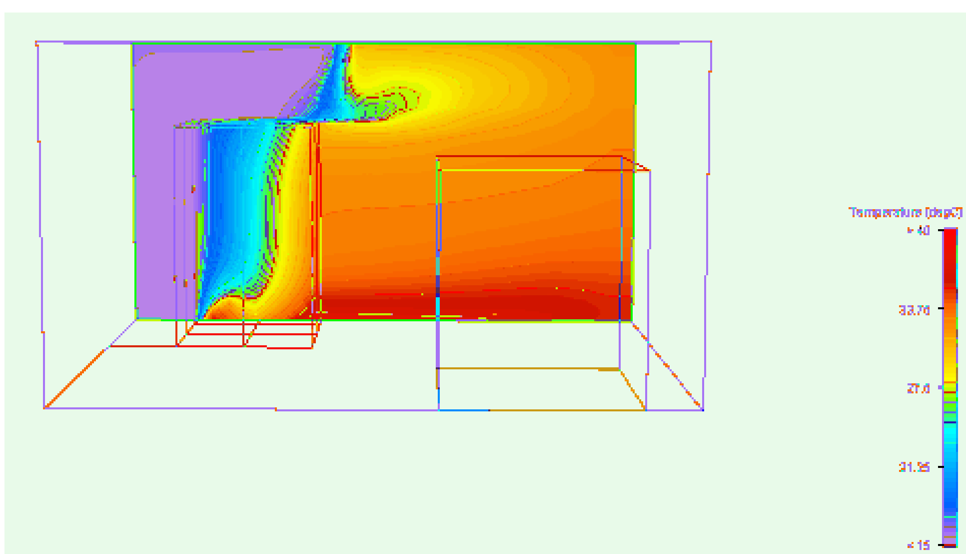


Fig 4.14 Temperature Contour of the Optimized Model

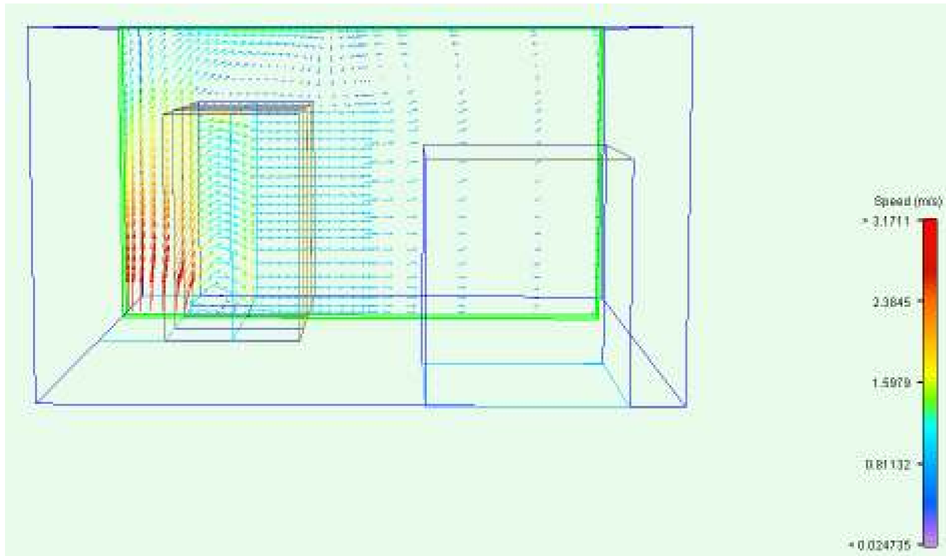


Fig 4.15 Velocity Contour of the Optimized Model

The flow pattern is given as below. We can see a very uniformly distributed flow as shown in the flow pattern below for the optimized case of 10000 cfm CRAC flow rate. As the flow is 100% of the Rack flow rate best performance could be predicted for the optimized location for this flow rate.

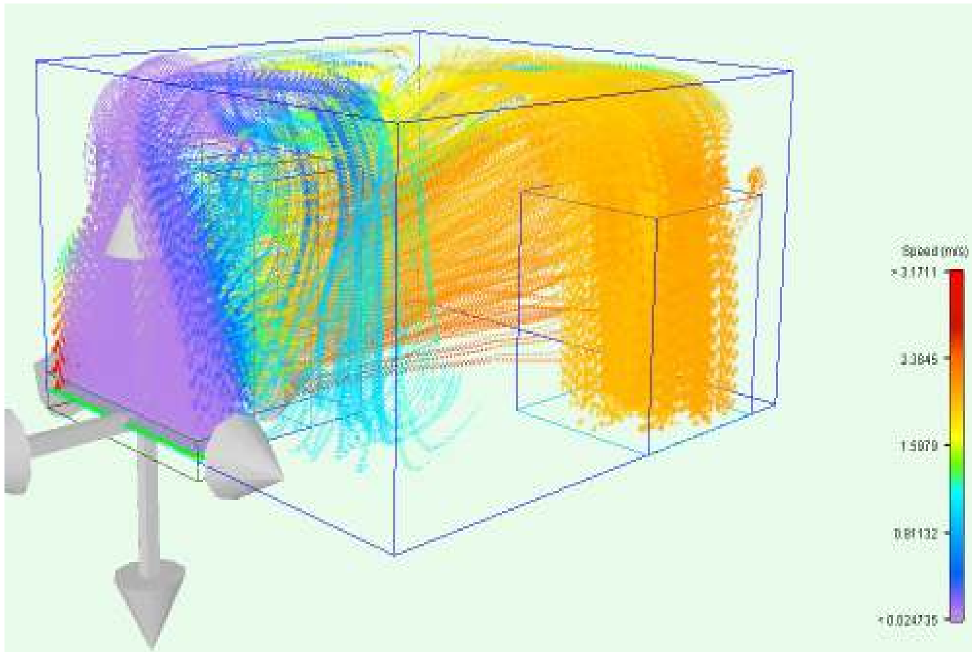


Fig 4.16 Flow Pattern for Optimized Location

Results for all the 3 cases with percentage improvement are tabulated below in table 4.1.

The table below shows the comparison of results of the three different flow rate cases as well as the CRAC location optimization. The improvement can be seen for each case in the Tmax (Maximum Rack Inlet Air Temperature) & Tavg (Average Rack Inlet Air Temperature). Also, one can compare Benchmark model with the optimized model when 100% flow rate is considered.

Table 4.1 Performance Comparison of all 3 Cases of Flow rates

CRAC Flow (cfm)	**Temp (°C)**	**Initial Model**	**Optimized Model**	**Opt X Location (ft.)**	**Opt Y Location (ft.)**	**% Improvement**
6000	T_{avg}	25.29	24.39	4.25	8.22	4%
	T_{max}	51.61	47.49			8%
8000	T_{avg}	19.45	19.04	8.24	8.22	2%
	T_{max}	38.91	35.4			9%
10000	T_{avg}	18.15	16.12	11	9.6	11%
	T_{max}	38.1	21.34			44%

CHAPTER 5

CONCLUSION

From the results table, we get the best improvement for the CRAC flow rate of 10000 cfm case. We get nominal improvement for the 6K & 8K cfm cases. For 6000 cfm case, the flow rate delivered by the CRAC is not sufficient to cool the required load. Due to this air at the top of each rack has higher temperature (recirculation cells) and thus the average inlet temperature of air increases. But as the flow rate increases, amount of recirculation cells form decreases and hence the average inlet temperature of air also drops. But formation of recirculation cells does not depend solely on flow rates but it also depends on CRAC location.

If the flow rate coming out of tile is less, but the CRAC is located nearer to rack, we get comparatively better performance than if the CRAC is located at some other location. For higher flow rates, if the CRAC is located far away from rack, more recirculation cells are observed. Similarly if the CRAC is very near to rack (for higher flow rates) then bottom of the rack do not get sufficient air and hence temperature of air at the bottom is high. From the results we can say that performance of data center largely depends on location and corresponding flow rate of the CRAC. In the optimized location case for the 10000 cfm flow rate we see that the cold air supply is extremely good that it actually cools the upper side of the rack as well. So, we may have more servers stacked in this case and still get optimum cooling.

In future, effect of plenum height coupled with CRAC location will be studied. Also, the ceiling height is one of the major factors which affect the performance of a Data Center [4]. We need to study these parameters carefully and find out their combined effect on the performance of the Data Center room. Also, we can reduce the real estate of the Data Center by predicting the CRAC location well before the actual construction of the Data Center room. It would be really helpful to the industry to get optimum cooling at the design stage & still further changes could be done at the Design stage well before the construction and thus reducing the equipment setup cost and the overall installation cost.

APPENDIX A

LIST OF VARIABLES USED IN THIS METHODOLOGY

CFD: Computational Fluid Dynamics

CRAC: Computer Room Air Conditioning

C_p = the specific heat of the fluid

V = characteristic velocity

$\dot{M}$ =characteristic mass flow rate

u, v and w= the velocity resolutes in cartesian coordinate directions x, y and z,

p = pressure

T = temperature of the fluid and/or solid materials

Ep = Termination Residual for mass continuity

Ws = Weight Factors

Rs = Output Variables

Tavg = Average Rack Inlet Air Temperature

Tmax = Maximum Rack Inlet Air Temperature

Q = Total Heat Load

REFERENCES

[1] Energy smart data centers: Applying Energy Efficient Design & Technology to the Digital Information sector, a Research report on renewable Energy Policy Project (REPP) http://www.repp.org

[2] Kotov V., "Virtual Data Centers & their Operating Environments", a Technical report by HP Laboratories

[3] Guggari S., "A Hybrid Methodology for the Optimization of Data Center room layout", Masters thesis, University of Texas at Arlington, August 2003

[4] Bhopte S., "Optimization of Data Center Layout to Minimize Rack Inlet Air Temperature", Masters Thesis, University of Texas at Arlington, May 2005

[5] Hot Spots in Data Centers by Dr. Roger Schmidt, IBM Corp., Electronic Cooling, August 2003.

[6] Schmidt, R., "Effect of Data Center Characteristics on Data Processing Equipment Inlet Temperatures", Advances in Electronic Packaging 2001(Proceedings of IPACK '01, The Pacific Rim/ASME International Electronic Packaging Technical Conference and Exhibition), Vol. 2, Paper IPACK2001-15870, Kauai, Hawaii, July 8-13, 2001, pp. 1097-1106.

[7] Schmidt, R. and Cruz, E., "Raised Floor Computer Data Center: Effect on Rack Inlet Temperatures of Chilled Air Exiting both the Hot and Cold Aisles", Itherm Conference, San Diego, California, June, 2002, pp. 580- 594.

[8] Schmidt, R. and Cruz, E., "Raised Floor Computer Data Center: Effect on Rack Inlet Temperatures when Rack Flow Rates are Reduced", Interpack Conference, Maui, Hawaii, July 6 - 13, 2003.

[9] Schmidt, R. and Cruz, E., "Raised Floor Computer Data Center: Effect on Rack Inlet Temperatures when High Powered Racks are Situated Amongst Lower Powered Racks", IMECE Conference, New Orleans, La., Nov., 2002.

[10] Schmidt, R. and Cruz, E., "Clusters of High Powered Racks within a Raised Floor Computer Data Center: Effect of Perforated Tile Flow Distribution on Rack Inlet Air Temperatures", IMECE Conference, Washington, D.C., Nov., 2003, to be published.

[11] Patel, C., Bash, C., Belady, C., Stahl, L., and Sullivan, D., "Computational Fluid Dynamics Modeling of High Compute Density Data Centers to Assure System Inlet Air Specifications", Advances in Electronic Packaging 2001 (Proceedings of IPACK '01, The Pacific Rim/ASME International Electronic Packaging Technical Conference and Exhibition), Vol. 2, Paper IPACK2001-15662, Kauai, Hawaii, July 8-13, 2001, pp. 821-829.

[12] Flotherm User Manual, Flomerics Ltd., U.K.

[13] Flotherm Version 6.1, Flomerics Ltd., U.K.

[14] Bedekar V., Karajgikar S., Agonafer D., Iyengar M., Schmidt R., “Effect of CRAC Location on Fixed Rack Layout of a Data Center”, Itherm 2006, San Diego, California, May 30-June 2, 2006.

[15] Schmidt R., Cruz E., “Raised Floor Computer Data Center: Effect on Rack Inlet Temperatures of Chilled Air Exiting both the Hot and Cold Aisles”, Itherm Conference, San Diego, California, June, 2002, pp. 580-594.

[16] Schmidt R., Karki K. and Patankar S., “Raised Floor Data Center: Perforated Tile Flow Rates For Various Tile Layouts,” Itherm Conference, Las Vegas, Nevada, July 2004.

[17] Sharma R.K., Cullen B.E., Patel C.D., “Dimensionless Parameters For Evaluation of Thermal Design And Performance of Large Scale Data Centers”, Paper No.

AIAA2002-3091, American Institute of Aeronautics and Astronautics Conference, 2002.

BIOGRAPHICAL INFORMATION

Vishwas Bedekar has completed his Bachelor of Engineering in Mechanical Engineering degree at Mumbai University, India in December 2002. He enrolled University of Texas at Arlington in the program of Master of Science in Mechanical Engineering in Fall 2004. His major area of interest was Electronic Packaging. After Graduating with his Master's degree he plans to continue for his PhD degree at University of Texas at Arlington in Materials Science & Engineering program. His research interests are MEMS & materials properties.