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Air Flow Management Inside Open Aisles Data Centers

إدارة سريان الهواء داخل مراكز بيانات الممرات المفتوحة

A Thesis Submitted in Partial Fulfillment of the Requirements for the Degree of Doctor of Philosophy in Mechanical Engineering (Power) By Courses and Dissertation

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DEDICATION

I dedicate my dissertation to my beloved father’s soul. A special feeling of gratitude to my loving parents, whose words of encouragement and push for tenacity always rings in my ears.

My wife and son have never left my side and are very special. I also dedicate this dissertation to my friends and colleagues who have supported me. I will always appreciate what they have all done. Thank you.

My love for you all can never be quantified. Allah bless you.

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ABSTRACT

The growth in the heat densities of information technology servers leads to a rise in the energy needed to cool them. However, many data centers feature redundant air conditioning systems that contribute to inefficient air distribution, which significantly increases energy consumption. This remains an insufficiently explored problem in data centers.

This dissertation deals with air flow management inside Data centers. First, the data center components are introduced and cooling challenges are described. A data center with a raised floor is investigated for different ways of air flow management and control. Computational Fluid Dynamics is used to simulate the data center. The beta index and the energy utilization index were used in order to evaluate the results of thermal and bypass air phenomenon. The beta index decreased when closing gaps between racks and directing supply air flow towards racks. Using the optimal supply air temperature uniforms the heat distribution inside the data center. The simulations show that there is a better trend of the beta index and energy utilization index at a closed aisle compared with a free open aisle. Especially with high air flow rate, the beta index decreases and the energy utilization index increases considerably. Moreover, the results prove the closed aisles can not only significantly improve the airflow distribution, but also reduce the mixture of cold and heat flow, and therefore improve energy efficiency. In addition, it proves the design of the closed aisles can meet the increasing density of installations.

مستخلص

يؤدي نمو الكثافات الحرارية لخوادم تقنية المعلومات إلى ارتفاع الطاقة اللازمة لتبريدها. ومع ذلك ، تتميز العديد من مراكز البيانات بأنظمة تكييف هواء زائدة عن الحاجة تساهم في توزيع الهواء غير الفعال ، مما يزيد بشكل كبير من استهلاك الطاقة. لا تزال هذه مشكلة تم استكشافها بشكل غير كاف في مراكز البيانات.
تتناول هذه الرسالة إدارة تدفق الهواء داخل مراكز البيانات. أولاً ، يتم تقديم مكونات مركز البيانات ووصف تحديات التبريد. يتم فحص مركز البيانات ذي الأرضية المرتفعة بحثًا عن طرق مختلفة لإدارة تدفق الهواء والتحكم فيه. يتم استخدام ديناميكيات السوائل الحسابية لمحاكاة مركز البيانات. تم استخدام معامل بيتا ومؤشر استخدام الطاقة من أجل تقييم نتائج ظاهرة الهواء المتجاوز والحراري. انخفض مؤشر بيتا عند إغلاق الفجوات بين الرفوف وتوجيه تدفق الهواء نحو الرفوف. يؤدي استخدام درجة حرارة هواء الإمداد المثلى إلى توحيد توزيع الحرارة داخل مركز البيانات. تظهر عمليات المحاكاة أن هناك اتجاهًا أفضل لمؤشر بيتا ومؤشر استخدام الطاقة في الممر المغلق مقارنةً بالممر المفتوح الحر. خاصة مع ارتفاع معدل تدفق الهواء ، ينخفض مؤشر بيتا ويزداد مؤشر استخدام الطاقة بشكل كبير. علاوة على ذلك ، أثبتت النتائج أن الممرات المغلقة لا يمكنها فقط تحسين توزيع تدفق الهواء بشكل كبير ، ولكن أيضًا تقلل من مزيج تدفق البرودة والحرارة ، وبالتالي تحسين كفاءة الطاقة. بالإضافة إلى ذلك ، فإنه يثبت أن تصميم الممرات المغلقة يمكن أن يلبي الكثافة المتزايدة للمنشآت.

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LIST OF SYMBOLS/ABBERVIATIONS

A	m^2	Surface
Cp	kJ/kg.K	Specific heat constant at constant pressure
H	m	Hydraulic diameter
κ	m^2/s^2	Kinetic energy
Dh	m	Hydraulic diameter
H	m	Head losses across the rack
P	kW	Power
PD	kW/m^2	Power density
Pe		Peclet number
Pr		Prandtl number
R	m	Radius
Re		Reynolds number
RH		Relative humidity
S		Source term for the momentum equation

T	°C	Temperature
$U\_$		Velocity vector
(u ,v ,w)		Velocities in x, y and z directions ,respectively
(x,y,z)		Cartesian Coordinates
Win	KW	Compressor work of DX CRAC unit

Greek symbols

β		Beta Index
η_r		Energy Utilization Index
ρ	kg/m^3	Density
α	m^2	Permeability
υ	m^2/s	Kinematic viscosity
μ	N. s/ m^2	Dynamic viscosity
γ	N/ m^3	Specific weight
μ_t	N. s/ m^2	Eddy viscosity
ɜ	m/s	Velocity scale for the turbulent model
ι	m	Length scale for the turbulent model

Superscripts

*		Non – dimensional quantities

Subscripts

Equip		Equipment
H		Outside environment
HI		High range
i		Inlet
Lo		Low temperature range

o	Outlet
R,Carnot	Refrigeration Carnot cycle
Return	Return air to the cooling unit
s	Surface
Supply	Supply air to the data center
Tot	Total
(u,v,w)	The components of velocity in x ,y and z direction
Acronyms	
ADS	Air Distribution Systems
ADU	Air Distribution Unit
CFD	Computational Fluid Dynamics
CI	Cooling Index
CLF	Cooling load Factor
COP	Coefficient of Performance
CRAC	Computer Room Air Conditioning
DCE	Data Center Efficiency
DCIE	Data Center Infrastructure Efficiency
DCP	Data Center Productivity
IT	Information Technology
O-CS/CR	Overhead Distribution – CRAC flooded Return
O-CS/FR	Overhead Distribution – CRAC Flooded Supply/Fully Ducted Return
O-CS/LR	Overhead Distribution – CRAC flooded supply/Locally ducted Return

O-LS/CR	Overhead Distribution – Locally ducted Supply/CRAC flooded Return
O-LS/FR	Overhead Distribution-Locally ducted Supply/Fully ducted Return
O-LS/LR	Overhead Distribution –Locally ducted Supply/locally ducted Return
PDUS	Power Distribution Unit Supply
PLF	Power Load Factor
PUE	Power Usage Effectiveness
RCI	Rack Cooling Index
RTI	Return Temperature Index
SHI	Supply Heat Index
U-FS/CR	Underfloor distribution-Fully ducted supply/CRAC flooded Return
U-FS/FR	Underfloor distribution- Fully ducted Supply/Fully ducted Return
U-FS/LR	Underfloor distribution – Fully ducted supply/Locally ducted Return
U-LS/CR	Underfloor distribution – Locally ducted supply/CRAC flooded Return
U-LS/FR	Underfloor distribution – Locally ducted supply/Fully ducted Return
U-LS/LR	Underfloor distribution- Locally ducted supply/Locally ducted Return
UPS	Uninterruptible Power Supply

CHAPTER ONE

INTRODUCTION

1.1 Introduction

This is a computer life age. All searches and information are available on the Internet. Stocks are traded on computers and people use online banking. When we use a credit card, the transaction is instantaneously verified and approved. Large companies have their inventory, purchase orders, invoices, and all accounting computerized. Medical records are stored on computers. We use email and text messaging to communicate with others. The modern cell phone is a small computer that communicates with the rest of the world. The list goes on. Whereas the visible transaction takes place at the “point of sale” on a personal computer or a small device, the whole mechanism can function only if all the relevant data is held at one place and processed at a very fast speed. Therefore, behind the small visible devices such as a desktop computer, a laptop, or a cell phone are large and powerful computer servers located in one place. For a telecommunication company, it is common to have a large room housing over server racks. There are also co-location facilities, where different companies can place a few server racks each for their own use. Such a huge computer room is called a “data center”. It has become an essential part of any modern-day large business.

The most important requirements in data center is its interruption, zero-downtime operation. An interruption caused by equipment failure would entail costly repairs and replacement. But even more serious is the cost of business interruption; the business may lose thousands or even millions of dollars for every minute of downtime. For uninterrupted operation, two things are crucial: power and cooling. Uninterrupted power is assured by having several backup sources of power that can be automatically brought on line as soon as a power failure is detected. Cooling is a more complex issue, which is discussed in this research.

1.2 Problem Statement

The optimal operating parameters for a cooling system are a top priority for engineers. This is in order to get maximum utilization from a cooling system and reduce power consumption. Bypass air and recirculation which result from air distribution inside data centers are the main consideration of this research project.

1.3 Overview

Data center is a facility hosting servers, processors, computer equipment's and auxiliary systems. These systems are power supply, air conditioning, and environment monitoring, firefighting and security systems. Telecom equipment's are installed inside racks. These racks are organized front to front and back to back to form aisles. Cold aisle is where the cold air is supplied and hot aisle is where the hot air is exhausted from racks. Each server rack in a data center consumes electrical energy and dissipates a large amount of heat in the range of 2 to 20 kW. For the electronic devices to function properly, it needs to be cooled and kept at an acceptable temperature level. Overheating may cause the equipment to malfunction, melt, or burn; but more commonly, safety devices on the server racks will detect high temperatures and shut down the equipment. It is this interruption that presents serious problems for data centers and needs to be prevented. Normally, cold air enters a server rack through the front face and hot air exits from the rear face. In a large room, in which 2000 server racks may be spread all over the room, it is not easy to supply cooling air to each rack. This task is accomplished by a clever concept called the raised-floor data center. The server racks are installed on a tile floor that is raised from 0.3 to 0.6 m above the real solid floor. Air-conditioners are used to supply cold air into the space below the raised floor. The floor tiles are removable and some of the solid tiles can be replaced by perforated tiles or grilles to permit the cold air to enter the above-floor space. By locating perforated tiles at the foot of the server racks, cooling air is delivered to them. The hot air then finds its way back to the air-conditioners.

The raised-floor arrangement gives unlimited flexibility. If the layout of the server racks is changed, all that is needed is to rearrange the perforated tiles so that cooling air is delivered at the new locations of the server racks. Since there is no permanent ducting, no elaborate dismantling or construction is necessary. The raised-floor design makes it possible to create, but not guarantee, proper cooling of the server racks. How much cold air do we need? How is it distributed in the whole data center? Are we meeting the individual demands of all server racks? Does the cold air introduced at the floor level reach the top of the server rack? Can the hot air coming out of one rack enter the inlet of another rack and damage its cooling? Cooling data center in its current configuration is a difficult challenge in itself. But data centers are dynamic; their equipment layout continually needs to change. Business conditions require that new server racks are installed and the old ones are removed.

Typically, ten percent of the equipment in a data center is replaced each month. The cooling design has to keep pace with this frequent change. Cooling system in a data center must be designed to maintain operating conditions within a recommended range using minimum power consumption. There are three main ways for energy saving inside data centers: (1) selection of an air conditioner with a high energy efficiency ratio; (2) managing of auxiliary systems; and (3) optimization of air flow. Proper designed airflow will lead to perfect cooling & improve efficiency. Bypass air and recirculation are the most challenging issues when considering air flow management. Bypass air flow is cold air supply that is returning back to computer room air conditioner units without passing through telecom racks. Recirculation is the bypass air partner. When insufficient air is delivered to the rack, the racks will compensate missed air by pulling it from warm air circulating nearby.

1.4 Case Study

This dissertation will take Canar Telecommunication Company Data Center located at Khartoum, Sudan as a case study. This data center contains four down flow Computer Room Air – Conditioning (CRAC) units installed inside the servers' room. The CRACs unit was part of the raised floor room layout with cooling air passing through plenum and venting in the room through vent tiles. The racks were arranged in three rows and have individual air flow and heat load.

Cooling in a data center is an excellent application for Computational Fluid Dynamics (CFD). It offers a new challenge for meeting the cooling conditions. One can try a computer model of the whole data center, complete with the raised floor, air-conditioning units, perforated tiles, and server racks. The CFD simulation then provides a detailed distribution of air velocity, pressure, and temperature throughout the room. The simulation can be used to analyze an existing data center, but more importantly, any proposed layout for a new or reconfigured data center. One can detect hot spots in a simulation before they arise in reality and explore ways of mitigating them. As already mentioned, data centers are dynamic environments; their equipment layout changes frequently. A CFD simulation provides invaluable help in planning the changes and ensuring proper cooling. The Computational Fluid Dynamics (CFD) tools have been found appropriate to perform the flow analysis. Owing to recent improvements in CFD, simulation and thermal analysis is now practicable for industrial purposes.

1.5 The Objective

From this research accepted design modifications for air flow parameters will be focused on to minimize the effect of bypass air and recirculation air inside data centers so as to increase cooling efficiency and reduce power consumption.

1.6 Expected Results

1. At the end of this research the data center will be investigated based on rack level.
2. Effect of bypass air and recirculation phenomena’s will be predicted and minimized.
3. Energy utilization will be increased.
4. To give guidance to consulting engineers to design new data centers or renovate existing ones.

CHAPTER TWO

LITERATURE REVIEW

2.1 Introduction

This chapter deals with literature review about the cooling of data centers. Several studies have been addressed to describe Data Center in several sides such as the configuration of data center layout, the power supplied to the data center, the environmental condition inside the data center, the cooling configuration that can be applied inside the data center, and the thermal analysis inside the data center. The Information Technology (IT) density within data centers increases extremely and rapidly with time, thus the efficiency of the cooling process to keep the data center in good condition is an important criteria (Mitchell et al, 2014) .The power required to operate the data center is approximately 40 times more than that required in operating a standard office building (Patterson, 2008). The rate of heat load that is produced by the data center increases as the server loads increase in density. Therefore, the energy required to maintain the data center at the correct temperature and humidity increases along with increasing the heat load inside the data center. The power that is used to operate Information Technology equipment's and electronics varies inside date center; on average, it is about 30% to 40% of the total power required to operate the data center. The remainder of this power is used for the purpose of cooling (Rambo, Joshi, 2006). Therefore, the cooling system must be designed to maintain the servers' operating temperature within the reliable limits whatever the server's power density. At the same time the energy consumptions of the cooling system must be maintained as minimum as possible. Efficient air distribution, cooling and thermal management systems in data centers are required to satisfy these requirements. Managing air flow for cooling Information Technology servers enhances cooling system effectiveness and reduces energy consumption.

2.2 Data Center Overview

The cold-hot aisle arrangement is a popular arrangement that is used in most Data Centers. The supply air and the exhaust air of the units are divided into zones in order to minimize the recirculation issue.

Figure (2-1) shows the arrangement of the racks in the data center. There are two aisles, which are cold aisles and hot aisles. The cold aisles contain the floor tiles or vents that supply the air at the front of each server rack. The cold aisles separate the rack rows at the front (intakes); whereas, the hot aisles separate the rack server rows at the back (outlet). So the rows of racks are positioned so that they are facing each other at the front in the cold aisle.

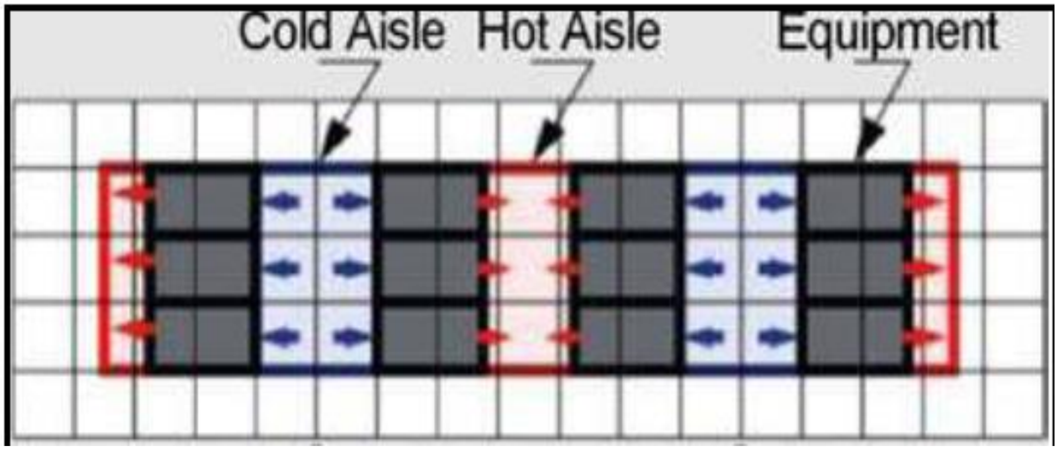


Figure (2-1) the Cold - Hot aisle arrangement

In the raised floor data center situation, the cold air is supplied by the computer room air conditioning (CRAC) units to the plenum, as shown in Figure (2-2). It then flows through the tiles that face the rack at the front, passing through the servers and exiting at a higher temperature through the rear of the rack. The hot air flows back to the CRAC units to cool them down and supply it again to the rack servers. The CRAC contains fans and cooling coils. The cooling process takes place in the cooling coil. It acts as a heat exchanger between the cooling agent in the cooling coil and the hot air pushed by the fans. The CRAC deliver the air at 16-20ºC but it reaches the rack at 18-20ºC due to the recirculation action within the data center and gaining heat on its way to the servers (Barrosos, Holzle, 2009). The air temperature exits the rear of the server racks around 27ºC.

The important point in the cold and hot aisles arrangement is to avoid the gaps between thr racks, because the hot air could be recirculated from the hot aisle to the cold aisle and increase the temperature of air entering the racks and damage the cooling.

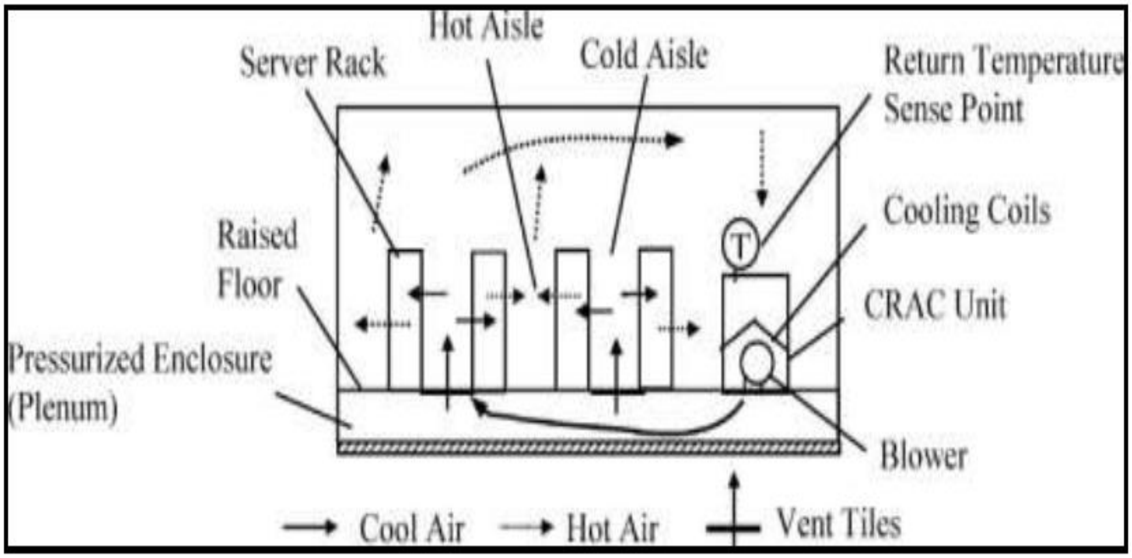


Figure (2-2) typical raised-floor data center configuration

2.3 Data Center Power Supply System Layout

Due to the high power consumption of data center, commercial power is mostly supplied through dedicated transformers. Standby Generator is used as a backup source in case of commercial power off. In addition to that, uninterruptible power supply (UPS) is used to power telecom equipment's to ensure no power interruption when commercial power fails.

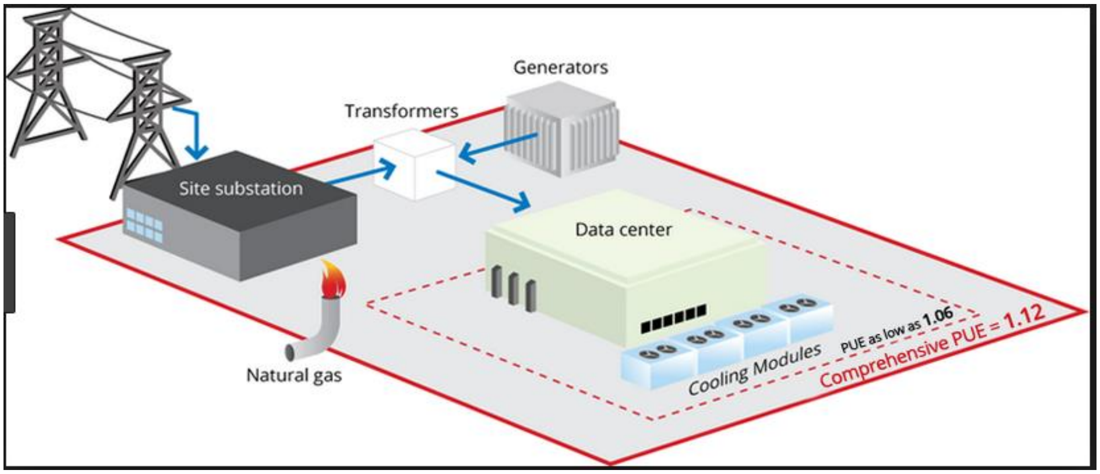


Figure (2-3) the main components of a typical data center

Electrical power is supplied to the system and utilized in lighting, Computer Room Air Conditioner units(CRAC), the monitoring office and the uninterruptible power supply (UPS) that powered servers. The power density (PD) of the data center is expressed as power supply divided by area.

Power Density (PD) = $\frac{P_{tot}}{A}$ (Kw/m^2) (2.1)

Total electricity supply (P tot,) includes the power rate of the equipment, the office, UPS, lighting, CRAC units and electricity demand in the cooling system, e.g. The compressors. Area (A) could be expressed as the area occupied by rack, the so-called ‘‘footprint’’, the total area of the computer room or the total area of the whole data center facility.

2.4 Environmental Requirements

Suitable temperatures and humidity should be taken into account during the design stage in order to achieve good operating conditions inside data center. According to the ASHRAE TC 9.9 standards, the appropriate inlet temperature should be between 15ºC and 25ºC and the humidity should be between 40% and 60%. Data center design with poor temperature or humidity control could damage the equipment in the data center. The recommended zone for operating the data center is specified by using a Psychometric chart, as shown in Figure (2-4).

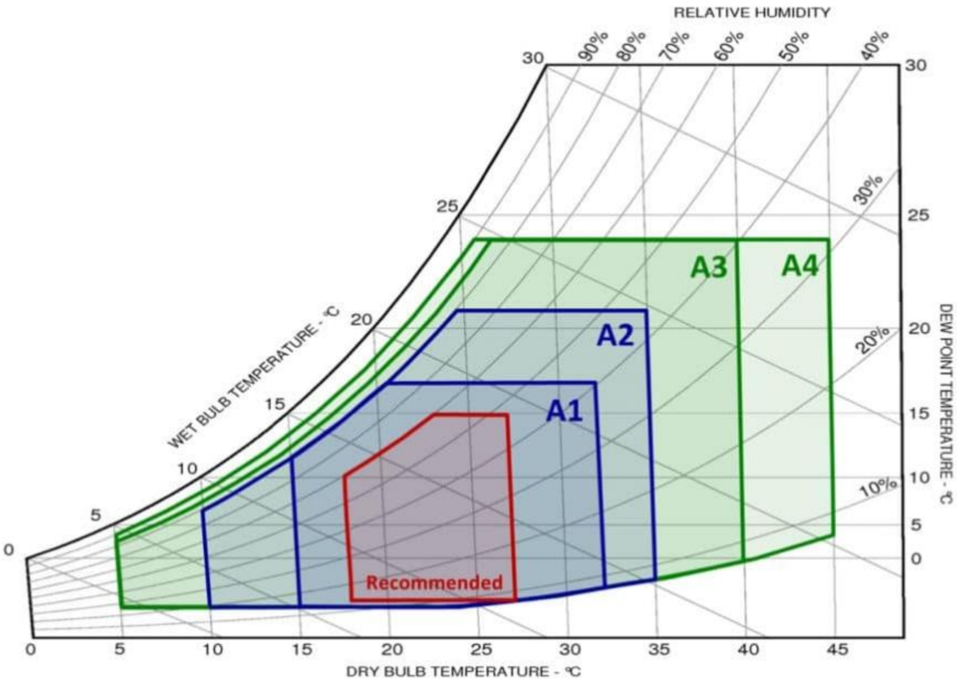


Figure (2-4) ASHRAE - Recommended environmental conditions for data centers

The recommended envelope, as shown in Figure (2-4), demonstrate the recommended temperatures and the humidity limits that can be applied in a data center. However, A1 envelope, A2 envelope, A3 envelope and A4 envelope are the allowable envelopes for the specific range of the server blades with controlling of dew point temperature inside the data center to avoid condensation that caused damage to equipment (ASHRAE, 2019).

2.5 Data Center Efficiency

There is a common term used to describe the data center efficiency called Power Usage Effectiveness (PUE), which is the amount of total power divided by the amount of power used to power on the computer infrastructure. The best efficiency of the data center can be achieved as the Power Usage Effectiveness (PUE) value reduces to reach **1**. Most data centers have an operational PUE value between 1.2 to 3, where the PUE of 1.2 is a very efficient data center. On the other hand, the data center with 3 is considered to be a very inefficient data center (Haywood et al, 2012). The Data Center Efficiency (DCE) is defined as the inverse of the PUE value multiplied by 100, and its value varies between 0 to 100%. The data center productivity (DCP) is a new factor and has been defined by Green Grid. DCP is defined as the useful work Divided by the total facility power. The Green Grid expressed the PUE, as follows

$$\text{PUE} = 1 + \text{Cooling Load Factor (CLF)} + \text{Power Load Factor (PLF)} \qquad (2.2)$$

1 represents the normalization of the IT load.

$$\text{CLF} = \frac{\text{Total Power consumed by cooling system and its auxilaires}}{\text{Information Technology Load}} \qquad (2.3)$$

$$\text{PLF} = \frac{\text{Total Power Consumed by switch gear UPS and power distribution unit}}{\text{Information Technology Load}} \qquad (2.4)$$

The calculation of the PUE is not straightforward because it is difficult to calculate the exact amount of both total power and Information Technology equipment power. Furthermore, there is no exact point to measure either total power or Information Technology power. This difficulty was solved by defining a standard method to calculate PUE. Four main reasons that make the calculation of PUE difficult are listed (Avelar, 2009), as follows:

a) The way to calculate the power used by devices in a data center is not clear.

b) Sometimes some systems used by data centers are outside the data center.

c) Some systems can be classified as both data center and non-data center equipment.

d) The difficulty in specifying the proper location to take the power measurements.

A three-part methodology has been developed to overcome most problems that face the calculation of PUE. This method states the following;

i. The description of the types of subsystem used in data center: whether it is Information Technology load, infrastructure or not-included load.
ii. The approximate assumption can be used, either if subsystems are joined with other non-data center loads or the measurement load of the subsystem is difficult due to technical problems.
iii. The estimation of power consumed by the subsystem, such as Power Distribution Unit (PDU), can be done when there is a difficulty performing the measurement, such as the existence of obstruction barriers.

2.6 Layout and Cooling

Data center energy efficiency can be enhanced in several ways, such as improving the cooling system, improving the rack layout, using the concept of a green data center (data center in which the mechanical, lighting, electrical and computer systems are designed for maximum energy efficiency and minimum environmental impact) and improving the data center power system by decreasing the power required to cool data center by using some cooling techniques such as air side economizer.

Efficiency losses in the data center are due to overload on cooling system and its auxiliaries by using a lot of power to cool down the data center with wrong rack layout, so careful design of the data center and the best operation might help to improve the data center efficiency. The reduction of electricity consumption of data centers is a very important issue because as the power goes to high demand, then the cost increases and the environment will be impacted. Rasmussen (2003) discussed common mistakes that could occur during the design and operation of data centers.

There are several issues that might reduce the cooling efficiency by 20% or more. The most important parameters that affect the cooling performance of data centers can be summarized, as follows:

1. Rack air flow.
2. Rack layout.
3. Layout of delivered and returned air of data center.
4. Cooling setting
5. Distribution of load.

The air flow problems appear either as mixing of hot and cold air before the Computer Room Air Conditioners (CRAC) intake or if air flow is blocked by obstructions. The blanking panel which is a panel that is used inside the rack to fill the gaps between server blades and it could be used to improve the cooling performance in the rack by avoiding the mixing of hot and cold air streams. The cooling setting (such as changing the supply temperature and air flow rate) is another critical parameter that has a direct effect on the cooling performance of data centers. So, as the supply temperature of the CRAC unit increases within an acceptable range (20ºC-25ºC) as the cooling performance of the CRAC unit increases, and vice versa.

2.6.1 Data Center Layout

The servers with high demand should be distributed and deployed so as to eliminate recirculation and hot spot problems without adding new CRAC units or changing the inlet temperature. The layout of delivered and returned air is very important in terms of the cooling performance. The correct layout leads to minimized hot spots and to reduce recirculation, as well. Therefore, the cooling efficiency will be improved. Also the data center layout can be improved by changing the geometry inside the data center, such as moving the vents closer to the intake of the racks in the cold aisle to provide the rack with sufficient cooling requirements. The effect of the floor plan on the number of racks, Information Technology power densities, power and cooling and electricity consumption was analyzed by Rasmussen and Torell (2007), who also introduced a method for designing the floor layout of a data center. The number of racks in a data center can be estimated by dividing the room area by 2.6 m2/ rack. The basic principle layout involves many parameters that should be taken into account, such as controlling the air flow using hot-cold aisles, controlling the tiles' location, reducing the isolated Information Technology (IT) devices and predesigning for the equipment layout. Additionally, the structure layout plays a significant role in power and cooling performance by locating the windows and walls in a data center. Optimization of the cooling system of the data center can be achieved by changing the rack layout and cooling settings. In terms of rack layout, the cooling performance can be improved by using the partitions at the end of cold aisles to reduce the recirculation phenomena, as shown in Figure (2-5).

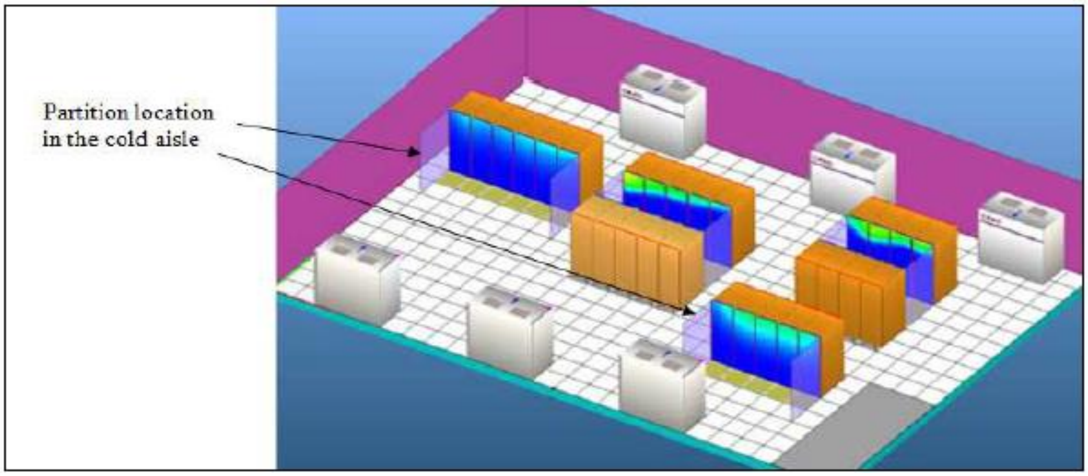


Figure (2-5) Partitions' location that covers the cold aisles in the data center

The cooling and design principles have been discussed by Intel information technology (2006) in order to cool a high-performance data center (HPC). The affecting factors on the cooling system have been tested by studying four data center layouts. There are several factors that have a significant effect on the data center, such as;

1. Using a return ducted type.
2. Using barriers on the top and bottom of the racks.
3. Changing the location of the cables to under the floor in the hot aisles.
4. Placing racks such that they are parallel to the air flow from the CRAC units.

The results show that the combination of these factors leads to huge improvements in cooling efficiency by raising the supply temperature to 21ºC instead of 15º C. Changing the data center layout corresponding with the capture index (CI) was discussed by Jensen(2007). The capture index (CI) is an index that is calculated via CFD analysis and it is based on the flow rate concept. CI is used to detect the air flow rate streams for both cold and hot aisles at each rack which is an important parameter to define the air flow path inside the data center. Two CIs are extracted from the main capture index, which are for hot and cold aisles.

If CI = 100% then the paths of all air flow streams for both cold and hot aisles reach the correct points. (Where all the cold air flow to the rack inlet section, and all the exhaust hot air flow to the CRAC unit) and when CI= 0%, the path of all air flow streams for both cold and hot aisles is not optimal. The best rack layout leads to high values of CI, which means the air stream flow path is optimal to carry out all heat dissipated from the racks. The results given from the real-time measurements show that a symmetrical layout of racks based on the best cold-hot aisles arrangement leads to the highest possible CI percentage (70%-90%).

Bhopte et al(2006) discussed the strategy to minimize the inlet air temperature to the rack by analyzing the room layout, including the depth of plenum and the ceiling height. Also, optimization has been applied to obtain the best design with respect of the inlet air temperature of the racks. The results are as follows:

- Large plenum depth leads to more uniform distribution of cold air.
- Increasing ceiling height leads to an increase in the recirculation phenomenon, thus the inlet air temperature will be increased.

2.6.1.1 Cold Aisle Containment and In-Row Cooling with Hot Aisle Containment.

The cold aisle and hot aisle containments were presented by Niemann(2008). These two methodologies have been applied in the data center to manage the air flow inside in order to eliminate the hot/cold air mixing. Also the comparison between these two techniques has been discussed in this research. The concept of cold aisle technique is to apply the physical barriers on the cold aisle to prevent the mixing between the hot and cold streams, as shown in Figure (2-6). The concept of using hot and cold air containments is to obtain a high degree of separation between the hot and the cold air streams. With respect to the hot aisle containment, the hot aisle is covered with barriers to block the exhausted hot air and send it to the in-row cooling units. The cooling units then cool the air and distribute it again to the cold aisle, as shown in Figure (2-7). Once these techniques are applied, a lot of benefits might be captured to improve the power performance and cooling efficiency; for example, the recirculation phenomena will be dismissed and the supply temperature can be increased within the acceptable operation temperature range (15ºC-25ºC) because the supply temperature will be equal to the rack inlet temperature (i.e., there is no increasing of temperature due to the hot stream migration). Thus, energy will be saved and the cooling efficiency will be improved; also, the humidification and dehumidification can be reduced because the hot and cold air streams are separated.

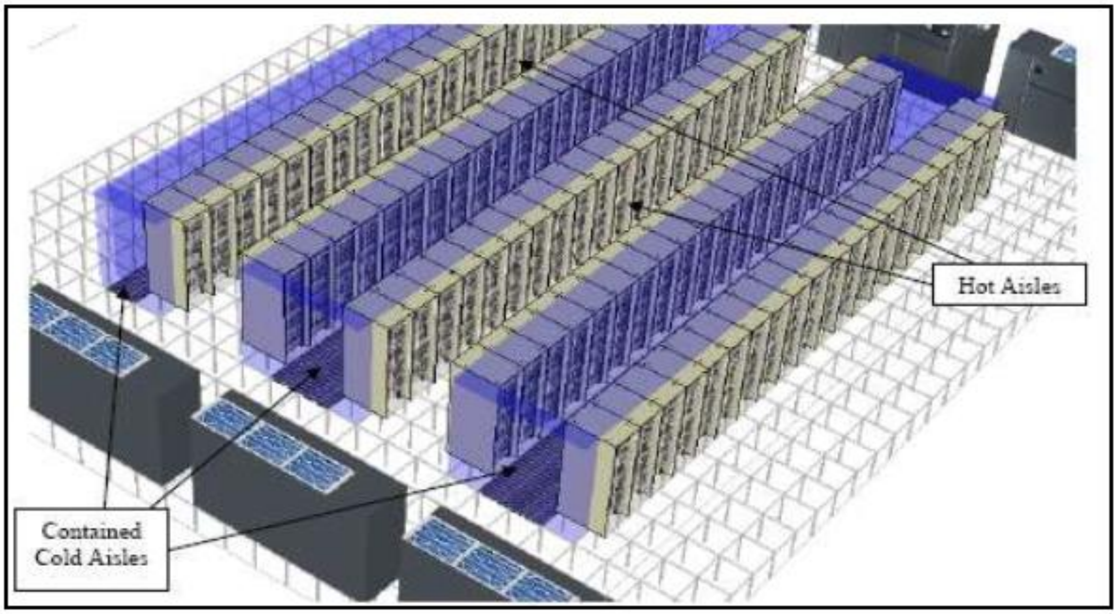


Figure (2-6) the cold aisle containment technique

However, the cold aisle containment technique has some drawbacks, such as all cold aisles should be covered to improve the cooling efficiency. This means if there are any racks missing in the row, a blank panel should be filled to connect the row. Another issue is that the room temperature will increase due to the separation of the cold and hot aisles. So, these drawbacks will affect the operating condition but this technique is still better than the traditional one. These drawbacks could be overcomes by using in-row cooling with hot aisle containment.

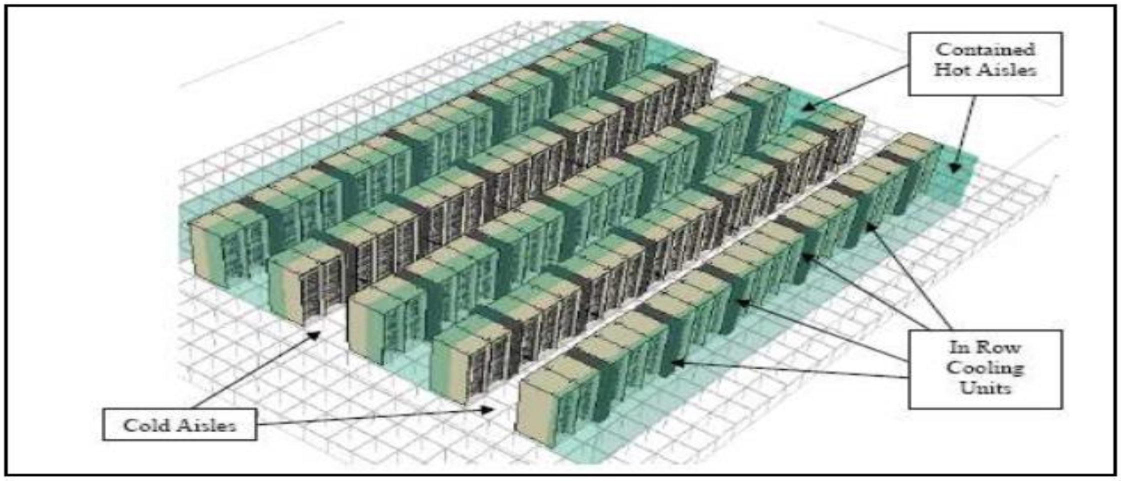


Figure (2-7) In-row cooling with hot aisle containment technique

2.6.1.2 Cabinet Ducted To Hot Air Plenum

Chatsworth Products, Inc (2006) invented a new approach to manage the exhaust air flow within the cold-hot aisle data center by taking it directly to the cooling source without any mixing with cold air streams. This method is called the ducted exhaust cabinet. The ducts are attached at the top rear of the rack cabinets to suck all of the hot air and send it through the top plenum to the cooling source (CRAC), as shown in Figure 2-8.

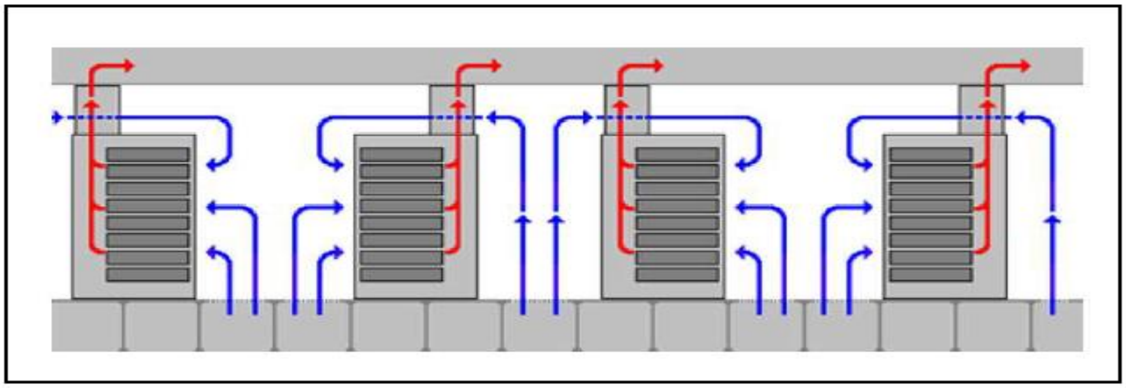


Figure (2-8) the ducted exhaust cabinet technique

There are several benefits that are claimed by Chatsworth Products in using this technique, such as controlling the rack orientation (i.e., no need for front-to front and back-to-back arrangements) and also the ability to use all exposed floors as the supply for the cold air, which means that all servers will take enough flow rate to improve their cooling efficiency. Furthermore, the supply air from the raised floor is not the only technique to supply the air; other supply techniques can be implemented in a high density data center. In addition, the above ducted system is adequate for up to 30 kW per rack. So, it offers a good solution for the high density data center. Thus, this technique can be installed easily without any constraints and it offers a high degree of separation between cold and hot air streams. However, the pressure drop might increase so that additional fan power would be required to overcome this pressure drop (Chatsworth, 2006).

2.6.2 Data Center Cooling

2.6.2.1 Information Technology Load In Data Center

The power required for data centers has been increasing due to the introduction of high-performance computer facilities (HPC). Thus, the need to provide additional cooling will increase strongly. Furthermore, the traditional hot cold aisle configuration is not sufficient to carry away dissipated heat in a high density data center due to the increase in rack exhaust temperatures. So, new cooling approaches have been invented to assist the traditional cooling system (hot cold aisle cooling system).Recently these methods have been deployed in some data centers to cope with the excessive heat dissipation from the racks. In such, the power consumption trend is increasing.

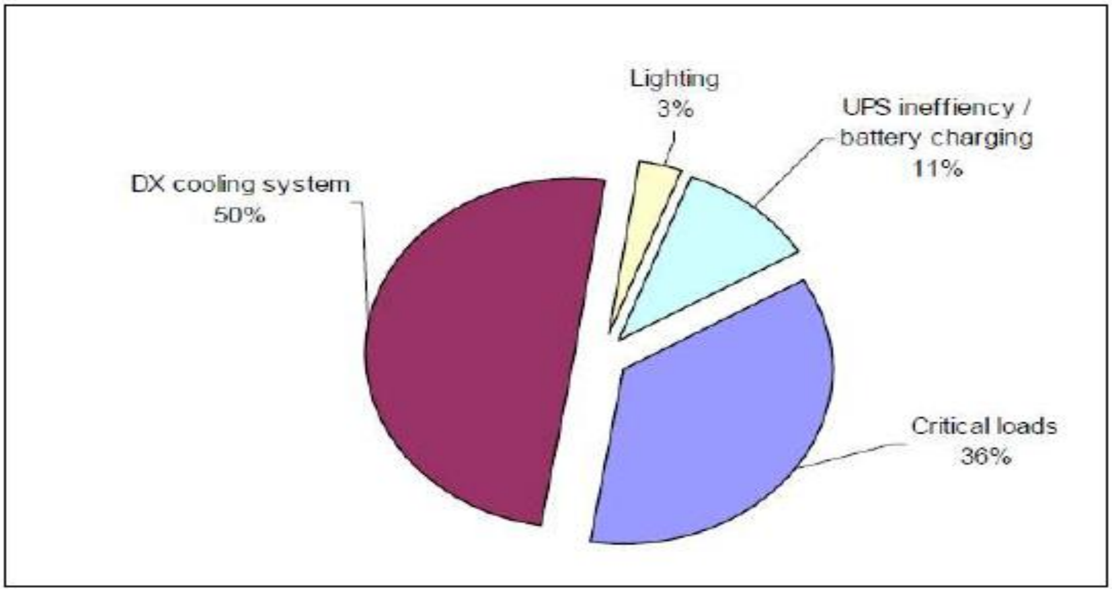


Figure (2-9) Breakdown for the power inside a typical data center (Christopher et al,2008)

Some high performance data centers now have racks with 30 kW or more per rack (University of Leeds, as an example). It is shown in Figure 2.9 that the most power goes to the cooling system, whereas the Information Technology load draws 36% of the total input power for the data center with an area of 465 m^2, and with rack units of 50 kW(Richard,2004). Malone et al(2008) came up with a new rack design that uses blade servers in order to reduce the power consumption associated with groups of fans that have the ability to carry higher back pressure to minimize the air flow bypass. The concept behind Malone's approach is to reduce the back air flow of the servers, thus decreasing the power consumption of the rack fans. As a result of using blade servers, the air flow can be reduced by up to 25% of the air flow value of traditional 1U rack servers; also, the power consumption can be reduced by up to 48% when using blade servers rather than 1U rack servers, as shown in Figure 2-10. Also, in this analysis, the comparison of using blade and 1U rack servers has been discussed. In such, the recirculation problem can be eliminated by implementing blade servers in cold-hot aisle data centers. Thus, the CRAC air flow can be reduced, leading to a saving in the energy requirements of the CRAC unit. Furthermore, the inlet temperature of 1U servers is 8 K higher than the blades for the same CRAC temperature set-point, due to the recirculation problem. So, as the supply air temperature from the CRAC increases, the coefficient of performance (COP) of the CRAC increases, indicating that the data center becomes more efficient and consumes less power.

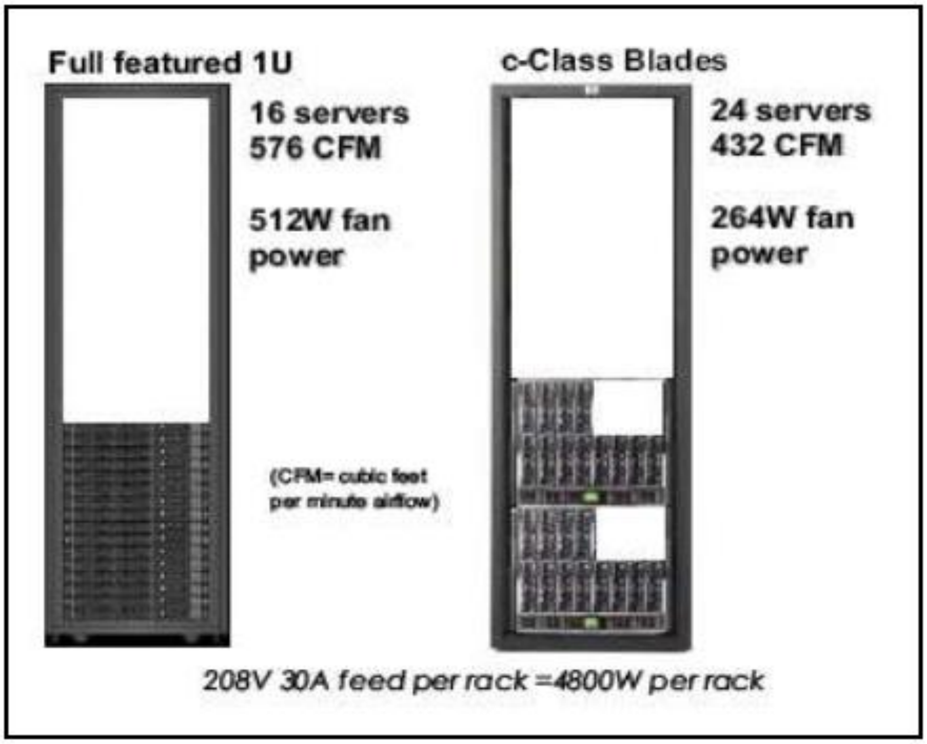


Figure (2-10) Comparison between a 1U rack and a blade rack (Malone et al, 2008)

2.6.2.2 Air distribution Systems for Data Center

Six air distribution systems were introduced by Cho et al(2009). Each of these systems have different return and supply types. Here, six air distribution types have been implemented and evaluated with respect to the temperature and velocity fields. The six distribution systems are as follows:-

1. Overhead distribution-CRAC flooded supply/fully ducted return (O-CS/CR).In this configuration, the cold air is supplied by CRAC unit to the data center. Whereas the hot air coming from the rack exhaust is ducted. In this case

insufficient chilled air will be provided for the racks that are far away from the CRAC unit. Also, mixing between hot air and cold air will occur.

2. Overhead distribution-CRAC flooded supply/locally ducted return (OCS/LR). In this configuration, the cold air is supplied by CRAC by using overhead duct at the rack inlet. Whereas, the hot exhaust air return directly to the CRAC unit.
3. Overhead distribution-locally ducted supply/CRAC flooded return (OLS/CR). It is good to provide the chilled air to the upper server’s inside racks, but this does not provide enough chilled air to the bottom server. The recirculation of hot air may be reduced by using an overhead supply.
4. Overhead distribution-locally ducted supply/locally ducted return (OLS/LR). In this case, the supply air from the CRAC unit is introduced to the rack by using duct. Similarly, the hot exhaust air is sucked by the overhead duct at the hot aisle. Then Case 4 is the best case among other cases due to its ducted return method to prevent the recirculation of hot air to the cold aisle.
5. Underfloor distribution-locally ducted supply/CRAC flooded return (ULS/CR). This is the most common configuration that is used in data centers. This configuration is beneficial in providing the chilled air to the lower servers’ inside racks. However, the mixing between hot and cold air may occur.
6. Underfloor distribution-locally ducted supply/locally ducted return (ULS/LR), as shown in Figure 2-11. As in case 4, this case is used to avoid recirculation by using a return duct.

It is shown from Figure (2-11) that the main difference between the air distribution methods is the way in which they provide the supply air and take out the exhaust air. So, it is shown that the supply air can be provided directly from the CRAC unit, underfloor or overhead by using ducts. Similarly, the exhaust air can be taken out by the CRAC unit, or by using the ducts connected to the CRAC unit. As an example, in case 4, the supply air is introduced to the rack inlet by using Overhead supply ducts that are connected with the CRAC unit. Whereas, the exhaust hot air is sucked in also by using the overhead return duct, the return hot air then is cooled down by the CRAC unit, which then supplies it again to the data center. It is shown from the results that case 4, which is an O-LS/LR, is a suitable method with respect to air flow and temperature fields inside the data center; this is because in this case, the recirculation problem is reduced due to using the ducts for both supply and return. Therefore, the hot spots inside the data center are minimized.

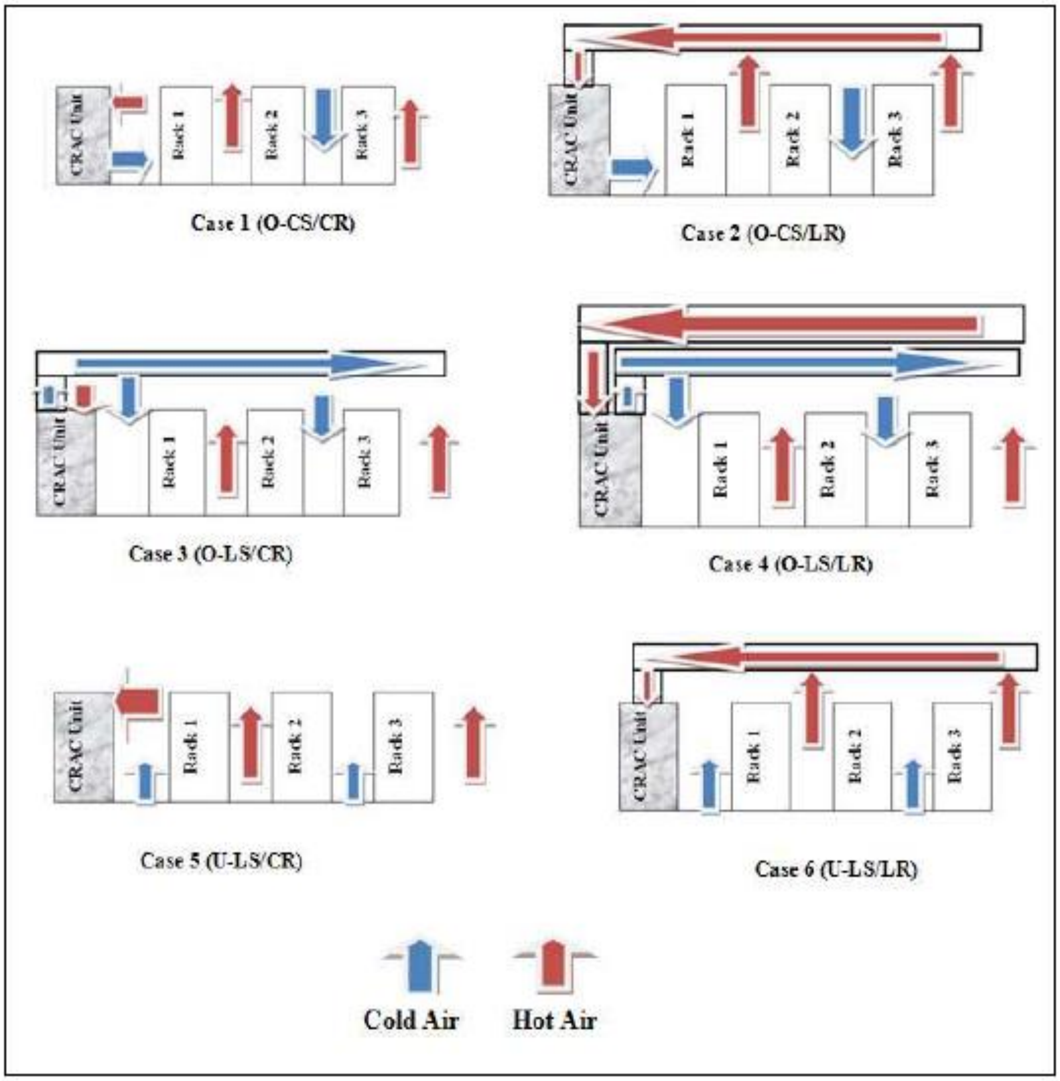


Figure (2-11) Six types of air distribution systems.

The effect of installation of blanking panels (installed in the unused vertical space in the rack) on the cooling performance was discussed by Rasmussen(2005).Blanking panels are physical barriers used to fill the vertical space between the servers in the rack, as shown in figure (2-12).

The blanking panels are not commonly used because of a lack of knowledge of this technology and also because of the difficulty of installation. Figure (2-12) shows the effect of the blanking panel on the inlet air temperature of the servers. The experiment was carried out to test the effect of blanking panels on the inlet air temperature to the servers in the rack. The inlet air temperature at the servers can be reduced between 2.8º C to 8.3º C by deploying blanking plate technology because the mixing is reduced between cold and hot air.

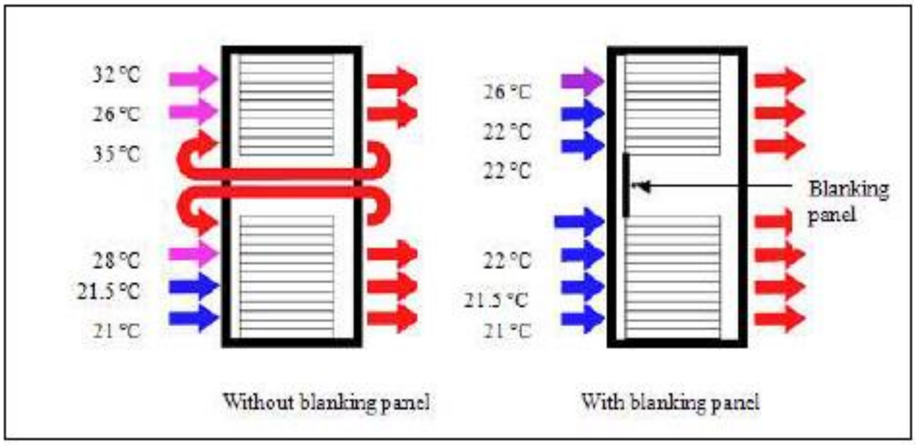


Figure (2-12) Effect of installation of blanking panel on server air inlet temperature.

Karki et al (2003) discussed a number of techniques that can be used for controlling airflow distribution. These techniques include changing the plenum height and opening area of the perforated tiles, and installing thin (solid and perforated) partitions in the plenum. A number of case studies, using a mathematical model, are presented to demonstrate the effectiveness of these techniques. Also a computational study of various techniques for controlling the airflow distribution in raised-floor data centers has been presented. The key to controlling the airflow distribution is the ability to influence the pressure distribution (or the flow field) in the plenum. For specified (horizontal) floor dimensions and total flow rate, the pressure distribution is governed by parameters such as the plenum height, the open area of perforated tiles, the distribution of the vents on the floor, the relative positions of CRAC units and perforated tiles, and the presence of underfloor blockages.

The results of this study have been summarized, as following:

- The pressure distribution becomes more uniform as the plenum height is increased. (So the plenum depth must be taken into account in the design stage, because the changing of plenum depth for the existing data center is very difficult.)
- The results indicated that the thin partitions offer significant flexibility for controlling the airflow distribution, especially in an existing data center. The effect of the air supply flow rate coming from vents in both cold and hot aisles on the inlet air temperature of the racks was analyzed by Schmidt et al(2002). In addition, CFD models have been applied to show the temperature distribution along the racks in a data center. The analysis includes the effect of the CRAC units' location to the inlet air temperature of the racks. The result shows the following:
- As the flow rate of supply air coming through the vents increases, the room temperature of the data center decreases and vice versa because as the flow rate increases, the heat transfer increases, leading to a decrease in the room temperature.
- The inlet air temperature of the rack increases, as more supply air is utilized in the hot aisle than in the cold aisle.
- The location of the CRAC units has an insignificant effect on the inlet air temperature.

Most strategies to manage the environment of data centers consider the return air temperature to the CRAC units; so the hotter the supply air to the CRAC units, the more efficient their operation. Boucher et al (2006) studied several ways to improve the thermal management and energy performance of the data center by using three main actuators placed on the CRAC supply to control the supply temperature, the CRAC fan to control the flow rate, and the plenum vent tile opening. Furthermore, the new non-dimensional index that describes the amount of hot and cold air mixing (Recirculation) is called the Supply Heat Index (SHI) and it is defined, as follows:

$$\text{SHI} = \frac{(T_i - T_v)}{(T_o - T_v)} \tag{2.5}$$

Where;

T_i = the inlet temperature.

T_o = the corresponding outlet temperature at the same rack at the same height.

T_v = the air temperature from the adjacent plenum vent.

The results show that in the linear relationship between the CRAC temperature and the inlet temperature, the fan speed has significant effect on the SHI; additionally, the opening area of the vents tile has a direct relation with the rack closer to the CRAC and an inverse relation to the rack farther away.

The cooling and energy efficiencies of the data center were analyzed by Herrlin (2008). He defined two indices used to indicate both cooling and energy performances. These indices are rack cooling index (RCI) and return temperature index (RTI). Rack cooling index (RCI) measures the cooling efficiency of the equipment in the data center, whereas the return temperature index (RTI) measures the energy efficiency of the data center. Also the Computational Fluid Dynamics analysis has been implemented to calculate these indices by obtaining both return and supply temperatures of the CRAC unit. There are two indices, RCIHI and RCILO, which can be extracted from RCI at both ends of high allowable intake temperature and low allowable intake temperature.

ASHRAE describes that the range of intake temperature varied between 20°C and 25°C. However, the allowable range is between 15ºC and 32.5°C. Return temperature index (RTI) is written, as follows:

$$\text{RTI} = \left[\frac{T_{Return} - T_{Supply}}{\Delta T_{Equip}}\right]100\% \qquad (2.6)$$

Where

T_{Return}: return temperature

T_{Supply}: supply air temperature.

ΔT_{Equip}: Temperature rise across the electronic equipment.

RTI = 100% target (the best energy performance)

RTI < 100% by-pass (the cold air return to the CRAC without cooling the racks)

RTI > 100% recirculation (mixing between hot and cold air)

And the RCIHI definition is as follows:

$$RCI_{HI} = \left[1 - \frac{Total\ over - Temp}{Max\ Allowable\ Over{-}Temp}\right]100\% \qquad (2.7)$$

Where the total over-temperature refers to the summation of the server intake temperature subtracted from the maximum recommended temperature; whereas, the maximum allowable over temperature refers to the subtraction of maximum allowable temperature and the maximum recommended temperature multiplied by the number of servers. The interpretation of the index is as follows:

RCIHI = 100% All intake temperatures ≤ max recommended temperature.

RCIHI < 100% At least one intake temperature > max recommended temperature.

The RCILO definition is as follows:

$$RCI_{Lo} = \left[1 - \frac{Total\ under - Temp}{Max\ Allowable\ under{-}Temp}\right]100\% \qquad (2.8)$$

Where the total under-temperature refers to the summation of the subtraction of the minimum recommended temperature and the server intake temperature, when the Server intake temperature is less than the minimum recommended temperature.

RCILO = 100% All intake temperatures ≥ min recommended temperature

RCILO < 100% At least one intake temperature < minimum recommended temperature.

These indices are useful to ensure that all the server racks are within the acceptable range of temperature (15ºC-25ºC).

2.2.6.3 Air, Water and Refrigeration Cooling Systems in a Data Center

Hannemann and Chu(2007) reported the comparison between five alternative cooling systems for a data center to achieve the best one based on the cooling performance and the total cost (capital and operation). This study considered a 30 kW heat dissipation rack in a high-density data center in order to compare these systems. The five alternative cooling approaches are:

(1) Standard air cooling, which is used, chilled air coming from the CRAC unit to cool the rack, as shown in Figure (2-13)(a), where the pink and the blue lines are hot return refrigerant and cold supply refrigerant in the condenser respectively.

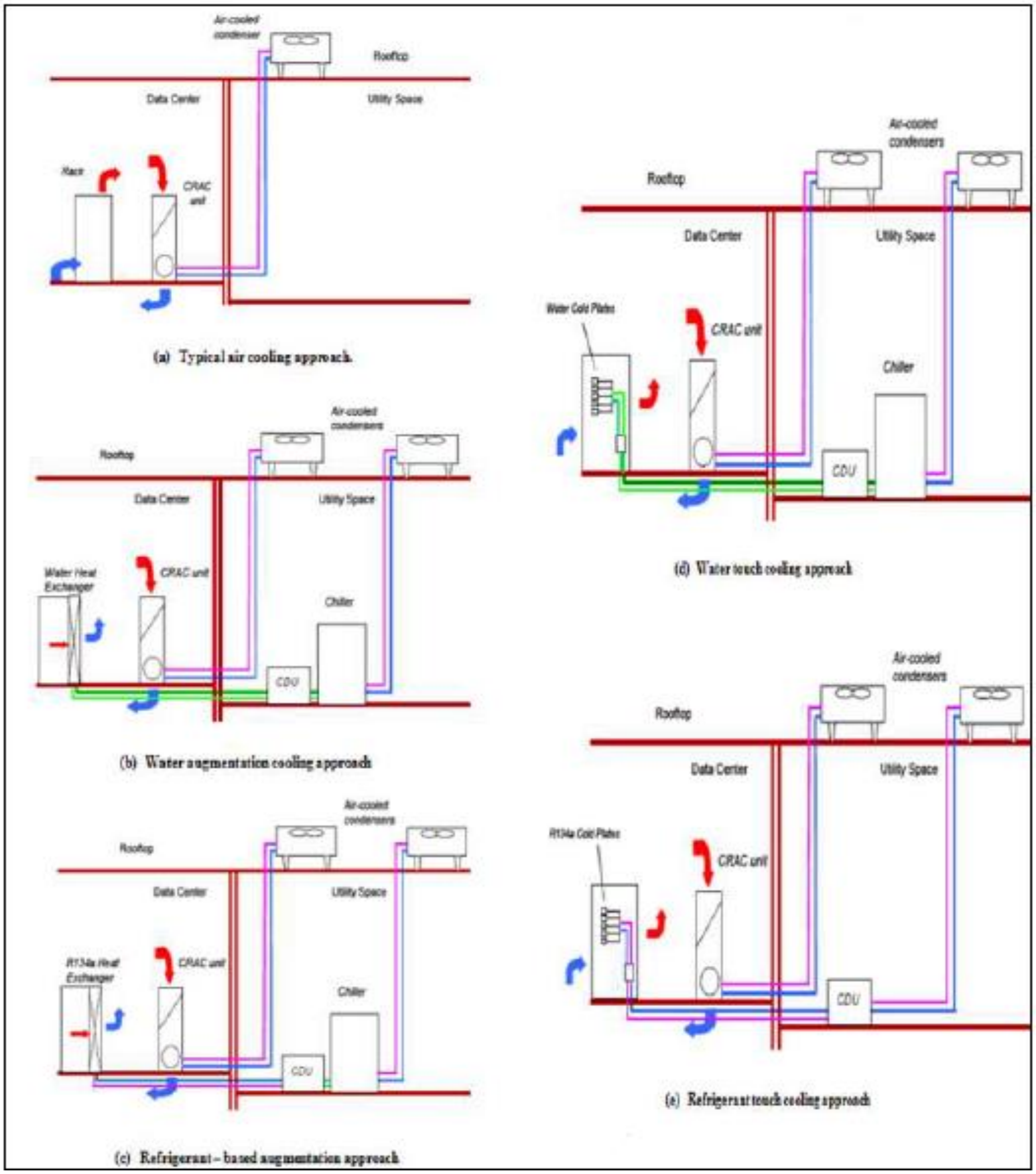
(2) Water augmentation cooling, in which the heat dissipation from the rack is removed by both chilled air from the CRAC unit and the back door water heat exchanger, as shown in Figure (2-13)(b), where the light green and dark green lines are cold supply water and hot return water in the chiller, respectively. In this case, the heat will be removed directly from the rack. However, this method has a high cost of installation and maintenance, and also the risk of forming the condensation at the rear heat exchanger may lead to a failure in the system.

(3) Refrigerant based augmentation; in this approach, the idea is the same as the water approach, except the refrigerant type R134a in back door heat exchanger is used rather than a water heat exchanger, as illustrated in Figure (2-13) (c).

(4) Water touch cooling system; in this approach, the cooling water plates are introduced inside the rack to accomplish the direct cooling of heat source and the

CRAC unit is used to remove the part of heat dissipation by the rack, as shown in Figure (2-13)(d).

(5) Refrigerant touch cooling, which is the same idea as the water touch approach, but the refrigerant R134a plates are used rather than water plates. Also, this system does not need a chiller unit, as shown in Figure (2-13) (e). In case (a), the typical air cooling is used to cool the rack inside the data center. In this system, the refrigeration cycle is used to cool the hot return air from the data center. Both condenser and compressor are kept outside the data center, whereas the evaporator and expansion are located inside the CRAC unit where the heat exchange takes place between the hot return air and the refrigerant agent. The results show that the refrigerant touch cooling approach has the best results among all of the approaches for saving floor space, cooling power, capital cost and operational costs.



(a) Typical air cooling approach.

(b) Water augmentation cooling approach

(c) Refrigerant – based augmentation approach

(d) Water touch cooling approach

(e) Refrigerant touch cooling approach

Figure (2-13) five alternative cooling systems for data center

2.2.6.4 Air Side Economized System

An air side economizer is discussed here as the alternative solution that could be used under the category of air flow management solutions. An air side economizer is a mechanical device that is used to regulate the outside air brought inside the data center. A full study of economizer systems for data centers was presented by

Anubhav et al.(2008), and it was found that the energy of the chiller could be reduced up to 50% with increasing the inlet temperature from 20°C to 25°C. The two main economizer systems are airside economizer systems and fluid based economizer systems. The air side economizer system uses the fresh outside air to cool the data center with cooperation from the fan and filter systems, as shown in Figure (2-14).

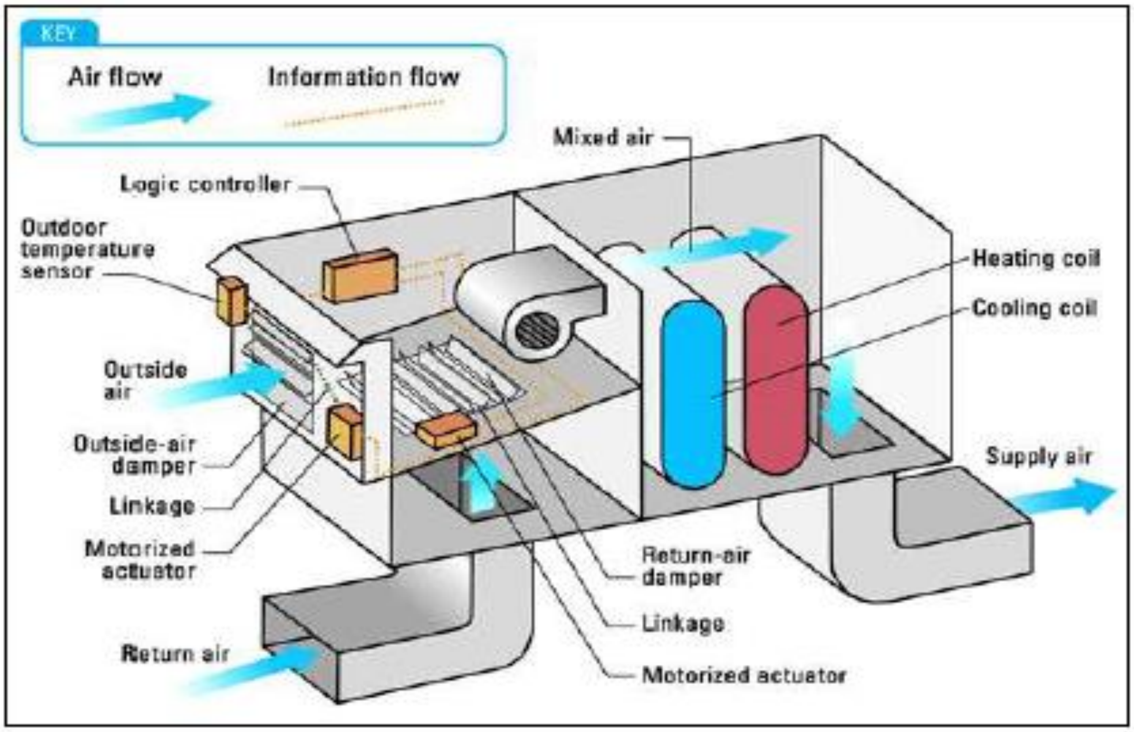


Figure (2-14) Air side economizer system

The principle of an airside economizer can be described as introducing the fresh outside air to the cold aisle, whereas the hot return air is rejected directly to the outside ambient environment. Next, the room air mixed with cold outside air is fed back to the CRAC unit. In this technique, the humidification and dehumidification are critical parameters that have been taken into account to achieve the recommended relative humidity (40%-55%) in the data center. As a result, the saving of cost and energy using this system can reach up to 40% compared with using the traditional cooling system in a data center. However, this system cannot be used in hot or humid weather because it is used to supply the data center air with low temperature and suitable humidity.

2.2.6.5 Overhead Cooling Method

A heat exchanger cooling system for the data center was implemented by Patel et al.(2001). The data center prototype with a cooling system was analyzed by using CFD. The cooling system simply has water-air heat exchangers located in the ceiling of the data center that are called the Data Cool system. These heat exchangers have been deployed such that a heat exchanger is located above each rack, as shown in Figure 2-15.

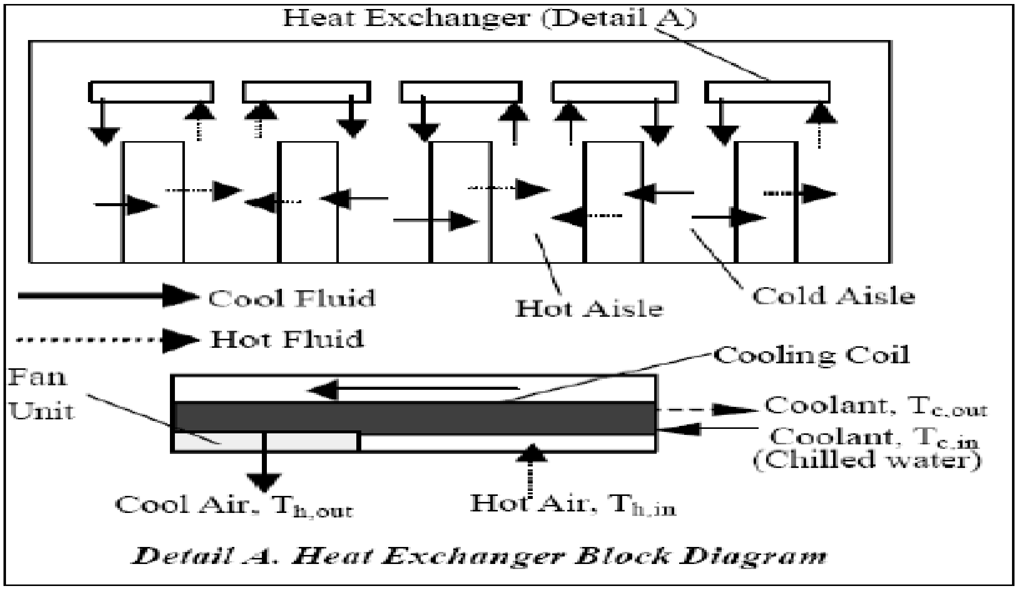


Figure (2-15) Data Cool system in cold-hot aisle arrangement

The idea of this system is to cool the exhaust air coming from the hot aisle in the heat exchanger by using chilled water. The main advantage of this system is a reduction in usage of floor area compared with the traditional system (hot-cold aisle arrangement data center). It was found that the data cool system which is described by Patel et al (2001) is an efficient system to reduce the rack inlet temperature, leading to reduction of the probability of recirculation problems compared to the raised floor system.

A further development to the smart cooling system was invented by Patel et al(2001).This approach provides a controlled amount of the cooling fluid flow rate to each heat exchanger based on the heating dissipation required for each rack. This system contains variable capacity compressors and variable speed fans in order to control both the volume flow rate of the air and the speed of the cooling fluid. This approach leads to a reduction of the power consumption by the CRAC units. Also in this technique, the data center layout (CRAC units) may be changed based on the heating dissipation by the racks in order to achieve the optimal operating manner for CRAC units. An alternative of cooling that uses overhead units to cool the data center was described by Stahl et al (2003). As per Patel et al (2001), the cooling heat exchangers are located in the ceiling of the data center to provide the cooling air to the racks; it is called the overhead cooling system. This system has a heat exchanger associated with the fan to draw the hot air from the rack exhaust and flow it again at a low temperature to the rack intake, as shown in Figure (2-16). The heat exchanging occurs between the hot air and the coolant (either chilled water or refrigerant) used inside the pipe of the heat exchanger.

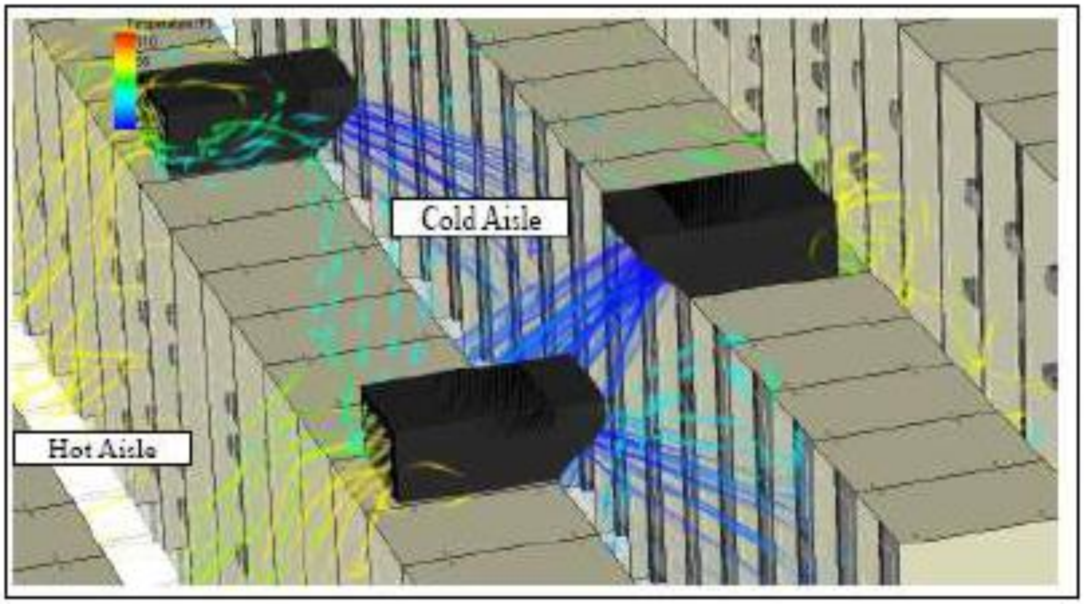


Figure (2-16) Overhead cooling system in a data center.

2.2.6.6 Portable Data Center with a Cooling System

Ice cube data centers are portable data centers with easy mobility. The cooling concept of this data center is represented by using the rows of heat exchangers and each heat exchanger consists of two opposite rack servers, as shown in Figure (2-17). The hot air is drawn from the back of each server in the same heat exchanger and it flows through the plenum, located at the back of the rack. The hot air then is cooled down by the heat exchanger using a closed loop, chilled water system. Finally, the cooled air is introduced again in the cold aisle at a temperature of 24ºC. This technique can operate up to 1500 W/ft² of complete data center space.

Figure (2-17) Ice cube cooling technique

2.2.6.7 Back Door Cooling System

In high density data centers, were the server rack produces up to 30 kW, the back door cooler is one technique used to maintain the thermal environment. Figure (2-18) shows a typical arrangement of a back door cooler (heat exchanger). According to Almoli et al (2012), up to 90% of the heat could be removed from CRAC unit by deploying both an active and passive back door cooler. Both active and passive back door coolers can be defined as an air-water heat exchanger attached at the rack exhaust to reduce the rack exhaust temperature. In an active back door cooler, the additional fan is used to increase the air flow rate to the heat exchanger. In the passive heat exchanger, the server fans are only used to push the air through the heat exchanger. It is considered as an efficient way to cool the racks cooperating with CRAC units; also, this technique uses less space than traditional data center (cold hot aisle- arrangement) and has the ability to control the environment inside the data center. However, this technique is expensive because each rack needs a chilled water system. Also it may lead to water leakage on the floor of the data center due to a large amount of couplings connecting the chilled water pipes.

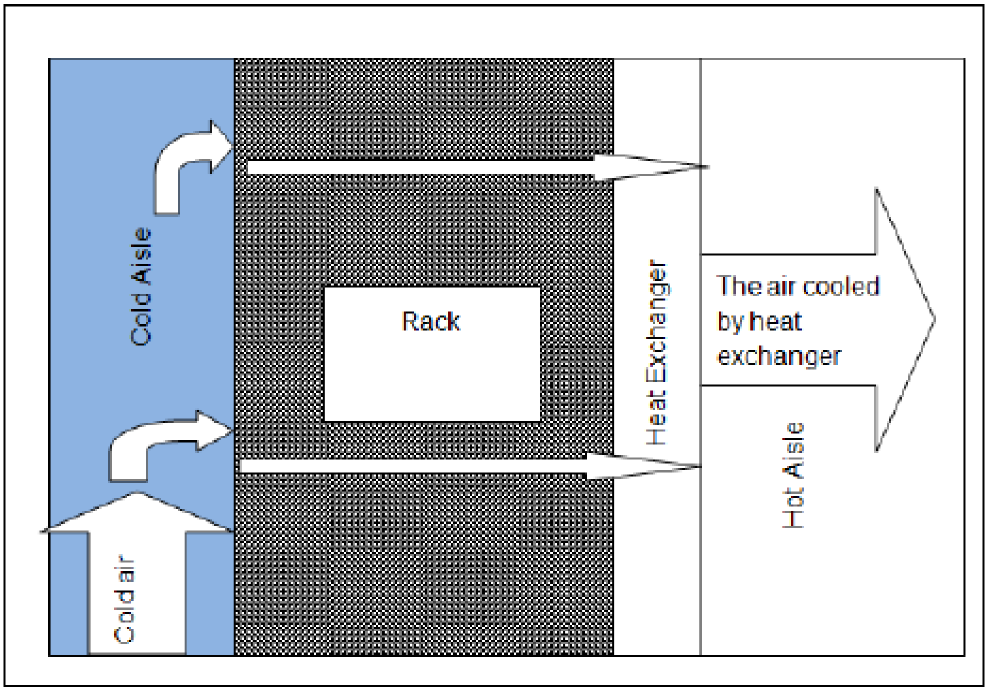


Figure (2-18) Rack backdoor cooler

The hybrid cooling system for the racks in a data center was tested by Udakeri et al(2008). The effect of using a water-air heat exchanger (hybrid cooling system) at the back of the rack is observed in this study with two different supply arrangement types, which are overhead supply and underfloor supply. With the overhead supply the chilled air is provided from the top of the rack; in the under floor supply, the chilled air is provided from the raised floor vents as in a hot-cold aisle configuration data center. The idea of the hybrid cooling system is to use a water-air heat exchanger, which is either a plate and fin or tube and fin heat exchanger. The results show that the hybrid cooling system has a significant effect on inlet temperature, return temperature and the thermal energy. The inlet temperature could be reduced down to 15ºC and the return temperature can be reduced by using the hybrid solution for both overhead supply and underfloor supply arrangements. Moreover, the energy consumed by the CRAC unit can be reduced up to 55% because the hybrid system gets red with a lot of heat.

2.2.6.8 High Performance Computing (HPC) Data Center

High Performance data center (HPC), also are sometimes called super computer data centers and can be defined as the data center that uses multiple processers to run programs in less time and to run advanced applications with a reliably fast turnaround. The term HPC is mainly used for a system that can function above a teraflop, which is a measure of the computer performance in trillions of floating point operations per second. The HPC data center is usually used to execute complex applications by academic, military and government research facilities. HPC data centers have large volumes of internal components inside the server racks that provide large amounts of primary memory and processors. The level of usage of the CPUs in these centers is greater than that of normal data centers, which can lead to large power consumption per rack. The Power consumption per rack typically reaches 20 kW and sometimes reaches more than 30 kW per rack. High-performance computing equipment that uses blade servers consumes much more power per rack than a traditional data center, leading to more heat production. In such, efficient cooling systems are required to reduce the risk of server failures (Schott et al,2008).Some HPC systems have racks with 30 kW or more, so the HPC data center requires special cooling systems to maintain an appropriate range of temperature and humidity, as specified by ASHRAE(2004). According to the TOP 500 organization(Almoli , 2013), an organization that ranks the supercomputers by their performance to determine the world's 500 fastest super computers, the United State possesses the majority of the world's supercomputers; however, there are 14 other countries that also possess them, as of June 2010, as shown in Figure (2-19).

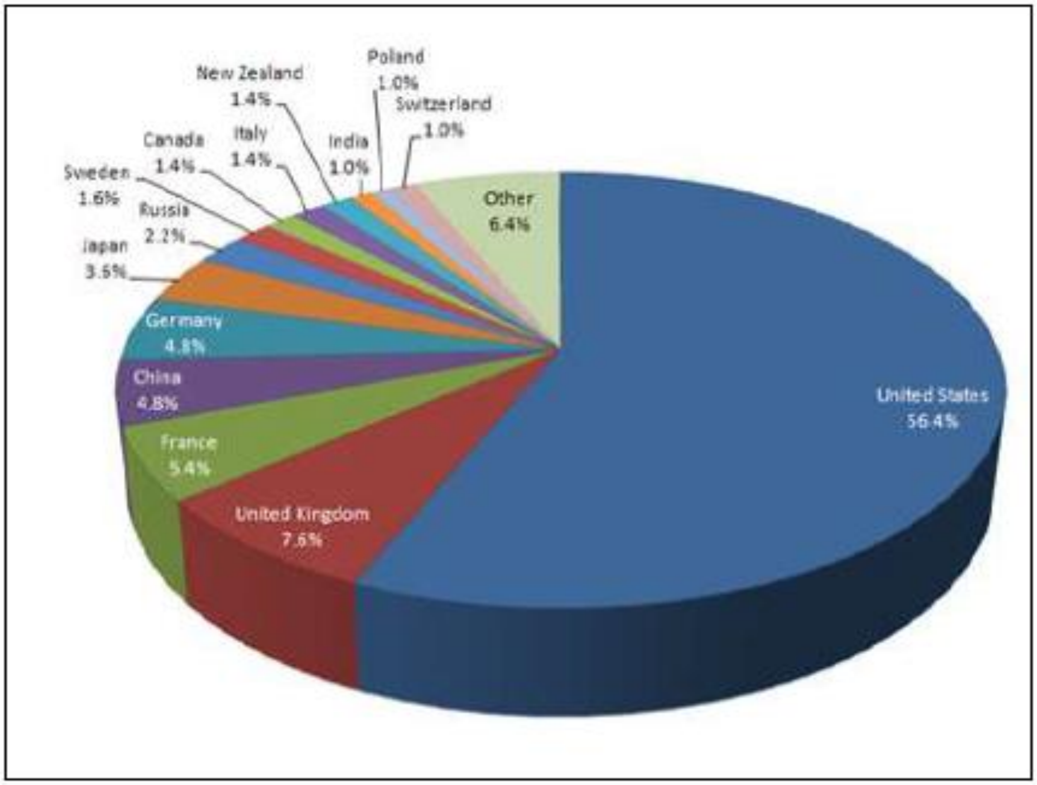


Figure (2-19) Supercomputers countries share.

The high density data center can be defined as a data center with a rack that produces at least 14 kW, which clearly produces more heat than a low data center density of less than 10 kW per rack. The traditional cooling approach (cold hot aisle arrangement) cannot provide high density data centers with sufficient cooling. Therefore, other techniques are usually adopted to cool this type of data center. The reliability of the servers inside data centers has been discussed by Moore et al. (2005). It is shown from these studies that the reliability (i.e., the mean time between failure (MTBF) or mean time to failure (MTTF)) of the servers could be decreased by 50% when the temperature is increased by 10ºC over 21ºC.Moreover, the failure rate can increase by factors of two for servers that operate at a temperature that is 15ºC over 21ºC.

2.7 High Performance Computing (HPC) Data Center Cooling Configuration

In most data centers, CRAC units are used to provide the cold air, as heat is exchanged between the Information Technology exhaust hot air streams and the chilled water. Heat exchange takes place inside the liquid (or refrigerant) coils, which are placed inside the CRAC units within the data center and this is the most common approach for commercial data centers. However, this cooling method is limited for a data center with a rack of up to 8 kW as a maximum limit for heat dissipation; whereas, in The HPC data centers, a large amount of heat is produced and this is considered to be the greatest challenge in cooling the data center. Racks with heat dissipation of 30 kW are now more common in HPC data centers, and as such, are difficult to cool via normal CRAC units, causing difficulty in keeping the data center in the recommended temperature limits (Patterson, 2007). Therefore, new cooling methods, such as liquid cooling, could be used in order to cool down the rack inside the HPC data center. Usually, the chilled water, which is used in liquid cooling techniques, is supplied between 8ºC and 15ºC when the air conditioner is used. The liquid cooling of HPC data centers can be implemented in different configurations, such as the following:

- Using a back door liquid loop heat exchanger, which sits in front of the rack exhaust (either active, with fans, or passive back door coolers).
- Using cooling pipes that come close to the CPU, which is the main heat source of the server.
- Overhead heat exchangers, which are placed above the rack to cool the hot exhaust air and supply cold air to the rack inlet. In this technique, an air water heat exchanger is used.

Air cooling techniques can also be implemented to remove heat inside HPC data centers with either cold or hot aisle containment. Containment is an efficient air management technique, since it prevents the mixing between cold and hot air inside the data center. Managing heat loads inside HPC data centers with the cooling load for the CRAC units will be analyzed in the following section.

2.8 Thermodynamics of a Data Center

The heat that is produced inside data centers by the Information Technology equipment is removed by the cold air coming from the CRAC unit. The equation that is used to evaluate the amount of heat removed from the data center and chiller unit can be expressed as

$$Q = \dot{m} C_p \Delta T \qquad (2.9)$$

Where,

Q: is the amount of heat (W)

$\dot{m}$: is the mass flow rate of air (kg/s)

C_p : is the specific heat of the air or water (J/kg.K)

ΔT: Temperature difference (K)

From Equation (2.9) the amount of heat removed from the data center exactly equals the amount of heat removed from the air by the chiller water inside the CRAC unit for a set supply or return air temperatures.

2.8.1 Computer Room Air Conditioner (CRAC) Unit Types

2.8.1.1 Direct Expansion (DX) CRAC Units

The Direct Expansion (DX) CRAC unit was presented by Evans(2007). In this type of CRAC unit, the simple vapor compression refrigeration cycle is used to cool down the hot return air coming from the rack exhaust, as shown in Figure (2-20). The indoor unit components (evaporator and expansion valves) are located inside the CRAC unit, whereas the outdoor unit components (compressor and condenser) are located outside the data center. Refrigerants such as R-134 A which is used as the cooling agent. The chiller system is predominantly used to provide cooling for a large data center (200 kW or more) because it has greater heat removal capacity than a CRAC unit (Schmidt, Iyengar, 2009).

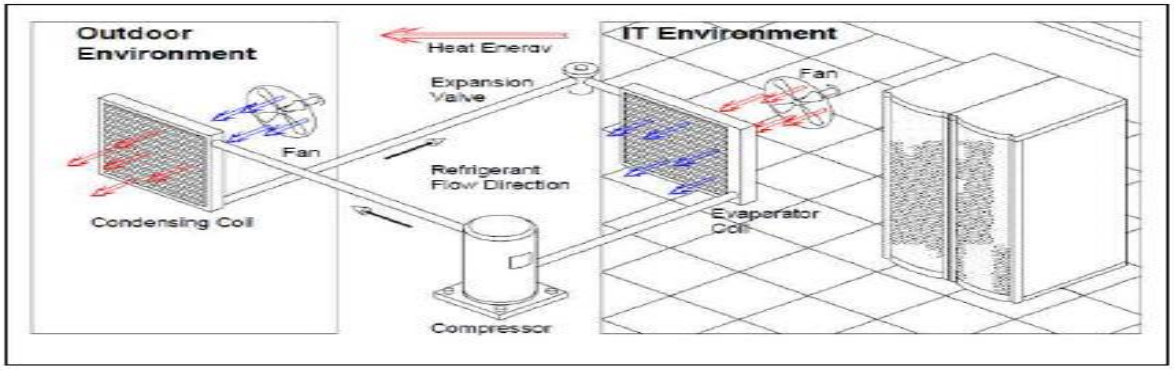


Figure (2-20): direct expansion CRAC unit type

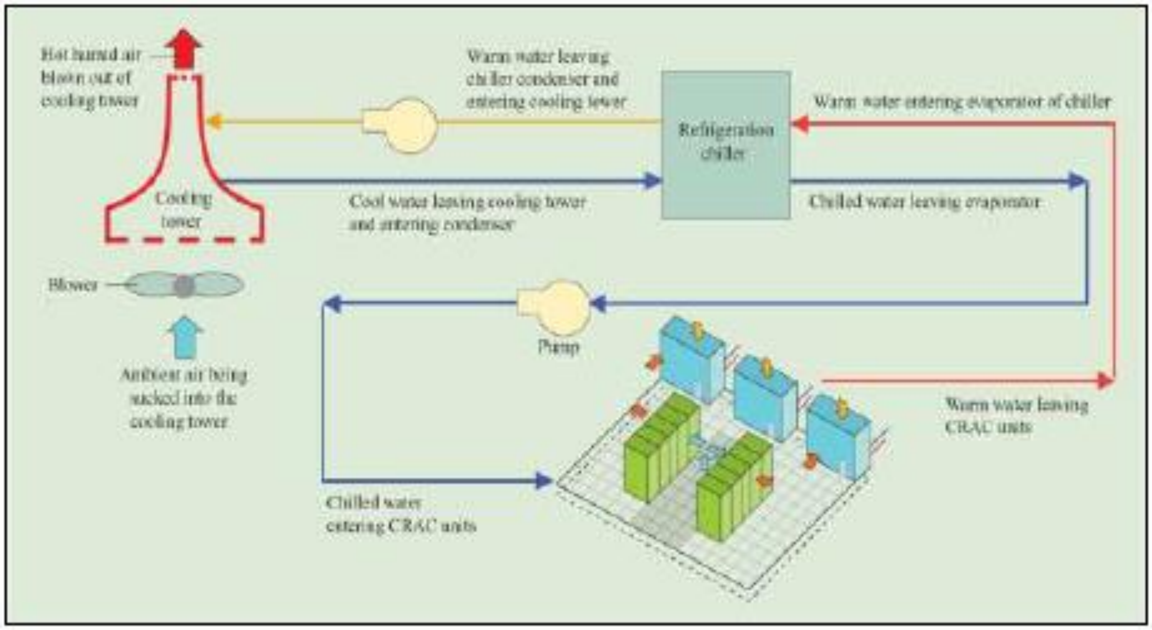


Figure (2-21): Cooling loop for the data center with chiller system

2.8.1.2 Chiller System CRAC Unit

Figure (2-21) shows the cooling loop of the data center by using a refrigeration chiller cycle and cooling tower. The refrigeration chiller is a simple vapor compression cycle with a refrigerant cooling agent. Whereas, the cooling tower cools the water by an evaporative cooling concept. The cooling procedure can be described as follows:- First of all, the chilled water (8ºC-15ºC) is pumped from the chiller unit to the CRAC unit in order to remove the heat inside the data center. The chilled water is used to cool the air that is introduced to the data center. The hot exhaust air from the data center then flows to the cooling coil inside the CRAC unit. The heat exchange happens between the hot air and chilled water inside the cooling coil to cool the supply air again by transfer of sensible heat (heat transfer by changing the temperature) and latent heat (heat transfer during phase change with constant temperatures), from the air to the chilled water. Finally, the warm water is pumped into the chiller unit to be cooled again by using cooling towers. In the cooling towers, the warm water is sprayed and then the heat is transferred to the outside environment by the evaporative cooling concept. In the evaporative cooling, the temperature of the water can be significantly reduced during the phase change between the liquid water to the water vapor.

2.8.2 Coefficient of Performance (COP) of the Data Center

The Coefficient of Performance (COP) is a term that is used to represent the efficiency of the refrigerator (Cengel, Turner, 2005). The main purpose of a refrigerator is to carry out the heat from the refrigerated space. To achieve this, the supply power should be enough to carry out the heat from the refrigeration space. The aim of calculating the COP of the CRAC unit is to detect the efficiency of the CRAC unit inside the data center. In this chapter, the COP of the DX-CRAC unit will be used to detect the effectiveness of different data center configurations. The COP of the refrigeration cycle in each CRAC unit can be expressed as

COP = $\frac{\text{Cooling Load (KW)}}{\text{Compressor Work (KW)}}$ (2.10)

Where the cooling load in each CRAC unit can be determined, as shown in Equation (2.9)

Cooling load = $\dot{m}C_p(T_i - T_{ref})$ (2.11)

Where,

$\dot{m}$: is the air mass flow rate at the CRAC intake (kg/s)

Cp : is the specific heat of air at constant pressure (kJ /kg. ºC)

T_i : is the air inlet temperature of CRAC unit (ºC)

T_{ref} : is the CRAC air supply temperature (ºC)

Also, the COP can be calculated from the Carnot refrigeration cycle to give an indication of the effect of the supply temperature on the COP values, as follows:

$Cop_{R,Carnot} = \frac{T_L}{T_H - T_L}$ (2.12)

Where$Cop_{R,Carnot}$, $T_L$and T_H are the coefficient of performance of the Carnot refrigeration cycle, The COP of the DX CRAC unit of a traditional data center (raised floor, hot cold aisle arrangement) varies from 3 to 4.5(Darrow , Hedman,2009). Moore et al (2005) found the relationship between the COP of the chiller system and the supply temperature inside the data center, as shown in Figure 2.22. The relationship can be expressed as

COP = $0.068T^2 + 0.0008T + 0.458$ (2.13)

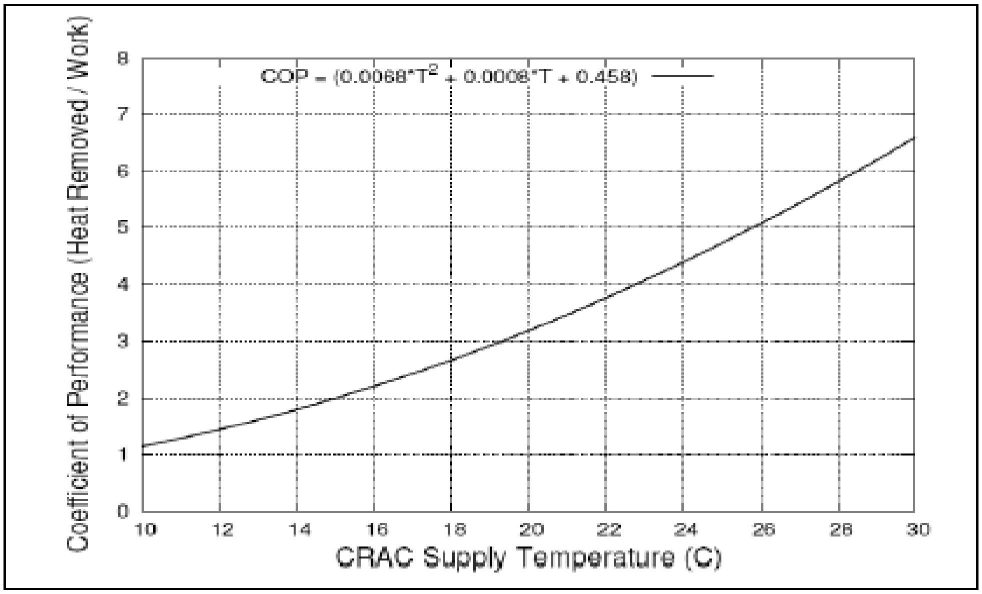


Figure (2-22) COP vs. CRAC supply temperature from the HP experiment

Where, T is the CRAC supply temperature in (ºC) and it is between 10ºC and 30ºC (Moore et al, 2005).The study was completed for the HP labs utility data center. It was found that as the supply temperature increases within the allowable limit, the COP also increases, while the CRAC unit uses less energy. So, raising the inlet temperature by 5ºC within the temperature range (15ºC-25ºC) leads to a saving of up to 40% of the CRAC power.

2.9 Evaluation Index

In order to study the thermal and bypass phenomena, two assessment indexes will be used in this research. Namely the βindex and the energy utilization index η_r (Ni, et al, 2017). The reason behind using these indexes is because they indicate whether a facility is working well from a thermal/airflow point of view. The β Index is proposed to evaluate the temperature rising in local rack (Arghode,et al,2013) and this index could be defined as:

$$\beta = \frac{T_{in} - T_{ref}}{T_{out} - T_{in}} \tag{2.14}$$

Where $T_{in}$the mean temperature in the inlet, T_{out} is the mean temperature in the outlet, T_{ref} is the reference cooling temperature.The β index ranges are between 0 and 1.When the β index value is 0, it illustrates no recirculation of airflow. While the β index value is above 1, it means the phenomenon of self-heating. In order to meet the utilization energy efficiency of airflow, energy utilization index is corrected and its expression is (Xu, 2015):

$$\eta_r = \frac{T_{out} - T_{ref}}{\frac{T_{out}+T_{in}}{2} - T_{ref}} \qquad (2.15)$$

Where $T_{out}$the air temperature in the outlet is, T_{in} is the air temperature in the inlet and T_{ref} is the air temperature of the cooling in the rack. In Equation (2.15), the low η_r shows a bad airflow organization, and has a hot air self-circulation between racks.

CHAPTER THREE

MATHEMATICAL AND ICEPAK MODELLING

3.1 Introduction

The cooling techniques and energy consumption inside the data center are the most concern for the mechanical engineering area as it was mentioned in a lot of previous studies as in chapter 2. The objective and methodology that have been used in this research will be described in this chapter.

3.2 Case Study

The dissertation will take Canar Telecommunication Company Data Center located at Khartoum, Sudan as a case study. This data center contains four down flow Computer Room Air – Conditioning (CRAC) units installed inside the servers' room. The data center is working on 24/7 basis. The Computer room air conditioner units were part of the raised floor room layout with cooling air passing through plenum and venting in the room through vent tiles. The Data center contains servers & information technology equipment's. All these equipment's were manufactured by Huawei Company. The power equipment's & batteries are housed at a separate room called the power room. There are no above ground cables as all cables are extended below the raised floor. The racks were arranged in three rows and have individual air flow and heat load. Heat dissipation and air flow rate were defined for all racks from the specifications model of Ansys Icepak.

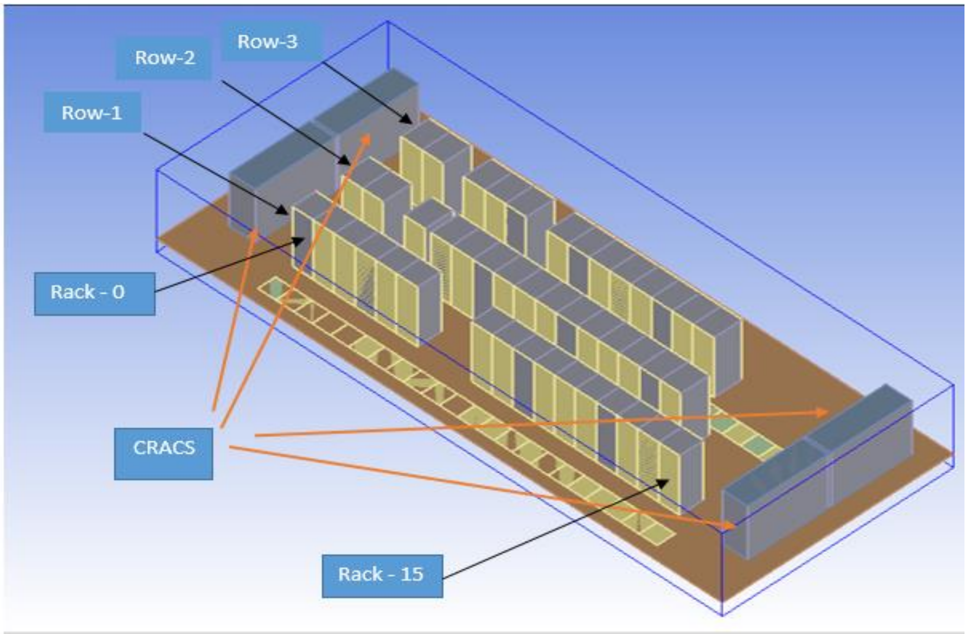


Figure (3. 1) A 3D Model of a data center

The detailed description of data center and data center components, air flow through racks and vent tiles are summarized in below tables;

Table 3.1

Data center description

Data Center layout	Raised Floor with Room Return
Room Dimensions	L=19m ,W=7.76m , H=3.05m
Supply Plenum Height	0.5m
Dimensions of each CRAC	L=2.7m ,W=0.86m , H=1.97m
Total flow Through CRAC Units (4)	12 m³/s
Supply Air Temperature and Relative Humidity	17 °C , 50%
Number of Rack Rows	3
Total Number of Racks	44
Total Racks Heat load	144 KW

Total Air Flow Through Racks	10.52 m^3/s
Number of Tile Rows	2
Dimensions of each Tile	L=0.6m ,W=0.6m
Number of Tile for Each Row	22
Tile Open Area	50%
Operating temperature of racks inside Data Center (Huawei,2011)	Recommended range : 15ºC – 27ºC Maximum Temperature: 42ºC

Table 3.2

Heat dissipation, air flow and Dimensions of Racks

Row 1			
Number of Racks	Heat dissipation(W)	Air Flow(m3/s)	Dimensions (Width*Depth*Height)m
0	740	0.05	0.7*0.8*2.2
1	740	0.05	0.7*0.8*2.2
2	330	0.05	0.7*0.8*2.2
3	330	0.05	0.7*0.8*2.2
4	330	0.05	0.7*0.8*2.2
5	330	0.05	0.7*0.8*2.2
6	1500	0.25	0.7*0.8*2.2
7	1500	0.25	0.7*0.8*2.2
8	1500	0.25	0.7*0.8*2.2
9	1500	0.25	0.7*0.8*2.2
10	1500	0.25	0.7*0.8*2.2
11	1500	0.25	0.7*0.8*2.2

12	1500	0.25	0.7*0.8*2.2
13	1500	0.25	0.7*0.8*2.2
14	1500	0.25	0.7*0.8*2.2
15	1500	0.25	0.7*0.8*2.2
Row 2			
Number of Racks	Heat dissipation(W)	Air Flow(m3/s)	Dimensions (Width*Depth*Height)m
16	2700	0.35	0.7*0.95*2.2
17	170	0.05	0.7*0.95*2.2
18	1800	0.25	0.7*0.95*2.2
19	200	0.05	0.7*0.95*2.2
20	200	0.05	0.7*0.95*2.2
21	200	0.05	0.7*0.95*2.2
22	200	0.05	0.7*0.95*2.2
23	2400	0.35	0.7*0.95*2.2
24	2400	0.35	0.7*0.95*2.2
25	460	0.05	0.7*0.95*2.2
26	2250	0.35	0.7*0.95*2.2
27	2250	0.35	0.7*0.95*2.2
28	900	0.15	0.7*0.95*2.2
29	900	0.15	0.7*0.95*2.2
30	900	0.15	0.7*0.95*2.2

Row 3			
Number of Racks	Heat dissipation(W)	Air Flow(m3/s)	Air Flow(m3/s)
31	2700	0.35	0.7*0.95*2.2
32	450	0.05	0.7*0.95*2.2
33	1300	0.25	0.7*0.95*2.2
34	1300	0.25	0.7*0.95*2.2
35	500	0.05	0.7*0.95*2.2
36	2000	0.35	0.7*0.95*2.2
37	1200	0.25	0.7*0.95*2.2
38	0 (Joint box)	0.05	0.7*0.95*2.2
39	0 (Joint box)	0.05	0.7*0.95*2.2
40	0 (Joint box)	0.05	0.7*0.95*2.2
41	0 (Joint box)	0.05	0.7*0.95*2.2
42	0 (Joint box)	0.05	0.7*0.95*2.2
43	0 (Joint box)	0.05	0.7*0.95*2.2

3.3 Computational Fluid Dynamics (CFD)

3.3. 1 Mathematical Model

The commercial CFD software package Icepak 18 was used as a basic tool for the simulation. The reasons behind this selection are as follows;

1. Icepak software provides robust and powerful computational fluid dynamics for electronics thermal management.
2. Object oriented approach to building models, allowing drag and drop construction.

3. Integration with all major mechanical and electronic Computer Aid design systems for simplified geometry import.
4. Flexible, Automatic Meshing.
5. Built on the industry leading solver, ANSYS FLUENT.
6. Specialized result visualization and interrogation tools.

During the simulation the followings assumptions have been considered;

1. The flow was a steady turbulent flow.
2. Adiabatic walls were chosen for the room. The room was isolated and the effects of heat transfer outside it were neglected.
3. The effects of radiation were ignored in the room according to the steady heat assumption, and heat transfer on the surface of the server was uniform.
4. The impact of disturbance from air leakage or personnel movement was ignored.

3.3.2 Continuity and Momentum Equations

The motion of each phase was governed by the corresponding mass and momentum conservation equations. The continuity equation is:

$$\frac{\partial \rho}{\partial \tau} + \frac{\partial(\rho u_x)}{\partial x} + \frac{\partial(\rho u_y)}{\partial y} + \frac{\partial(\rho u_z)}{\partial z} = 0 \tag{1}$$

Where u_i is the velocity of the i-th phase. The subscript i represents the x, y or z axis. The equation for the conservation of momentum is:

$$\rho(\frac{\partial u_x)}{\partial t} + \frac{\partial u_x}{\partial x} u_x + \frac{\partial u_x}{\partial y} u_y + \frac{\partial u_x}{\partial z} u_z = (\frac{\partial \sigma_x)}{\partial x} + \frac{\partial \tau_{xy}}{\partial y} + \frac{\partial \tau_{xz}}{\partial z}) + \mathrm{f}x' \tag{2a}$$

$$\rho(\frac{\partial u_y)}{\partial t} + \frac{\partial u_y}{\partial x} u_x + \frac{\partial u_y}{\partial y} u_y + \frac{\partial u_y}{\partial z} u_z = (\frac{\partial \sigma_y)}{\partial y} + \frac{\partial \tau_{yx}}{\partial x} + \frac{\partial \tau_{yz}}{\partial z}) + \mathrm{f}y' \tag{2b}$$

$$\rho(\frac{\partial u_z)}{\partial t} + \frac{\partial u_z}{\partial x} u_x + \frac{\partial u_z}{\partial y} u_y + \frac{\partial u_z}{\partial z} u_z = (\frac{\partial \sigma_z)}{\partial z} + \frac{\partial \tau_{zx}}{\partial x} + \frac{\partial \tau_{zy}}{\partial y}) + \mathrm{f}z' \tag{2c}$$

$$\sigma_i = -\rho + 2\mu \frac{\partial u_i)}{\partial i'}, \tau_{ij} = \mu \left(\frac{\partial u_i}{\partial j} + \frac{\partial u_j}{\partial i} \right) \quad (3)$$

where ρ is density in kg/m3; fi is the interfacial force acting on phase i due to the presence of phase j, which includes drag force, interphase turbulent dispersion force, virtual mass and lift force; μ is shear viscosity in N·s/m^2; and p is pressure in N/m^2[6,8].

The energy equation is as follows:

$$\frac{\partial \rho T)}{\partial t} + \frac{\partial \rho u_x T}{\partial x} + \frac{\partial \rho u_y T}{\partial y} + \frac{\partial \rho u_z T}{\partial z} = \frac{\partial}{\partial x}\left(\frac{k}{c_p}\frac{\partial T}{\partial x}\right) + \frac{\partial}{\partial y}\left(\frac{k}{c_p}\frac{\partial T}{\partial y}\right) + \frac{\partial}{\partial z}\left(\frac{k}{c_p}\frac{\partial T}{\partial z}\right) + S_T \quad (4)$$

Where T is the fluid temperature in K, $c_p$is the specific heat capacity of the fluid at constant pressure in J/gK, k is the fluid thermal transfer coefficient in m^2/s and S_T is the term for viscous dissipation.

3.3.3 Turbulence Model

The flow regime in room-level data center considered belong to the turbulent mix. (Dun et al, 2015). Compared to the k-ω, SST, RSM, and RNG k-ε models, the k-ε turbulent model is used to simulate the flow characteristic, which has better performance and results.

The basis for all two equation turbulence models is the Boussinesq eddy viscosity assumption, which postulates that the Reynolds stress tensor ,$\boldsymbol{\tau_{ij}}$, is proportional to the mean strain rate tensor, $\boldsymbol{S_{ij}}$, and can be written in the following way:

$$\boldsymbol{\tau_{ij}} = 2\mu_t S_{ij} - \frac{2}{3} \rho k \delta_{ij} \quad (5)$$

Where μ_ta scalar property is called the eddy viscosity which is normally computed from the two transported variables. The last term is included for modelling incompressible flow to ensure that the definition of turbulence kinetic energy is obeyed:

$$k=\frac{\overline{u_i' \, u_i'}}{2} \tag{6}$$

3.3.4 Boundary Conditions

The boundary conditions, the initial conditions and the iteration scheme were set for the numerical simulations in the Icepak 18 software package. The pressure was discretized using the body force weighted scheme and the momentum and temperature through the second order scheme. The relaxation factors are shown in the below table

Table 3.3

Factors concerning relaxation.

Pressure	0.7
Momentum	0.3
Temperature	1
Viscosity	1
Body Force	1
Joule Heating potential	1
H_2O	1

3.3.5 Convergence & Solution Monitors

The residuals have been monitored during the iterations. The convergence criterion for flow was set at 1×10^{-3} and that for energy and H_2O specie was set at 1×10^{-6}. The simulation was stopped when it was determined to have reached a steady state.

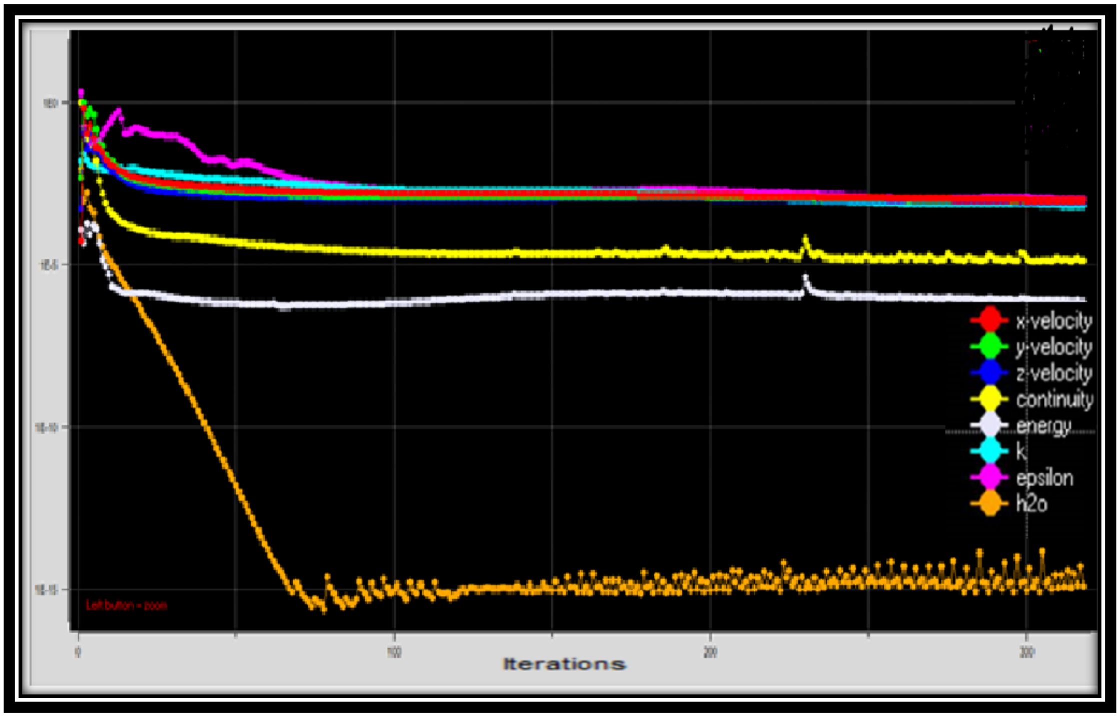


Figure (3. 2) Solution residuals

For the solution monitors, the exhaust temperature of the computer room air conditioner units has been monitored during the iterations.

3.3.6 Grid Independent and Model Validation

The mesh generation of geometric models has a great influence on the numerical simulation results. With the increase of the number of grids, not only the performance requirements of computer can be improved, but also the computation time also increase. Therefore, in order to improve the accuracy and efficiency of numerical simulation, finding a suitable mesh generation is the foundation of numerical simulation.

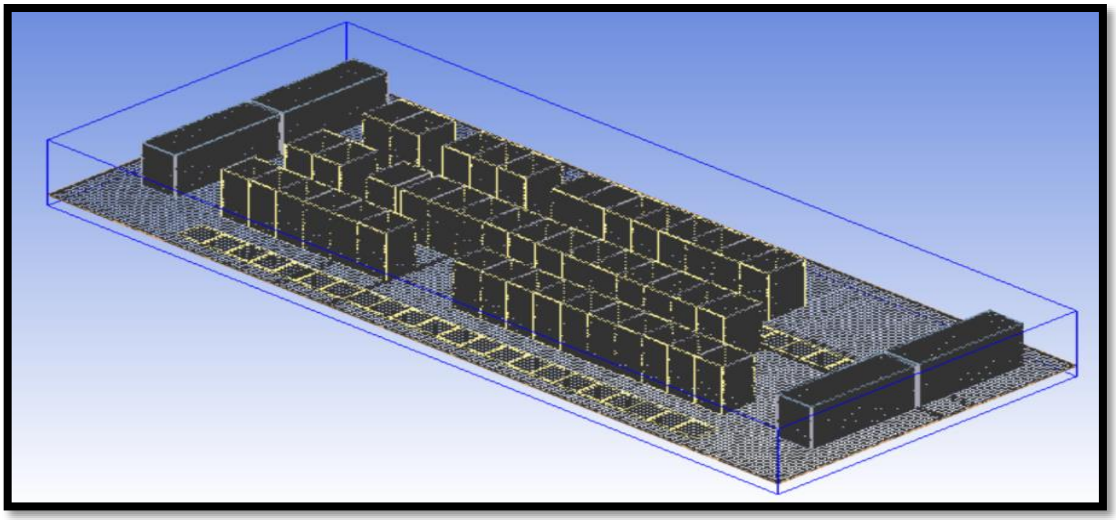


Figure (3. 3) Mesh of a data center

Table 3.4

The influence of grid size on performance indexes.

Mesh(Nodes)	Supply Air Temperature (°C)	Rack 0		Rack 15	
		Beta index	Energy index	Beta index	Energy index
217787	17	0.16	1.40	0.56	1.18
653360	17	0.27	1.47	0.69	1.24
762254	17	0.30	1.52	0.78	1.29
871147	17	0.34	1.56	0.85	1.33
1088934	17	0.35	1.59	0.88	1.36
1306721	17	0.35	1.59	0.88	1.36

The mesh with number of nodes of 1,088,934 is the optimal in which the minimum volume 1*10^{-6} $(m^3)$and the maximum volume 8.28712*$10^{-4}(m^3)$was used in the present work for the data center. At this volume the solution is confirmed independent from Mesh.

In order to verify the accuracy of grid mesh and CFD model, the exit temperature of Racks located at Row-1 was measured using on-line thermocouple method (the measuring point is 0.08 m away from the center of each rack). These values were compared to the simulation results, as shown in the below figure.

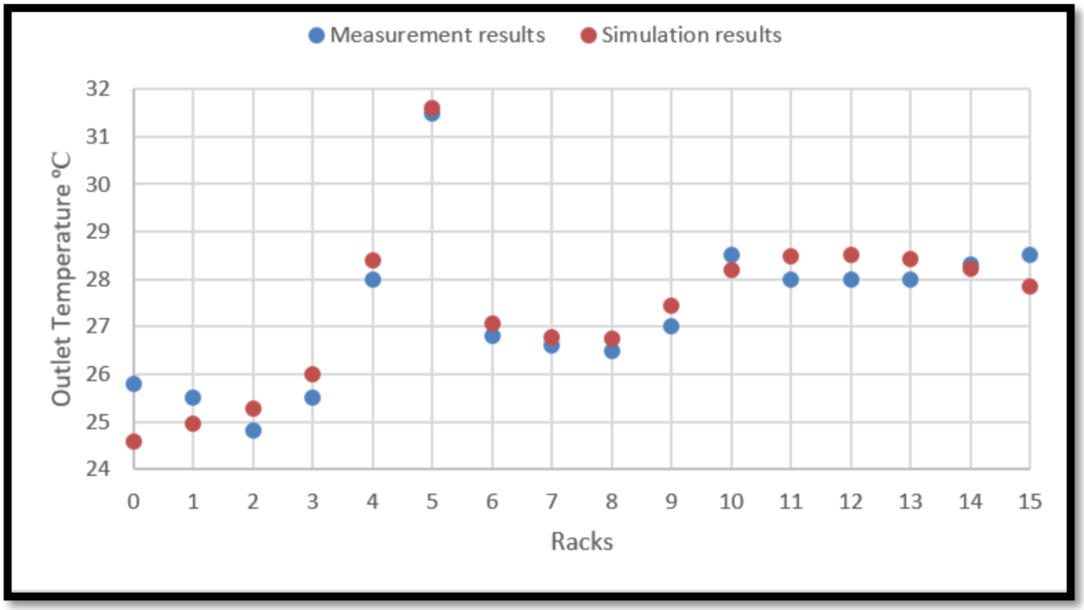


Figure (3. 4) the temperature comparison between the simulation and the measurements at the outlet of racks

From the results, there is a maximum deviation of 0.92°C temperature difference between the simulation and the measurements, which proved that the model and simulation method are feasible.

CHAPTER FOUR

RESULTS AND DISCUSSIONS

4.1 Open Aisle Data Center

Proper layout of racks is one of the parameters that may affect thermal management inside data centers. Normally racks are placed in a row in a contiguous manner. However, there may be gaps between them. These gaps are created by removing the racks or replacing them by another one smaller in size. Hot air from the back of the racks can leak inside the cold aisle through these gaps and increase the temperature of air entering into the racks. Figure (4-1) shows a plot of temperature distribution across a data center.

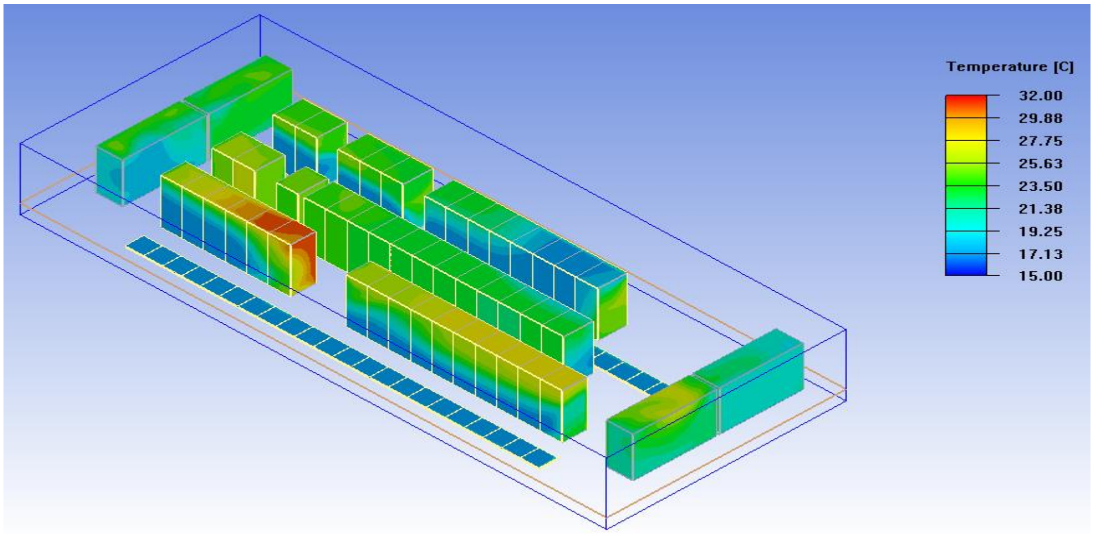


Figure (4-1): Temperature contours inside a data center

The highest temperature recorded inside the data center was at the rack 5 located closest to the gap in Row - 1. Figure (4-2) shows the velocity vector inside the data center. Hot Air from the back of the racks leaked to the cold aisle and increased the inlet temperature of air entering the racks. In order to minimize this recirculation, partitions are recommended to be installed to close the gaps between the racks.

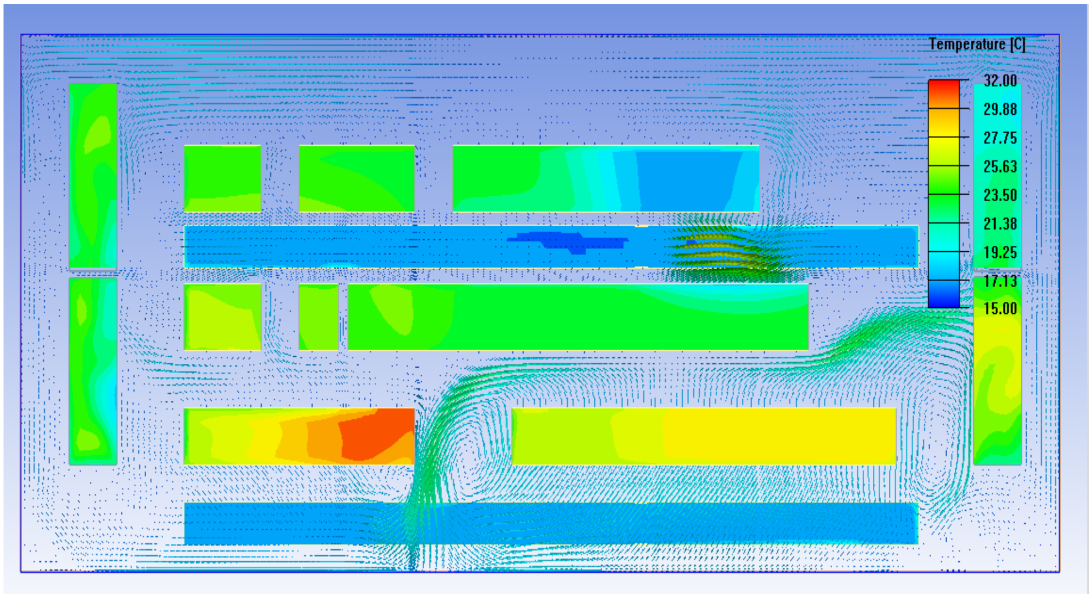


Figure (4-2): Temperature contours and velocity vectors on a horizontal plane(Y=1.6 m).

4.2 Data Center with Partitions

In order to enhance the air flow distribution inside the data center, seven partitions will be installed to close the gaps between the racks to isolate the hot aisle from the cold aisle. The use of partitions is inexpensive and a fast solution.

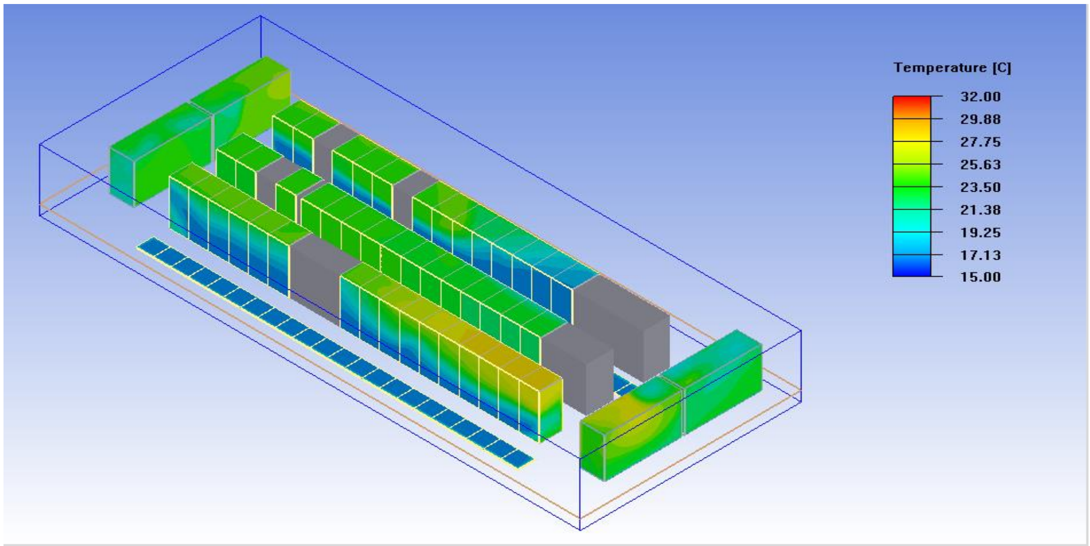


Figure (4-3): Use of partitions to prevent hot air recirculation

From Figure (4-4) the air flow becomes more uniform after closing the gaps between the racks and the global temperature was reduced. The hot air is now concentrated in the hot aisle & there is no air mixing through gaps.

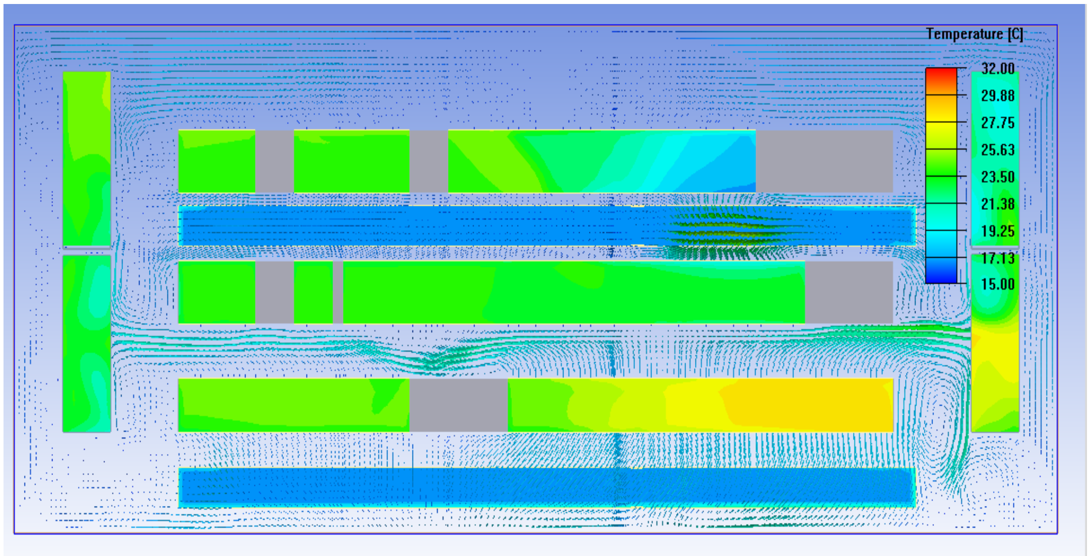


Figure (4-4): Temperature contours and velocity vectors on a horizontal plane of a data center with partitions (Y=1.6 m).

4.3 Investigation of Data Center on Rack Level

Further investigation for air flow distribution inside the data center could be done based on rack level.

Row -1 was chosen because it contains racks with higher heat density and it has a dedicated perforated tile. That’s why it will be considered for analysis (highlighted in red at Fig (4-5)). The total number of racks in row-1 is 16. The racks is numbered from 0 up to 15.

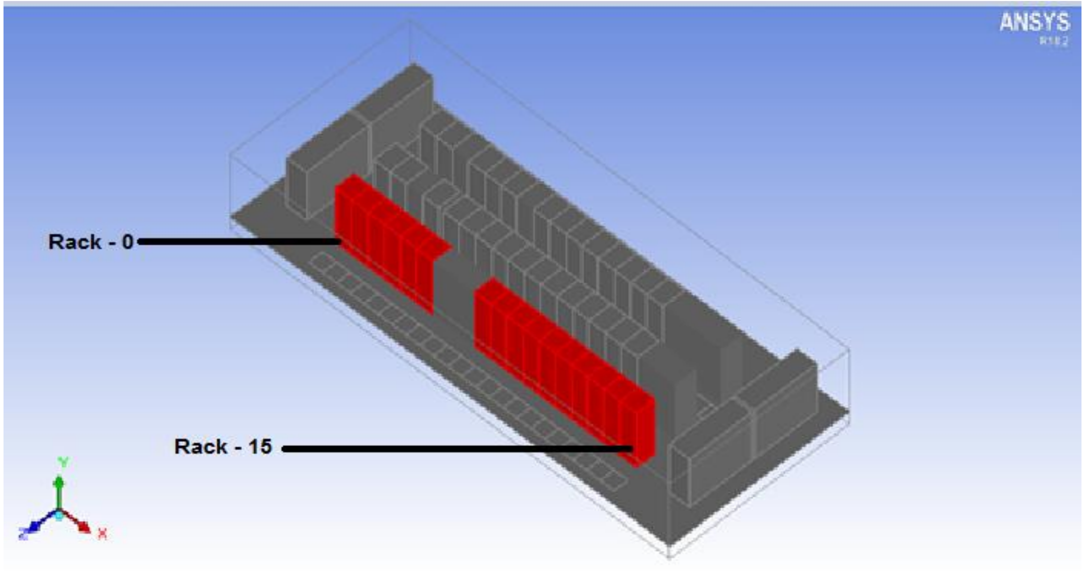


Figure (4-5): High density rack in a data center

β index and the energy utilization index η_r defined by equations (2.14) and (2.15) are used for this study. Results are shown on Figure (4-6) below. It is obvious that rack no. 5 has got the maximum value of β index and the minimum value of utilization energy efficiency. This is due to hot air recirculation from the hot aisle to the inlet of rack 5 through the nearest gap.

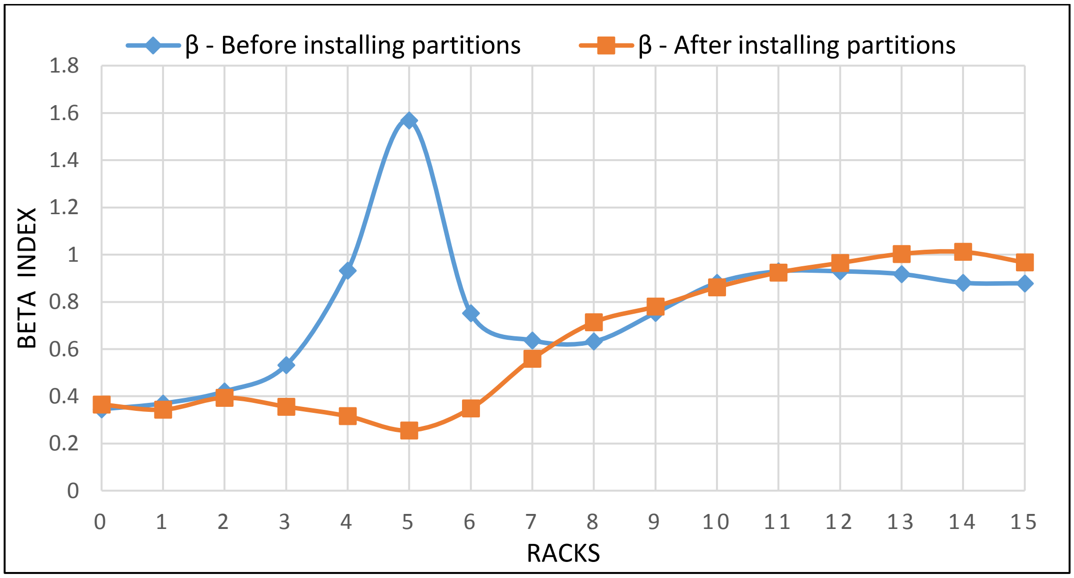


Figure (4-6): Efficiency measurements for open aisle data center

After closing all the gaps between the racks, the air flow distribution was enhanced. βindex and energy utilization index η_r of Rack 5 were improved.

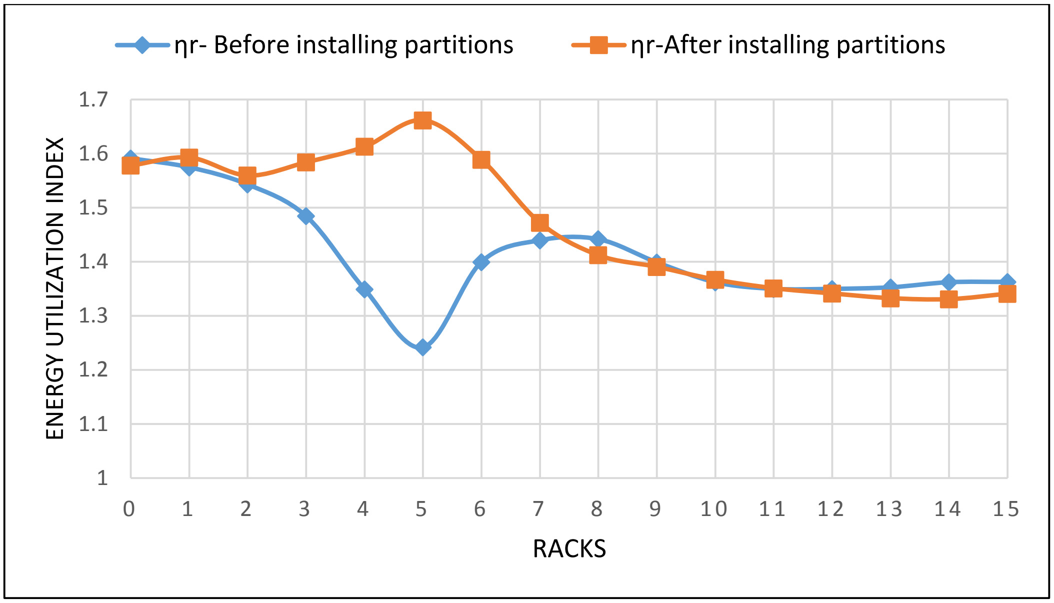


Figure (4-7): Efficiency measurements of a data center with partitions

4.4 Effect of Airflow Outlet Angle

In standard tiles, air leaves at an outlet flow angle of 90º. This leads part of the cold air to bypass without passing through the racks. In order to reduce this effect, directional perforated tiles will be used to guide cold air towards the racks. Different air flow outlet angles from tiles will be investigated and the corresponding values of βindex and utilization energy efficiency will be evaluated to determine the best air flow outlet angle.

Table 4.1

βindex for different air flow outlet angle.

Rack	30°	45°	60°	75°	90°	120°
0	0.61	0.38	0.30	0.40	0.37	0.74
1	0.44	0.29	0.26	0.30	0.34	0.64
2	0.46	0.37	0.36	0.36	0.39	0.51
3	0.48	0.36	0.36	0.35	0.36	0.41
4	0.49	0.32	0.36	0.34	0.32	0.38
5	0.47	0.25	0.33	0.31	0.26	0.32
6	0.50	0.44	0.34	0.32	0.35	0.51
7	0.84	0.70	0.60	0.54	0.56	0.81
8	1.03	0.79	0.78	0.70	0.71	0.89
9	0.94	0.86	0.70	0.63	0.78	0.99
10	1.16	1.04	0.86	0.76	0.86	1.18
11	1.33	1.11	0.99	0.88	0.92	1.26
12	1.47	1.12	1.10	0.99	0.96	1.21
13	1.44	1.13	1.15	1.05	1.00	1.16
14	1.37	0.99	1.11	1.03	1.01	1.07
15	1.14	1.08	1.13	1.05	0.97	1.16

From table 4-1, the values of βindex are at air outlet angles of 30° & 120° are high. At 30°, most of air is concentrated at the bottom of the racks thus upper racks suffer from insufficient air. Recirculated air from hot aisle substitute this air and increased the inlet air temperature. At air flow outlet angle of 120°, cold air from the tiles is mixed with the room warm air before entering the racks. With the increase of flow outlet angles more than 30°, the values of beta improved. Most of the minimum values of beta are available at 45°, 60° 75°& 90°.

Table 4.2

Energy utilization efficiency for different air flow outlet angle**.**

Rack	30°	45°	60°	75°	90°	120°
0	1.45	1.57	1.62	1.56	1.58	1.40
1	1.53	1.63	1.66	1.63	1.59	1.44
2	1.52	1.58	1.58	1.58	1.56	1.50
3	1.51	1.58	1.58	1.59	1.58	1.55
4	1.50	1.61	1.58	1.59	1.61	1.57
5	1.52	1.66	1.60	1.62	1.66	1.61
6	1.50	1.53	1.60	1.61	1.59	1.50
7	1.37	1.42	1.45	1.48	1.47	1.38
8	1.33	1.39	1.39	1.42	1.41	1.36
9	1.35	1.37	1.42	1.44	1.39	1.34
10	1.30	1.32	1.37	1.40	1.37	1.30
11	1.27	1.31	1.33	1.36	1.35	1.28
12	1.25	1.31	1.31	1.34	1.34	1.29
13	1.26	1.31	1.30	1.32	1.33	1.30
14	1.27	1.34	1.31	1.33	1.33	1.32
15	1.30	1.32	1.31	1.32	1.34	1.30

From table 4-2, the behavior of the values of energy utilization index is the same as the beta index. The maximum values are at outflow angle of 45°, 60°, 75° & 90°.

Since the difference between values is very small and non-regular we need an additional evaluation criteria in order to choose the optimal outlet angle of flow, therefore, temperature contours at cold aisle will be investigated.

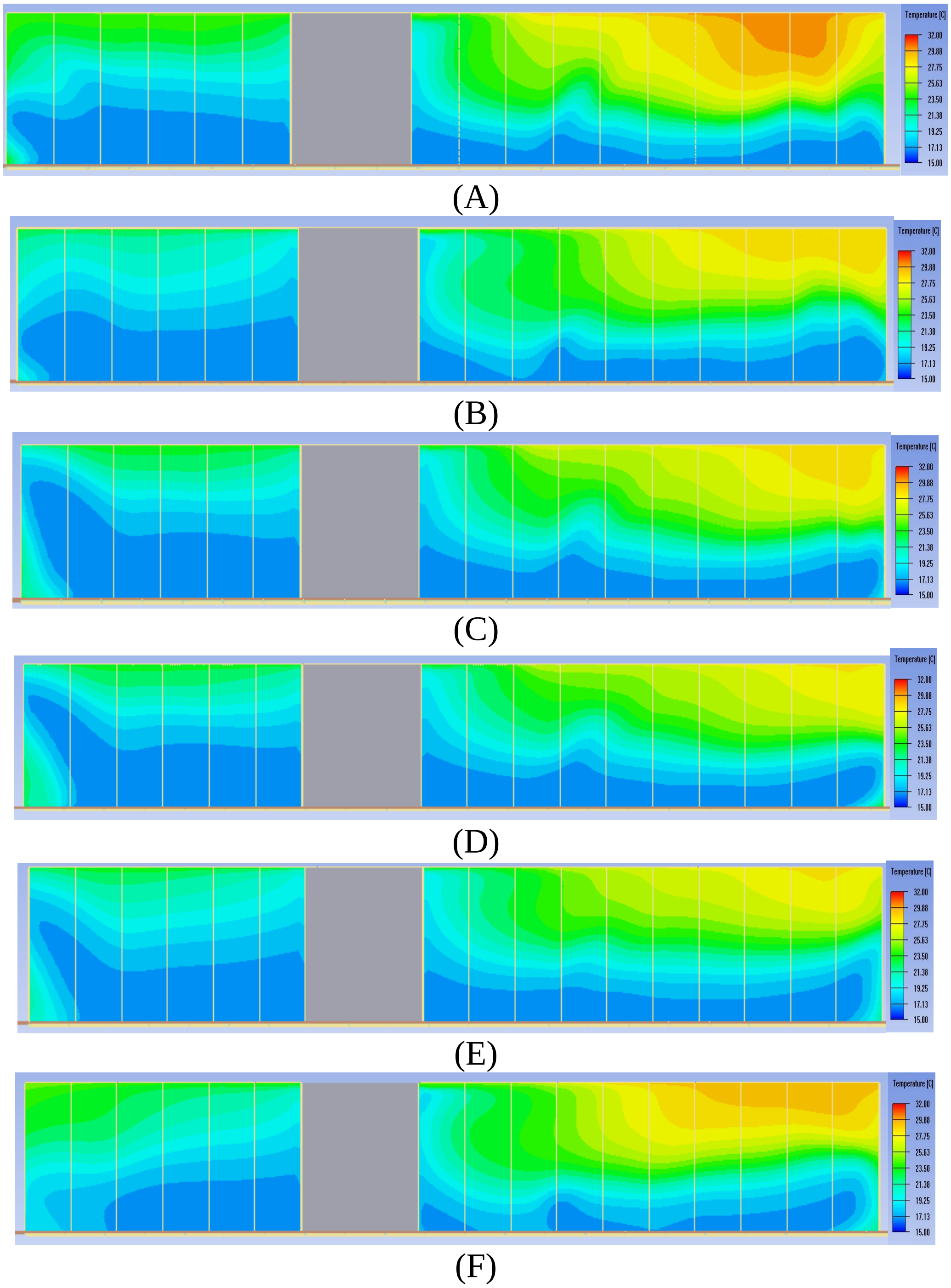


Figure (4-8): Temperature contours in the cold aisle: (A) 30º, (B) 45º, (C) 60º, (D) 75º, (E) 90º (F) 120º

Figure (4-8) shows the contours of local temperature of Row - 1. The temperature at the upper part of the racks is higher than the surrounding area due to circulation of air from hot aisle to cold aisle through the top side of the racks. The thermal distribution at an airflow outlet angle of 60º at the tiles was the optimal for racks - 0 up to rack - 5 and the optimal air flow outlet angle for rack - 6 up to rack - 15 is 75 º. Figure (4-9) shows the temperature contours of row-1 with outlet flow angle of 60° for racks 0 to 5 and 75° for racks 6 to 15.

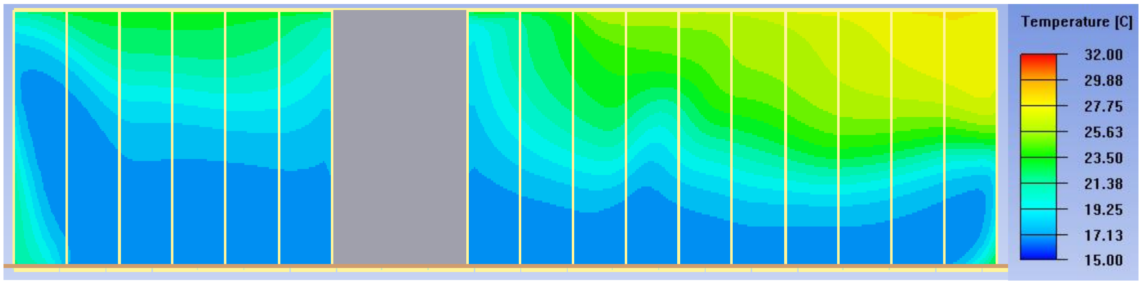


Figure (4-9): Temperature contour in the cold aisle for 60º & 75º air flow outlet angle

When considering the optimal outlet angle for each rack and compared with 60° & 75° , the result is shown in figure(4-10) below,

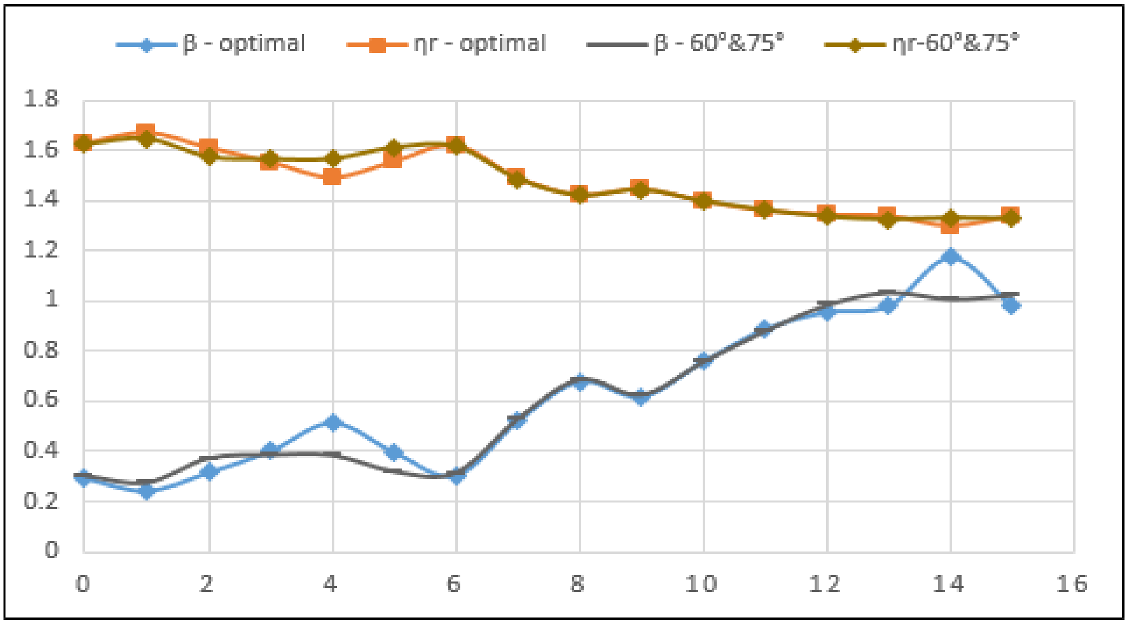


Figure (4-10) Beta and energy utilization index

The values of performance index for optimal outlet angle of flow for each rack compared with outlet angle of 60° & 75°, shows that the second configuration is better for overall values of beta and energy utilization index.

4.5 Effect of Supply Air Temperature

Using low supply air temperature will reduce the operating temperature of the conditioned equipment's and increase power required by air conditioning system and vice versa. The optimal supply air temperature will ensure acceptable operating temperature for equipment's and low power consumption for air conditioning system. This will be achieved by studying beta and energy utilization indexes for each rack.

Table 4.3

βindex for different supply air Temperature**.**

Rack	15°C	16°C	17°C	18°C	19°C	20°C
0	0.30	0.29	0.30	0.30	0.30	0.27
1	0.27	0.27	0.27	0.27	0.27	0.26
2	0.37	0.37	0.37	0.36	0.37	0.39
3	0.38	0.38	0.39	0.38	0.39	0.40
4	0.38	0.38	0.38	0.38	0.39	0.40
5	0.31	0.34	0.32	0.31	0.32	0.35
6	0.31	0.31	0.31	0.31	0.32	0.42
7	0.53	0.53	0.53	0.53	0.53	0.64
8	0.68	0.68	0.69	0.68	0.69	0.73
9	0.62	0.63	0.62	0.60	0.63	0.68
10	0.76	0.76	0.76	0.73	0.76	0.79
11	0.87	0.88	0.88	0.86	0.89	0.87

12	0.98	0.98	0.99	0.96	0.99	1.04
13	1.03	1.03	1.04	1.01	1.04	1.11
14	1.00	1.01	1.01	0.97	1.02	1.08
15	1.02	1.02	1.03	0.96	1.03	0.98

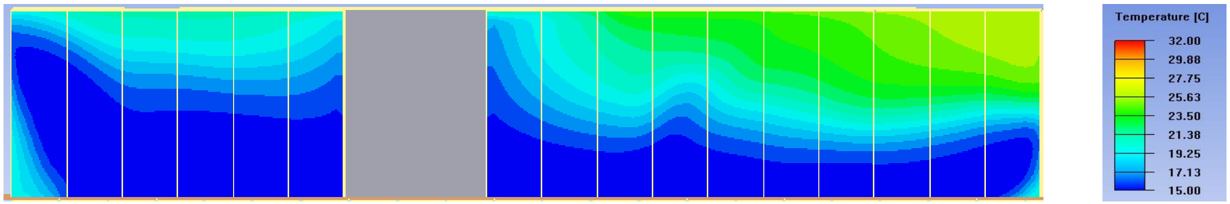
From tables (4-3) & table (4-4), the values of beta and energy efficiency for all supply air temperature are almost in a stable region.

Table 4.4

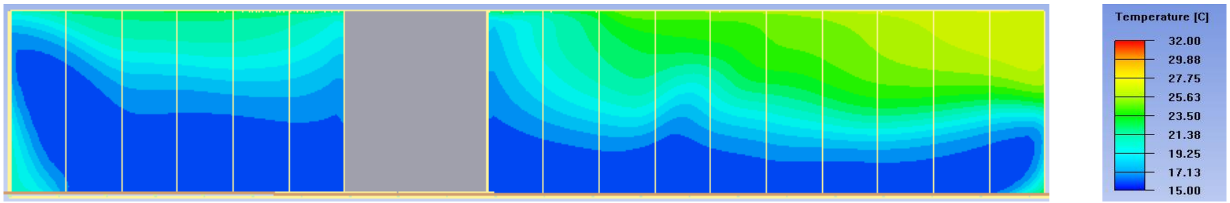
Energy efficiency index for different supply air Temperature**.**

Rack	15°C	16°C	17°C	18°C	19°C	20°C
0	1.63	1.63	1.62	1.63	1.63	1.65
1	1.65	1.65	1.65	1.65	1.65	1.66
2	1.58	1.58	1.57	1.58	1.57	1.56
3	1.57	1.57	1.56	1.57	1.56	1.55
4	1.57	1.57	1.57	1.57	1.56	1.55
5	1.61	1.60	1.61	1.61	1.61	1.59
6	1.62	1.62	1.61	1.62	1.61	1.55
7	1.49	1.49	1.49	1.49	1.48	1.44
8	1.42	1.42	1.42	1.42	1.42	1.41
9	1.44	1.44	1.45	1.45	1.44	1.42
10	1.40	1.40	1.40	1.41	1.40	1.39
11	1.36	1.36	1.36	1.37	1.36	1.36
12	1.34	1.34	1.34	1.34	1.34	1.32
13	1.33	1.33	1.33	1.33	1.32	1.31
14	1.33	1.33	1.33	1.34	1.33	1.32
15	1.33	1.33	1.33	1.34	1.33	1.34

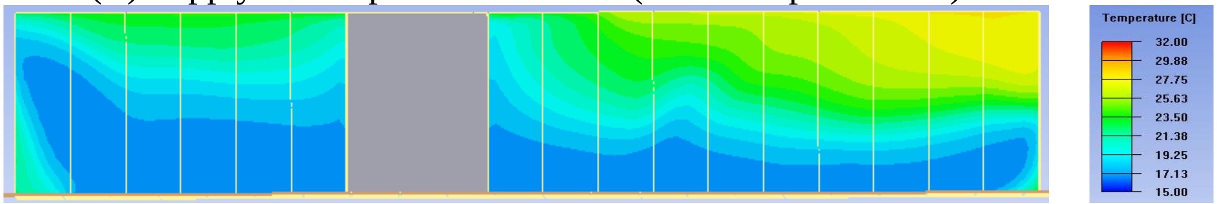
Since the equations of Beta and energy efficiency depend on temperature differences and the differences in temperature change with a fixed rate with the changing of supply air temperature, the evaluation method will fail. Accordingly, Computational fluid dynamic (CFD) will be used to have a better insight about the effect of supply air temperature distribution inside the data center.Temperature contour in the cold aisle will be investigated.



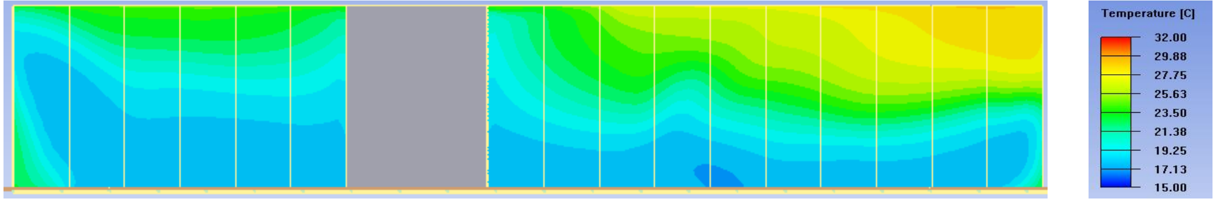
(A) Supply air temperature is 15°C - (Max Temp 27 °C)



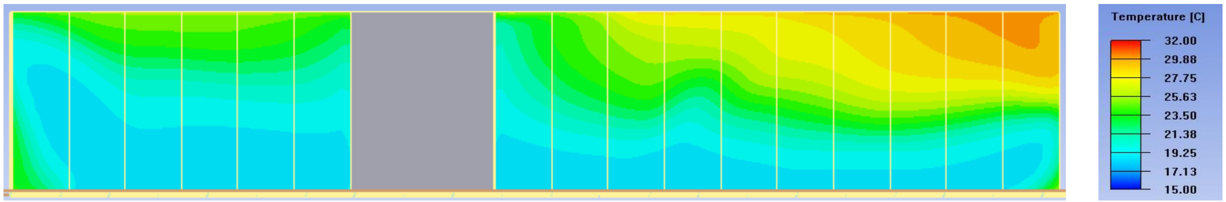
(B) Supply air temperature is 16 °C (Max Temp 28.13 °C)



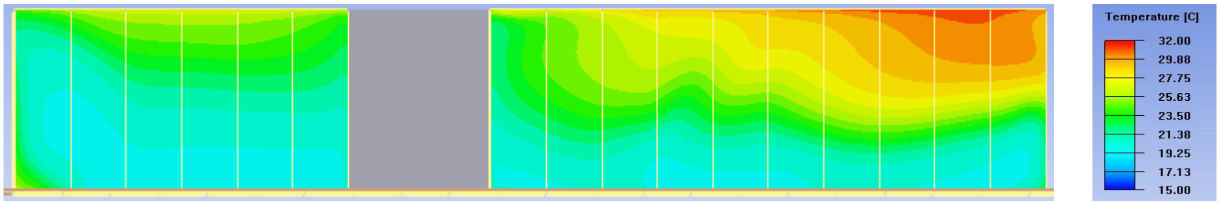
(C) Supply air temperature is 17°C (Max Temp 29.14 °C)



(D) Supply air temperature is 18°C (Max Temp 30.01 °C)



(E) Supply air temperature is 19°C (Max Temp 31.19°C)



(F) Supply air temperature is 20°C (Max Temp 32°C)

Figure (4-11) Temperature contours in the cold aisle for different supply air temperatures

A range for supply air temperatures have been tested in order to choose the optimal supply temperature. In order to choose the optimal supply air temperature we need to select the highest temperature that ensures the recommended operation requirements for equipment's. The maximum temperature of racks should not exceed 27°C as recommended by the manufacturer of equipment's (Huawei, 2011).

Table 4.5

Supply air temperature verses maximum temperature of Row -1

Supply air temperature of computer room air conditioner unit (°C)	Maximum temperature at row -1(°C)
15	27
16	28.13
17	29.14
18	30.01
19	31.19
20	32

From table (4.5), the optimal operating condition is achieved when using supply air temperature of 15°C. Figure (4-12) shows the temperature contours inside the data center with air flow outlet angle of 60° &75° for tiles supplied air to racks located at row-1 with supply air temperature of 15°C.

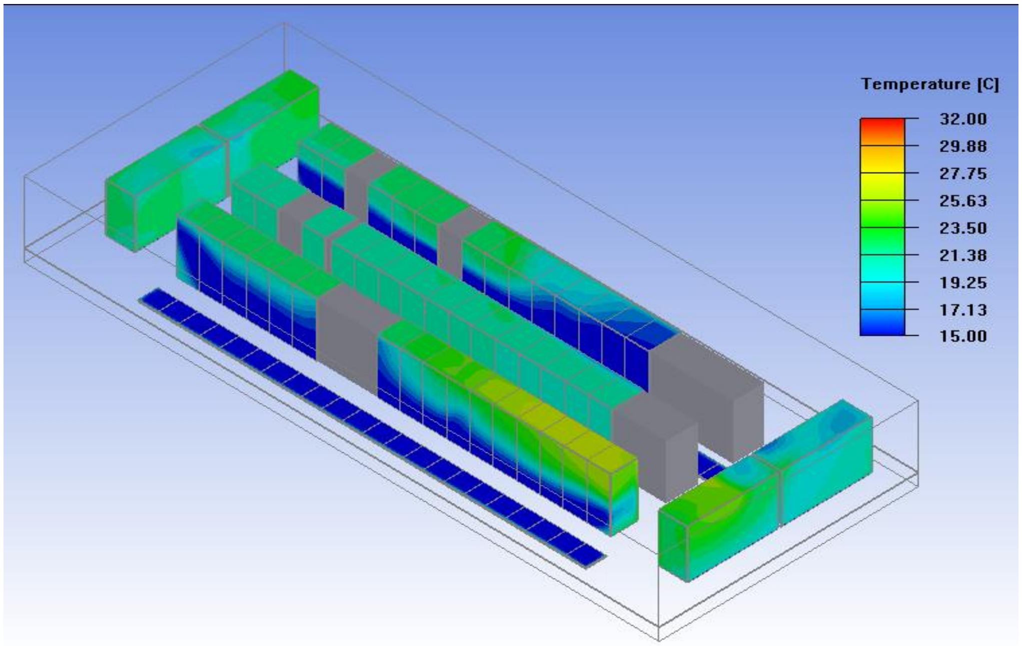


Figure (4-12) Temperature Contours inside data center for supply air temperature of 15º and air flow outlet angle of 60º&75° for row 1.

4.6 Effect of Tile Open Area

Air flow rate from perforated tiles has a direct effect on heat transfer inside servers. Increasing the tile open area will increase the flow rate and vice versa.

Using of suitable tile open area will optimize air flow distribution. Optimal tile open area will be investigated by using βindex and utilization energy efficiency. The optimal flow rate is achieved when hot airflow concentrates in the hot aisle with less mixing of air at the cold aisle. Also the majority of cold air should pass through the racks to hot aisle with less bypass air.

Table 4.6

βindex for different tile open Area**.**

Rack	40%	50%	60%	70%
0	0.64	0.30	0.15	0.13
1	0.59	0.27	0.14	0.13
2	0.62	0.37	0.16	0.14
3	0.62	0.38	0.16	0.14
4	0.59	0.38	0.14	0.12
5	0.52	0.31	0.09	0.08
6	0.53	0.31	0.12	0.10
7	0.68	0.53	0.19	0.15
8	0.80	0.68	0.26	0.21
9	0.79	0.62	0.28	0.24
10	0.86	0.76	0.31	0.25
11	0.94	0.87	0.36	0.30
12	1.02	0.98	0.40	0.34
13	1.07	1.03	0.46	0.39
14	1.07	1.00	0.46	0.40
15	1.20	1.02	0.60	0.59

From table (4.6), with the increase of the tile open area, βindex decreased. Major decrease occurred at tile open area of 60%. Further increase of tile open area at 70% will decrease the values of βindex but at minor values.

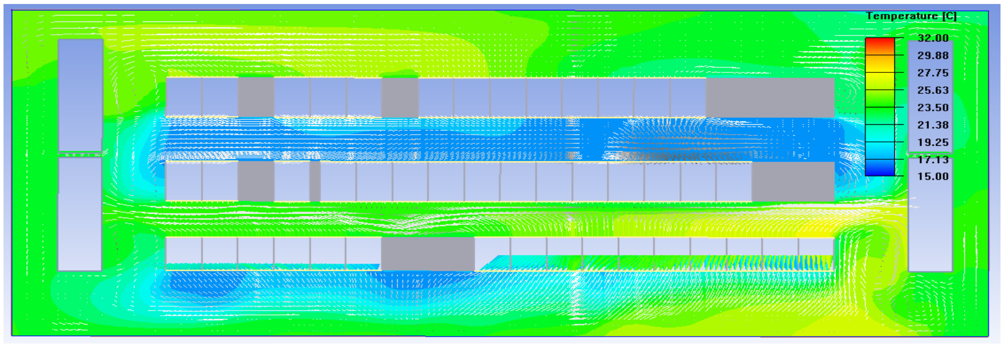
Table 4.7

Energy efficiency index for different tile open area**.**

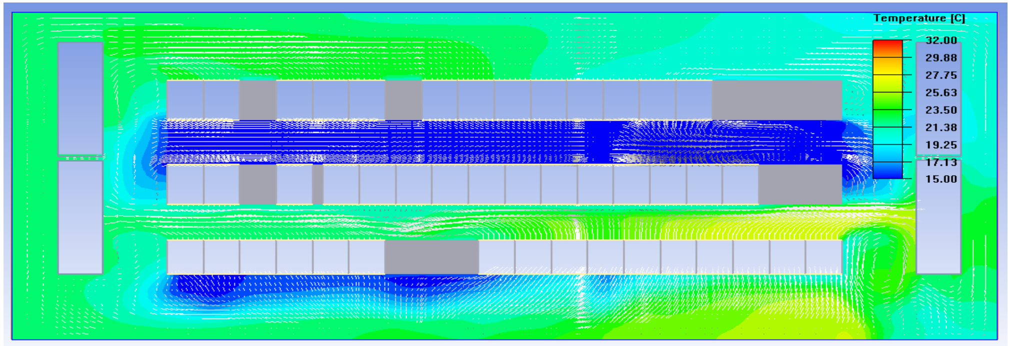
Rack	40%	50%	60%	70%
0	1.44	1.63	1.77	1.80
1	1.46	1.65	1.78	1.80
2	1.45	1.58	1.76	1.78
3	1.45	1.57	1.76	1.78
4	1.46	1.57	1.78	1.80
5	1.49	1.61	1.84	1.86
6	1.48	1.62	1.81	1.83
7	1.42	1.49	1.73	1.77
8	1.39	1.42	1.66	1.71
9	1.39	1.44	1.64	1.68
10	1.37	1.40	1.62	1.66
11	1.35	1.36	1.58	1.62
12	1.33	1.34	1.55	1.59
13	1.32	1.33	1.52	1.56
14	1.32	1.33	1.52	1.56
15	1.29	1.33	1.45	1.46

With the increase of tile open area, utilization energy efficiency increased. The major increment occurred at tile open area of 60%. Further increase of tile open area will increase the values of utilization energy index. From table 7 & 8, the optimal percentage of open area for tiles supply air to row 1 is 60%.

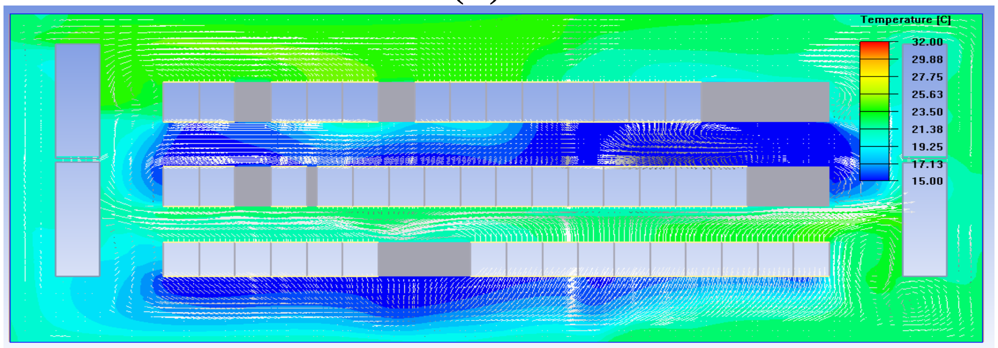
To have a better insight of the effect of tile open area on temperature distribution inside the data center, plane cut through y-axis will be investigated.



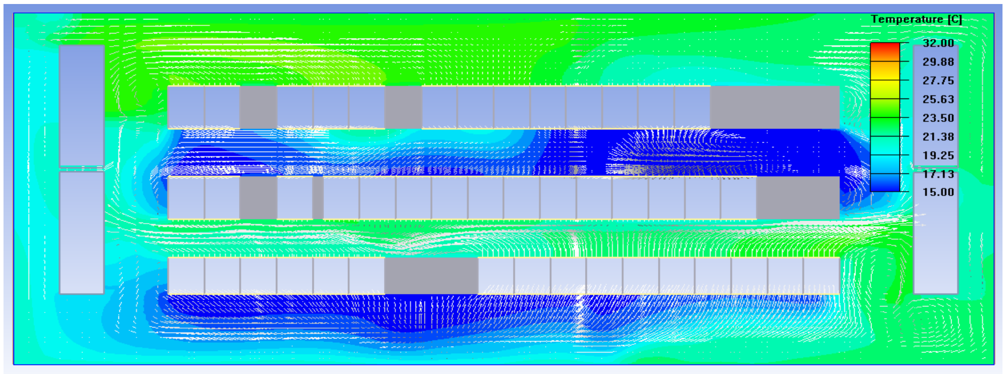
(A)



(B)



(C)



(D)

Figure (4-13) Temperature contours at XZ plane (Y=1.6 m) inside a data center for different tile open area of row 1: (A) 40%, (B) 50%, (C) 60% & (D) 70%.

From Figure (4-13), hot air recirculation exists through row 1 when using tile open area of 50%. This effect is reduced by increasing of tile open area from 50% to 60%.Further enlargement of open area more than 60 % will have a minor effect and consume more cold air. Therefore, the optimal tile open area is at 60%.

Figure (4-14) shows the temperature contours inside the data center at supply temperature of 15ºC and tile supplied air to Row1 with open area of 60% and air outflow angle of 60 º &75º.

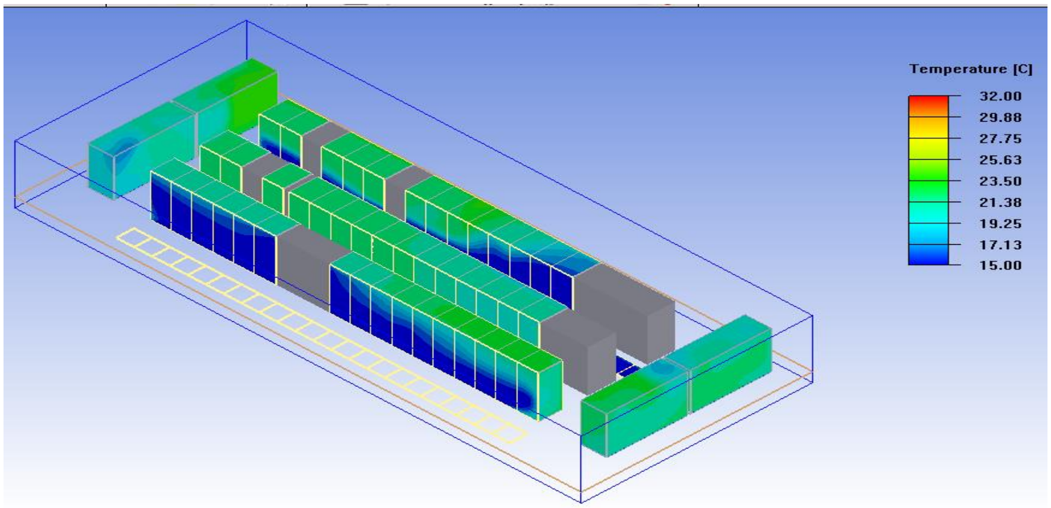


Figure (4-14) Temperature contour inside a data center

The thermal distribution of row 1 is enhanced as shown in Figure 13. However, the performance of racks located at the end of the row is poor due to bypass and recirculation from end sides.

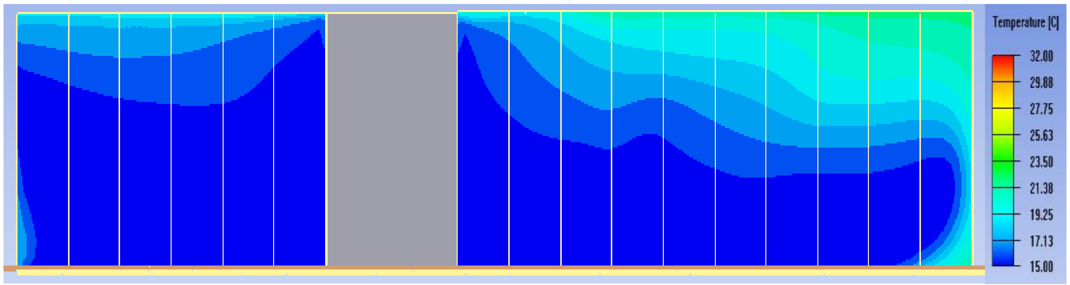


Figure (4-15) Temperature contour in the cold aisle of row 1 at 15ºC, tile of air flow outlet angle 60°&75º and tile open area of 60%

4.7 End Effect

Racks located in the middle of the data center have better air flow distribution than racks located close to the computer room air conditioner units. The reason behind this, is the pressure distribution under the raised floor. For this reason, racks with high heat density are recommended to be installed far away from computer room air conditioner units so as to ensure enough air flow rate. For the same reason by closing the perforated tiles in front of block installed at Row -1, the air flow distribution will be interrupted.

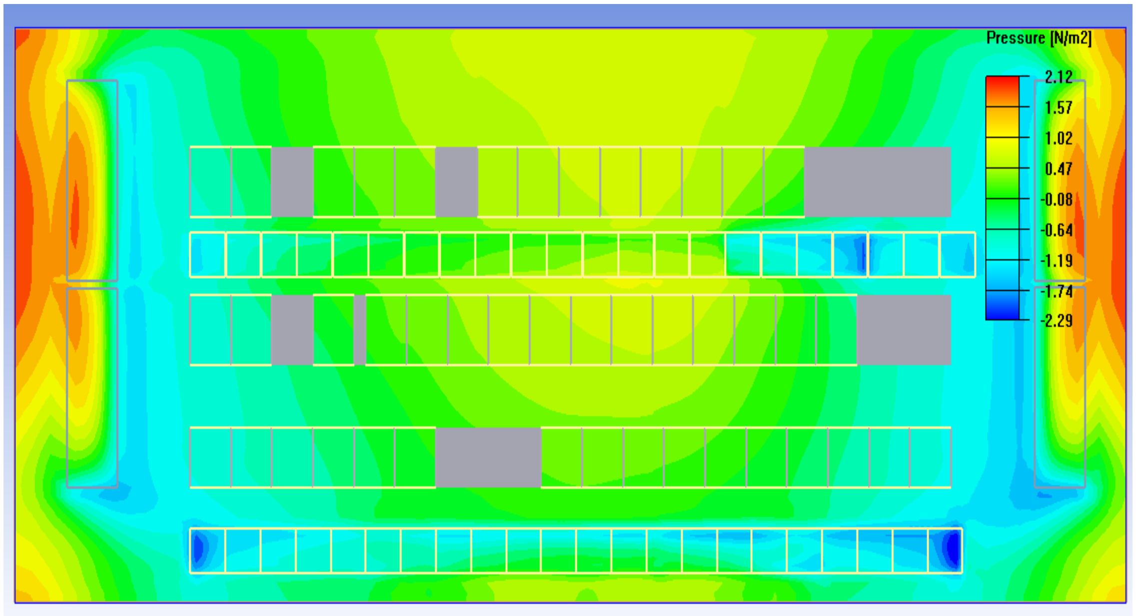


Figure (4-16) Pressure distribution under raised floor (plenum height = 0.5 m)

Considering the current data center under study, the high heat density racks which are located at the end of row 1 require a lot of air flow since they suffer from insufficient air flow. For this reason, air is returned from the hot aisle to the inlet of racks and thus increase the temperature of air supply.

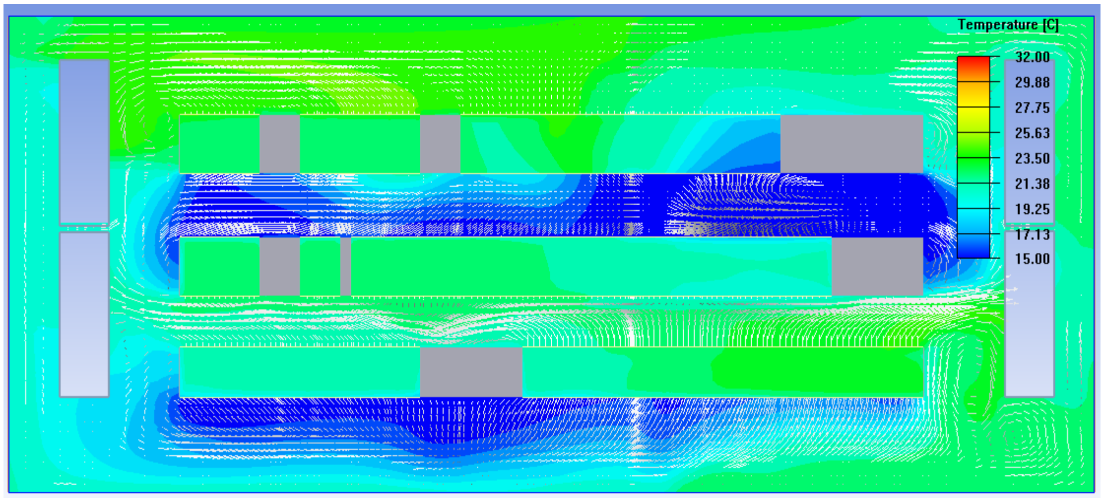


Figure (4-17) Temperature contour and velocity vector at XZ plane (Y=1.6m)

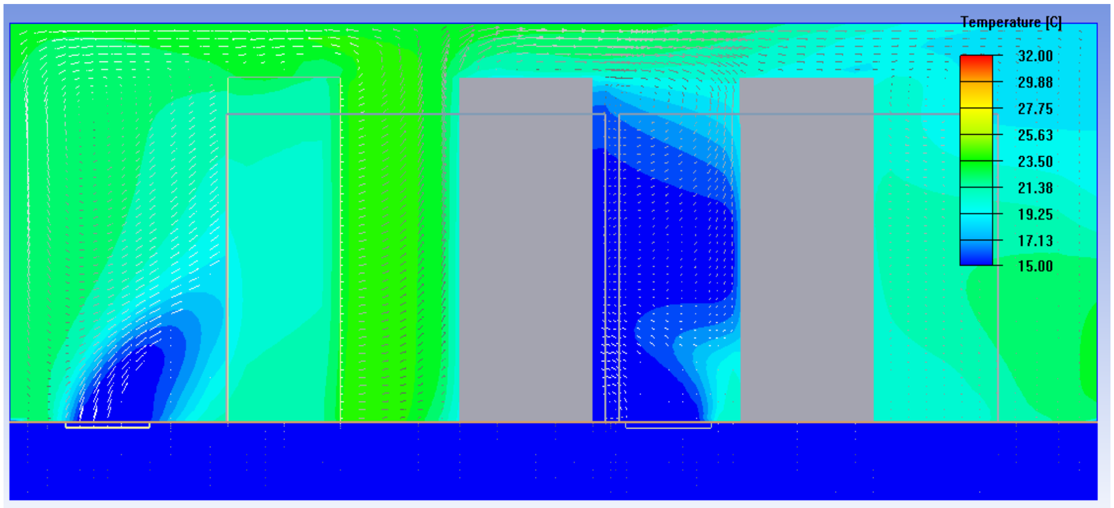


Figure (4-18) Temperature contour and velocity vector at YZ plane (x=15.96m)

In order to enhance the air distribution at the end of the row we need to prevent hot air returning to the inlet of the racks. The suggested remedy is to install additional tiles at both ends of Row-1 to act like an air curtain as shown in Figure (4-19).

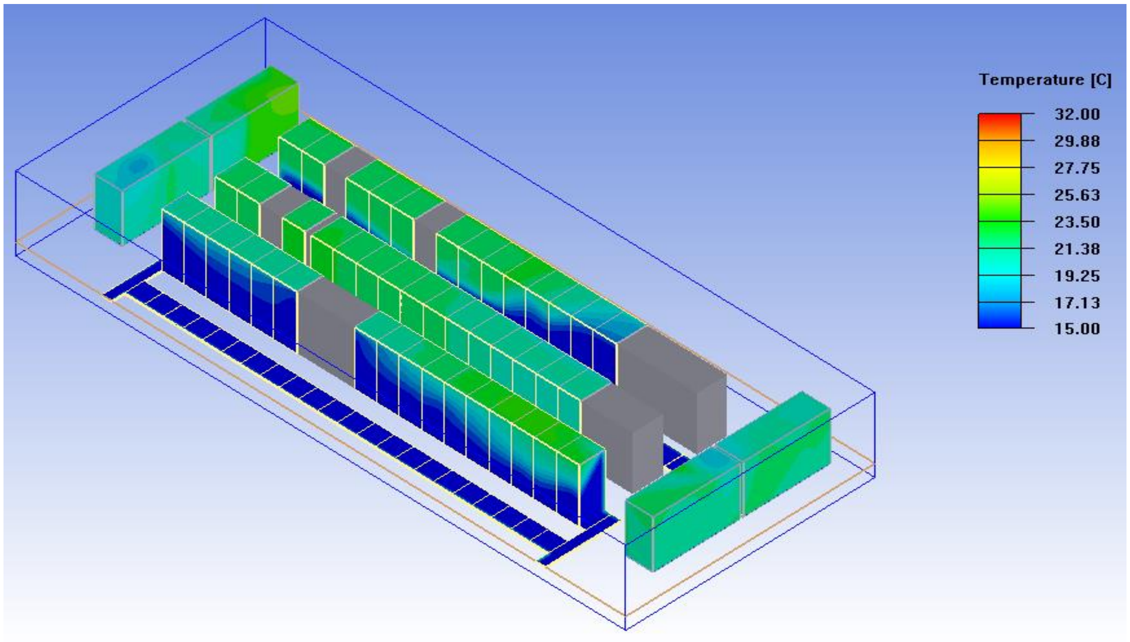


Figure (4-19) Temperature contour inside data center for supply air temperature of 15º, air flow outlet angle of 60° &75° for Row 1 and air curtain

After installing air curtains at both ends of tiles supply air to row 1, the temperature contour in the cold aisle is improved as shown in Figure (4-20) and Figure (4-21) below.

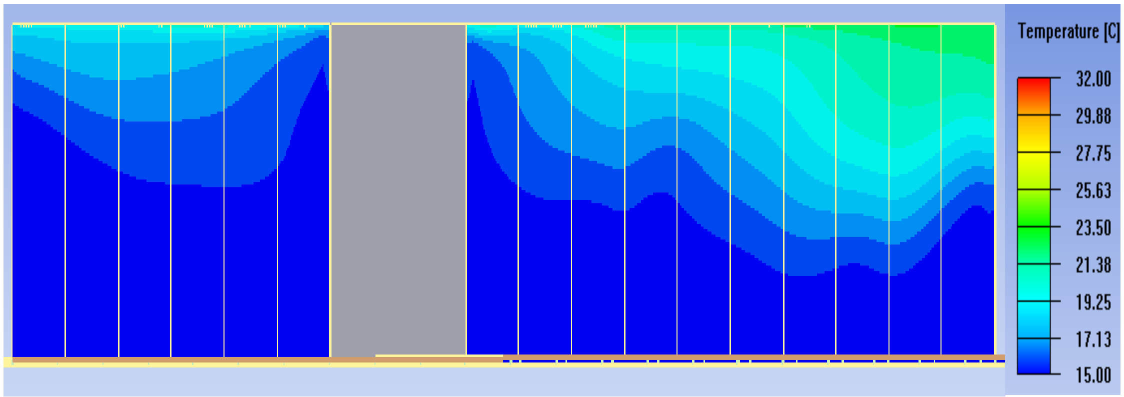


Figure (4-20) Temperature contour in the cold aisle of row 1 at 15ºC, tile of air flow outlet angle 60°&75º and tile open area of 60% with air curtain

From figure (4-21), the disadvantage of using air curtains at end racks is that the surplus air leaks from cold aisle to hot aisle. That's why the decision of using air curtains should be done carefully. On the same regards, the air flow distribution of racks located in the middle of Row -1 will be effected.

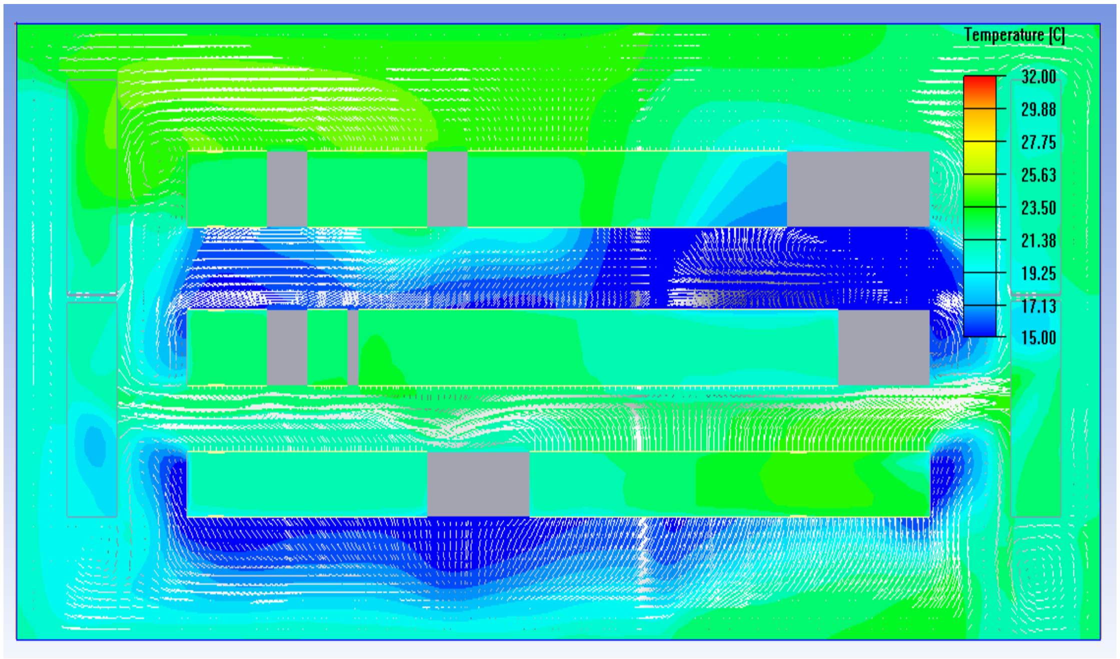


Figure (4-21) Temperature contour and velocity vector at XZ plane (Y=1.6 m)

From figure (4-22), after installing air curtains at both ends of row 1, the temperature distribution of rack 0 is slightly improved while the temperature distribution of the Rack 15 has obviously changed because air recirculation at this side is very high. However, there is still recirculation from the top side of the racks causing the upper side of the racks to become non-uniform. For this reason closed aisle data center is recommended wherever possible.

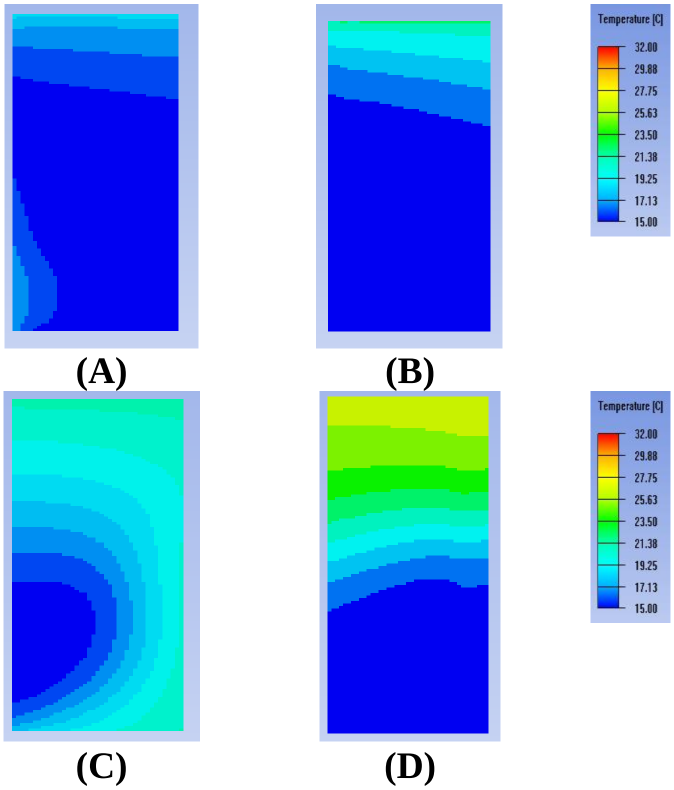


Figure (4-22) Temperature contour in the cold aisle (A) rack 0 before installing air curtain, (B) rack 0 after installing air curtain, (C) rack 15 after installing air curtain, (D) rack 15 after installing air curtain

The air flow distribution of rack -15 could also be showed from the side view as shown in figure (4-23).

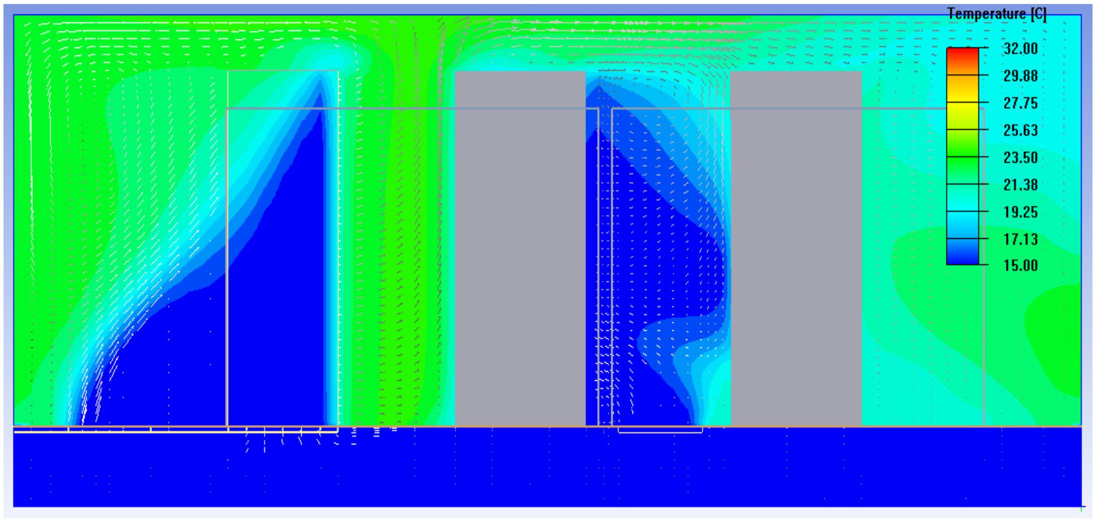


Figure (4- 23) Temperature contour and velocity vector at YZ plane (x=15.96m) after installing air curtain

4.8 Closed Aisle Data Center

In order to completely avoid recirculation and air bypass, closed aisle data is the recommended solution. Accordingly aluminum partition will be installed in the cold aisle to prevent air bypass to hot aisle and hot air recirculation from hot aisle. This is called Cold aisle containment.

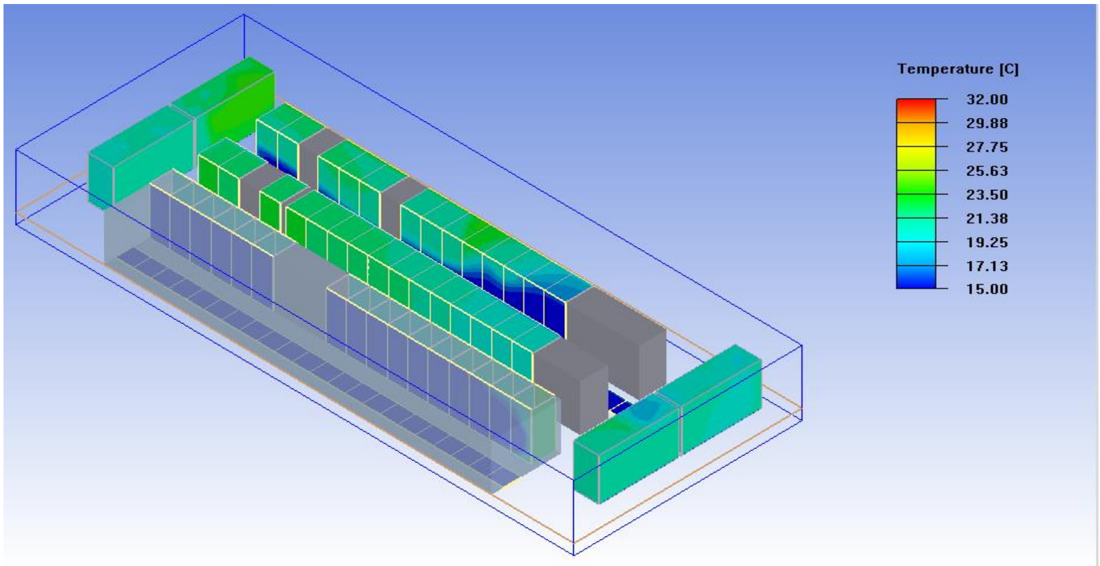


Figure (4- 24) Temperature contour inside a closed cold aisle data center

After deploying the cold aisle containment, the temperature distribution of row -1 is enhanced as shown in below figure while rack 15 is still suffering from the end effect.

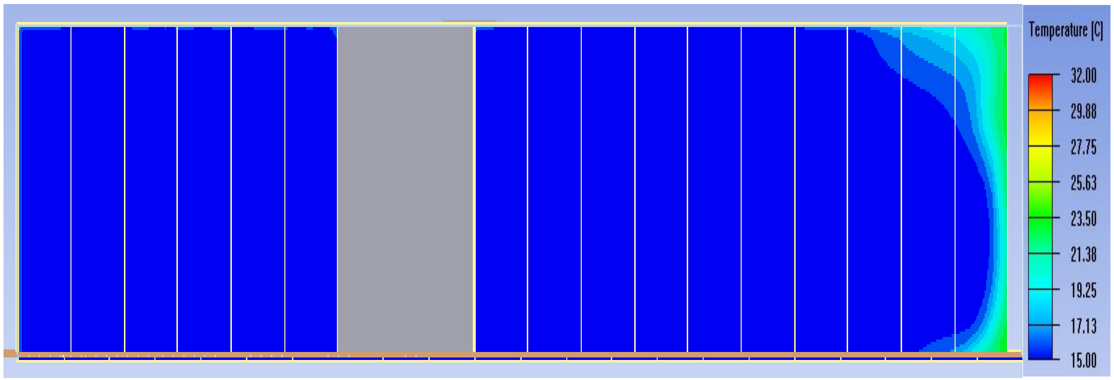


Figure (4-25) Temperature contour in row -1 for the closed aisle data center

4.9 Relative Humidity Inside Data Center

The relative humidity of air entering the racks has a great impact on equipment's life time. The low relative humidity will increase the risk of damage from electrostatic discharge while the high relative humidity will increase the risk of damage due to corrosion and hygroscopic dust failures. Using of proper relative humidity inside data center will also save water, energy and equipment.

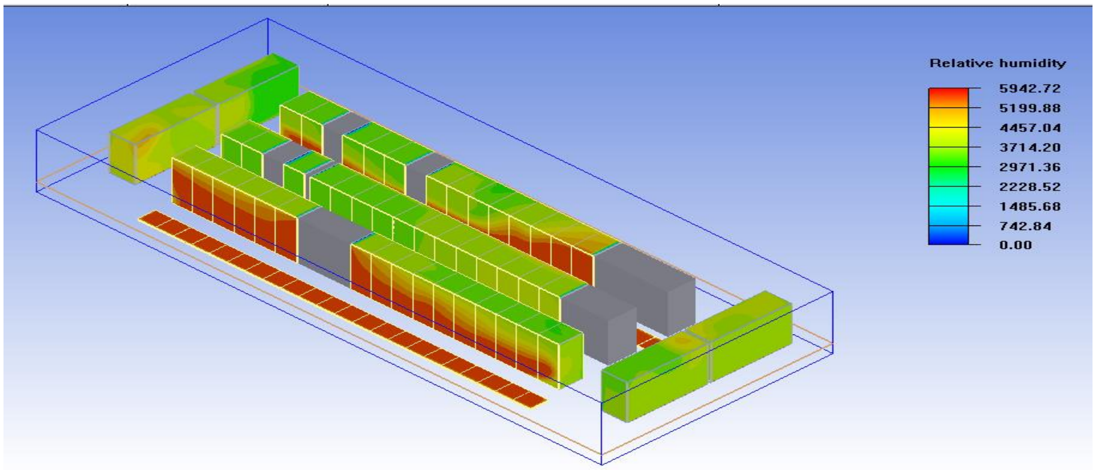


Figure (4- 26) Relative humidity contour inside the cold aisle data center

Figure (4-27) shows the contour of relative humidity for racks located at row -1. The values of the relative humidity are within the recommended range (ASHRAE, 2019). The values of relative humidity at the right end and upper side are low compared to the rest of racks surface, this is due to dry air recirculation from hot aisle to cold aisle.

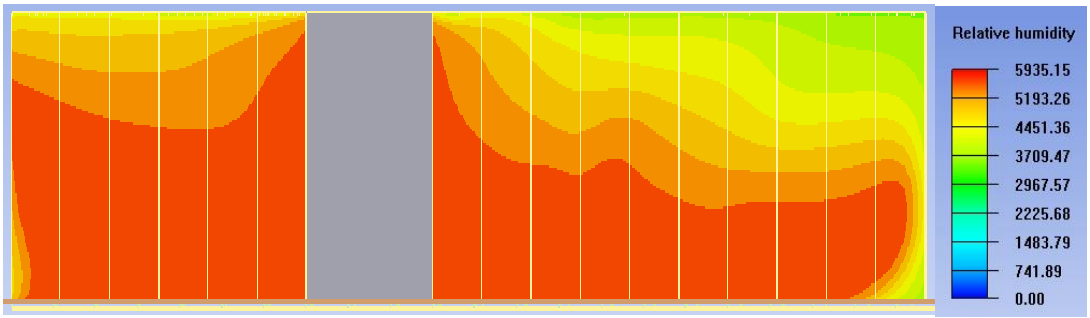


Figure (4-27) Relative humidity contour of racks located at row -1

4.10 Summary of Results

The summary of work done with the effect on the values of beta index and utilization energy index for row 1 is shown in below tables.

Table 4.8: Beta index – summary of results

Rack	Open Aisle Data Center	Data Center with Partition	Air flow outlet angle	Supply Air Temperature	Tile Open Area	Air Curtain	Closed Aisle Data Center
0	0.35	0.37	0.30	0.30	0.15	0.14	0.03
1	0.37	0.34	0.27	0.27	0.14	0.19	0.01
2	0.42	0.39	0.37	0.37	0.16	0.21	0.01
3	0.53	0.36	0.39	0.38	0.16	0.21	0.01
4	0.93	0.32	0.38	0.38	0.14	0.18	0.01
5	1.57	0.26	0.32	0.31	0.09	0.12	0.01
6	0.75	0.35	0.31	0.31	0.12	0.14	0.01
7	0.64	0.56	0.53	0.53	0.19	0.21	0.00
8	0.63	0.71	0.69	0.68	0.26	0.28	0.00
9	0.75	0.78	0.63	0.62	0.28	0.29	0.00
10	0.88	0.86	0.76	0.76	0.31	0.33	0.01
11	0.93	0.92	0.88	0.87	0.36	0.41	0.01
12	0.93	0.96	0.99	0.98	0.40	0.51	0.01
13	0.92	1.00	1.04	1.03	0.46	0.58	0.04
14	0.88	1.01	1.01	1.00	0.46	0.59	0.12
15	0.88	0.97	1.03	1.02	0.60	0.49	0.52

Average	0.77	0.64	0.62	0.61	0.27	0.30	0.05

Table 4.9: Energy utilization index – Summary of results

Rack	Open Aisle Data Center	Data Center with Partition	Air flow outlet angle	Supply Air Temperature	Tile Open Area	Air Curtain	Closed Aisle Data Center
0	1.59	1.58	1.62	1.63	1.77	1.79	1.94
1	1.57	1.59	1.65	1.65	1.78	1.73	1.98
2	1.54	1.56	1.57	1.58	1.76	1.70	1.98
3	1.48	1.58	1.56	1.57	1.76	1.70	1.99
4	1.35	1.61	1.57	1.57	1.78	1.73	1.99
5	1.24	1.66	1.61	1.61	1.84	1.81	1.99
6	1.40	1.59	1.61	1.62	1.81	1.78	1.99
7	1.44	1.47	1.49	1.49	1.73	1.70	1.99
8	1.44	1.41	1.42	1.42	1.66	1.64	1.99
9	1.40	1.39	1.44	1.44	1.64	1.63	1.99
10	1.36	1.37	1.40	1.40	1.62	1.60	1.99
11	1.35	1.35	1.36	1.36	1.58	1.55	1.99
12	1.35	1.34	1.34	1.34	1.55	1.49	1.98
13	1.35	1.33	1.33	1.33	1.52	1.46	1.92
14	1.36	1.33	1.33	1.33	1.52	1.46	1.80
15	1.36	1.34	1.33	1.33	1.45	1.51	1.49
Average	1.41	1.47	1.48	1.48	1.67	1.64	1.94

CHAPTER FIVE

CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

Data center has been simulated using CFD simulation software (Icepak). According to the thermal and the bypass phenomena, two evaluation indices have been used, the beta index and the energy utilization index. The summary of work is shown below;

1. Temperature and velocity contours across data center was shown and the effect of gaps between the racks was highlighted. Data center was rectified by closing gaps with partitions in order to prevent hot air recirculation from hot aisle to cold aisle. Results showed improved temperature distribution after this remedy.
2. The effect of air flow outlet angle was analyzed using beta index and energy utilization index. Different air flow outlet angles were tested. The minimum beta index and a maximum energy utilization index were at an angle of 60° for racks with low heat density & 75° for racks with medium heat density, which represented better air distribution.
3. Using the same approach for the different supply air temperature, the optimal value was found at 15ºC which gives the best utilization of cooling capacity.
4. Also the effect of tile Open area was investigated considering optimal parameters obtained for outlet flow angle & air supply temperature. The best tile open area founded for this case was 60%.
5. The end effect of racks was shown and enhanced by using additional tiles to act like an air curtain.
6. The advantage of a closed aisle data center was shown.

7. Finally, the Relative humidity was checked and confirmed within recommended range.
8. The outcome of this study has the potential to contribute in treating the problems of airflow and thermal distribution in data centers through simulation models and computational analysis involving detailed 3D Computational Fluid Dynamics calculations.

5.2 Recommendations

1 This study indicates the importance of CFD simulation to analyze air flow inside the data center and choosing the optimal operating parameters.

2 This study can also be used as the foundation for further research on airflow distribution and thermal consumption by sustainability considering such parameters as equipment arrangement, server loadings, air curtain outlet angle, cooling configurations, and other cases of cooling.

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APPENDIXES

Appendix 1

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