DESIGN AND MODELING TECHNIQUES FOR COOLING OF TELECOMMUNICATION SYSTEMS

By

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Presented to the Faculty of the Graduate School of

The University of Texas at Arlington in Partial Fulfillment

of the Requirements

for the Degree of

MASTER OF SCIENCE IN MECHANICAL ENGINEERING

THE UNIVERSITY OF TEXAS AT ARLINGTON

December 2011

ACKNOWLEDGEMENTS

I would like to thank Dr. Dereje Agonafer for his continuous guidance and support over the last two years of my research and study at the University of Texas at Arlington. It has been a constant learning process for me under his expertise in terms of understanding engineering concepts and molding myself as an experienced engineer. His inspiration and motivation is beyond words.

I would like to thank Dr. Haji-Sheikh and Dr. Seiichi Nomura for serving on my committee. I would also like to take the opportunity to thank Mr. Mark Hendrix, Mr. Deepak Sivanandan and Mr. Gary Irwin of Commscope Inc. for all their expertise and continuous support and feedback in all the projects. Their industrial expertise has been really important for my research and I am very grateful to them.

I am obliged to Ms. Sally Thompson who has been of immense help in assisting me in all educational matters. I also want to thank the entire EMNSPC team, especially Niket Shah, Bharath Muralidharan, Fahad Mirza, Richard Eiland, Betsegaw Gebrehiwot, John Fernandez and Marianna Vallejo for all the help they have provided.

I would also like to acknowledge the help and support extended by all my friends and colleagues who have made my stay at UTA a memorable one.

Finally, this acknowledgement would not be complete without mentioning my parents, Mr. M.D. Kannan and Mrs. Jayanthi Kannan and my sister, Mrs. Narmada Anand who have served as a beacon of inspiration. I am forever indebted to them for providing their support and the opportunity to pursue my dreams.

October 28, 2011

ABSTRACT

DESIGN AND MODELING TECHNIQUES FOR COOLING

OF TELECOMMUNICATION SYSTEMS

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Conventional data centers are extremely large buildings that have complex power distribution and cooling systems. These traditional brick and mortar data centers employ relatively expensive cooling systems and are inefficient. It has in turn led to an increase in construction and operational costs.

These inefficiencies of traditional data centers can be overcome by partitioning the server load into modular sections which can be deployed, powered and cooled depending on availability and requirement. Furthermore, improvements in efficiency and operational costs can be achieved by employing “free cooling” to cool the IT equipment. Free cooling involves the introduction of outside air through a series of filters to directly remove the heat from the server racks and cool the IT equipment, thus foregoing expensive computer air conditioning units (CRACs).

The first part of the thesis will discuss the design and thermal analysis of IT telecommunication switches using commercially available CFD software. Network switches are the central core of the network infrastructure. The CFD modeling and analysis will include the study of side breathing network switches which are classified based on their air flow pattern.

The issues addressed are cooling performance differential between 6 and 12 inch wide vertical cable managers located between two alternating side breathing switches; even and odd number of side breathing switches; and even and odd number of side breathing switches with and without top blanking panels. These network switches draw cold air in through one side of the chassis and release hot air out of the opposite side.

The second part will discuss the CFD modeling and analysis of a modular data center. Free cooling is adopted for cooling the data center. Several free cooling approaches are available for introducing outside air into the data center. One such approach will be discussed and the resulting thermal performance of the system will be analyzed.

The study was done in collaboration with an industrial partner and as such most of the results of this study have been adopted in actual telecommunication systems.

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NOMENCLATURE

ρ	Density (kg/m^3)
k	Thermal Conductivity (W/m-K)
$\boldsymbol{v}$	Velocity (m/s)
μ	Viscosity (N/m^2S)
ε	Kinematic Rate of Dissipation (m^2/s^3)
$\dot{m}$	Mass Flow Rate (kg/sec)
Q	Heat Load (KW)
P	Power (W)
$\dot{v}$	Volumetric Flow Rate (cfm)
p	Pressure (Pa)
T	Temperature (K)
C_P	Specific Heat Capacity (J/kg-k)
R_e	Reynolds Number
l	Characteristic Length (m)

CHAPTER 1

INTRODUCTION TO MODULAR DATA CENTERS AND LITERATURE REVIEW

1.1 Introduction to Modular/Containerized Data Centers

1.1.1 Modular Data Centers: An Introduction

Traditional data centers or Legacy data centers have been around for the past few decades which form the backbone of the telecommunications industry. These data centers are continuing to expand day by day in terms of size, technology, power, density etc. Adding to this is the initial cost of setting up these massive structures on such a large scale and the maintenance required to prevent them from failure. Expansion of traditional data centers is an extremely difficult task unless accounted for at the beginning of their construction. Expansion in terms of capacity is also considerably difficult as systems have to be ordered, shipped and delivered to the data center where they must be racked and installed. The process would require skilled labor in addition to cost of shipping and delivering the systems.

Modular data center, also termed as containerized data center or data center in a box refers to a portable self-contained environment designed for rapid deployment, energy efficiency and computing density. They are portable and can be deployed much faster than a traditional data center. They are macro modules consisting of thousands or more systems. Instead of building and shipping single systems or racks of systems, the modules are built within shipping containers with all the necessary equipment, configured and shipped as a fully operational unit ready to be powered up. All that is required upon delivery is provision of power, internet connectivity and chilled water supply. Therefore, modular data centers can be deployed anywhere around the world.

The first modular data center was introduced by Sun Microsystems (currently owned by Oracle Corporation) known as Project Blackbox or Sun modular data center which was a portable data center built into a standard 20 foot shipping container. The modular data center required power supply and an external chiller to be operated. Sun Microsystems claimed that the container could house up to 280 servers and that it could be shipped and immediately deployed to any location where construction of a traditional data center was not possible. Since then, several companies such as Commscope, Google, Hewlett Packard, PDI, Microsoft Amazon, etc. have developed containerized data centers featuring state of the art technologies.

Figure 1.1: Sun Microsystems Modular Datacenter: Project Blackbox [1]

1.1.2 Importance of Modular Data Centers and Need for Cooling

Modular/Containerized data centers have gained importance in the recent years primarily because of their simplicity and the ease at which they can be quickly deployed to expand existing IT infrastructure. They are much more energy efficient and do not require high maintenance as opposed to traditional data centers.

These data centers could be located anywhere from onsite data center facilities to parking lots, garages, and warehouses. Their main advantage is for providing quick expansion for rapidly growing IT infrastructure and for companies that reach their full capacity until a new one is constructed. Modular data centers are of particular interest to startup companies and also companies transitioning to new data centers.

With sizes of these data centers ranging from 20 to 40 feet and the capacity to house several servers, a large amount of power is utilized and a tremendous amount of heat is generated. The servers along with other electronic components generate a large amount of heat and hence it is crucial to ensure that the air temperature inside the containerized data center is within the prescribed limits in order to avoid hot spots. Hot spot formation and thermal stresses can lead to equipment failure, short term reliability etc. Several factors such as ambient temperature, humidity, location and solar loading play an important role as thermal conditions are based on ambient conditions as well as conditions inside the container. Also, reduction in chip size and high chip utilization rates has led to an increase in heat density of chips at a rapid rate. Therefore, in order to maintain optimum performance of these devices, thermal management is very important at the device, board, and rack and room level.

1.2 Modular Data Centers Description

1.2.1 Why Modular Solutions Should Be Considered

Modular data centers are an alternative for traditional data centers. Their main advantage is the relative ease of shipping and deployment, lesser capitol for investment and lower operating costs compared to traditional data centers. Maintenance and management of these containers is much easier and since power densities are not as high as traditional data centers, thermal management of these containerized data centers comparatively reduces. Also, use of free cooling techniques such as air side or water side economizers, utilization of outside ambient air temperature etc. can be implemented and monitored in these modular data centers which would help during the construction of traditional data centers or legacy data centers.

1.2.2 First Generation Modular Data Centers

First generation modular data centers refer to those units which require chilled water systems or refrigerant cooling coils as cooling infrastructure support or utilize direct expansion cooling units. For direct expansion cooling units, the compressors and condensers are usually located outside the container. First generation configurations can be offered in a number of different configurations for the cooling systems and IT infrastructure. The most common configuration is similar to a hot aisle/ cold aisle data center configuration where the equipment are housed in racks in a single row with aisles on either side for access and all the cooling equipment located right above, behind or to the sides of the equipment racks. This configuration prevents mixing of hot and cold air and hence provides excellent hot/cold aisle containment. However, this configuration may serve only as a short term solution for immediate expansion of existing facilities or in locations where free cooling techniques are not favorable. These units are typically not very energy efficient and can be expensive. Also, first generation units tend to be less energy efficient and more expensive than second generation units. On the other hand, they are typically not affected by ambient air temperature and humidity.

1.2.3 Second Generation Modular Data Centers

Second generation modular data centers eliminate the need for chilled water supply or direct expansion cooling. These systems use free cooling, chilled water or direct expansion methods. Evaporative cooling, another highly efficient technique, is sometimes paired with free cooling when ambient air temperature reduction is needed. These systems may also include chilled water or direct expansion cooling units as backup when outside air temperatures dictate that use of economizers may not be favorable.

SGI's ICE Cube Air is an example of a second generation modular data center unit configuration illustrated in Figure 1.2.

Figure 1.2: SCI ICE Cube Air [2]

1.2.4 Comparison between Traditional and Modular Data Center Configurations

Table 1.1: Comparison of Primary Attributes [3]

Primary Attributes	**Traditional "Brick and Mortar" Data Center**	**First Generation Modular**	**Second Generation Modular**
Time to Deployment	Long – typically two years from design to commissioning	Potentially short – perhaps in months depending on site conditions and available infrastructure	Same as First Gen. Modular with advantage that reduced cooling infrastructure is required
Capital Cost	Highest – generally thought to range from 10- $20 million per MW of IT capacity	Lower – though there is a lack of documented deployment costs	Lowest – marginal increase in cost of unit, made up for by reduced infrastructure costs
Operating Cost	Variable, with legacy data centers having PUE's exceeding 2.0 and best-in-class designs approaching 1.2 or lower if using outside air for cooling	Similar to traditional data center using the same cooling type. Pre-engineering and better system integration may provide some advantages.	Similar to best in class legacy data centers that use air-side cooling.

1.3 Modular Data Center Considerations

Several considerations are involved in selection of modular data centers depending on the requirement. Some of these include selection of the most energy efficient cooling technology, IT infrastructure requirements, power requirements and several other considerations.

1.3.1 Selection of Cooling Technology

Selection of cooling technology varies primarily depending on the location, geography, environmental conditions and availability of existing resources in the vicinity where modular data centers are set up. The selection of cooling systems can be divided in to three categories, namely air side systems, water side systems and other miscellaneous systems. In order to increase free cooling, selection of air side systems are preferred. When environmental conditions are not favorable for operation of air side systems, water side systems and miscellaneous systems such as evaporative coolers and dry coolers can be utilized. These systems can be used in combination with conventional cooling systems such as water cooled chillers, chilled water towers and direct expansion units to support IT equipment depending on outdoor conditions.

Apart from these factors, selection of cooling technology also depends on certain attributes such as humidity control, availability of chilled water supply, power supply for IT equipment and cooling systems and selection of filters and frequency of replacement.

1.3.2 Additional Requirements and Considerations

Deployment of modular data centers depends on several additional requirements such as availability of maintenance and service in the instance of failure of cooling system components such as fans, filters and control systems. Cooling units using refrigerants require more maintenance to those of which use water. Control systems which are used for monitoring the devices should be compatible with existing building management, power management and energy management systems. Failure of even one such management system can lead to loss of considerable amount of data. These modular data centers must be in close proximity to existing power and chilled water distribution systems. Fire suppression systems and smoke detection systems should be installed and periodically monitored to avoid hazardous situations [3].

Various other considerations such as availability and existence of infrastructure surrounding the site where modular data centers are deployed should be analyzed. It should be determined if chilled water supply distribution systems, power supply and backup power are available in existing sites or whether such infrastructure has to be provided for the containers.

Where modular units with air side economizers are used, module orientation with respect to wind direction will improve free cooling and energy efficiency [3].

1.3.3 Attributes of Modular Data Centers

The most important attribute of modular data center designs is the ability to offer improved energy efficiency performance. This is possible because they are much more compact than traditional data centers. Traditional data centers are larger in size and occupy more area. They require power and cooling on a greater scale. Conventional cooling systems such as chilled water systems are used since free cooling on such a large scale is very difficult to provide for.

Advantages of energy efficient modular data centers are [3]:

1) Lower Power utilization effectiveness (PUE) value.
2) The ability to use higher chilled water supply.
3) Variable speed fans used in cooling systems and effective control systems that monitor device temperatures and air flow requirements.
4) Use of air side economizers and other free cooling systems such as evaporative coolers which are cost effective and can improve efficiency.
5) Improved hot aisle/cold aisle containment. By doing so, this can reduce the amount of flow rate and the fan power required to supply it.

1.3.4 Power Usage Effectiveness: Metric for Energy Efficiency

Power usage effectiveness (PUE) is a standard/metric developed by The Green Grid consortium in order to determine energy efficiency within a data center [4]. Since power and cooling are two of the biggest challenges in data centers, companies require different solutions to reduce costs and maximize energy efficiency. By doing so, companies can increase computing; achieve lower energy costs and reduce the total cost of ownership (TCO) [5].

Power usage effectiveness (PUE) is defined as the ratio of the total power used by a data center facility to the IT equipment power supplied. The ideal PUE value is 1.0 which would indicate 100 percent efficiency. This means all the power is being used up by the IT power only. PUE values are generally between 2.0 to 3.0 for data centers, but can be brought down significantly by designing them much more efficiently.

PUE = Total Facility Power/IT Equipment Power

Total facility power includes all the components which support the IT equipment load such as power systems like generators, UPS systems and batteries and power distribution units, cooling systems such as chillers, cooling towers, computer room air handling units (CRAHs), mechanical components such as compressors and condensers, pumps and direct expansion systems [6].

The IT equipment power includes the IT equipment load such as computing and storage devices (servers), network equipment and other additional devices such as computers, workstations and laptops and KVM switches which are used for monitoring and controlling the data center [6].

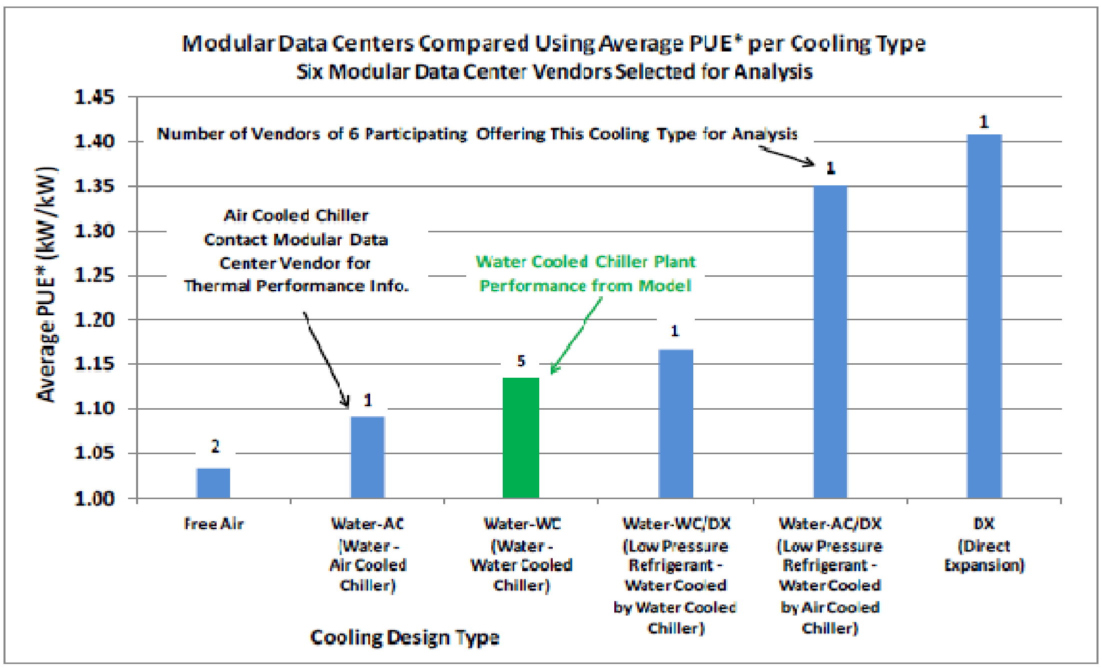

Figure 1.3: Example of PUE Comparison for Different Cooling Designs [3]

1.4 Literature Review

1.4.1 Modular Data Center Technologies

Modular data centers or containerized data centers are widely being considered as a replacement to traditional data centers requiring expansion capabilities. This is primarily due to the fact that they are easier to ship and deploy, much quicker to set up, have reduced operating costs and are maintenance friendly. Sun Microsystems owned by Oracle corporation introduced the concept of containerized data centers with the launch of Project Blackbox or Sun Modular data center. Also, Google was awarded a patent for a portable data center in a shipping container suggesting existence of such units since 2005. Several other companies such as Amazon, Microsoft, Hewlett Packard, Dell etc. have come out with different designs for modular data center solutions giving importance to energy efficient cooling systems, power supply and network connectivity.

Schmitt et al. [7] patented an enclosure comprising of a processing subsystem and infrastructure subsystem in separate shipping containers which cooperate to process information between each other. The processing subsystem houses the information handling systems in one shipping container and the infrastructure equipment is housed in the second shipping container. These shipping containers are arranged in a stacked configuration as a result of which the cooled air and exhausted air are exchanged through vents located in the ceiling and floor of the stacked shipping containers. The intake and exhaust vents of the processing subsystem are located in a floor and the processing subsystem container rests on top of the infrastructure subsystem shipping containers. Chilled water is provided from an external source to the infrastructure subsystem shipping container through coil assemblies.

Jimmy Clidaras et al. [8] developed a solution for modular data centers which includes a connecting hub and a plurality of containers. The connecting hub in turn may have a plurality of docking stations to which the containers are connected and powered up. The connectivity hub is configured with each of these docking stations in order to supply electrical power, network connectivity, cooling fluid supply and cooling fluid return. The docking station of each container is attached to a central power spine. Each shipping container would include a number of processing units or servers. The cooling technology adopted includes a first heat exchange circuit where heat is transferred from the servers to a heat exchanger and a second heat exchange circuit comprising of the heat exchanger, cooling fluid supply and cooling fluid return so that heat is transferred from the heat exchanger inside the container to an external system using cooling fluid through the cooling fluid supply and cooling fluid return.

The docking stations which connect to the spine would receive the cooling fluid from the cooling fluid supply, and discharge return cooling fluid to the cooling fluid return.

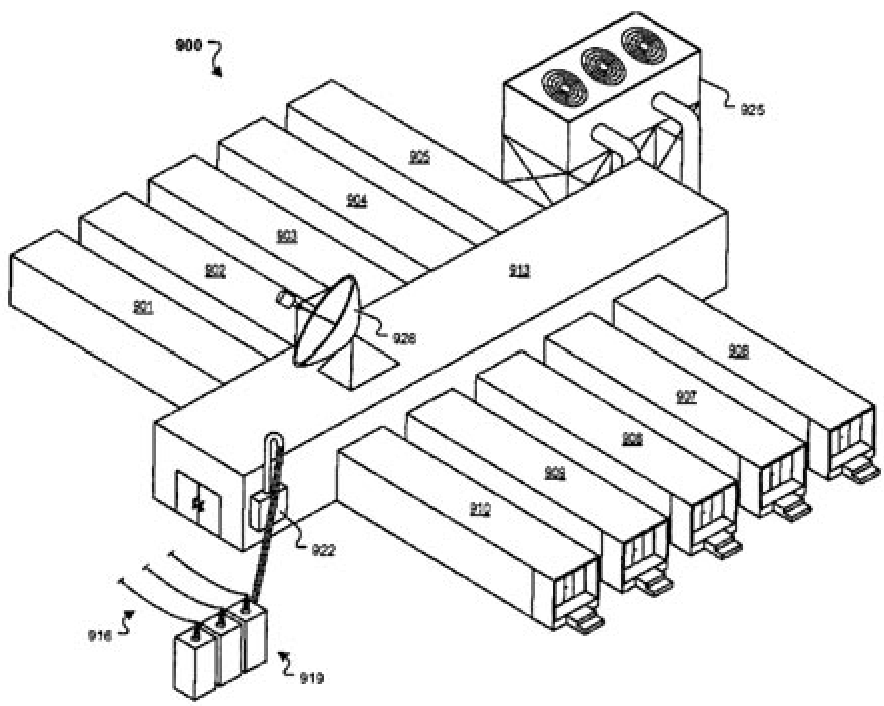

Figure 1.4: Containerized Data Centers with a Connecting Hub by Google [8]

Jimmy Clidaras et al. [8] also indicated that another solution for modular data centers would include stacking shipping containers one above the other which would also include a facility level cooling system.

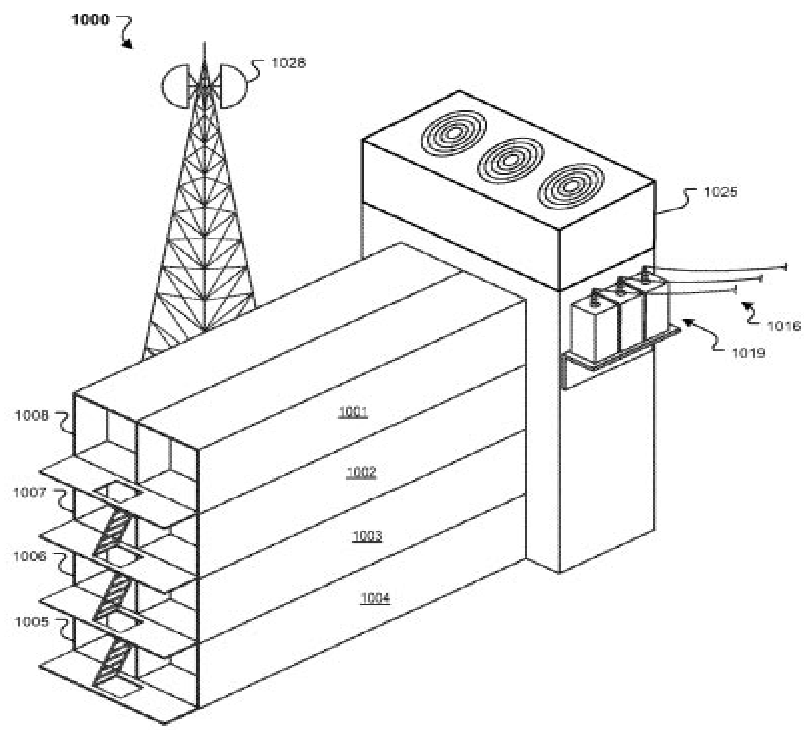

Figure 1.5: Stacked Data Center Containers by Google [8]

Hewlett Packard's Performance Optimized Data Center [9] also known as the EcoPOD features two 40-foot containers joined together in order to increase expansion capacity. This modular design uses outside air as the cooling mechanism. The EcoPOD can house 44 racks of IT equipment and includes two cold aisles and an 8-foot hot aisle due to the wider design. Apart from the use of outside air, the cooling module also features a direct expansion cooling system and depending on environmental conditions and heat load, the cooling module can automatically adjust to use ambient air and switch to direct expansion cooling during a warmer climate. The EcoPOD modular design has an expected Power Usage Effectiveness rating of 1.05 to 1.30.

Figure 1.6: Hewlett Packard Performance Optimized Data Center [10]

Figure 1.7: Cisco Containerized Data Center [11]

Cisco's Containerized Data Center [11] is a 40-foot container which uses chilled water cooling technology. The containerized data center can house 16 racks, each with 44 rack units and is capable of supporting up to 25 kilo watts. Each rack in the container has a sensor that controls and monitors rack inlet and exhaust temperatures, humidity, coolant leaks, rack cooling fans and rack coolant flow rates. [12]

Brewster Kahle, founder of the Internet archive, studied and applied the containerized transport and delivery approach to data storage. Kahle proposed and built the Petabox [13] which is a storage subsystem supporting a petabyte of storage in a standard shipping container that could be efficiently deployed and transported anywhere in the world.

Rackable systems [13] focus primarily on power and cooling of standard 40 foot shipping containers in order to achieve power densities as high as 750 watts/sq ft and achieve cooling savings approaching 30%. The Rackable systems containerized data center design houses 1,152 systems.

The Sun Microsystems modular data center [14] is designed to cool up to 200 KW of load with 22 KW reserved for its own infrastructure and external solar loading in high temperature conditions. Hence, it is capable of supporting up to 178 KW of equipment load. The Sun modular data center has eight 19 X 32 inch standard racks with 40 rack units per rack. The outer surface of the modular data center is designed to operate in environmental conditions where in the temperature ranges from -20℉ to as hi gh as 130℉ with a relative humidity of 100 percent. The container is designed to withstand inside operating temperatures ranging from 50℉ to 95℉ with a relative humidity between 20 to 80 percent. The Sun modular data center uses chilled water for cooling with two redundant chilled water attachments. Heat exchangers are used for distribution of cooling between equipment racks. A heat exchanger is placed between each pair of racks and contains cooling coils and ten variable speed fans. Each of the fans has a maximum operating capacity of 1100 CFM. Filter banks provided at one end restrict the entry of particulate matter. The heat exchanger fans run at only 20 percent in order to maintain cooling resulting in major energy savings.

CHAPTER 2

INTRODUCTION TO FREE AIR COOLING AND SIDE BREATHING SWITCHES

2.1 Introduction to Free Cooling

2.1.1 Introduction

Servers have become an integral part of today's computational world. They are the source for data storage and enormous computational power. Data centers have become the source for housing and powering large volume of servers. Until recently, the performance of processors and servers in terms of energy and power utilization has been of less concern compared to their computational performance. Although the initial capital for these powerful servers has become comparatively cheaper due to Moore's law and lower manufacturing prices [15], operating these devices for longer and continuous durations require significant amount of energy. Consumers are demanding higher server performance due to increased computing power at the chip level. Although these devices have become extremely efficient in terms of computational output per watt, however due to high performance, it has led to an increase in power density. Continuous operation of these devices leads to the generation of a large amount of heat. One of the major goals is to reduce the power usage effectiveness in order to improve efficiency of data centers. The average power usage effectiveness value ranges between 2 and 2.5. Cooling systems play a very important role in removing heat from server racks, but require significant amount of power. This has caused an increase in electricity and as a large amount of energy is required for cooling systems.

Figure below shows a graphical representation of energy consumption for different systems within a data center. It can be observed from the figure that apart from the critical IT load, cooling takes up a large amount of the facilities power. Therefore, it is very important to reduce energy consumption of cooling systems in order to improve efficiency and reduce power usage effectiveness of the entire data center.

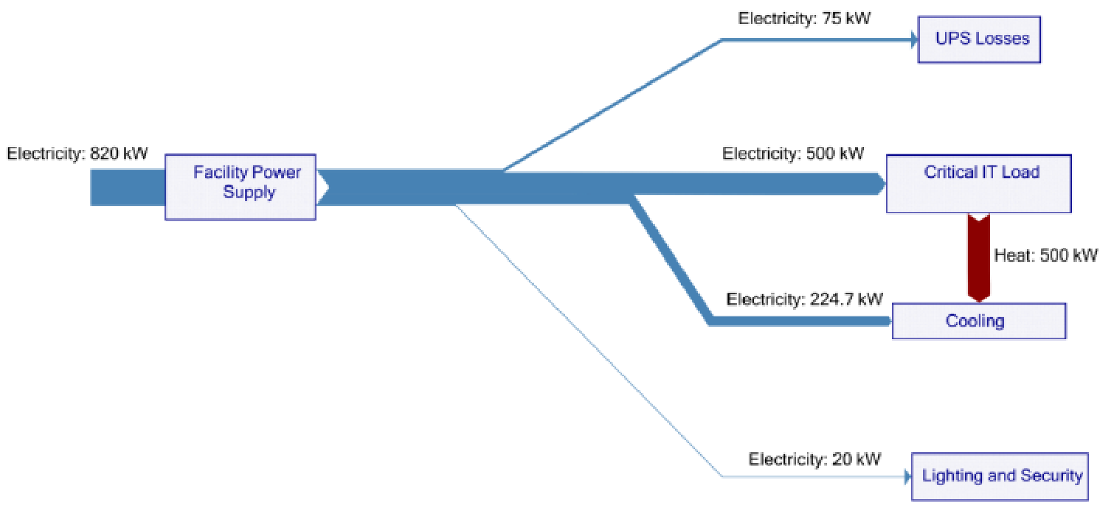

Figure 2.1: Data Center Energy Flow Diagram [16]

In order to significantly reduce the usage of chilled water systems and cooling towers, free cooling technique is widely being adopted which takes advantage of external conditions in order to cool servers and other electronic equipment's.

2.1.2 Free Cooling Definition

Traditional data centers use conventional/mechanical cooling systems such as chilled water systems. These cooling systems require large and heavy mechanical systems such as compressors and condensers for carrying heated air through the water which is either transferred to the outside atmosphere or circulated to external cooling towers. The liquid refrigerant absorbs the thermal energy and evaporates into vapor and in order to dissipate heat to the outside air, the refrigerant is compressed which increases its temperature. Once heat is rejected to the outside air, the refrigerant is allowed to expand back to its original state because of which its temperature reduces and the process is repeated. This entire process consumes a large amount of energy. On the other hand, free cooling provides an alternative to traditional cooling by making use of external ambient conditions and significantly reducing the use of mechanical systems. Free cooling is a more economical method of cooling which makes use of lower ambient temperatures to assist in cooling. It is very suitable for cooler climatic conditions. Although free cooling may significantly reduce the impact of mechanical cooling systems, they cannot completely replace them. However, they do pose a very good solution for cutting down energy costs.

2.1.3 Types of Free Cooling Systems

There are mainly two types of free cooling systems namely air side cooling and water side cooling. Miscellaneous cooling systems such as ground water cooling and sea water cooling are also commonly used. In air side cooling, cold air is pulled in from outside and circulated through the servers and other electronic equipment and the heat is carried back and driven outside. However, air side cooling requires a greater volume of air to cool a data center which in turn requires larger ducts for pushing so much air. Although this cooling technique sounds very simple, it may not be practical to apply for cooling large volumes of area within a data center as pulling in so much air and filtering it is extremely difficult. Filters the size of large ducts are required to prevent entry of any contaminants such as dust, moisture etc. Additionally, large fans are needed to pull in an enormous quantity of air through the filters. Filters will have to be replaced periodically as dirty filters would cause a lot of air resistance compared to clean ones. Water side cooling is more commonly used compared to air side cooling because water is much more efficient in transferring heat than air per unit volume. Free cooling can be achieved using water side cooling systems by integrating them with centralized chilled water systems and condensers with the addition of valves. Circulating water or a glycol water mixture is used for transferring heat to outdoor cooling towers without running chillers.

2.1.3.1 *Air Side Cooling*

As mentioned above, air side cooling systems make use of outside air for cooling large spaces. Some commonly used air side cooling systems are mentioned below:

2.1.3.1.1 *Air Side Economizers*

Air side economizers are used as a control mechanism to regulate the use of outside ambient air for cooling. They are the most commonly used air side cooling systems. These economizers are interconnected by large ducts to allow the entry of fresh outside air and drive out hot exhaust air. Air side economizers utilize a system of dampers and sensors to allow desired quantity of air for cooling purposes. The sensors are used for monitoring outside and inside air conditions and temperature. If external conditions are suitable for use of fresh outside air for cooling purposes, the economizer adjusts the position of dampers through a control system for the introduction of fresh outside air making it the primary source of cooling. As air passes through the ducts, it is filtered to remove contaminants. The filtered air is circulated across the portion that has to be cooled and heated air is exhausted out. In case large volumes of outside air are introduced into the system, exhaust dampers maintain the pressure by driving out unnecessary air. If external conditions are cooler than required, then the dampers allow a portion of the return air to mix with cold outside air which is either recirculated or exhausted back outside. Hence, air side economizers significantly reduce the use of air conditioning units and chilled water systems.

A study by Shehabi et al. [17] compares the energy implications of conventional data centers with newer technologies employing waterside and air side economizers in five different climate zones in the state of California. They report that airside economizer performs consistently better in all climate zones. In fact according to another study by Syska Hennessy Group [18], outside air can be used for almost entire year in San Francisco.

Intel's proof of concept test [19] has provided good insight on air side economizers. Intel IT used 900 production servers which ran at very high rate of utilization. This high density data center used 100 percent air exchange at 90℉ and without any humidity restrictions. The filtration was kept at minimal level. It was estimated that with the economizer in use 91 percent of the time, nearly 67 percent of energy can be saved. The proof of concept test also illustrated that no significant rise in failure rates were observed when air side economizer is used.

Intel has also conducted experiments on the implementation of air side economizers in New Mexico. The test setup consisted of many servers more than two years old which were housed in two experimental data centers. Each of them comprised of 8 racks with 4 blade chassis. The server inlet temperature was closely controlled at 20℃ and with good filtration. The economizer was controlled to bring in outdoor air at 18℃ and maintain the server inlet temperature by recirculating the hot exhaust air with the cold incoming air. DX cooling units were also used in case environmental conditions reached higher temperatures. It was estimated that an air side economizer would require only 26.9 percent of the energy removal as a fully closed system which would result in significant energy savings. The testing revealed that using the new ASHRAE recommended temperature and humidity ranges coupled with air side economizers and DX cooling systems would yield significant operational savings. Also, the use of ASHRAE standard 52.1-92 rated filters at 85 or 95 percent would ensure efficient filtration using air side economizers. [20]

A few suggestions made by Ron Spangler of Emerson Network Power are that air side economizers can save about 50 to 60 % of total power savings considering the CRAC units with the system as a whole. These savings would vary depending on the city and environmental conditions. Air side economizers provide about 60 % savings in moist coastal climates such as Portland Oregon. [21]

Saket et al. [22] studied the effect of air side economizers for various cases. Numerical models were designed and analyzed to determine their performance at various operating conditions. Four different scenarios were analyzed where the first configuration included a conventional data center with CRAC units and an under floor plenum supply. The remaining three configurations comprised of air side economizers for bringing in outside air into the data center. For all four scenarios, the system dimensions were the same and the parameters such as heat load, flow rate, rack layout and percentage open area ratio for the tiles remained the same. The results indicated that substantial energy savings can be made using air side economizers. The three scenarios where air side economizers were used yielded better results as compared to the model with the CRAC unit.

Air side economizers are classified into two types namely direct air side economizers and indirect air side economizers.

Direct Air Side Economizers – Direct air side economizers simply work on the principle that for a specific period of time during a year, the external environmental conditions meet the specifications which are in accordance to cool the data center. During this portion of time, cold outside air is simply pulled in from the outside and supplied to cool the data center. The working of direct air side economizer is similar to that described above. Control of humidity and filtration play a very important role when considering direct air side economizers. Humid air can cause corrosion of electronic equipment leading to failure. Dry air can cause static electricity discharge which can also lead to failure. Sensors can be used to control and regulate the amount of humidity entering a data center. Filtration and fire suppression systems ensure safety against the entry of harmful contaminants and smoke.

Indirect Air Side Economizers – Indirect air side economizers also utilize outside ambient air for cooling purposes. These economizers utilize air to air heat exchangers for transferring heat through a series of coils. The outside air cools the heated air which is circulated to the environment. Since the external air is not pulled in directly into the data center, these economizers maintain much more control over humidity and outside contaminants like dust and smoke. In addition to the filters, the heat exchanger also aids in removal of dust particles.

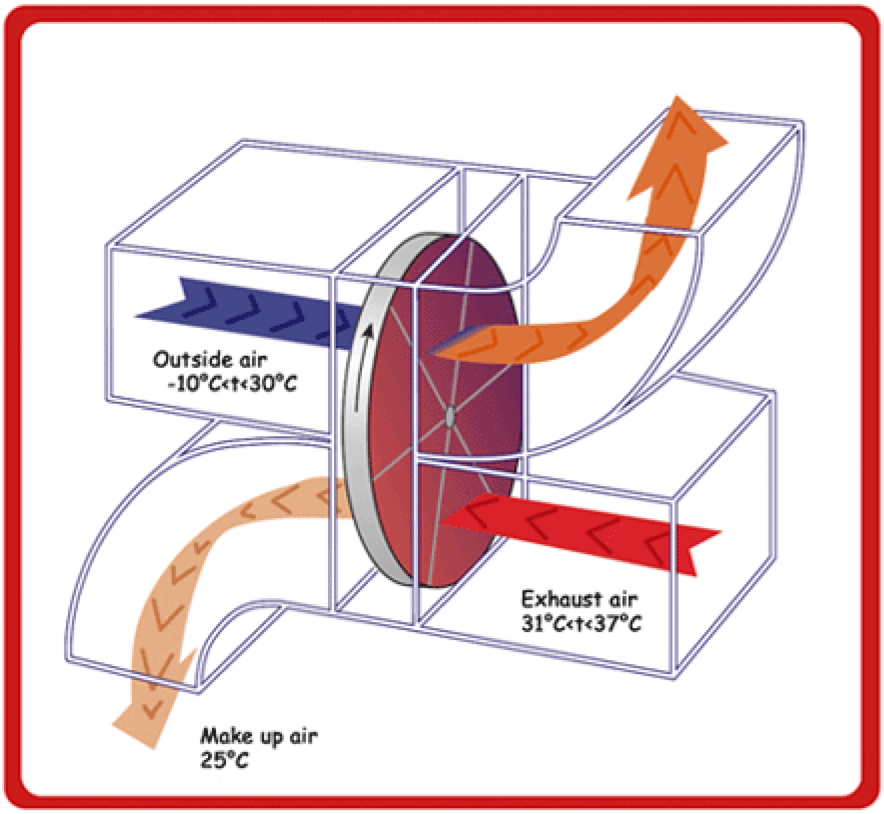

Figure 2.2: Diagram of thermal wheel or rotary heat exchanger [23]

An example of an indirect air side economizer is the Kyoto wheel or thermal wheel which consists of a rotary heat wheel air to air heat exchanger. The rotary heat wheel consists of a honeycomb matrix of heat absorbing material. The Kyoto wheel or the thermal wheel is placed within the supply and exhaust air streams of an air handling system and rotated slowly. As the wheel gradually rotates, heat is transferred from the exhaust air stream to the supply air stream through the matrix material, thereby raising the supply air temperature which is circulated for cooling. The matrix material that is commonly used is aluminum which possesses good heat transfer properties.

2.1.3.2 *Water Side Cooling*

Water side cooling is the most commonly adopted form of cooling. Water is an effective medium for transferring heat compared to air because of its high thermal conductivity, density and specific heat capacity. Water can transport heat over longer distances with a reduced temperature difference. Water side cooling is achieved using chilled water systems, cooling or evaporative towers, and dry coolers. Water side cooling systems are classified into direct water side systems and indirect water side systems. Free cooling can be incorporated using water side economizers.

2.1.3.2.1 *Direct Water Side Systems*

Water side economizers are an example of direct water side systems. These systems eliminate need for cooling via compressors and condensers by physically interconnecting the chilled water and condenser circuits. During favorable environmental conditions (free cooling operation), the heated water or warm return water is redirected to the economizer where the heat is rejected outside by a cooling tower or dry cooler. The return water is filtered, treated and cooled back to the desired temperature and returned to the chilled water supply. The advantage of direct water side systems is that they can significantly reduce energy usage. Direct water side systems require high maintenance in order to prevent dirty return water circulating back to the chilled water interconnects which could cause fouling of chilled water circuits leading to corrosion and blockage [24].

2.1.3.2.2 *Indirect Water Side Systems*

Indirect water side systems eliminate the problem of fouling and corrosion by rejecting heat to the cooling towers indirectly through a plate heat exchanger and by maintaining a closed loop circuit instead of interconnecting the chilled water circuit [24]. However, the use of a plate heat exchanger significantly reduces the capacity of free cooling that can be achieved using direct heat exchangers.

2.1.4 Miscellaneous Free Cooling Systems

Evaporative cooling and ground water cooling or sea water cooling are examples of miscellaneous cooling systems.

Evaporative Cooling or Swamp Cooling – The principle of operation of evaporative cooling differs from typical air conditioning systems. Air conditioning systems work based on vapor compression or vapor absorption cycles whereas evaporative coolers take advantage of water's large enthalpy of vaporization. An evaporative cooler cools air through evaporation of water by absorbing the latent heat during the evaporation process. Evaporative coolers draw fresh outside air through a large fan mounted with moist pads. As the warm air passes through the moist pads, it absorbs the water through the process of evaporation and the fan blows the cool air outside. Evaporative cooling is a very simple free cooling technique which is widely used in data centers.

Ground Water Cooling and Sea Water Cooling – Free cooling using ground water and sea water are being considered by a number of data center industries. This form of cooling is an innovative approach to completely avoid any mechanical components such as compressors and expensive refrigerants. But, cooling using ground water or sea water is based on several factors such as location, surplus availability of these natural resources, existing infrastructure and environmental conditions.

Google Inc. has come up with an innovative approach to use sea water cooling for its Hamina data center in Finland where raw sea water is pumped into a sea water tunnel built for an existing paper mill. The sea water is cleaned and filtered through a sequence of operations and sent to a water to water heat exchanger where it cools a separate water loop in order to cool the data center. The warmer sea water is sent back to a tempering building where it is mixed with fresh incoming sea water so that when it is returned back to the gulf, the temperature is approximately similar to that of the inlet temperature. In doing so, Google aims to minimize any environmental impact [25].

2.1.5 Conclusion

Each of the above mentioned free cooling techniques require certain environmental/ambient conditions to operate in. If such conditions are available for each of these free cooling technologies to operate, then they can reduce energy consumption taken up by mechanical systems such as compressors. Chilled water systems can be used much more efficiently leading to profitable savings.

2.2 Introduction to Side Breathing Switches

2.2.1 Cisco Nexus 7000 Series Side Breathing Switches

Data centers are becoming one of the single largest industrial energy users consuming 61 billion KW of power in the US alone which is almost 1.5 percent of all US electricity consumption [26]. Nearly 40 to 60 percent of this energy is being utilized by cooling systems for data center IT equipment.

Cooling is one of the key issues which are being addressed globally for data center cabinets. Cabinets are an important part of the data centers air flow management design and they have a major impact on the thermal performance. Air and liquid cooling are some of the common methods which have been incorporated for data center cooling. Liquid cooling is very efficient, however, requires an enormous volume of water to cool high density servers. According to a US geological survey, 39 percent of the water is consumed for power production alone in the United States. Also, liquid cooling is relatively expensive compared to free cooling With growing demands of power in the IT industry, several efforts are being adopted for improving the “Power Usage Effectiveness” (PUE) such as the implementation of free cooling techniques in the cabinet level. This can be achieved using Side Breathing Switches that have been developed for efficient energy savings and have widely grown into popularity. These switches are a modular switching system designed to deliver high Ethernet speeds and unified fabric, thereby reducing total cost of ownership. The Cisco Nexus 7000 series switches have been designed to meet the requirements of the most mission critical data centers. They offer the highest level of virtualization and flexibility and also help in reducing the power consumption. These switches utilize a structured cabling system to limit the blockage of air flow.

Figure 2.3: Cisco Nexus 7000 Series Switches [27]

These switches are powerful network switches which are widely used in data centers. They are classified depending on the air flow pattern such as Cisco Nexus 10 slot chassis which employs front to back air flow and Cisco Nexus 9 slot and 18 slot chassis which has side to side air flow. The 10 slot chassis offers a great solution for hot and cold containment due to the front to back air flow pattern. These switches have an improved design and offer better cooling, power, airflow and cable management solutions. The fabric modules, power supplies and fan trays are redundant and are located at the rear side of the chassis and can be easily removed and replaced without obstructing the cable management. Therefore, maintenance of these switches is easier which reduces the operational cost.

2.2.2 Cisco Nexus 7018 Series Side Breathing Switches

Figure 2.4: Cisco Nexus 7000 Series 18 Slot Chassis Switch [28]

The Cisco Nexus 7018 switches have an 18 slot chassis and are incorporated with a side to side air flow pattern. The chassis has two supervisor module slots and16 input/output module slots at the front. These switches have dual side integrated cable management and a protective front door panel for access and maintenance of the supervisor modules and the I/O modules. Five fabric module slots, two fan trays each housing twelve fans and four power supply slots are located at the back side of the 7000 series 18 slot chassis. The dimensions of the chassis are 43.5 x 17.3 x 33.1 inches (height x width x depth) and the chassis weight alone is 187 pounds. Environmental specifications include operating conditions between 32 to 104 degrees Fahrenheit (0 to 40 degrees Celsius) and relative humidity between 5 to 90 percent.

The maximum allowable heat dissipation is 18,000 watts per chassis. The Cisco 7000 series 18 slot chassis is mountable in a standard 19 inch rack and the chassis depth including the cable management and chassis doors is 38 inches [27].

2.2.3 Cisco Nexus 7010 Series Side Breathing Switches

Figure 2.5: Cisco Nexus 7000 Series 10 Slot Chassis Switch [28]

The Cisco Nexus 7010 series switches have a 10 slot chassis with a front to rear air flow pattern. The Cisco Nexus 7000 series 10 slot chassis has two dedicated supervisor module slots, eight input/output module slots, an integrated cable management door and an air filter at the front of the chassis. The rear side of the Nexus 7000 series 10 slot chassis contains five redundant fabric module slots, three redundant power supply slots, two system fan trays and two fan trays for the fabric modules. The dimensions of the 7000 series 10 slot chassis are 36.5

x 17.3 x 33.1 inches (height x width x depth). The weight of the Chassis only is 200 pounds. The chassis depth including the cable management and the chassis door is 38 inches and the chassis can be mounted in a standard 19 inch rack. Similar to the Cisco Nexus 7000 series 18 slot chassis, the Cisco Nexus 7010 series switches also have operating conditions between 32 to 104 degrees Fahrenheit (0 to 40 degrees Celsius) and relative humidity between 5 to 90 percent. The air flow direction is from the bottom front of the chassis to the top back. The maximum heat dissipation of the chassis is around 12,000 watts.

2.3 Supervisor Modules

The supervisor modules control the redundancy capabilities, power and environmental management, status monitoring and several other applications in the Cisco Nexus 7000 series switches. The Cisco Nexus 7000 series switches includes two dedicated supervisor modules which are completely redundant. The supervisor module has a high performance dedicated dual core Intel Xeon processor. One of the supervisor module runs as the active device while the other supervisor module is kept on standby mode or hot swapping mode. The dimensions of the supervisor module are 1.2 x 15.3 x 21.9 inches (height x width x depth). Operating temperature is between 32 to 104 degrees Fahrenheit (0 to 40 degrees Celsius), relative humidity is between 5 to 90 percent, storage temperature is between -40 to 158 degrees Fahrenheit and storage relative humidity is between 5 to 95 percent. [29]

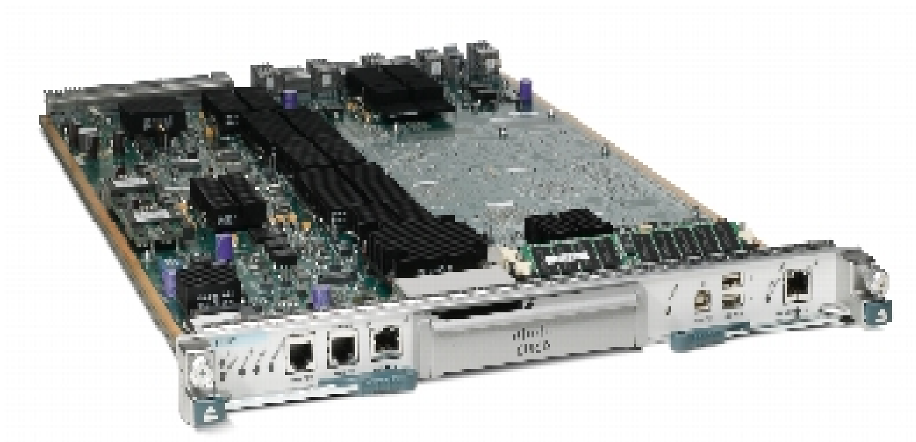

Figure 2.6: Cisco Nexus 7000 Series Supervisor Module [29]

2.4 Fabric Modules

The Cisco Nexus 7000 series fabric modules [30] located within the chassis are separate fabric modules which provide parallel fabric channels to each input/output slot and also the supervisor module slots. The 10 slot chassis and the 18 slot chassis have five redundant fabric modules which deliver speeds of around 230 gigabits per second per slot. The performance of each individual fabric module is around 46 gigabits per second. The dimensions of each fabric module in a 10 slot chassis are 1.733 x 14.93 x 7.33 inches (height x width x depth) and weighs around 4 pounds. The dimensions of each fabric module in an 18 slot chassis are 14.93 x 1.733 x 7.33 inches (height x width x depth) and weighs around 7.5 pounds. Operating temperature for the 10 slot and 18 slot chassis is 32 to 104 degrees Fahrenheit (0 to 40 degrees Celsius) and the relative humidity is 5 to 90 percent. The storage temperature and storage relative humidity is same as that of the supervisor module.

Figure 2.7: Cisco Nexus 7000 Series 18 Slot Fabric Module [30]

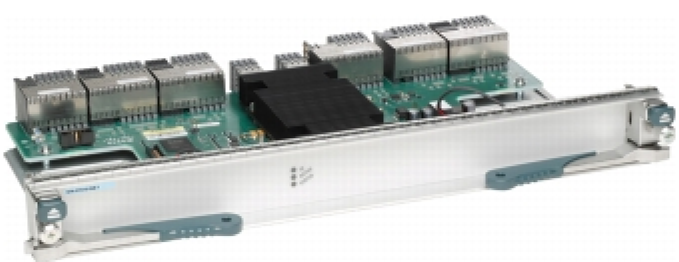

Figure 2.8: Cisco Nexus 7000 Series 10 Slot Fabric Module [30]

2.5 Fan Trays

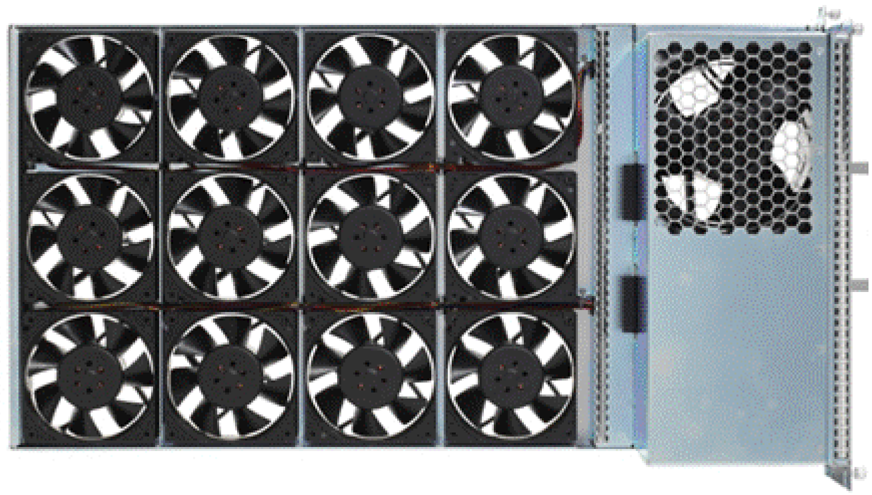

Figure 2.9: Cisco Nexus 7000 Series 18 Slot Fan Tray [31]

The Cisco Nexus 7000 series 10 slot and 18 slot chassis have variable speed fans which vary based upon the chassis temperature. The Cisco Nexus 7000 series 18 slot chassis has two system fan trays which are used for cooling the input/output modules, supervisor modules and the fabric modules. The fan tray is shown in Figure 2.9. Each fan tray has 12 variable speed fans which are based on the chassis temperature. The Cisco Nexus 7000 series 10 slot chassis has two system fan trays which is shown in Figure 2.10. Each fan tray has six variable speed fans which are hot swappable. The two fan trays are used for cooling the fabric modules. The fan trays are arranged horizontally above the fabric modules. The air flow path within the chassis using the fan trays is bottom to top. Another set of fans are used for cooling the input/output modules and the supervisor modules which is shown in Figure 2.11. These are exhaust, fixed flow fans and the air flow pattern within the chassis is front to back.

Figure 2.10: Cisco Nexus 7000 Series 10 Slot Fan Tray for Fabric Modules [31]

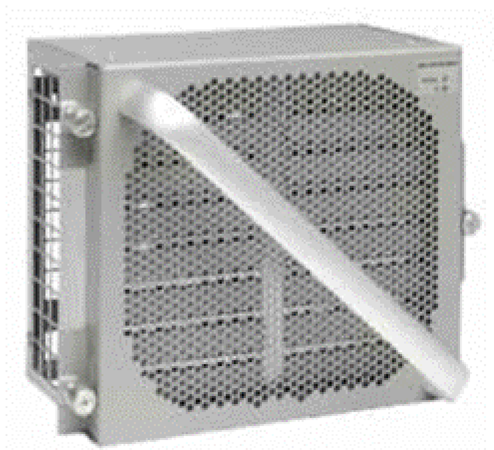

Figure 2.11: Cisco Nexus 7000 Series 10 Slot Fan for I/0 and Supervisor Modules [31]

2.6 Power Supply

Figure 2.12: Cisco Nexus 7000 Series Power Supply Module [32]

The Cisco Nexus 7000 series switches have two power supply modules based on the power supply capacity. The two types of power modules are the Cisco Nexus 7000 series 6.0 KW AC power supply module and the 7.5 KW AC power supply module. The 6.0 KW AC power supply module is shown in figure 2.12. The dimensions of the power supply module are 8.51 x 4 x 17.5 inches (height x width x depth). The 6.0 KW AC power supply weighs 18 pounds and the 7.5 KW AC power supply weighs 23 pounds. The operating temperature is between 32 to 104 degrees Fahrenheit (0 to 40 degrees Celsius) and operating relative humidity is between 10 to 90 percent. Storage temperature is between -40 to 185 degrees Fahrenheit (-40 to 85 degrees Celsius) and storage relative humidity is 10 to 95 percent. The Cisco Nexus 7018 switch contains four power supply slots and the Cisco 7010 switch contains three power supply slots. These are redundant power supplies which are completely hot swappable. The power supply modules are located at the back of the chassis and hence they do not obstruct the cable management at the front and are easy to maintain. The power modules have been designed to meet energy efficiency requirements and save power and reduce costs. The power supply modules have built in temperature sensors and controllers which monitor the internal temperature and shut down the power supply if threshold temperatures are exceeded and avoid any damage to the power supply unit.

CHAPTER 3

CFD (COMPUTATIONAL FLUID DYNAMICS) ANALYSIS

3.1 Introduction to CFD Analysis

CFD (Computational fluid dynamics) is the branch which deals with the numerical simulation and analysis of fluid flow, heat transfer characteristics and pressure characteristics. Computational fluid dynamics is applied in order to simulate and analyze the effect of fluids in various systems using numerical methods. The advantage of using these numerical methods is that the problem can be discretized based on a set of numerical parameters and solved. The simulation tools offer a repository of features that can be used such as grid generation, mesh sensitivity analysis and several other features. A numerical prediction is used for the generation of a mathematical model which represents the physical domain of interest to be solved and analyzed. In this particular case, the study involves the system level equipment such as the containers, the electronics and other equipment like the side breathing switches, battery components, UPS systems, etc. that are housed in them and the surrounding conditions like the ambient temperature, wind conditions, solar loading and dust and other contaminants.

The objective of CFD is to provide the engineer with a computer-based predictive tool that enables the analysis of the air-flow processes occurring within and around the electronic equipment [33]. CFD analysis is very important for various applications such as data center industries, systems with high heat loads, telecommunication industry, and several more.

3.2 Governing Equations

The numerical solution for heat transfer and fluid flow based problems is obtained by solving a series of three differential equations. These three differential equations are the conservation of mass, conservation of momentum and conservation of energy. They are very commonly known as the governing differential equations [34].

For a generalized case, the conservation of mass is given by:

$$\frac{\partial \boldsymbol{\rho}}{\partial \boldsymbol{x}} + \boldsymbol{\nabla}.(\boldsymbol{\rho u}) = \boldsymbol{0}$$

The conservation of momentum for a generalized case is given by:

$$\frac{\partial}{\partial \boldsymbol{t}}(\boldsymbol{\rho u}) + \boldsymbol{\nabla}.(\boldsymbol{\rho uu}) = \boldsymbol{\nabla}.(\boldsymbol{\mu gradu}) - \frac{\partial \boldsymbol{p}}{\partial \boldsymbol{x}} + \boldsymbol{B_x} + \boldsymbol{V_X}$$

The conservation of energy for a steady low velocity flow is given by:

$$\boldsymbol{\nabla}.(\boldsymbol{\rho uh}) = \boldsymbol{\nabla}.(\boldsymbol{kgradT}) + \boldsymbol{S_h}$$

3.3 Global Computational Domain or Solution Domain

The computational domain or the solution domain is the region or space within which the governing differential equations are solved. The solutions to these equations are obtained by fixing the boundary conditions for the solution domain. The boundary conditions for most computational problems include the external ambient temperature, solar loading, wind conditions, other environmental conditions and. It depends on the type of heat transfer such as conduction or convection and also any radiation factors. In addition, the conditions at the domain wall also need to be specified whether they are open, closed (adiabatic) or symmetrical in nature. The fluid properties namely conductivity, density, expansivity, diffusivity and specific heat need to be specified. [33].The governing equations for many complex problems can be solved by using various numerical techniques such as Finite Element Method where the elements are varied and approximated by a function; Finite Volume Method where the governing equations are integrated around the mesh elements whose volumes are considered for the solution and Finite Difference Method where the differential terms are discretized for each element.

The computational fluid dynamics code considered for the numerical analysis in Flotherm is the finite volume method where the solution domain is discretized into a large number of grid cells or control volume regions. Thus, the governing equations are solved by considering the volume of mesh elements and the variables to be calculated are located at the centroid of the finite volume.

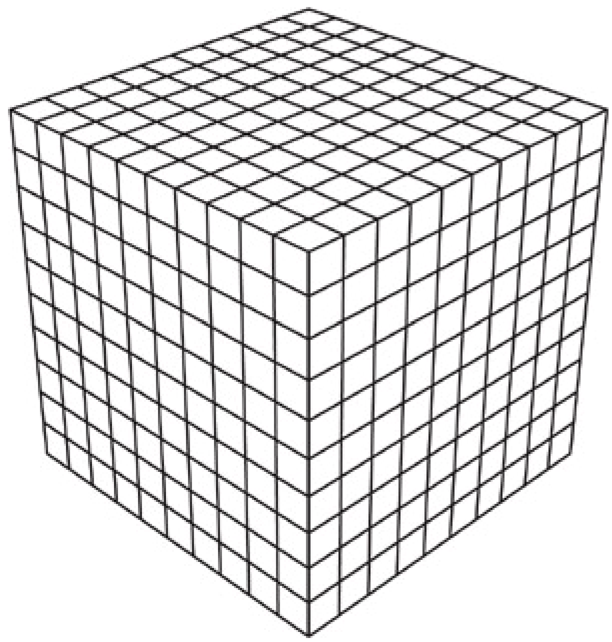

Figure 3.1: Graphical Representation of a 3 Dimensional Grid

The finite volume method for solving the governing equations namely conservation of mass, conservation of momentum and conservation of energy prove to be much more advantageous than the other computational methods. A series of algebraic equations are used for discretizing the results such that each of them relates a variable's value in a cell to its value in the nearest neighboring cell. As an example, the variable for temperature "T" can be calculated using the following algebraic equation:

$$\boldsymbol{T} = \frac{\boldsymbol{C_0 T_0 + C_1 T_1 + C_2 T_2 + C_3 T_3 + C_4 T_4 + \ldots C_n T_n + S}}{\boldsymbol{C_0 + C_1 + C_2 + C_3 + C_4 + C_n}}$$

Where $\boldsymbol{T_0}$ represents the temperature value within the initial cell; $\boldsymbol{T_1}, \boldsymbol{T_2}, \boldsymbol{T_3}, \boldsymbol{T_4}, \ldots \boldsymbol{T_n}$ are the temperature values in the neighboring cells; $\boldsymbol{C_0}, \boldsymbol{C_1}, \boldsymbol{C_2}, \boldsymbol{C_3}, \boldsymbol{C_4}, \boldsymbol{C_n}$ represent the coefficients that connect each cell value to each of its neighboring cell values; and S denotes the source term. These algebraic equations are solved for the field variables T, u, v, w and density ρ. This implies that if n cells are present in the domain, then a total of 5n equations are solved.

3.4 Turbulence Modeling

Turbulent flow is defined as a flow regime characterized by velocity fluctuations in all directions and infinite number of degrees of freedom. The flow is described as three dimensional with rapid changes in velocity and pressure. Flows at larger Reynolds number (more than a few thousand) are generally considered turbulent while those with a lower Reynolds number are considered laminar. Flotherm uses two common methods to model this low Reynolds number turbulent flow regimes namely LVEL turbulence model and K-Epsilon turbulence model.

3.4.1 LVEL Turbulence Model

LVEL turbulence model is a simple algebraic turbulence model which does not require the solution of any partial differential equations. The model requires calculation of the nearest wall distance (L), the local velocity (VEL) and the laminar viscosity to determine the effective viscosity [35]. In LVEL turbulence model, poisson's equation is solved initially to calculate the maximum local length scale and local distance to the nearest wall.

$$\boldsymbol{D} = \sqrt{|\ \boldsymbol{\nabla}\emptyset\ |^2 + \boldsymbol{2}\emptyset}$$

$$\boldsymbol{L} = \boldsymbol{D} - |\ \boldsymbol{\nabla}\emptyset\ |$$

Where: $|\ \boldsymbol{\nabla}\emptyset\ |^2 = -\boldsymbol{1}$ and $\emptyset = \boldsymbol{0}$ at the wall.

$\emptyset$ is the dependent variable.

The length and velocity scales are also computed for each cell in addition to the boundary layer wall functions to determine the turbulent viscosities for each cell [36].

3.4.2 K-Epsilon Turbulence Model

This model solves using two variables; the kinetic energy of turbulence (k) and the dissipation rate of kinetic energy of turbulence (ε) [37]. K-Epsilon turbulence model is also commonly known as two equation model and is widely used for turbulent flow modeling. The two equation model computes viscosity depending on the grid cells rather than calculating the viscosity due to the walls. The K-Epsilon model is applicable for problems with thin shear layers and recirculating flows [37]. Two transport equations namely kinetic energy of turbulence (k) and dissipation rate of kinetic energy of turbulence are solved [37].

The following are the transport equations: [38]

$$\frac{\partial(\rho k)}{\partial t} + \frac{\partial \rho k u_i}{\partial x_i} = \frac{\partial}{\partial x_i}\left[\left(\mu + \frac{\mu_t}{\sigma_k}\right)\frac{\partial k}{\partial x_i}\right] + G_k + G_b - \rho\varepsilon$$

$$\frac{\partial(\rho\varepsilon)}{\partial t} + \frac{\partial \rho\varepsilon u_i}{\partial x_i} = \frac{\partial}{\partial x_i}\left[\left(\mu + \frac{\mu_t}{\sigma_k}\right)\frac{\partial \varepsilon}{\partial x_i}\right] + C_{1S}\frac{\varepsilon}{k}(G_k + C_{3S}G_b) - C_{2S}\rho\frac{\varepsilon^2}{k}$$

3.5 Grid Constraints and Meshing

Grid constraints are used for specifying minimum and maximum number of cells across the geometry. As discussed before, Flotherm uses a Cartesian grid and the value for pressure and temperature is calculated at each cell center [33]. Grid keypoints appear when components are created in Flotherm. These keypoints are object associated. Grid lines may be classified as hard, coarse or fine grids. Localized grid cells can be created which are smaller cells used for meshing around an object. In localized meshing, the gridlines meet the edges of the object and truncate along the edges and disappear. Meshing is an important feature since a mesh sensitivity analysis can determine when a solution reaches grid independence. Grid independence is defined as the point at which the addition of a large number of grid cells no longer significantly affects the solution. Grid independence can significantly reduce computational time.

3.6 Flotherm Smart Parts

3.6.1 Cuboid

The cuboid smart part is the most basic smart part available in Flotherm. It is a solid block used for representing simple objects in space. Material properties and thermal properties including surface and radiational properties can be defined for the cuboid. Cuboids are generally used for compact modeling. This smart part can be collapsed to represent a plate and non-collapsed.

3.6.2 Enclosure

The enclosure smart part is a hollow smart part that can be used to define the outer boundaries of an object. This smart part is a hollow cuboid with six sides that can be used to represent the outer shell of an object. All the other components can be inserted within the enclosure smart part. Each side of the smart part can be assigned different properties such as adiabatic, non-adiabatic or symmetric. Thermal and surface properties can also be assigned. Thickness of the enclosure smart part can be specified or it can be retained as thin. The enclosure smart part is commonly used for modeling telecommunication systems, data centers, racks and servers.

3.6.3 Resistance

The resistance smart part is used to define a region of resistance to flow. It can either be collapsed, non-collapsed or angled. Collapsed resistances or planar resistances are used to define planar objects such as vents or any porous media. The free area ratio and loss coefficient must be defined in order to calculate the pressure drop. Non-collapsed resistances or volumetric flow resistances are used when thickness of an object has to be specified. They are mostly used for modeling filters. Perforated plates can also be used for creating holes.

Filters are devices which are used for trapping air contaminants such as dust particles, pollen etc. They are used for supplying and controlling the amount of clean air entering into a system. Filters are located at the inlet of various HVAC and telecommunication systems. Filters can arranged either in series or parallel configuration. Dirty filters have a higher resistance and increase the total static pressure. Clean and dirty filters can be compared by determining the system impedance curve for both filters and computing the increase in pressure drop across the filters. In doing so, the approximate life of a filter can be estimated. MERV (Minimum efficiency rating value) filters and pre filters are typically used for data centers and HVAC systems.

Hydrophobic filters can be used for controlling the amount of humidity in air when it enters into a system.

3.6.4 Source

The source smart part can be used for representing heat sources or objects that require the power to be defined. The source smart part is used for computing temperature, pressure and velocity over a planar or volumetric region within the solution domain.

3.6.5 Monitor Points

Monitor points can be located within the solution domain for various objects. This includes sources, filters, racks, and regions etc. They are used for monitoring critical regions to record the temperature. For example, monitor points can be used for recording server inlet and exhaust temperatures. These monitor points help prevent any mistakes in modeling.

3.6.6 Region

The region smart part is a post processing object which can be included around any component. It does not have any effect on the calculation results. This smart part is used for recording minimum, maximum and mean values of temperature, pressure and velocity across an object.

3.6.7 Fans and Blowers

Fans are devices which are used for cooling electronic equipment by creating air to flow through the device. Fans create air flow by converting the torque supplied to the propeller shaft to impart kinetic energy to the air flowing across the fan rotor. In doing so, these devices also increase the static pressure across the fan rotor.

The distinguishing characteristics that differentiate fans and blowers are the method used to move the air and the system pressure they must operate against [39]. The most commonly used fans in cooling applications are axial flow fans and centrifugal blowers. Axial flow fans deliver air flow in the direction parallel to the fan blade axis. These fans can deliver very high flow rates. They produce air flows with high volume and low pressure. They are used for cooling IT equipment and several other electronic devices. Axial fans can be classified into propeller fans, tube-axial fans and vane-axial fans [39]. On the other hand, centrifugal blowers deliver air flow in the direction perpendicular to the blower axis. They are used for moving air through large systems. These devices are used for delivering lower flow rates since they are designed for working against high pressure.

The following table indicates the difference between fans and blowers.

Table 3.1: Difference between Fans and Blowers [39]

Equipment	Specific Ratio	Pressure Rise (mm WG)
Fans	Upto 1.11	1136
Blowers	1.11 to 1.20	1136-2066

3.6.7.1 *System Curve Characteristics*

The system characteristics can be represented in the form of a system curve. The system curve is used for measuring the system resistance or system impedance. The system resistance is the sum total of static pressure losses in a system. The system resistance is a function of the free area ratio and the pressure drops across an object. The system curve is generated by plotting static pressure verses the flow rate. The system resistance increases as the flow rate increases. Similarly, system resistance decreases as flow rate decreases.

3.6.7.2 *Fan Curve Characteristics*

The fan curve is used for representing the fan characteristics. The fan curve is a measure of the static pressure verses the volume flow rate for a particular fan under certain conditions. These conditions may include fan speed, fan volume, system static pressure and power required to operate the fan. The system curve and the fan curve can be super imposed to determine the operating point. The operating point is the intersection of the system curve and the fan curve. By determining the operating point, the power required to drive the fan can be calculated. Figure 3.2 shows a simple system curve and fan curve to determine the operating point.

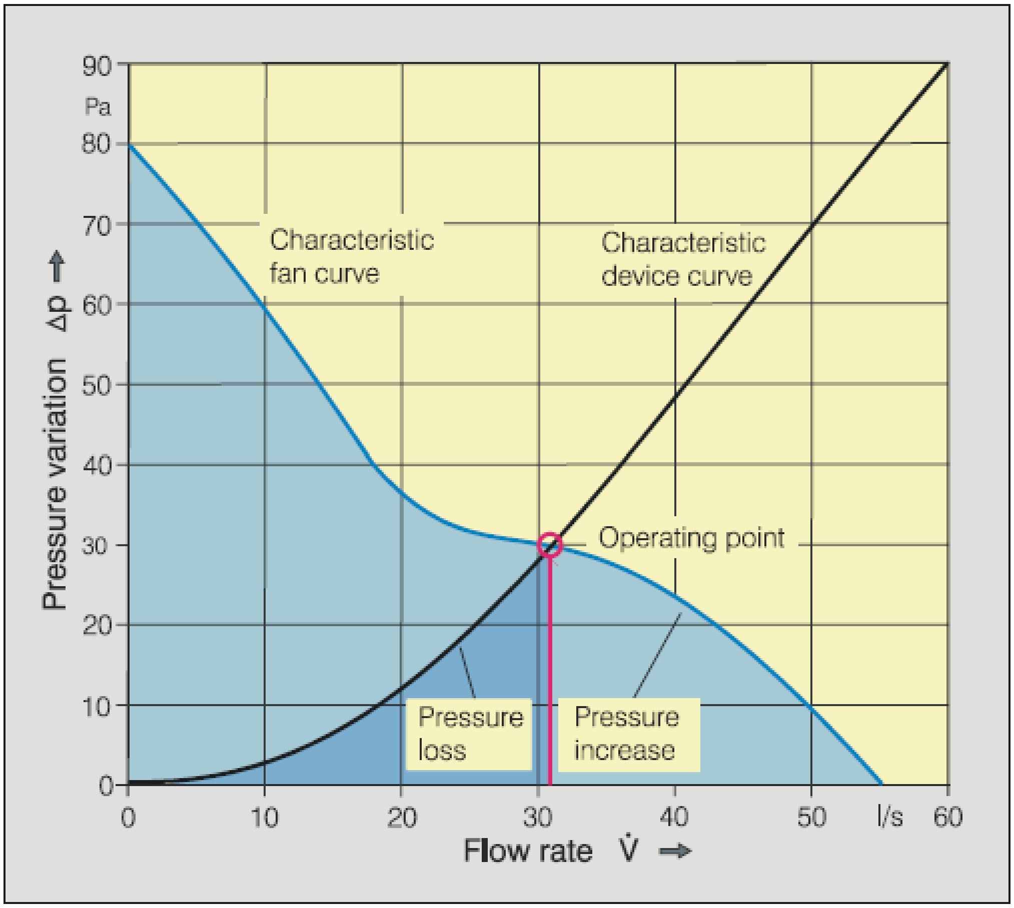

Figure 3.2: System Curve and Fan Curve [40]

3.6.8 Command Center in Flotherm

The command center in Flotherm is used for performing parametric analysis and mesh sensitivity analysis. Any changes to a model can be performed using input variables window located in the command center. A mesh sensitivity analysis can also be performed by varying the number of grid elements and performing a parametric study to obtain solutions to all trials simultaneously. Parametric analysis can be performed for fans with different fan curves, thickness, and fin count for heat sinks. Similarly, results that are of interest can be selected in the output variables window located in the command center. Specific monitor points and regions can be selected to determine minimum, maximum and mean temperature, pressure and velocity immediately.

CHAPTER 4

CFD MODELING AND THERMAL ANALYSIS OF SIDE BREATHING SWITCHES

4.1 Design Guidelines for Modeling Side Breathing Switches

Side breathing switches are the most widely used network switches. These switches help optimize heat transfer and dissipation from the electronic devices, increase efficiency and provide environmental protection for all the components inside them. They also optimize ease of installation due to their improved cable management system. These switches incorporate an efficient cooling system that meets the thermal requirements of the electronic devices. With increasing sensitivity to environmental impacts, the switch chassis and the cooling systems should have minimum aesthetic and acoustic impact on their surroundings.

4.2 Air Flow Pattern for Side Breathing Switches

The major air flow in the switch is the module air flow which is depicted in the figure 4.1 as the bold blue lines. Air enters the right side of the switch (when viewed from the front side of the switch) and is drawn across the modules, exiting on the left side of the switch.

A lower volume of air also enters the right side of the switch in a smaller opening located further rearward on the switch in order to provide cooling of the fabric modules and passes up across the modules and exits near the top of the switch near the left side.

The final airflow pattern enters the power supplies near the bottom front side of the switch and exits the rear lower side of the switch. This is the lowest air flow volume and is probably not as critical in terms of input temperature considered to the other air flow patterns. The port side mentioned in Figure 4.1 indicates the front side of the side breathing switches. Hence the port side of the first switch and that of the second are at opposite directions.

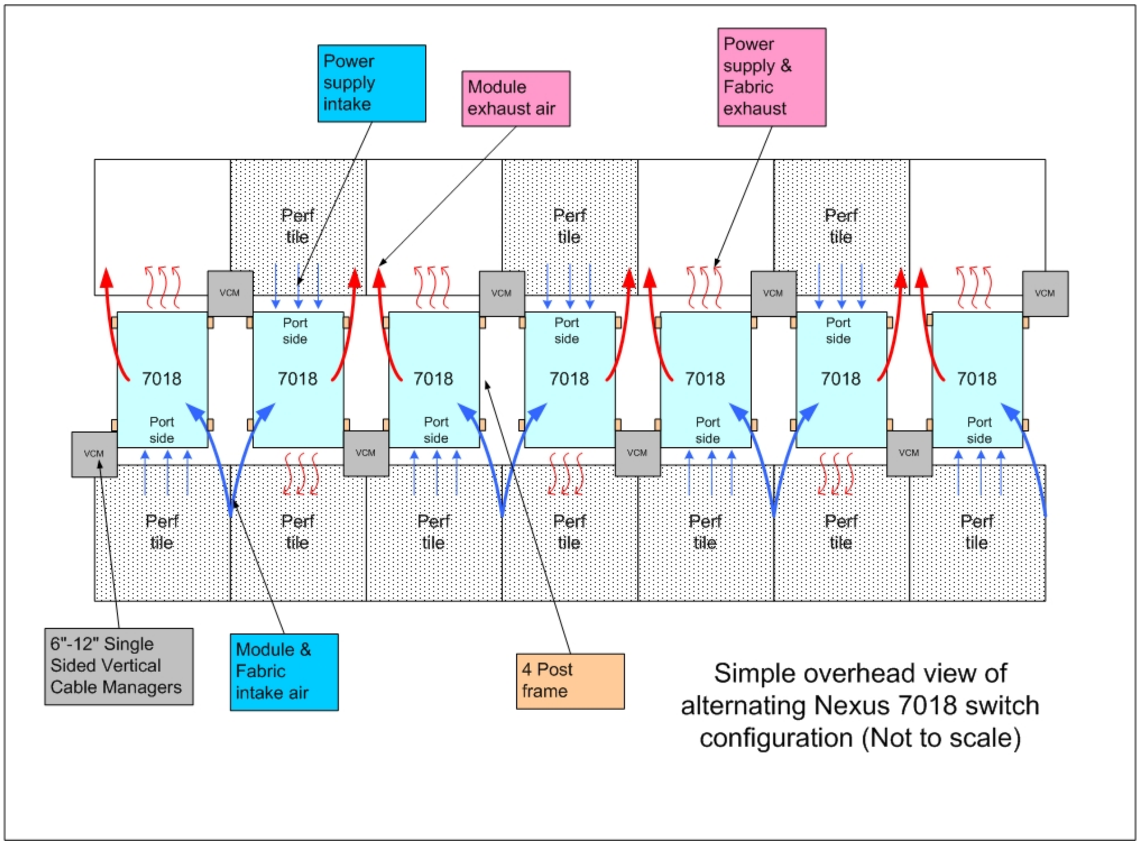

Figure 4.1: Simple Overhead View of Alternating Side Breathing Switches

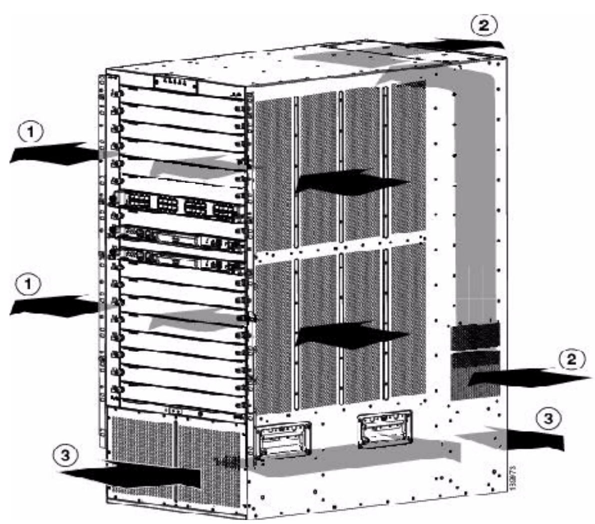

Figure 4.2: Air Flow Pattern for Side Breathing Switches [41]

Figure 4.2 illustrates the air flow patterns for side breathing switches.

Air flow pattern 1 represents the air flow for cooling the supervisor modules and input/output modules.

Air flow pattern 2 represents the air flow for cooling the fabric modules.

Air flow pattern 3 represents the air flow for cooling the power supply units.

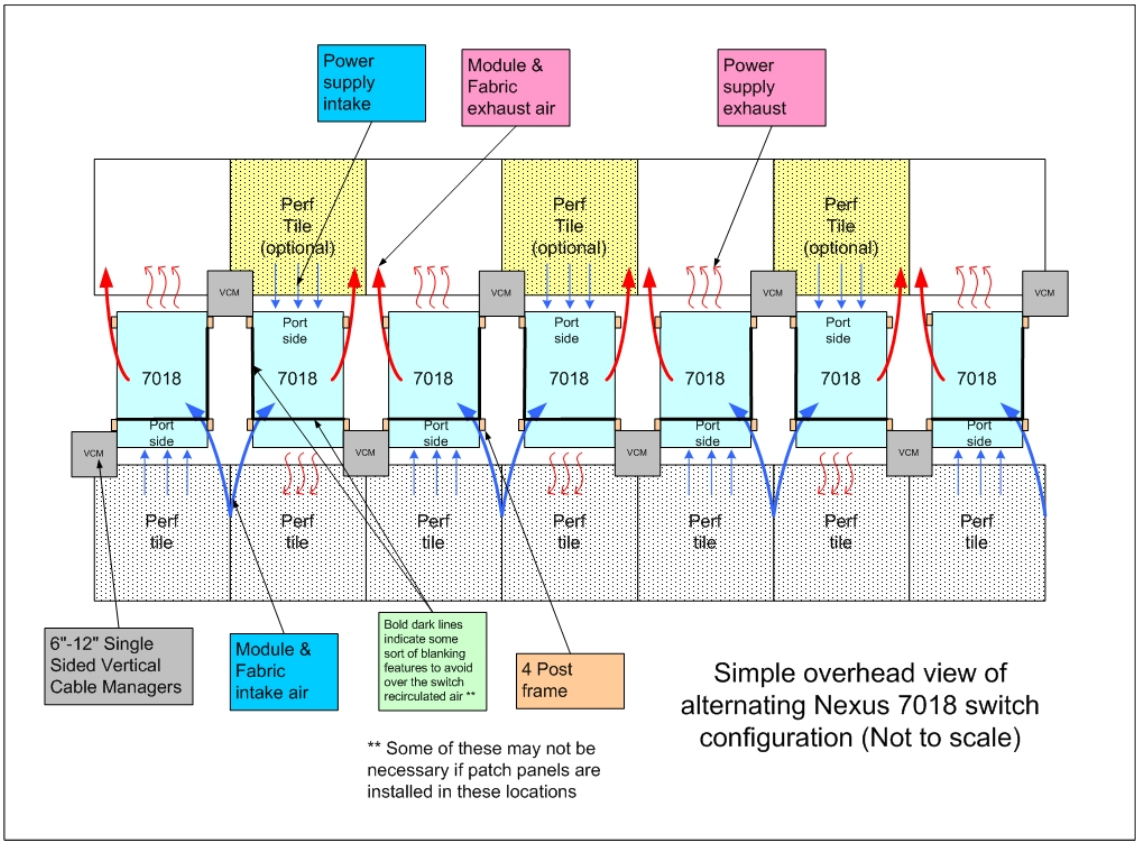

Figure 4.3: Proposed Layout for Side Breathing Switches

Figure 4.3 illustrates the proposed layout for the side breathing switches. The issues proposed are impact of width of 12 inch and 22 inch vertical cable managers between two alternating side breathing switches; effect of even number of side breathing switches with and without top blanking panels; effect of odd number of side breathing switches with and without top blanking panels; and comparison between even and odd number of side breathing switches. The front and side blanking panels are incorporated in all the computational models. Flotherm [27], a CFD code is employed for modeling the side breathing switches and perform optimization of the proposed guidelines.

4.3 Modeling of Side Breathing Switches

Figure 4.4 represents the Flotherm model of two side breathing switches. A computer room air conditioning unit supplies a total flow rate of 3500 CFM through the perforated tiles which are located at the front side of the side breathing switches.

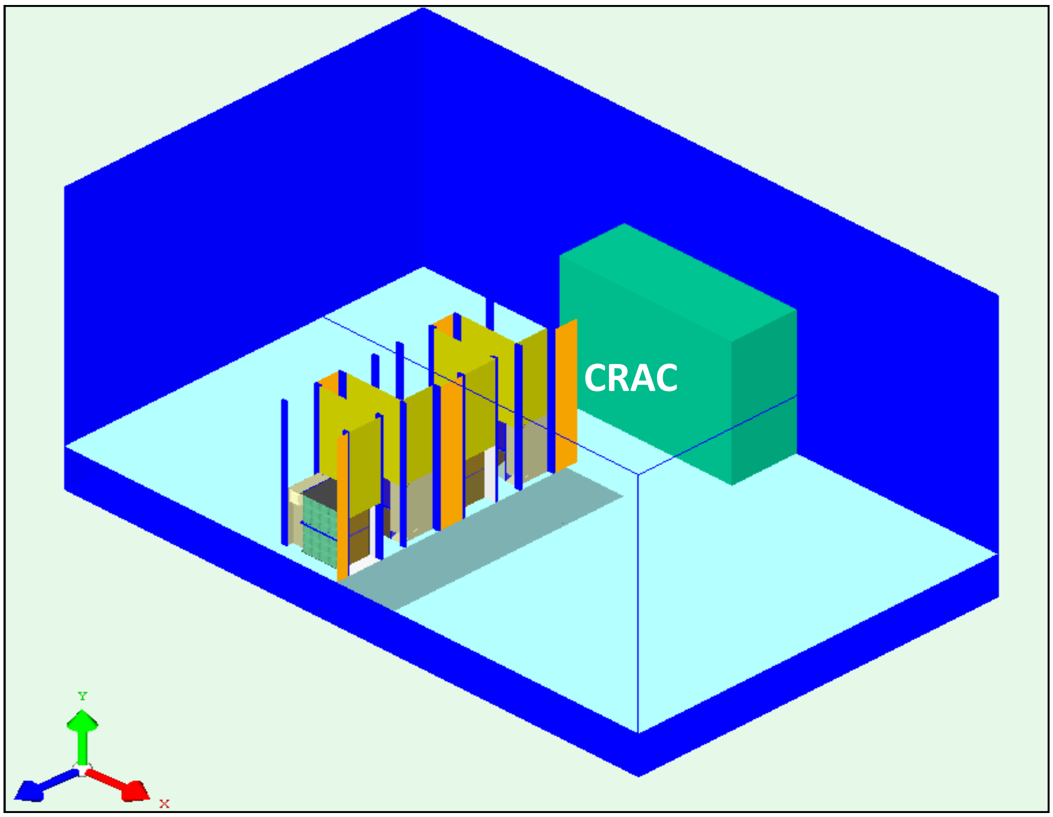

Figure 4.4: Flotherm Model Illustrating the Cooling Assembly

The dimensions of the enclosure are 315 x 165 x 197 inches (length x height x width) and that of the computer room air conditioning unit are 94.5 x 78.5 x 31.5 inches. The plenum floor is 315 x 40 x 197 inches in size. The short aisle located at the front is modeled as a resistance having dimensions as 31.5 x 40 x 31.5 inches. Figure 4.5 shows a closer view of the side breathing switches and other components associated with it. The side breathing switch is housed within a standard four post rack whose dimensions are 3 x 78.75 x 1.27 inches (width x height x thickness). The dimensions of the side blanking panel are 33.6 x 47.25 inches (width x height).The blanking panels at the front are 47.25 x 17 inches (height x width). The vertical cable managers or VCM's provide efficient cable management and their dimensions are 78.75 x 12 inches (height x width).

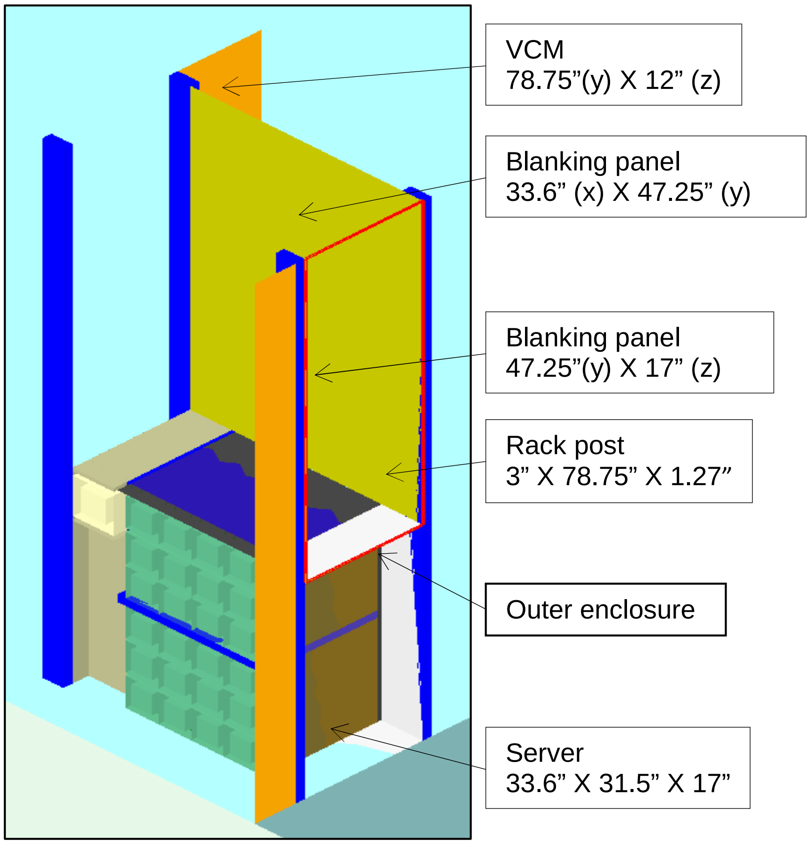

Figure 4.5: Vertical Cable Managers, Blanking Panels and Switch Model

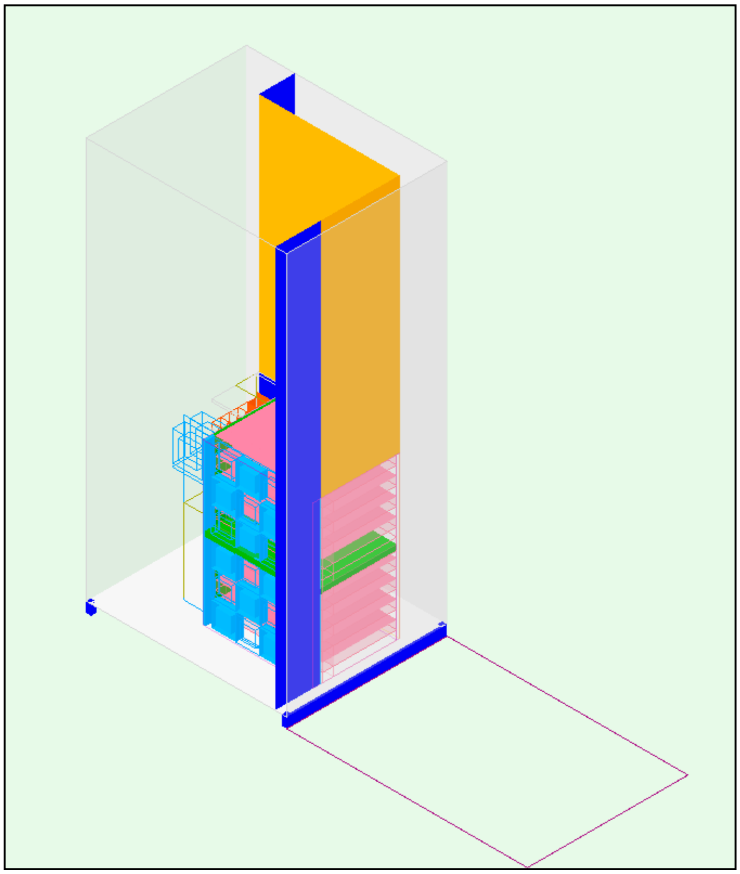

Figure 4.6: Internal Components of the Side Breathing Switch

Figure 4.7 represents the front side of the switch chassis. The chassis consists of a separator which divides the chassis into two portions namely the upper portion and the lower portion. The input/output modules and the supervisor modules are modeled as heat sources. The dimensions of the source are 24 x 15 x 21 inches. Each source has a heat load of 3300 watts and they are positioned on the upper and lower portions of the chassis respectively. The chassis comprises of two fan trays, each for the upper and lower portion which are modeled as a cuboid block. The dimensions of the fan trays are 152 x 21 x 150 inches. Each fan tray comprises of 12 variable speed external fans. The fans are modeled using a smart part available in Flotherm. Each fan has a hub diameter of 23.6 inches, outer diameter of 47.25

inches. The fan depth is 15 inches. The variable speed fans have a normal air flow pattern and an open volume flow rate of 240 CFM. These fans are employed for cooling the two heat sources which constitute the I/O modules and the supervisor modules. The inlet is located at the opposite side of the fan trays within the chassis from where the air enters.

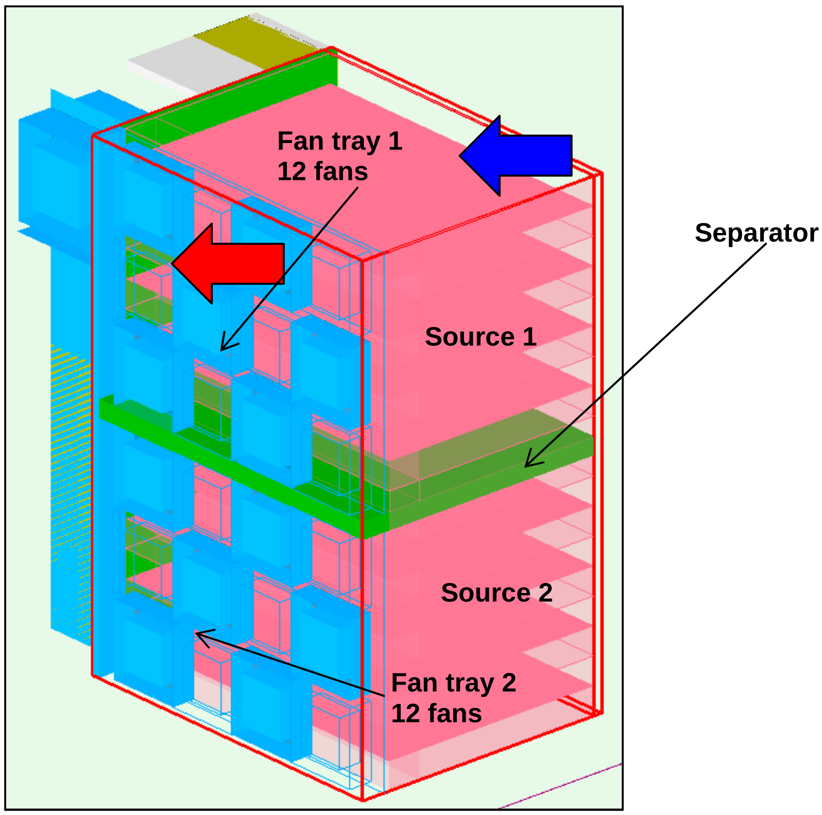

Figure 4.7: Front View of the Switch Chassis

Figure 4.8 shows the rear side of the switch chassis. The rear side of the chassis houses five fabric modules known as the spine card assembly. Each fabric module has a heat load of 150 watts. A compact heat sink is mounted on each fabric module. Also, two variable speed fans are located behind the side breathing switches. These fans are used for cooling the fabric modules. The fans have a hub diameter of 27.55 inches, an outer diameter of 59.05

inches and a fan depth of 23.62 inches. These variable speed fans have an open area flow rate of 500 CFM.

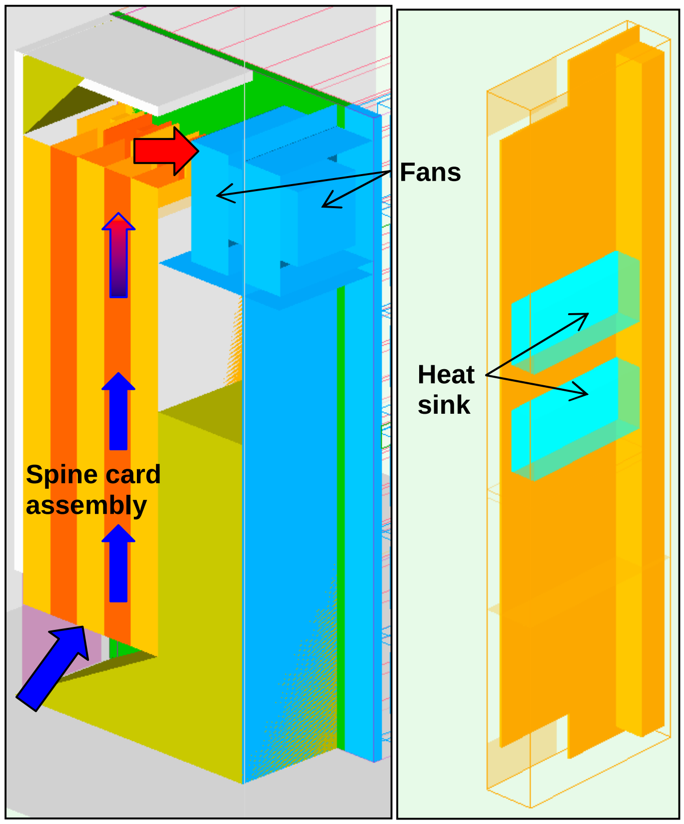

Figure 4.8: Rear View of the Switch Chassis

4.4 Results

4.4.1 Thermal Analysis of Different Configurations

The results for the different issues proposed are discussed in this section. The issues proposed are impact of width of 12 inch and 22 inch vertical cable managers between two alternating side breathing switches; effect of even number of side breathing switches with and without top blanking panels; effect of odd number of side breathing switches with and without top blanking panels; and comparison between even and odd number of side breathing switches.

Front and side blanking panels are incorporated in all the computational models. All the simulations are set to an ambient temperature of 20℃.

4.4.1.1 *Effect of Width of VCM's In Between Two Switches*

In order to determine the effect of width of vertical cable managers, two side breathing switches are considered, thus creating a cold aisle between them. As the air passes through the cold aisle, it moves sideways to cool the I/O modules, supervisor modules and fabric modules and exits from the rear side. The comparison is made by changing the width of vertical cable managers from 12 inches to 22 inches.

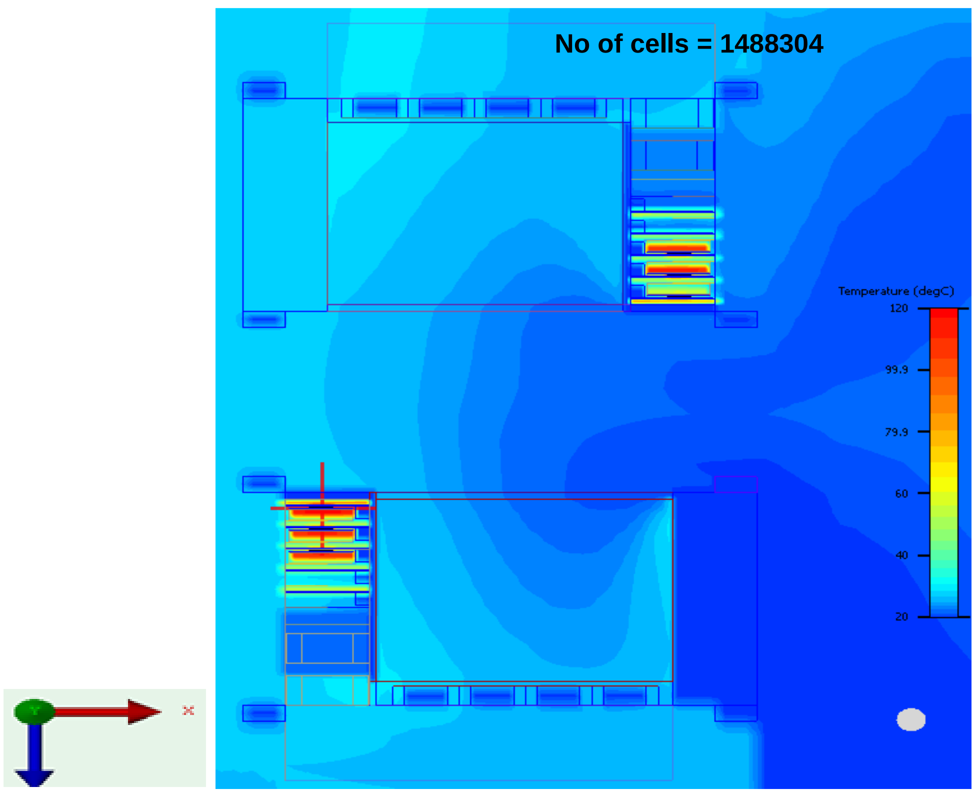

Figure 4.9: 12 inch Vertical Cable Manager

From figure 4.9 and 4.10 it can be observed that the maximum temperature using the 12 inch vertical cable manager is 120℃ while that of the 22 inch vertical cable manager is

122℃. Although the temperature is very negligible, the incorporation of the 12 inch vertical cable manager would be more feasible compared to the 22 inch vertical cable manager as it would save considerable floor area.

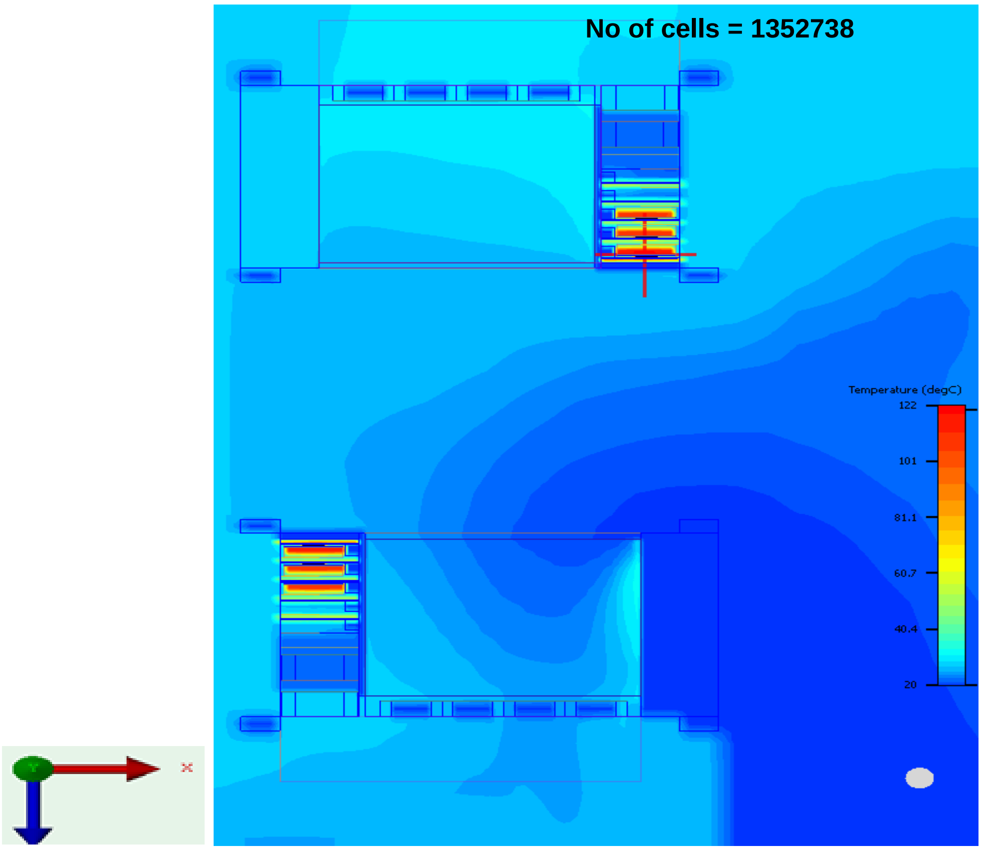

Figure 4.10: 22 Inch Vertical Cable Manager

4.4.1.2 *Mesh Sensitivity Analysis for Width of VCM'S In Between Two Switches*

A mesh sensitivity analysis is performed in order to verify that the solution obtained is independent of the mesh size and mesh count. For the vertical cable managers the number of elements is varied between 1.48 million cells to 4.27 million cells. Table 4.1 illustrates the comparison of mesh count approximately between 1.4 million, 2.2 million, 3.3 million and 4.7 million cells for 12 inch and 22 inch vertical cable managers. It is observed that as the mesh count is increased, the temperature decreases for the 12 inch vertical cable manager and the 22 inch vertical cable manager.

Table 4.1: Mesh Sensitivity Analysis for VCM's

12" vertical cable manager			22" vertical cable manager		
Trials	Mesh count	Temp (℃)	Trials	Mesh count	Temp (℃)
1	1488304	120	1	1352738	122
2	2283266	115	2	2143840	118
3	3359251	107	3	3362233	109
4	4278964	107	4	4226943	109

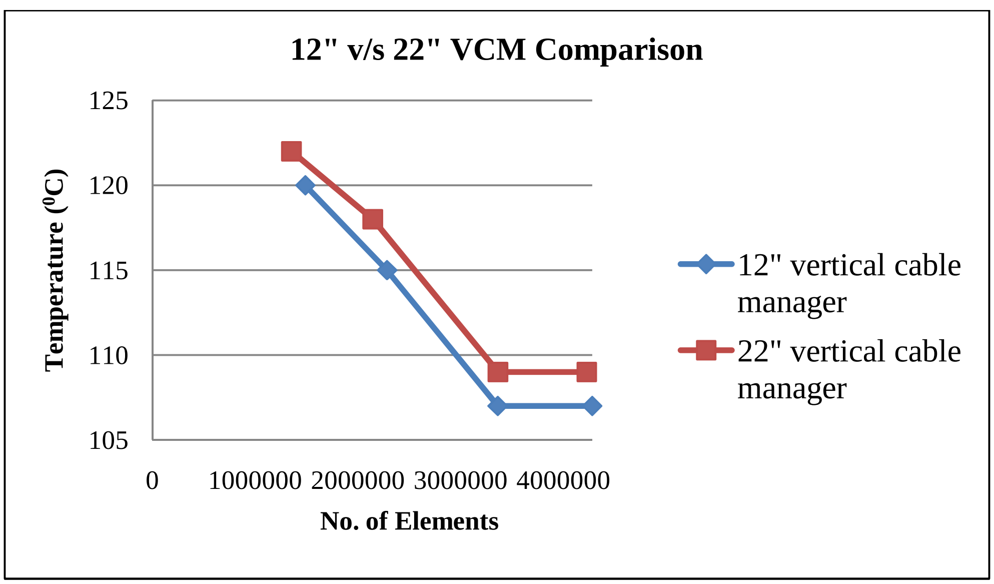

Figure 4.11: 12" v/s 22" VCM Mesh Sensitivity Analysis

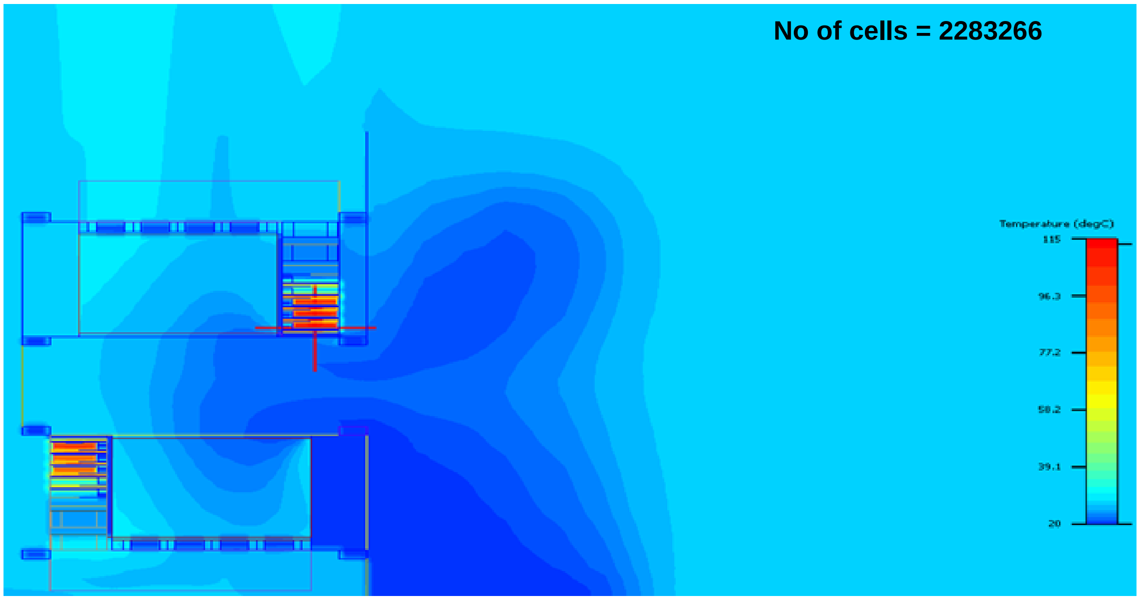

Figure 4.12: 12 Inch Vertical Cable Manager (2.28 Million Cells)

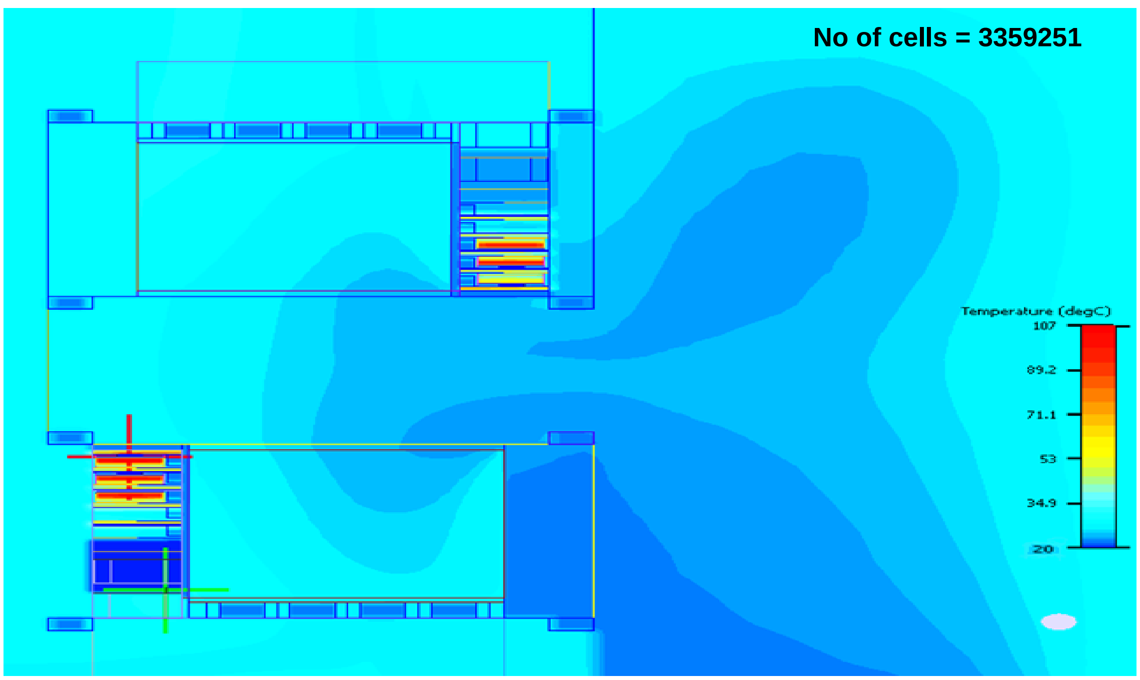

Figure 4.13: 12 Inch Vertical Cable Manager (3.35 Million Cells)

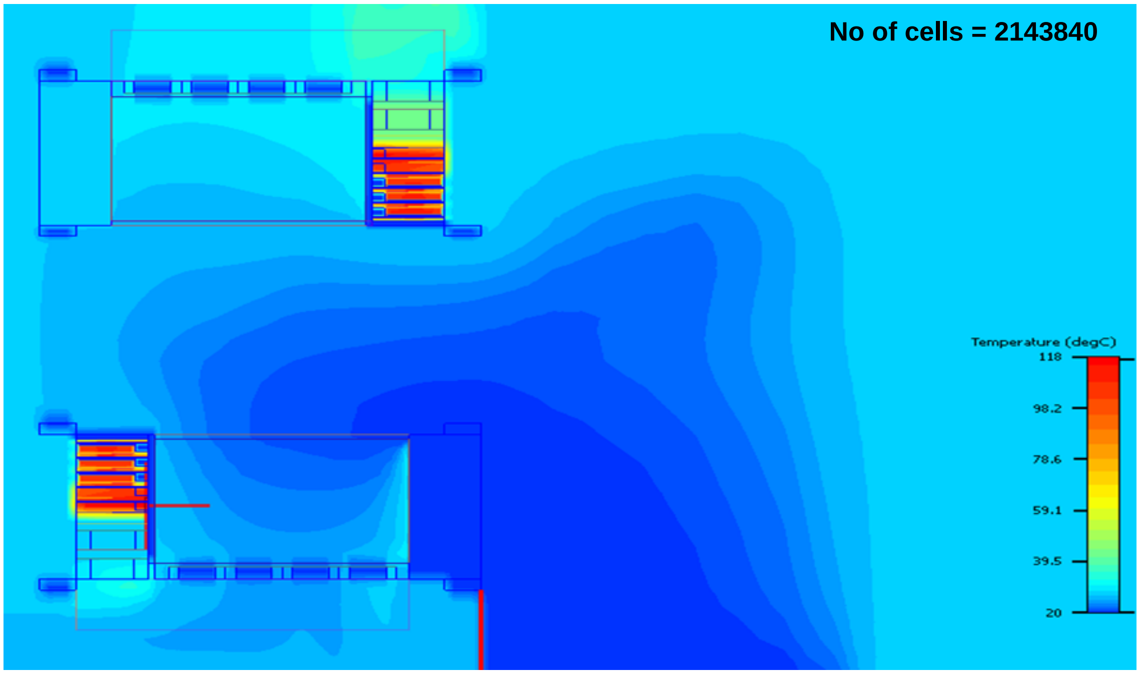

Figure 4.14: 22 Inch Vertical Cable Manager (2.14 Million Cells)

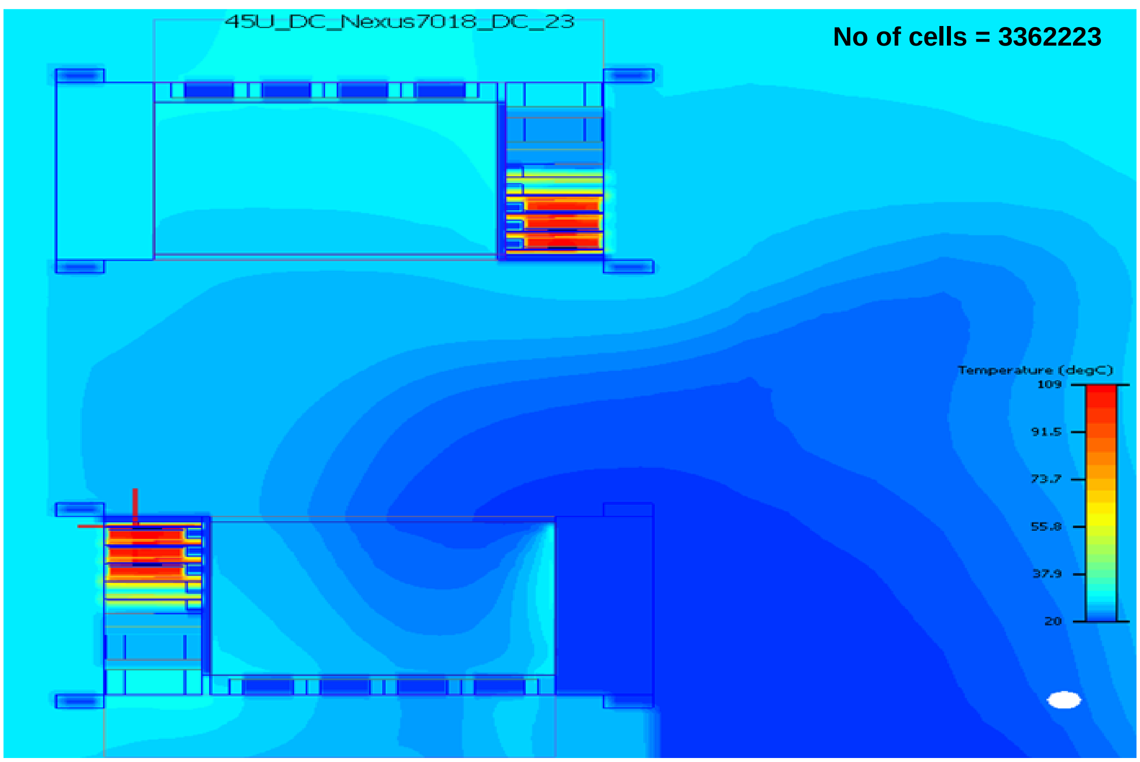

Figure 4.15: 22 Inch Vertical Cable Manager (3.36 Million Cells)

4.4.1.3 *Effect of Even Switches with and without Top Blanking Panel*

The results for even number of side breathing switches are displayed below. Four side breathing switches are considered. The total power using four side breathing switches is 28,200 watts. The port side of the first and third switch faces the short aisle while the port side of the second and fourth switch faces the opposite side. The distinguishing factor is the thermal effect of the top blanking panel. Analysis is performed to compare the effect of even side breathing switches with and without the top blanking panel. The top blanking panel is added above the cold aisle and the hot aisle to prevent air flow bypass and provide direct circulation of cold air into the side breathing switches. The results from Figure 4.16 and 4.17 indicate that the addition of a top blanking panel significantly reduces the temperature.

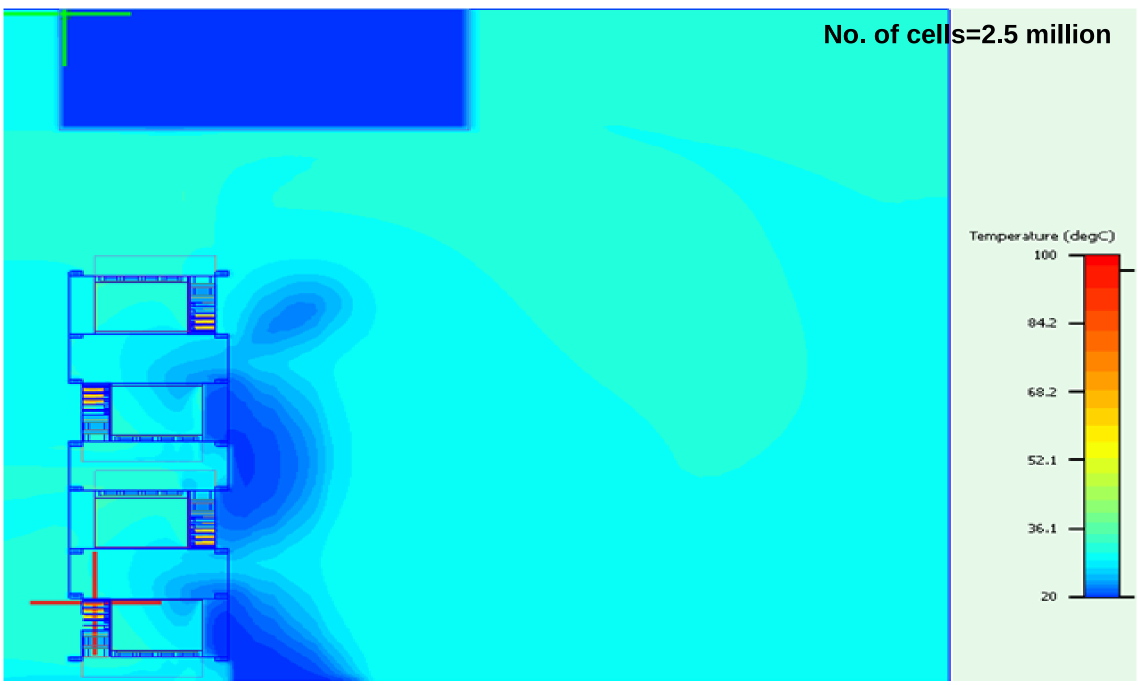

Figure 4.16: Four Switches with Top Blanking Panel

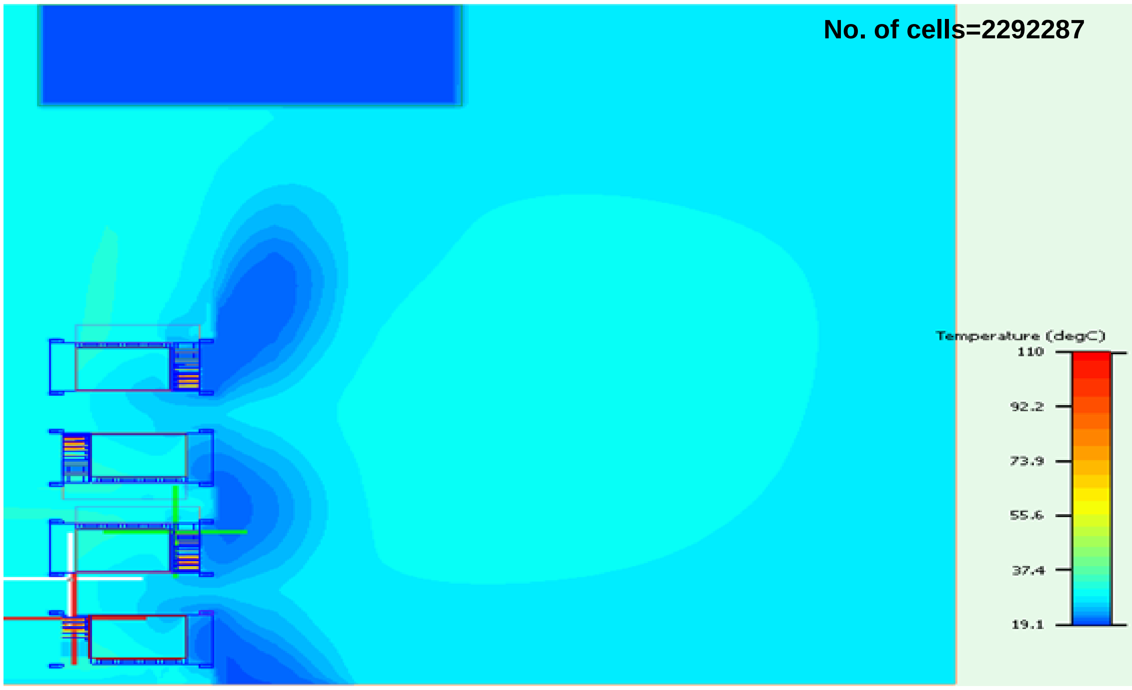

Figure 4.17: Four Switches without Top Blanking Panel

4.4.1.4 *Mesh Sensitivity Analysis for Even Switches with and without Top Blanking Panel*

The mesh sensitivity analysis for even number of switches reveals that the effect of top blanking panel significantly reduces the temperature. However, when the solution reaches mesh independence, a very small difference is observed using the top blanking panel. The addition of a blanking panel is always useful as it contributes in preventing air flow bypass. Table 4.2 shows the results of mesh sensitivity analysis for four side breathing switches with and without the top blanking panel.

Table 4.2: Mesh Sensitivity Analysis for Four Switches

Four Switches without top Blanking Panel			Four Switches with top Blanking Panel		
Trials	Mesh count	Temp (℃)	Trials	Mesh count	Temp (℃)
1	2292287	110	1	2500000	100
2	2974982	88.8	2	2987623	89.3
3	3389391	88.3	3	3634041	76.9
4	4187625	88.3	4	4123397	76.4

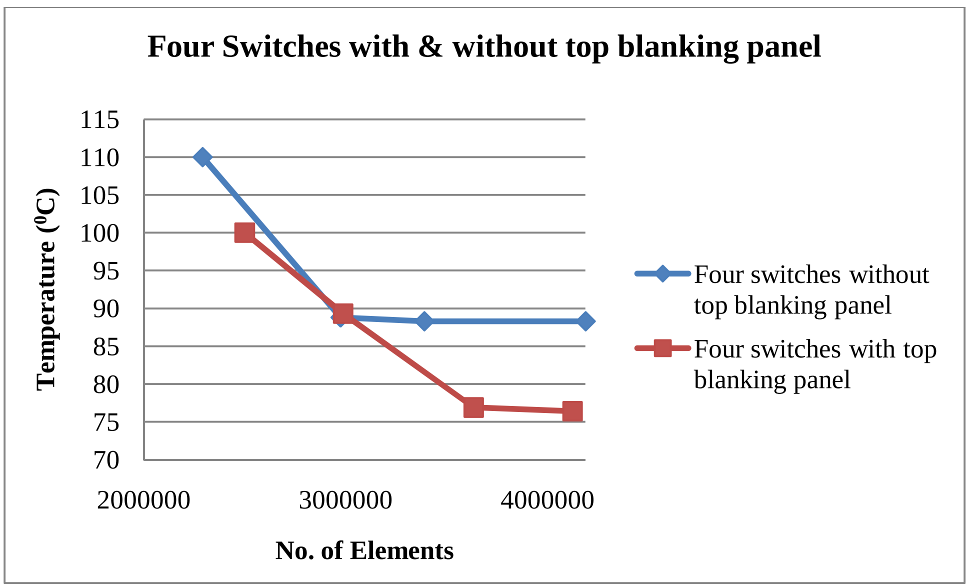

Figure 4.18: Mesh Sensitivity Analysis for Four Side Breathing Switches

Figure 4.19 and 4.21 indicate the thermal contours for trial 3. Though the solution reaches grid independence at about 2.98 million cells, it is observed that a finer mesh can drastically reduce the temperature. However, a large mesh count increases the computational time.

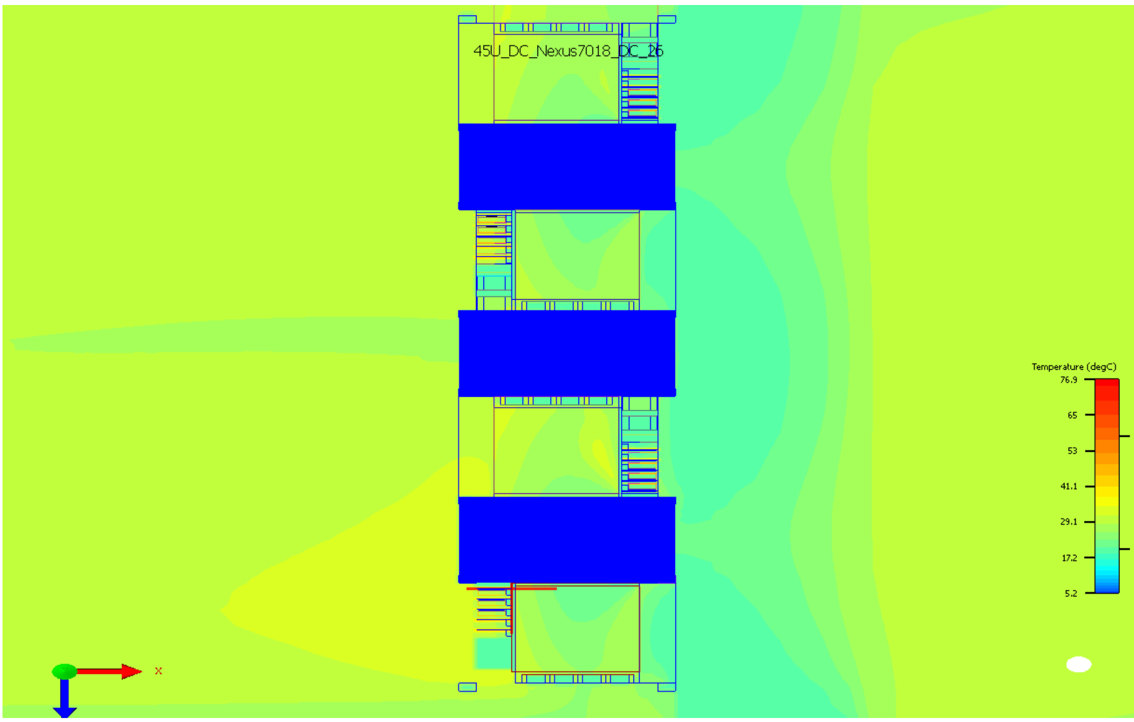

Figure 4.19: Mesh Sensitivity Analysis for Four Switches with Top Blanking Panel (Trial 3)

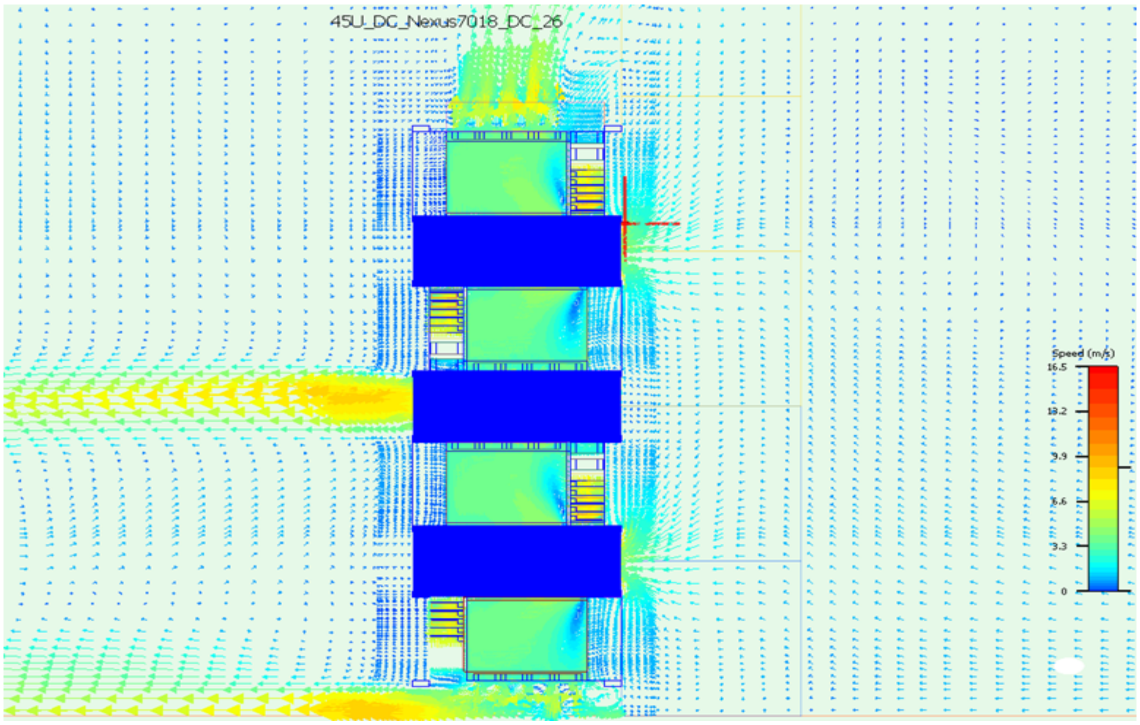

Figure 4.20: Vector Plot Indicating Air Flow Pattern (Trial 3)

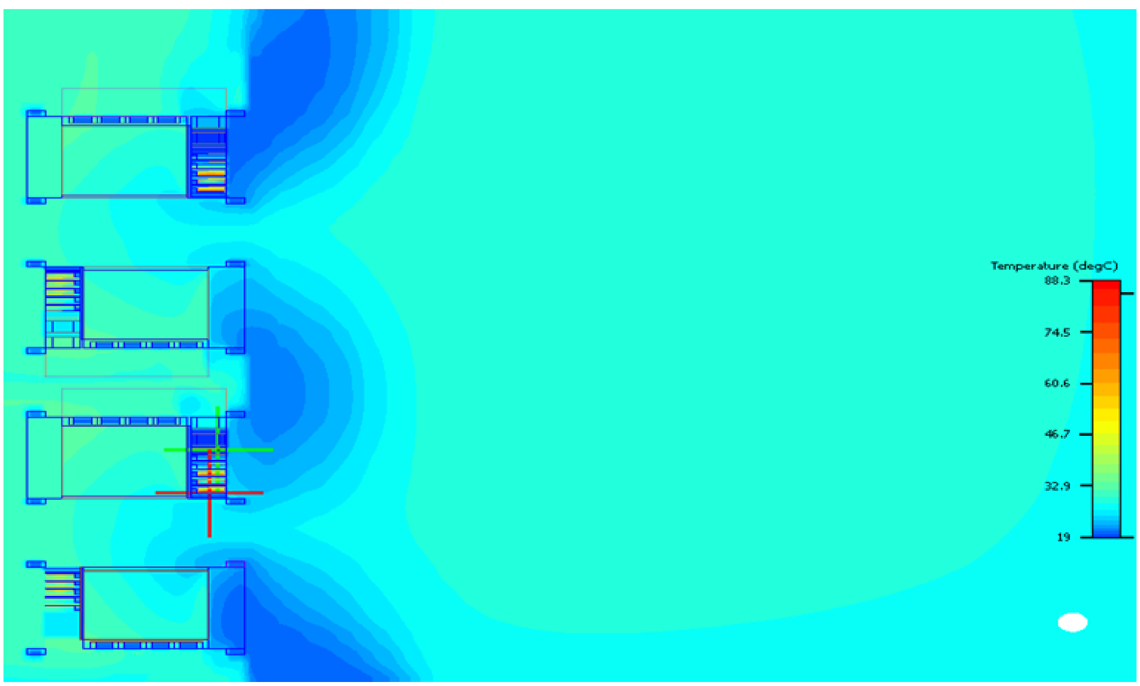

Figure 4.21: Mesh Sensitivity Analysis for Four Switches without Top Blanking Panel (Trial 3)

4.4.1.5 *Effect of Odd Switches with and without Top Blanking Panel*

Thermal analysis on the effect of side breathing switches with and without top blanking panel is also performed for odd number of switches. Five side breathing switches are considered for the analysis. The total power using five switches is 35,250 watts. Hence, the addition of another switch increases the power by a factor of 7050 watts. The number of hot aisles and cold aisles are equal when odd number of side breathing switches is used. Figure 4.22 represents the thermal contour for five switches without top blanking panel and the maximum temperature is observed to be 89.2℃ for th e second switch. The reason for such a high temperature in the second switch is probably because of some hot air recirculation. Figure 4.23 indicates the thermal contour for five switches with top blanking panel. The maximum temperature for both cases is negligible and the addition of a top blanking panel does not create much difference because of equal number of hot and cold aisles using five side breathing switches.

Figure 4.22: Five Switches without Top Blanking Panel

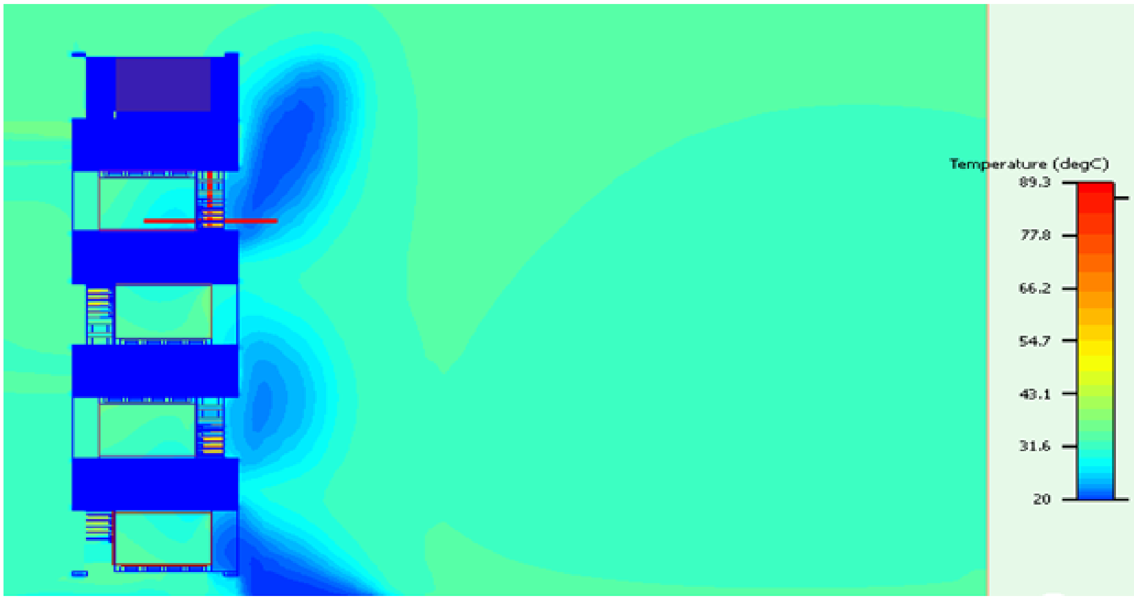

Figure 4.23: Five Switches with Top Blanking Panel

4.4.1.6 *Mesh Sensitivity Analysis for Odd Switches with and without Top Blanking Panel*

Table 4.3 indicates the mesh sensitivity analysis for five side breathing switches with and without top blanking panel. A very marginal difference in temperature is observed.

Table 4.3: Mesh Sensitivity Analysis for Five Switches

Five Switches without top Blanking Panel			Five Switches with top Blanking Panel		
Trials	Mesh count	Temp (℃)	Trials	Mesh count	Temp (℃)
1	2557773	123	1	2557773	123
2	3025619	89.2	2	3048030	89.3
3	3619073	89.2	3	3619073	89.3
4	4056321	88.9	4	4044954	88.8

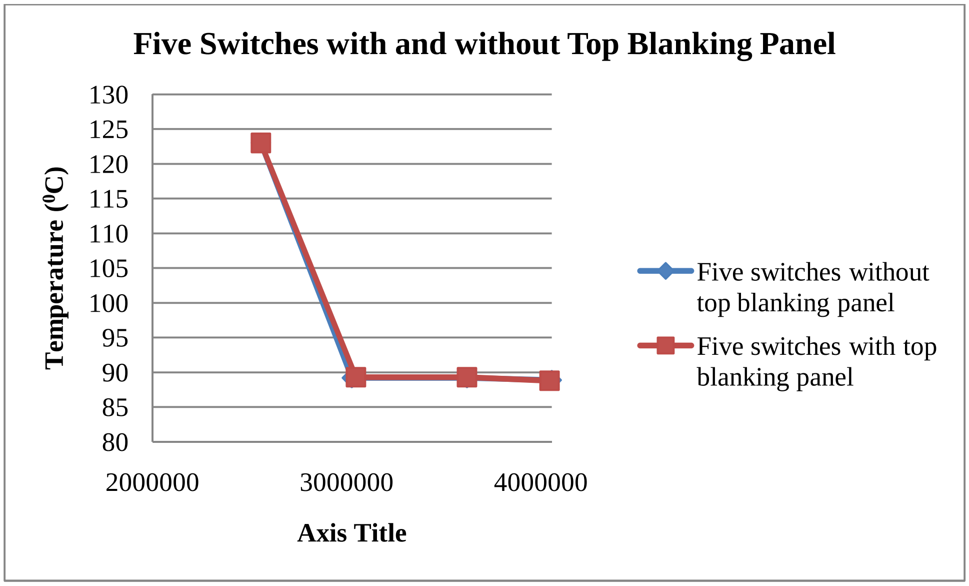

Figure 4.24: Mesh Sensitivity Analysis for Five Side Breathing Switches

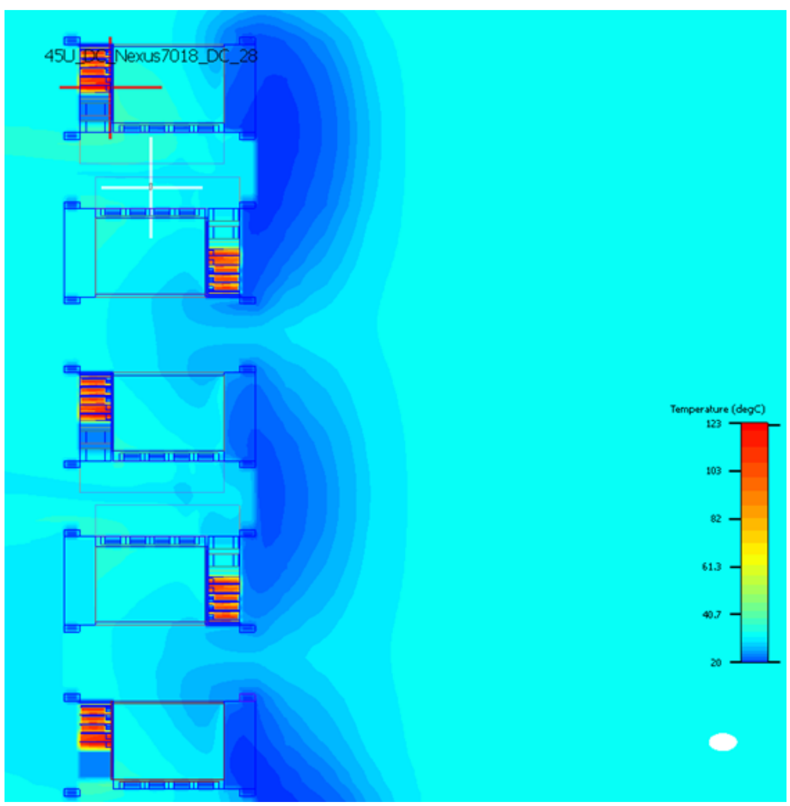

Figure 4.25: Mesh Sensitivity Analysis for Five Switches without Top Blanking Panel (Trial 1)

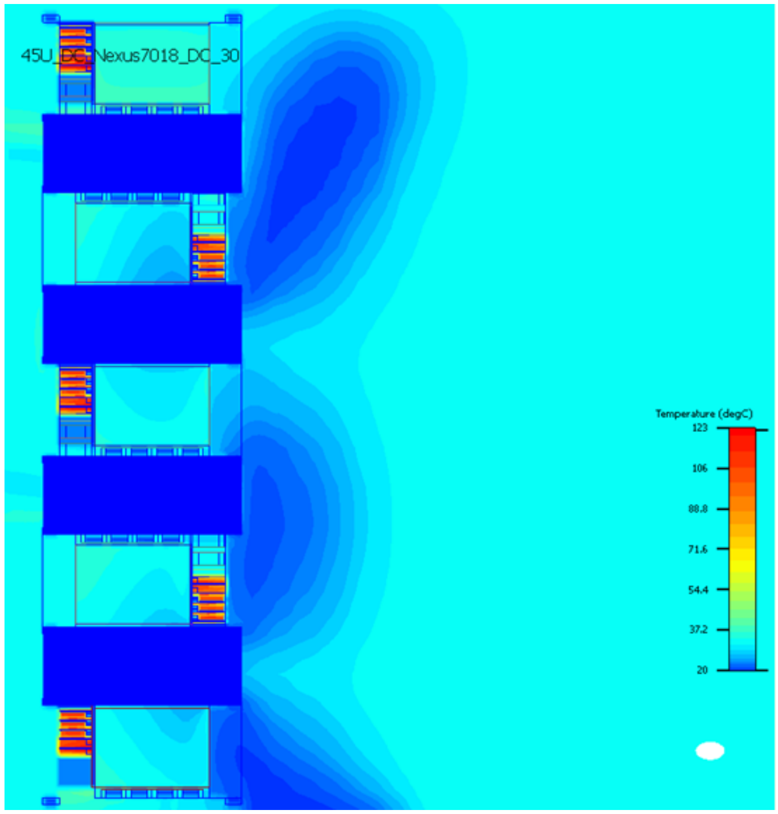

Figure 4.26: Mesh Sensitivity Analysis for Five Switches with Top Blanking Panel (Trial 1)

4.5 Conclusion

The comparison between 12 inch and 22 inch vertical cable managers yields a very negligible temperature difference. Results indicate that the temperature reduces using 12 inch vertical cable managers. The application of 12 inch vertical cable managers can also reduce the floor space and offers a quicker passage for the air flow. The study of the effect of top blanking panel has shown that it has considerably reduced the temperature for four side breathing switches. No difference is observed for the analysis of five side breathing switches. The advantage of employing top blanking panels is for preventing recirculation of hot air back into the cold aisles. Application of even or odd number of side breathing switches depends on the power requirements and the efficiency that has to be achieved. The power and other parameters are fixed. Computationally, odd number of side breathing switches can increase the mesh count and run time.

CHAPTER 5

THERMAL ANALYSIS OF MODULAR DATA CENTERS

5.1 Design Guidelines for Modeling Modular Data Centers

Modular data centers overcome the inefficiencies of traditional data centers because the server load is partitioned into a number of modular sections which are deployed, powered and cooled on more of an as needed basis. These modular sections are deployed in numerous locations and exposed to diverse environmental conditions. The servers, IT equipment and power modules generate significantly large amount of heat and must be maintained within their optimum temperature range. Cooling systems play in an important role in removing the heat from server racks and rejecting them outside. It is imperative to ensure that these cooling systems use minimum amount of energy. In doing so, operational costs can be reduced resulting in more efficient systems. “Free cooling”, a method of introducing outside air through filters to directly cool the IT equipment can be used to improve the efficiency. Obviously, the outside air must meet the intake temperature and humidity requirements of the server equipment. There are a number of approaches to introducing outside air into the data centers for free cooling. Here, one such approach is used to analyze thermal performance of the system using CFD modeling techniques. Flotherm [33] and Flovent [42] are CFD tools employed to propose guidelines for designing the modular data center.

5.2 Modeling of the Modular Data Center

A detailed model of the modular data center and its components can significantly increase the number of elements in the CFD model leading to longer solver time. Therefore, to minimize the solution time, it is necessary to simplify the complicated geometry. This can be realized using compact modeling. In this study, the electronic components are modeled using compact models. A uniform heat source is used for modeling power dissipating devices. Compact resistance models are used for modeling inlet exhaust openings.

5.2.1 Baseline Case

The modular data center has dimensions measuring 28 feet wide, 9.5 feet high and 8.5 feet deep. The modular data center has eight racks. Each rack houses an IT telecommunications switch. The modular data center discussed in this study comprises of the telecommunication switches, inlet and exhaust openings, an internal partition to separate the cold aisle and hot aisle, a blower tray comprising of five blowers on the cold aisle side and five dampeners on the hot aisle side and the power cabinet. The intake and the exhaust are modeled as holes for the baseline case. Figure 5.1 illustrates the isometric view of the modular data center for the baseline case. The internal partition that separates the cold aisle and hot aisle is shown in Figure 5.2.

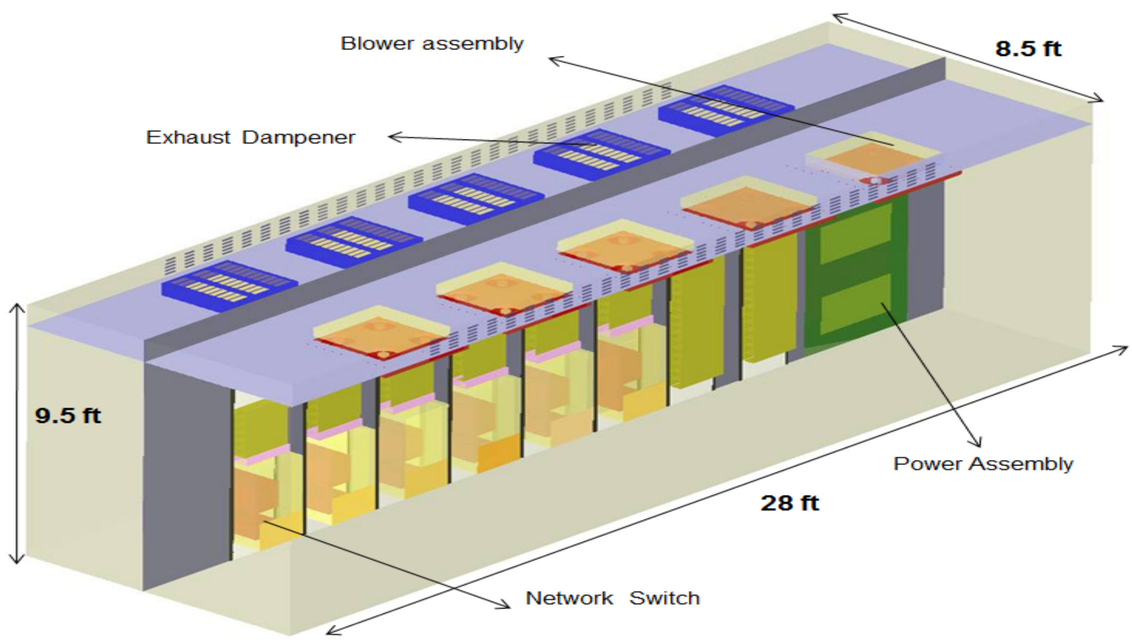

Figure 5.1: Modular Data Center – Baseline Case

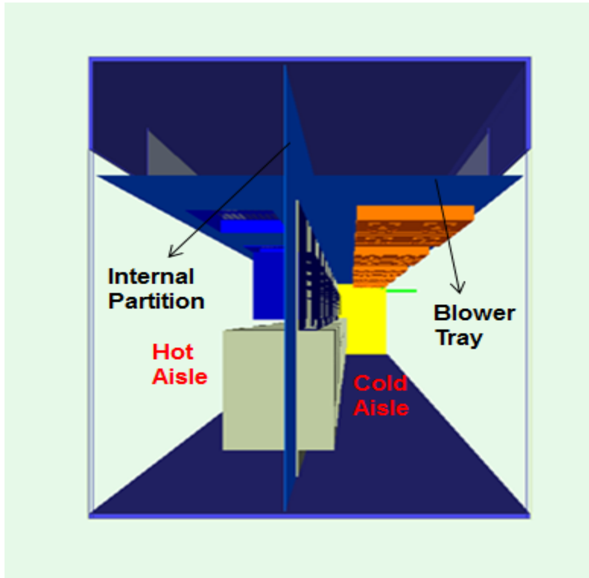

Figure 5.2: Separation of Cold Aisle and Hot Aisle

The network switch itself consists of I/O modules, supervisor modules, power supply and fabric modules, all of which dissipate heat into the system. The dimensions of the network switch are 18 inches wide, 37 inches high and 32 inches deep. For the baseline case, the fabric modules and I/O modules are modeled together as a solid block and the power supply is also modeled as a solid block. There are two exhaust fans for cooling all the electronic components.

5.2.2 Modular Data Center with Resistance Models for Intake and Exhaust and Updated Network Switch Design

The modular data center shown below in figure 5.3 has dimensions measuring 40 feet wide, 12 feet high and 9 feet deep. Figure 5.5 shows the components of the modular data center which includes the IT equipment, power cabinet and cooling assembly. In the baseline case, the inlet and exhaust were modeled as holes. In the updated model, the inlet and the exhaust are modeled using the resistance smart part available in Flotherm with 80% open area ratio. The number of racks in the updated model is 15. The rack post is 20 inches wide, 84 inches long and 1 inch thick. Figure 5.6 shows the rack components. The power cabinet is separated from the racks by a blanking panel and has a separate cooling system. The cooling system for the power cabinet includes an exhaust fan which rejects the hot air through the dampeners and out of the data center. Table 5.1 provides a summary of the heat dissipation.

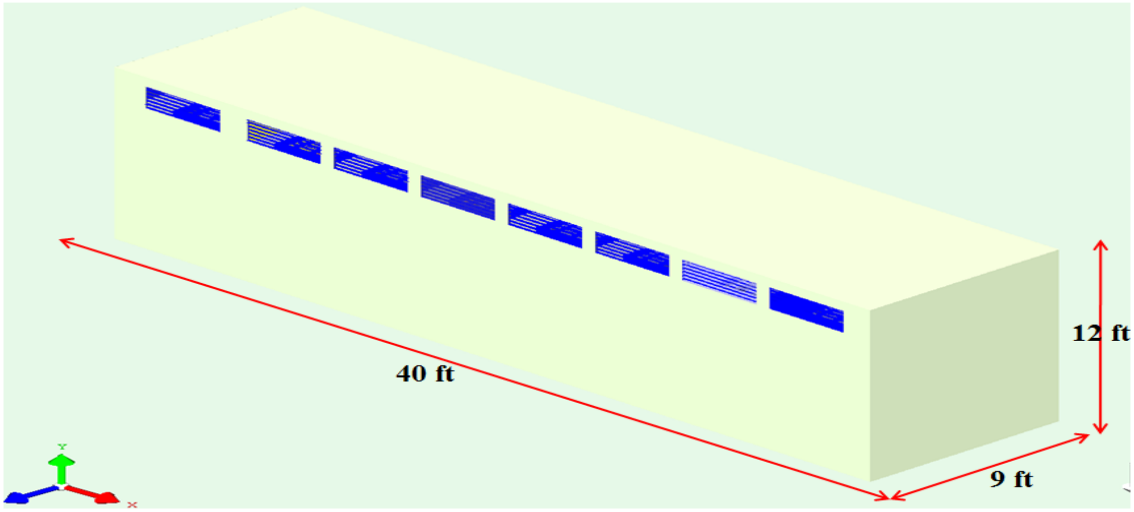

Figure 5.3: Updated Modular Data Center Design

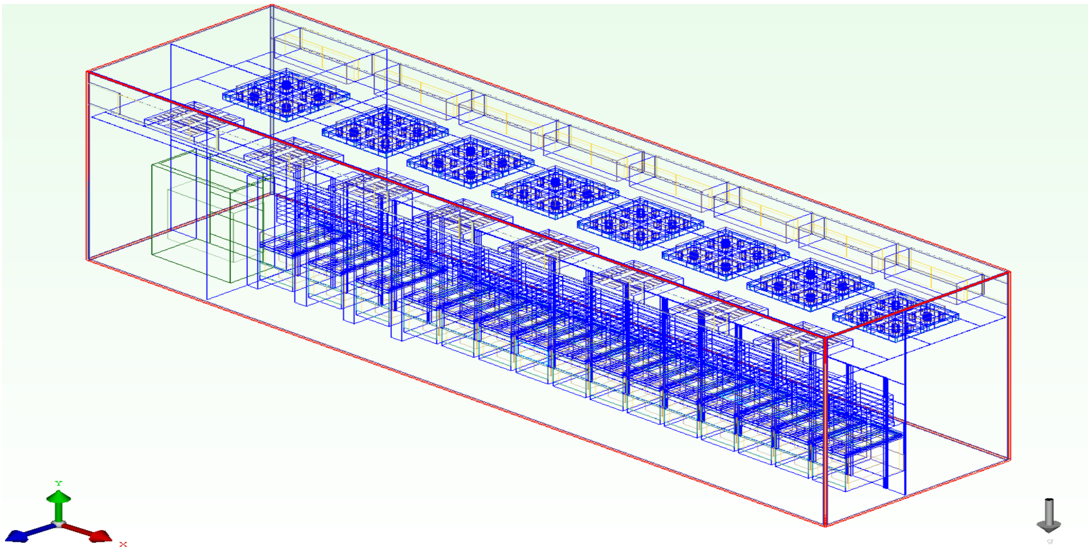

Figure 5.4: Wireframe Model of Modular Data Center

Table 5.1: Summary of Total Heat Load

Component	Heat Load (W)	No. of Components	Total Heat Load (W)
Telecommunication Switch	6500	15	97500
Power Cabinet	750	1	750
Total	7250		98250

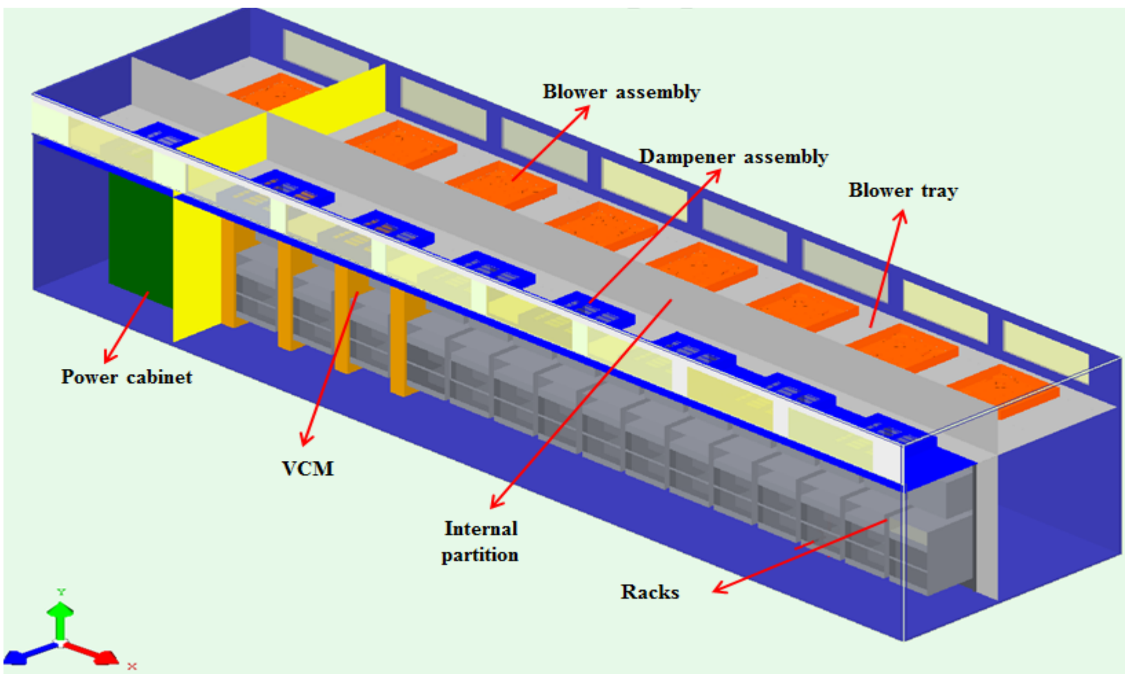

Figure 5.5: Components of Modular Data Center

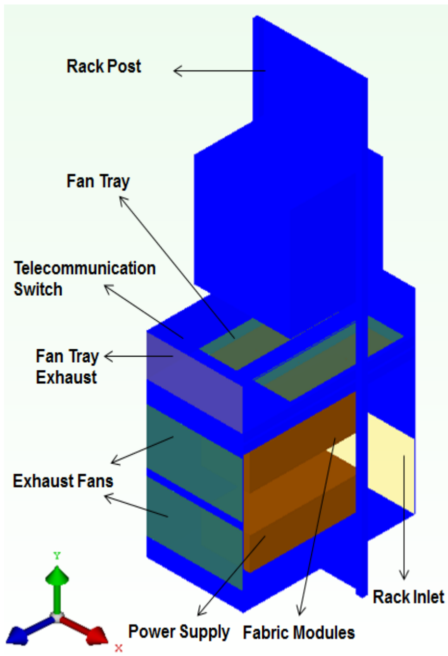

Figure 5.6: Rack Components

The blowers pull in the outside air which is filtered and directed downwards into the cold aisle section towards the network switches. Each blower assembly has four blower fans that bring in outside air. The maximum flow rate supplied by each blower assembly is 4000 cfm. The filtered air enters the front side or the inlet of the network switches located at the rear side of the partition i.e. the cold aisle. The air enters the network switch and is pulled upwards by two fan trays, each comprising of six fans. These fans are variable speed fans that adjust according to the environmental conditions. As the air passes upwards, it cools the I/0 modules and supervisor modules and it is rejected into the hot aisle through the fan tray exhaust. In this way, the air enters the bottom front side of the network switch chassis and exits at the top rear side of the chassis. In addition, the two exhaust fans pull some air to cool the fabric modules and the power supply. The power cabinet is separated from the racks by a blanking panel which has a separate cooling system. The hot air rejected from all the racks and the power cabinet in the hot aisle travels upwards through the dampeners and is directed outwards.

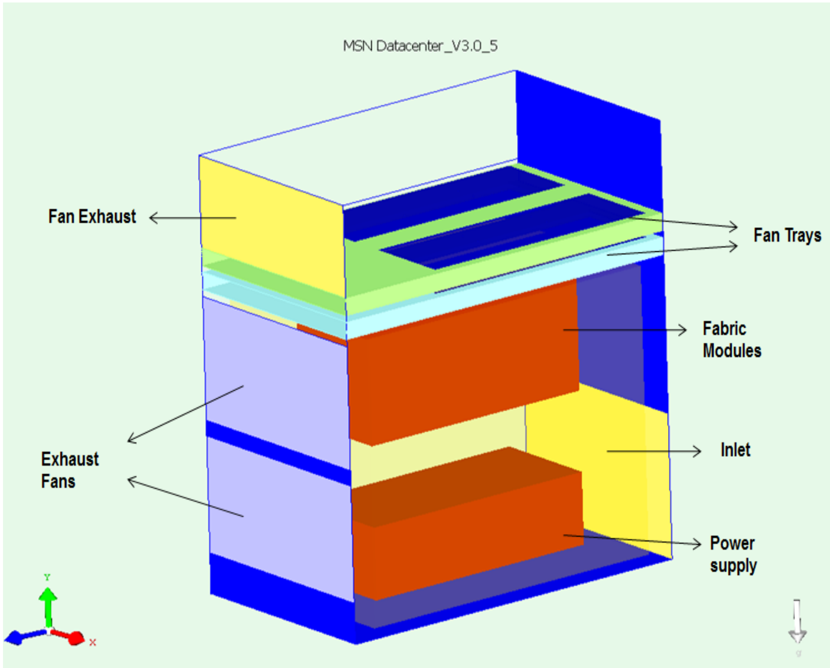

Figure 5.7: Network Switches with Fan Trays

5.2.3 Modular Data Center with Louvers for Intake & Exhaust and Filter Assembly

Figure 5.8 shows the data center model with the louver and filter assembly. The resistance smart part for the inlet and exhaust vents are replaced by louvers which are modeled using “inclined slope” smart part available in Flotherm. Each louver assembly comprises of six “inclined slope” smart parts. The data center has eight inlet vents and eight exhaust vents. The filter enclosure consists of standard MERV-11 (minimum efficiency ratio value) filters. The filters were experimentally tested to determine the system impedance curve which was imported into the Flotherm model. There are a total of eight filter assemblies which are located immediately after the inlet louver vents. The filters are used for removing any particulate contaminant matter in order to deliver clean air into the system. Figure 5.9 and figure 5.10 show the filter assembly and louver assembly respectively.

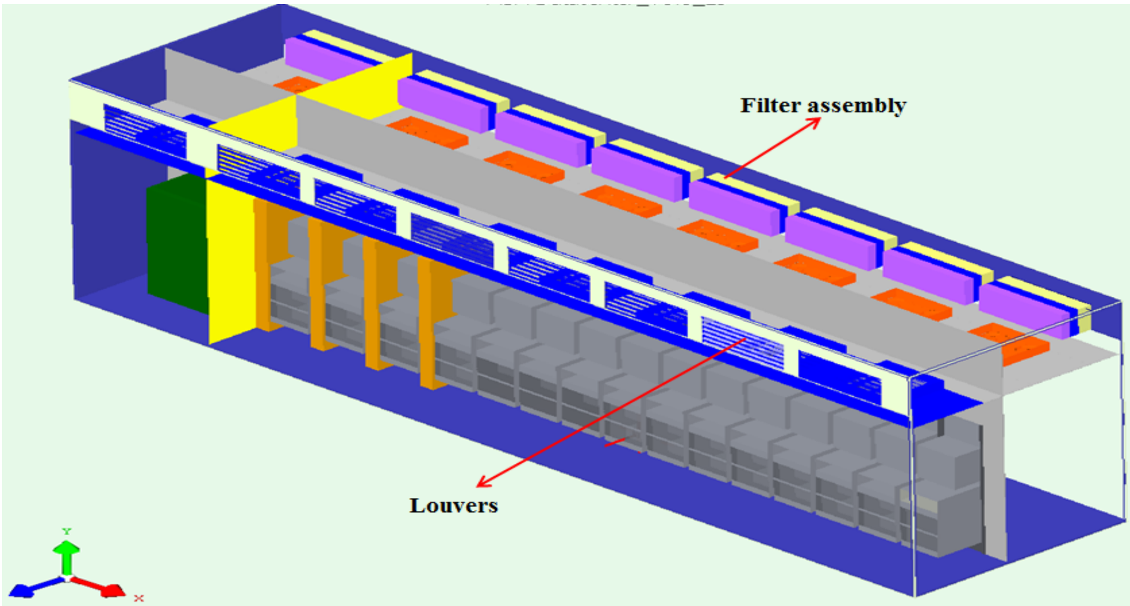

Figure 5.8: Modular Data Center with Louvers and Filter Assembly

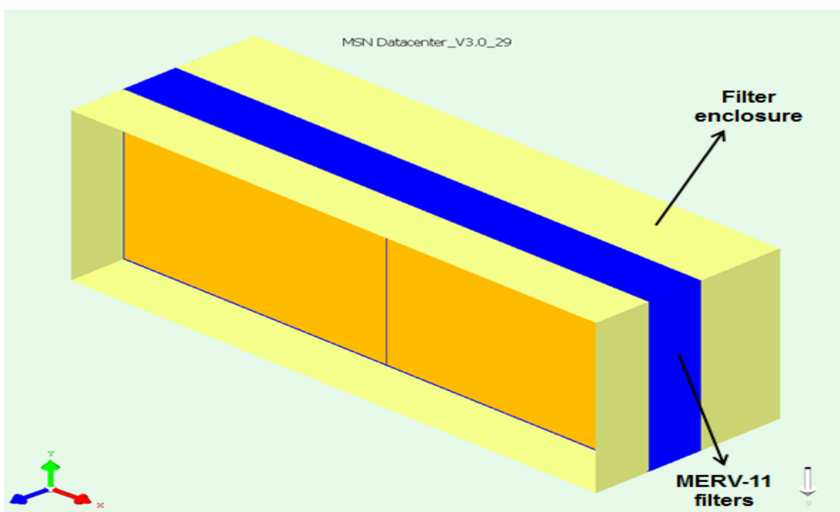

Figure 5.9: Filter Assembly

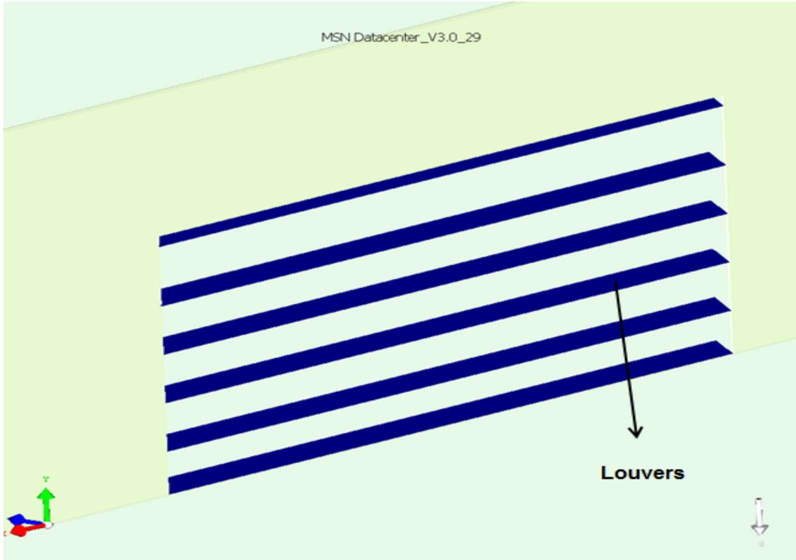

Figure 5.10: Louver Assembly

5.3 Results

5.3.1 Baseline Case Results

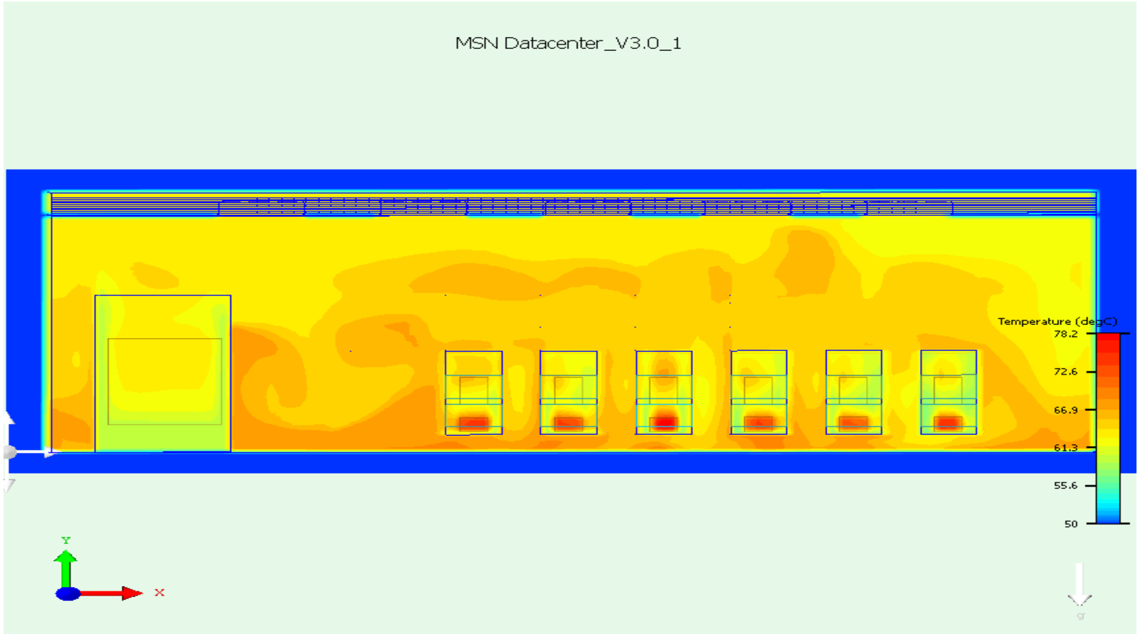

Figure 5.11: Thermal Contour for Baseline Case

From the baseline case, it was observed that the open area ratio for the holes was only 20% of the total inlet and exhaust area. As a result, the blowers were operating at a lower flow rate due to insufficient air supply at the container inlet. At the container exhaust, a very large amount of air recirculation was observed at the hot aisle and above the blower trays. Due to recirculation of air, a blanking panel is added to separate the power cabinet and the IT telecommunication switches in the following simulations. Figure 5.12 shows the air recirculation observed in the hot aisle.

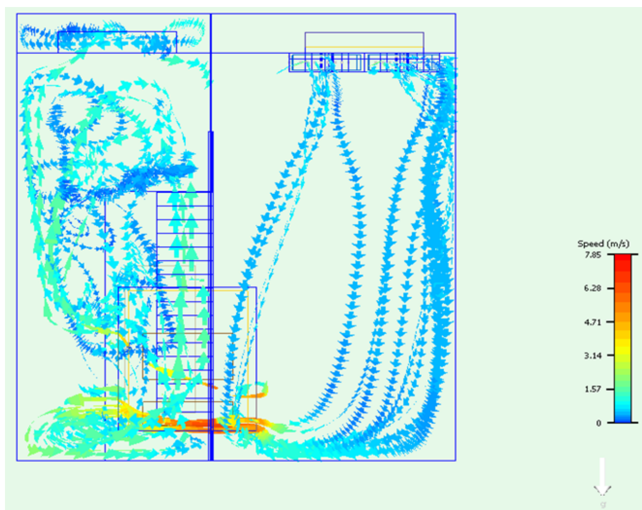

Figure 5.12: Velocity Contour Depicting Air Recirculation for Baseline Case

5.3.2 Results for Modular Data Center with resistance models for Intake and Exhaust

Figure 5.13 illustrates thermal contour plot using resistance smart part for inlet and exhaust vents. Percentage open area ratio for the resistance smart part is 80 %. It can be seen that due to 80 % open area ratio, a maximum temperature of 68.5℃ is observed near the power supply of the third rack. Figure 5.14 shows the air flow pattern through a telecommunication switch. Air recirculation can be observed within the chassis.

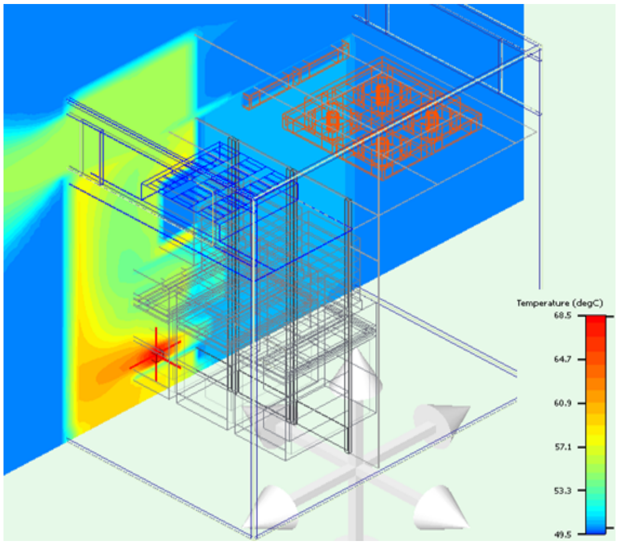

Figure 5.13: Thermal Contour Using Resistance Smart Part for Inlet and Exhaust

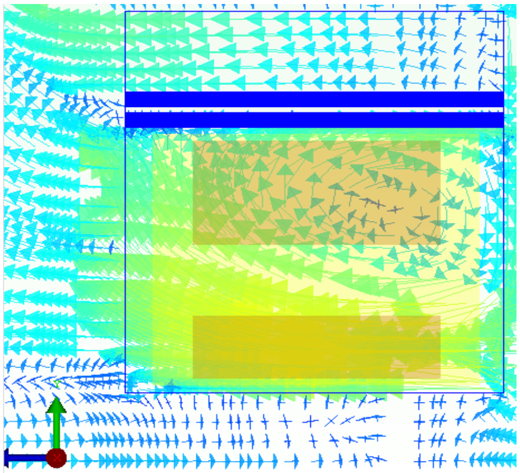

Figure 5.14: Vector Plot Showing Air Flow Pattern for Network Switch

5.3.3 Results for Modular Data Center with Louvers for Intake & Exhaust and Filter Assembly

Figure 5.15 represents thermal contour plot using louvers for inlet and exhaust vents. This model also has a filter assembly. It can be seen that the louvers restrict the flow of outside air due to their inclined vents. Outside air passes through the filters and is circulated by the blowers to cool the IT equipment. The addition of louvers and filter assembly increase the resistance as outside air passes through them. The louvers can be controlled by actuators to allow and restrict required amount of air.

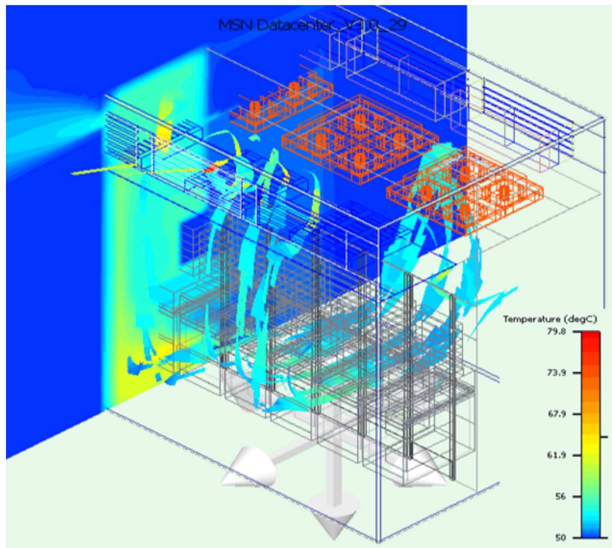

Figure 5.15: Thermal Contour Using Louver Smart Part for Inlet and Exhaust

5.3.4 Results with updated network Switch Design (Case – 1)

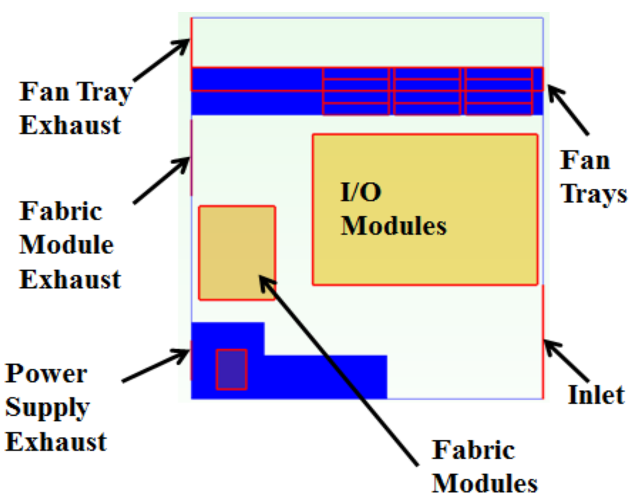

Figure 5.16: Updated Model of Network Switch

The above results are compared by designing a more detailed model of the telecommunication switch. The I/O modules are modeled as a solid plate and fabric modules and power supply are modeled in a detailed manner according to vendor specifications. Figure 5.16 shows the updated IT telecommunication switch design. In the previous cases, the fabric modules, supervisor modules and I/O modules were modeled together using a heat source smart part. In this case, they are modeled separately using the heat source smart part and corresponding power values are assigned. Figures 5.17 and 5.18 show the air flow pattern through the telecommunication switches. Results show that the updated design significantly reduces any air bypass. At the inner surface of the modular data center, an insulation thickness of 1 inch is provided. The inlet and exhaust are modeled with 80% open area ratio resistance models.

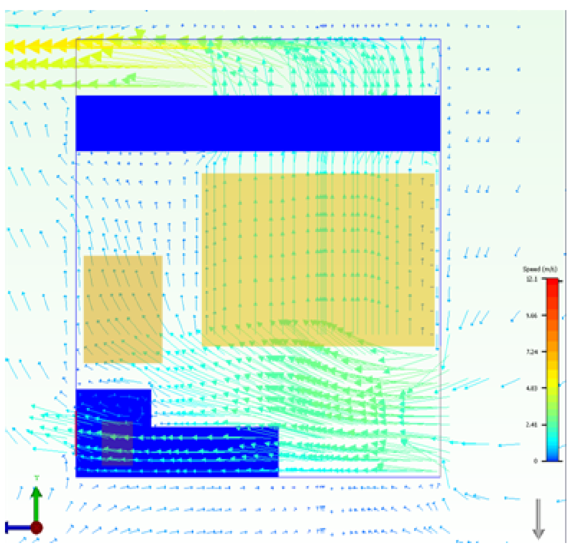

Figure 5.17: Vector Plot Showing Air Flow Pattern for Updated Network Switch

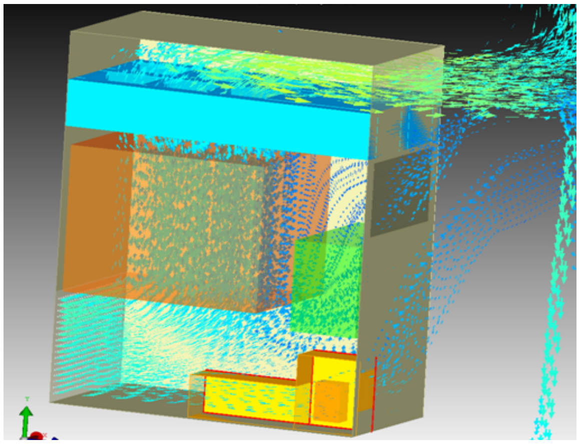

Figure 5.18: Vector Plot – Isometric View

The results for container inlet and exhaust temperatures and IT telecommunication switch inlet and exhaust temperatures are tabulated in the following tables.

Table 5.2: Container Inlet Temperatures

Container Inlet Temperature (℃)	
Inlet 1	27
Inlet 2	27
Inlet 3	27
Inlet 4	27
Inlet 5	27
Inlet 6	27
Inlet 7	27
Inlet 8	27

Table 5.3: Container Exhaust Temperatures

Container Exhaust Temperature (℃)	
Exhaust 1	32.3
Exhaust 2	51.6
Exhaust 3	52
Exhaust 4	52.3
Exhaust 5	52.2
Exhaust 6	52.7
Exhaust 7	52.3
Exhaust 8	51.9

Table 5.4: IT Telecommunication Switch Inlet Temperatures

IT Telecommunication Switch Inlet Temperature (℃)	
Inlet 1	29
Inlet 2	31.6
Inlet 3	29.5
Inlet 4	30.6
Inlet 5	30.2
Inlet 6	30.4
Inlet 7	29.5
Inlet 8	30.3
Inlet 9	31.1
Inlet 10	30.2
Inlet 11	33.3
Inlet 12	29.5
Inlet 13	31.9
Inlet 14	29.7
Inlet 15	29.2

Table 5.5: IT Telecommunication Switch Exhaust Temperatures

IT Telecommunication Switch Exhaust Temperatures (°C)			
Exhaust	Fan Tray Exhaust (℃)	Fabric Module Exhaust (℃)	Power Supply Exhaust (℃)
Exhaust 1	53.4	43.2	50.8
Exhaust 2	56.5	45.1	52.8
Exhaust 3	54.6	44.5	52.3
Exhaust 4	56	45.8	52.5
Exhaust 5	56	46.6	51.7
Exhaust 6	55.6	44.9	51.7
Exhaust 7	54.5	45.7	51
Exhaust 8	55.5	45.2	51.2
Exhaust 9	55.9	47	51.7
Exhaust 10	55.1	45.3	51.1
Exhaust 11	57.5	47.1	52.6
Exhaust 12	54.5	46.9	52
Exhaust 13	56.5	43.9	51.3
Exhaust 14	54.7	43.1	48.8
Exhaust 15	54.4	40.3	48.9

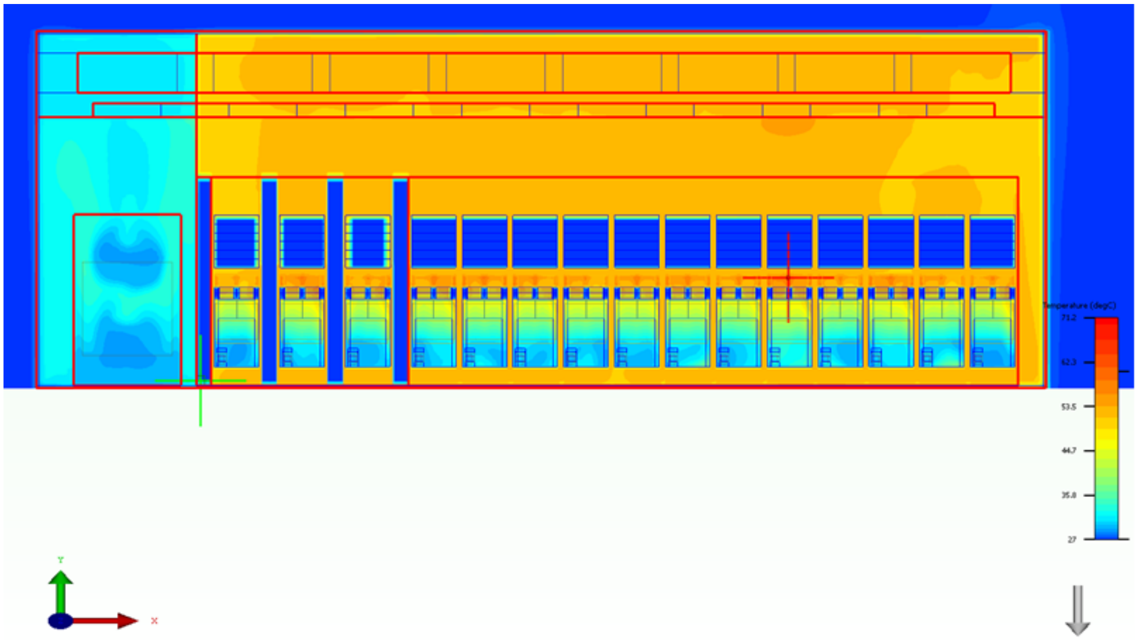

Figure 5.19: Thermal Contour of Modular Data Center

5.3.5 Results of Modular Data Center with Louver Simulation, hydrophobic filters and Heat Exchanger (Case – 1)

A CFD simulation of the louver assembly is performed in Flotherm using a test air flow bench model to determine the system curve. A planar resistance model is used for modeling the louver assembly in Flotherm using the system curve. The results for louver simulation are provided in appendix A. A hydrophobic filter is placed after the MERV 11 filters for removing excess moisture followed by a heat exchanger. The heat exchanger is modeled using a volumetric resistance model with 75% open area ratio. For the power cabinet blower assembly, only one blower is activated. The other three blowers are deactivated. The results are indicated below.

Table 5.6: Container Inlet Temperatures

Container Inlet Temperature (℃)	
Inlet 1	27
Inlet 2	27
Inlet 3	27
Inlet 4	27
Inlet 5	27
Inlet 6	27
Inlet 7	27
Inlet 8	27

Table 5.7: Container Exhaust Temperatures

Container Exhaust Temperature (℃)	
Exhaust1	31.2
Exhaust 2	48.2
Exhaust 3	49
Exhaust 4	49.4
Exhaust 5	49.7
Exhaust 6	49.7
Exhaust 7	49.6
Exhaust 8	48.9

Table 5.8: IT Telecommunication Switch Inlet Temperatures

IT Telecommunication Switch Inlet Temperature (℃	
Inlet 1	29.6
Inlet 2	31.6
Inlet 3	30.7
Inlet 4	31.5
Inlet 5	32.1
Inlet 6	30.6
Inlet 7	32.4
Inlet 8	31
Inlet 9	32.5
Inlet 10	30.6
Inlet 11	33.1
Inlet 12	31.4
Inlet 13	32.9
Inlet 14	31
Inlet 15	29.8

Table 5.9: IT Telecommunication Switch Exhaust Temperatures

IT Telecommunication Switch Exhaust Temperatures (°C)			
Exhaust	Fan Tray Exhaust (℃)	Fabric Module Exhaust (℃)	Power Supply Exhaust (℃)
Exhaust 1	49.2	40.3	37.1
Exhaust 2	51.3	42.2	37.3
Exhaust 3	50.3	41.8	37.6
Exhaust 4	50.8	45.1	37.2
Exhaust 5	51.3	45.9	39.2
Exhaust 6	50.1	42.3	37.1
Exhaust 7	51.7	45.7	38.6
Exhaust 8	50.3	44.4	37.9
Exhaust 9	51.9	45	39.8
Exhaust 10	49.9	44.3	37.2
Exhaust 11	52.5	45	40.6
Exhaust 12	50.6	45.6	37.9
Exhaust 13	52.3	45.8	38.7
Exhaust 14	50.2	44.7	38.3
Exhaust 15	49.5	39.5	36.4

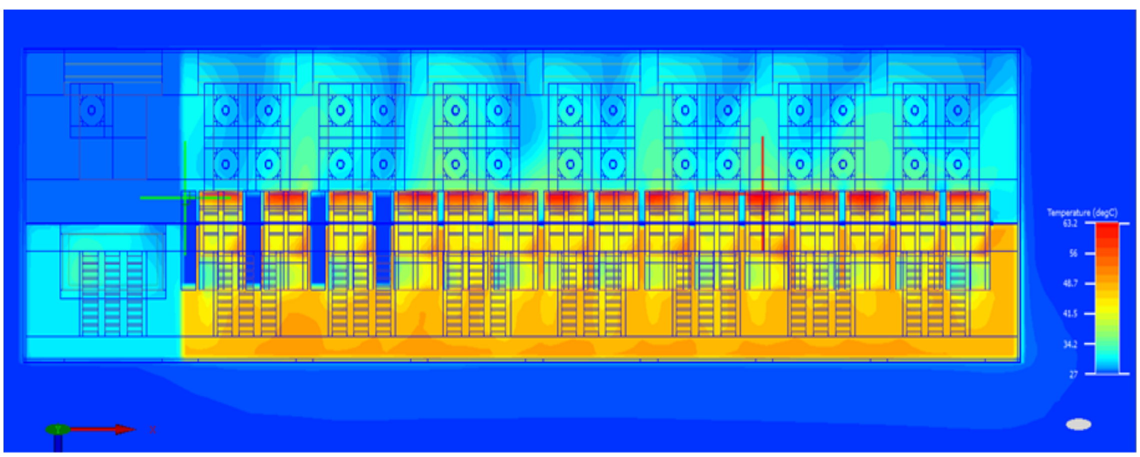

Figure 5.20: Thermal Contour of Modular Data Center with Louver, filter and heat exchanger assembly – Top View

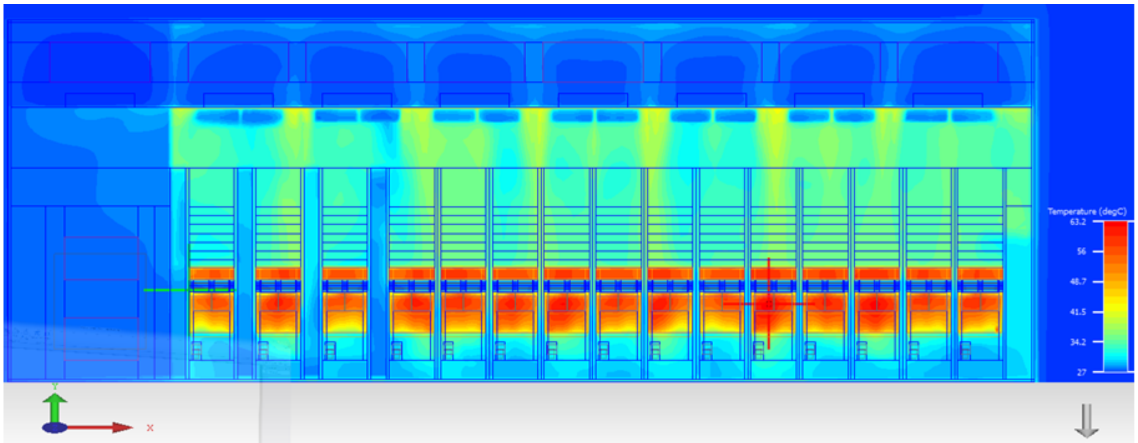

Figure 5.21: Thermal Contour of Modular Data Center with Louver, filter and heat exchanger assembly – Front View

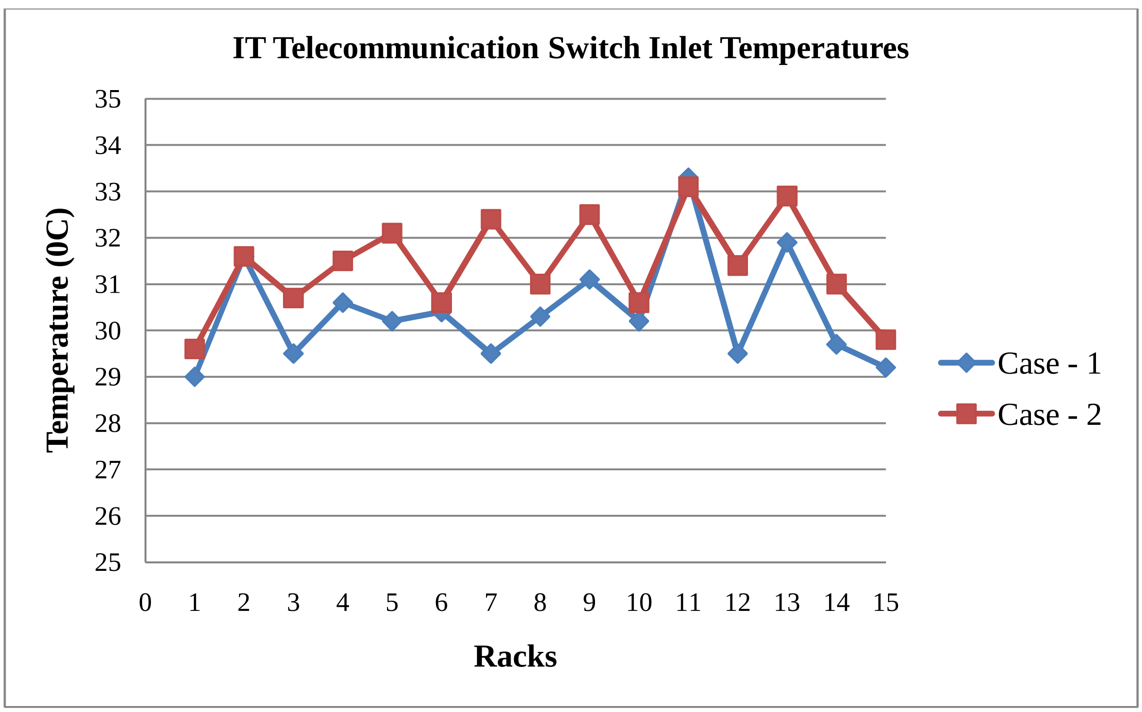

Figure 5.22: IT Telecommunication Switch Inlet Temperatures

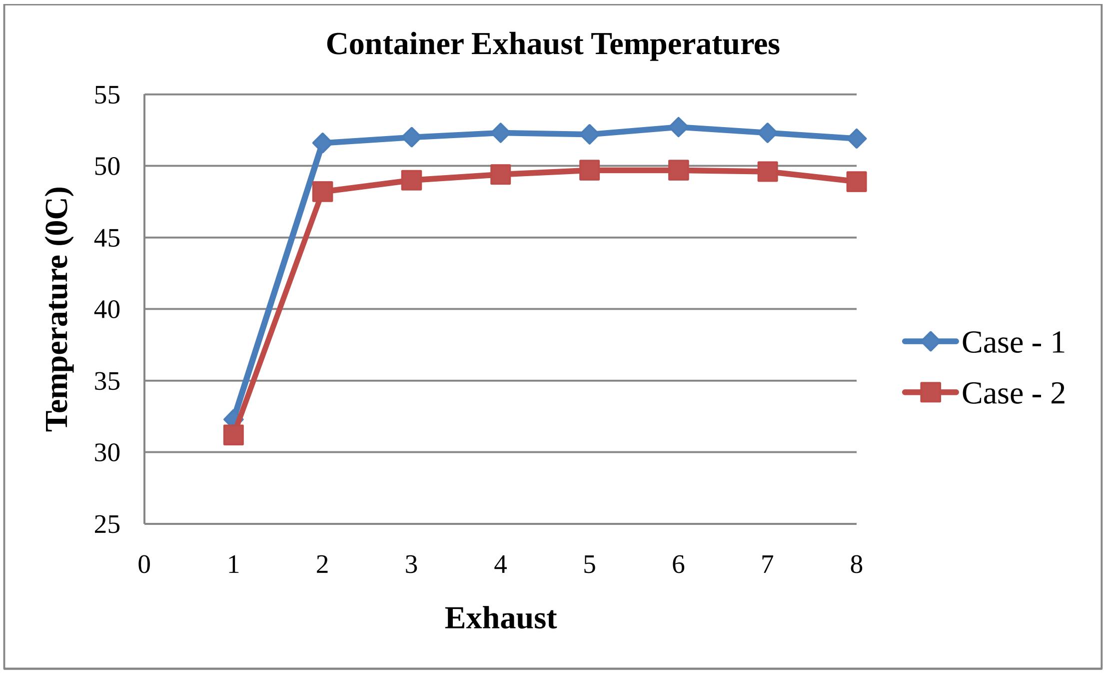

Figure 5.23: Container Exhaust Temperatures

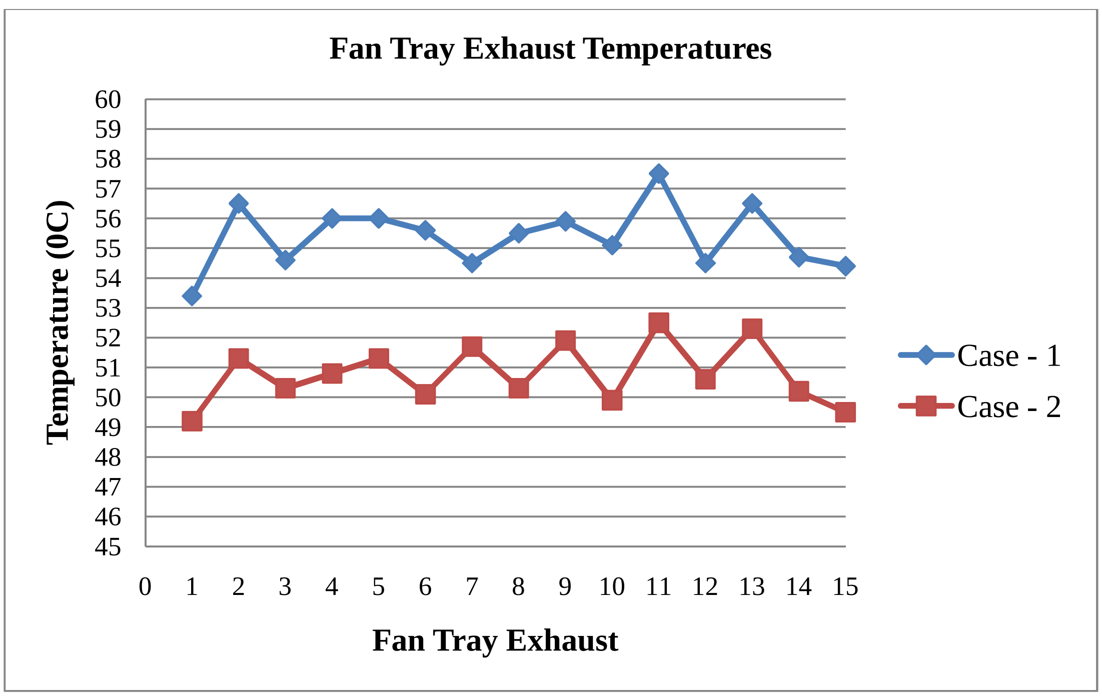

Figure 5.24: Fan Tray Exhaust Temperatures

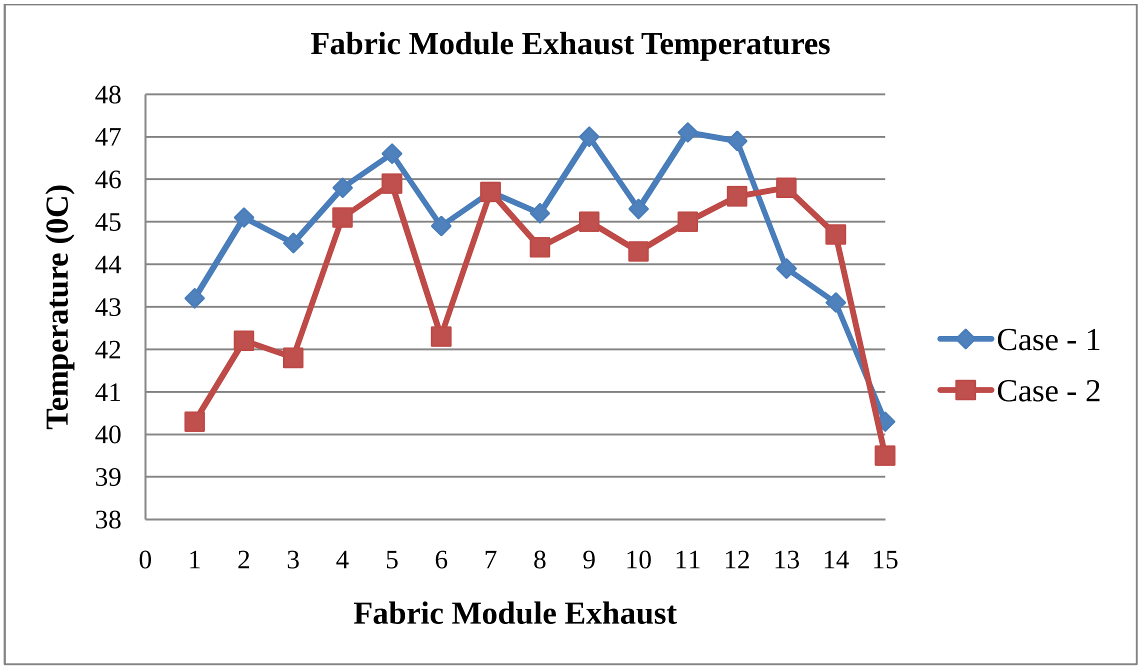

Figure 5.25: Fabric Module Exhaust Temperatures

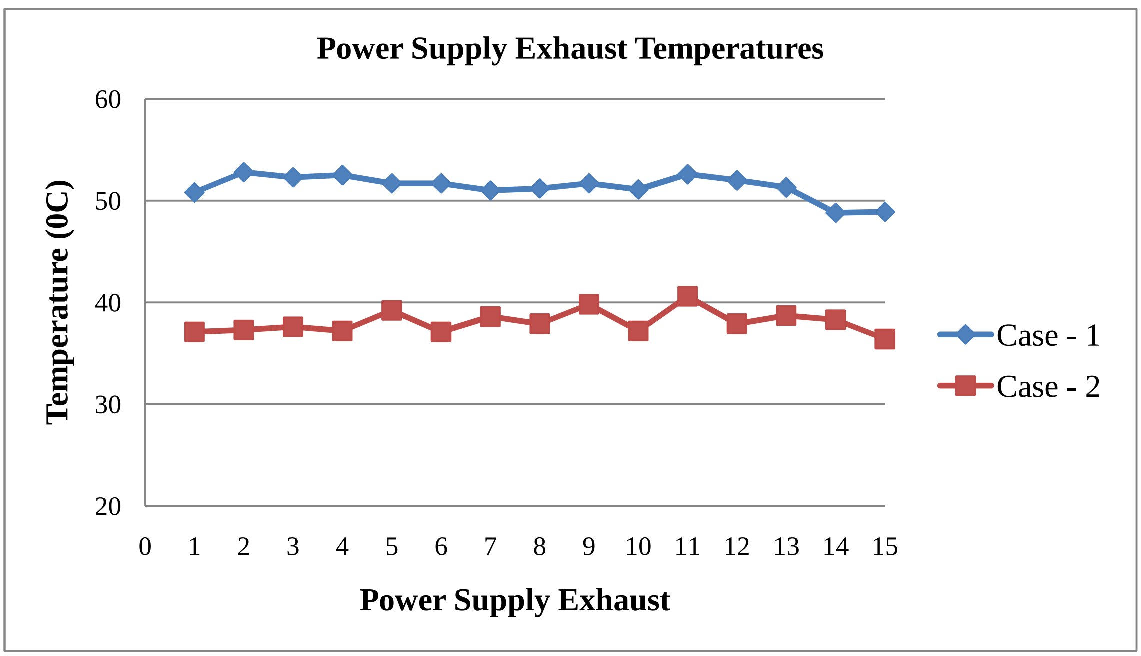

Figure 5.26: Power Supply Exhaust Temperatures

5.4 Conclusion and Future Work

Modular data center design using free cooling is discussed and thermal performance of the system is analyzed using CFD modeling techniques. Air flow patterns through the system are analyzed, particularly within the IT telecommunication systems. CFD analysis has shown recirculation in racks. Improvements in modular data center design and IT telecommunication switches can prevent such glitches. Also, server differential temperature (ΔT) significantly reduced from 20℃ to 15℃ which is typically ideal.

Future work would include mesh sensitivity analysis to verify grid independence of the solution. Also, thermal performance of the system at sub ambient temperatures can be performed to understand the need for heaters, their quantity and placement in the container.

APPENDIX A

CFD SIMULATION OF LOUVERS AND COMMPARISON
WITH COMPACT RESISTANCE MODEL

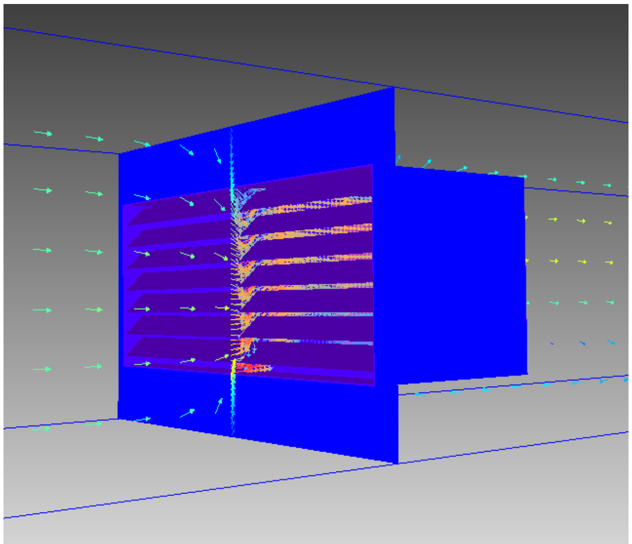

Figure A.1: PRO/E Model of Louver Assembly Imported into Flotherm

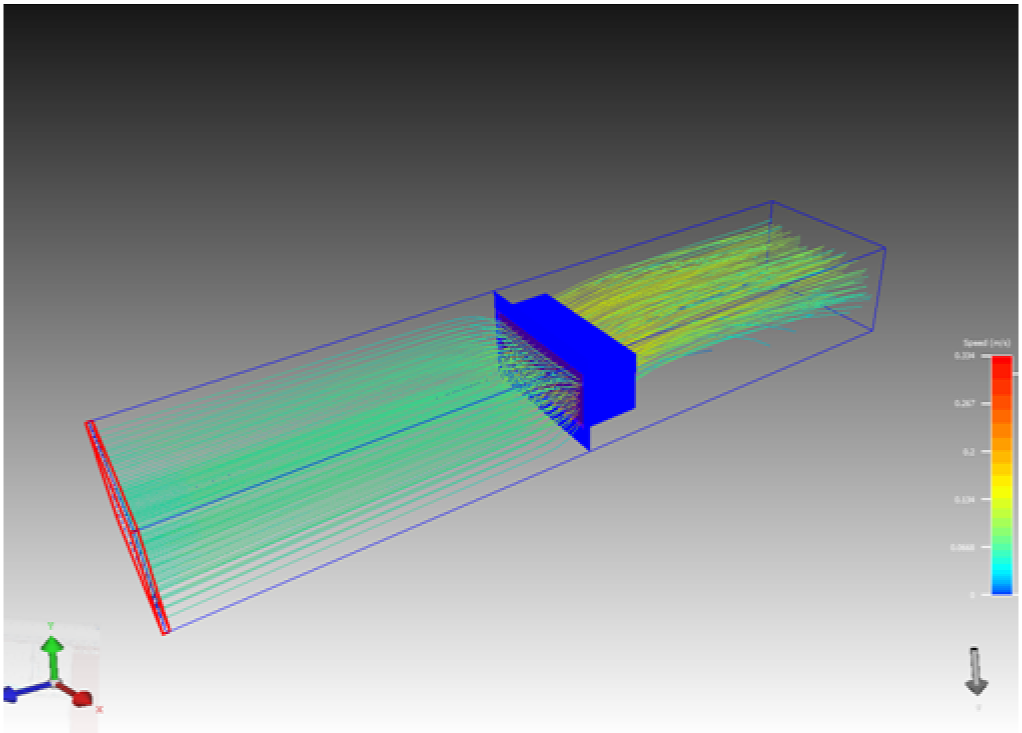

Figure A.2: CFD Analysis of Louver Assembly in a Test Air Flow Bench Simulation in Flotherm

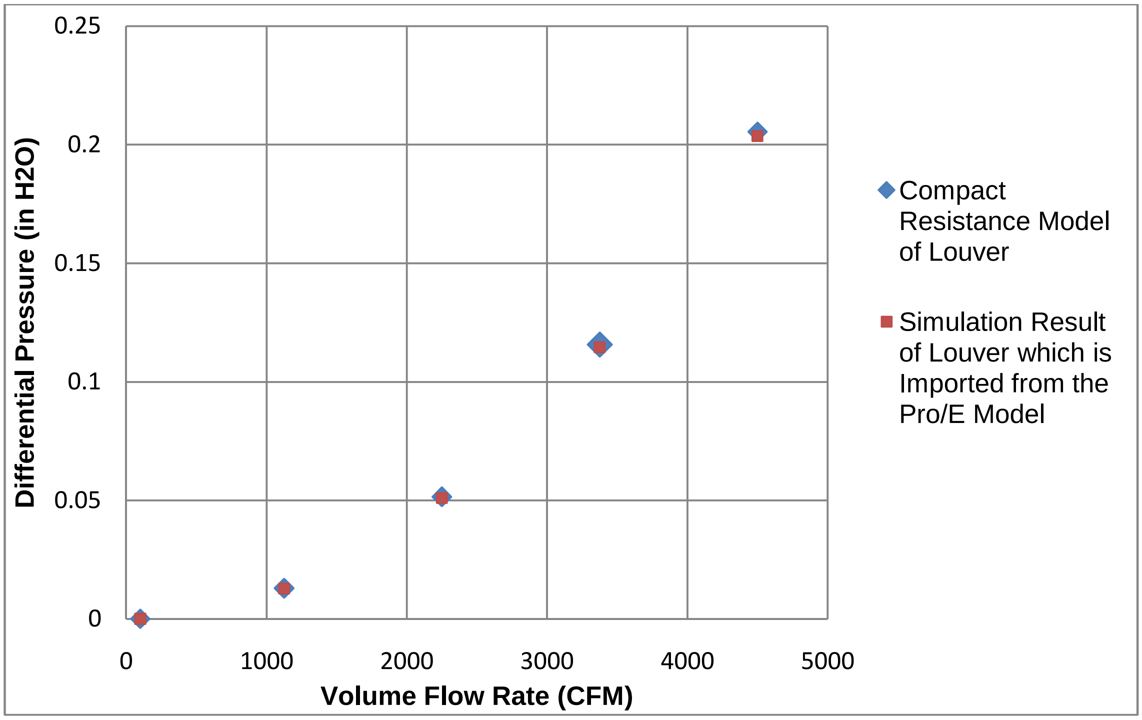

Figure A.3: Comparison of Louver Simulation Result with Compact Resistance Model

Table A.1: Tabulation of Simulation Results for Louver and Compact Resistance Model

	Louver Simulation	Compact Model	
Flow Rate (CFM)	Differential Pressure (in H_2O)	Differential Pressure (in H_2O)	Difference
1000	0.0001	0.0001	-0.03%
1125	0.0128	0.013	0.00%
2250	0.051	0.0515	0.00%
3375	0.1146	0.1157	0.00%
4500	0.2036	0.2054	0.00%

The Louver assembly is imported from the PRO/E model into Flotherm. A test air flow bench is modeled in Flotherm which comprises of a large rectangular duct. The louver assembly is placed at one end of the duct and a fan is placed at the opposite end. A CFD simulation is performed where in the fan supplies various flow rates across the louver assembly. Monitor points are located at the inlet and exhaust regions of the louver assembly for calculating the differential pressure at different flow rates. A system curve for the louver assembly is generated. This system curve is imported into the compact planar resistance model to replace the louver assembly.

APPENDIX B

FILTER CHARACTERIZATION

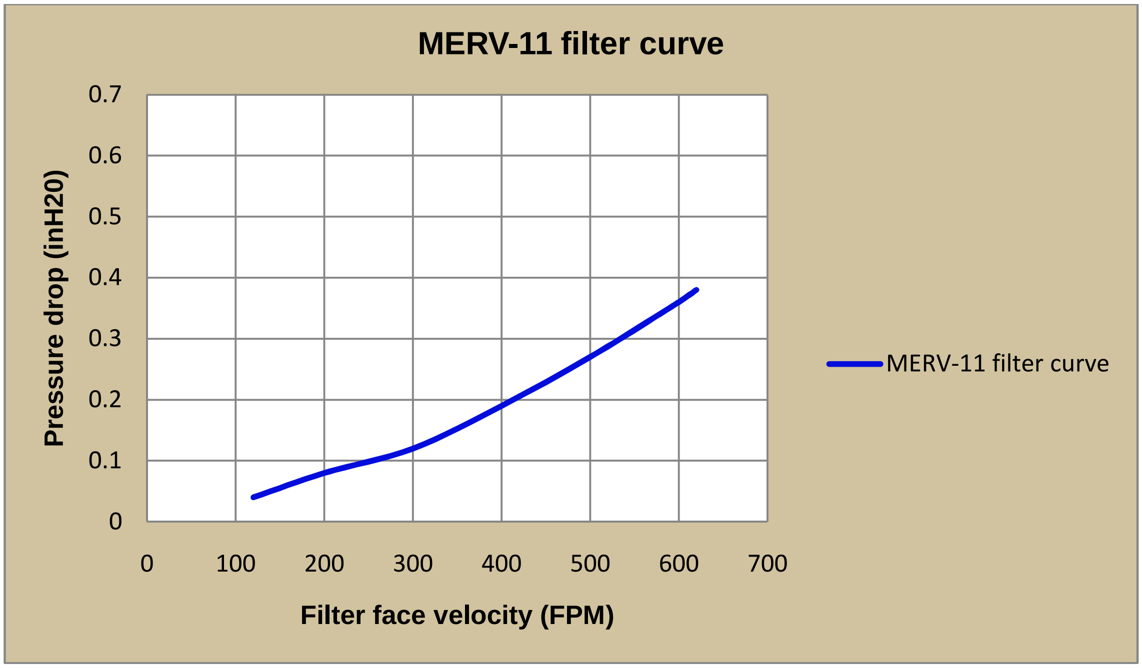

Figure B.1: Filter System Curve

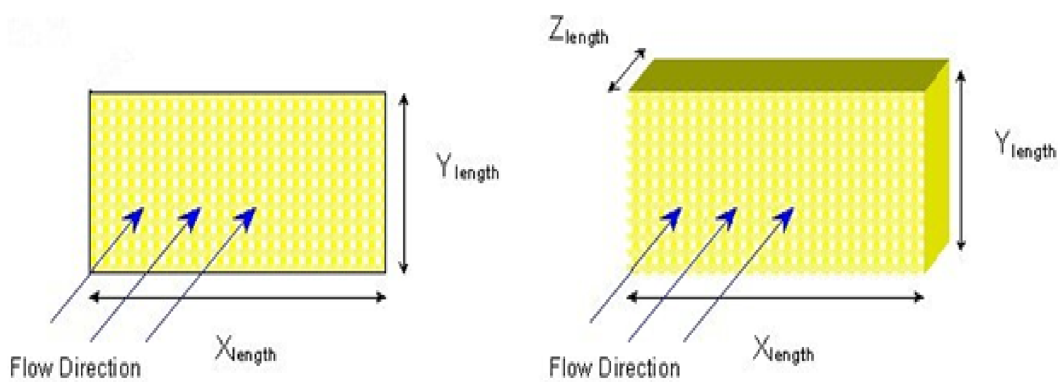

Figure B.2: Planar and Volumetric Resistance Models [43]

The system curve for the filter is determined experimentally by performing a wind tunnel test. The system curve is then imported into Flotherm's advanced resistance macro model which is used for calculating coefficients "A" and "B". These coefficients are imported into the volumetric resistance model which is used for representing the filters. Figure B.2 shows the planar resistance and volumetric resistance smarts available in Flotherm. The Flotherm solver solves the pressure drop equation [43] when the advanced resistance model is used.

$$\Delta \boldsymbol{P} = \boldsymbol{f}\left(\frac{\boldsymbol{\rho v^2}}{\mathbf{2}}\right)$$

Where $\Delta \boldsymbol{P}$ denotes the pressure drop and f represents the loss coefficient.

$$\boldsymbol{f} = \frac{\boldsymbol{A}}{\boldsymbol{R_e}} + \frac{\boldsymbol{B}}{\boldsymbol{R_e}}$$

$$\boldsymbol{R_e} = \frac{\boldsymbol{\rho l v}}{\boldsymbol{\mu}}$$

Where $\boldsymbol{R_e}$ denotes the characteristic Reynolds number, $\boldsymbol{\mu}$ denotes the dynamic viscosity and l represents the characteristic length.

Finally, the pressure drop equation becomes [43]:

$$\Delta \boldsymbol{P} = \left[\frac{\boldsymbol{A.\mu}}{\boldsymbol{2.l}}\right].\boldsymbol{v} + \left[\frac{\boldsymbol{B.\rho}}{\boldsymbol{2.l}}\right].\boldsymbol{v^2}$$

From the above pressure drop equation, the advanced resistance macro model calculates the coefficients of “A” and “B” using the system resistance curve; filter width, height and thickness and density and viscosity of the fluid. The fluid in this study is air.

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BIOGRAPHICAL INFORMATION

Naveen Kannan received his Bachelor's Degree in Mechanical Engineering from M S Ramaiah Institute of Technology, Bangalore, India in May 2009. He completed his Master of Science degree in Mechanical Engineering at the University of Texas at Arlington in December 2011.

Naveen has been involved in a number of projects ranging from the device level to the rack/room level. His research areas include electronic cooling, cooling of telecommunication shelters, data center cooling and modular data centers.

He has handled a number of projects such as thermal analysis of micro controllers in a quadruped robot; thermal analysis of side breathing switches; filter characterization to determine system impedance curves; vapor chamber cooling; cooling of telecommunication shelters and cabinets; and thermal analysis of modular data centers. He has worked on several industry projects during his research at the UTA.

Naveen also worked as an intern at Terremark. During the course of the internship, he primarily focused on building management systems, energy and power management systems for data center facilities. He is a member of Golden key international Honours society, ASHRAE, and surface mount technology.