IMPACT OF LOUVER ORIENTATION ON AIR FLOW DISTRIBUTION AND THERMAL MANAGEMENT OF DATA CENTERS

by

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ABSTRACT

IMPACT OF THE LOUVER ORIENTATION ON THE AIR FLOW DISTRIBUTION

AND THERMAL MANAGEMENT

OF DATA CENTERS

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Nowadays with the increasing use of technology, Traditional data centers are being replaced by the highly efficient Containerized or Modular Data centers. The cooling systems and constructional cost employed for Traditional Data centers is more and inefficient. The research intricate, about 23% of the power is consumed by HVAC cooling units and which in turn leads to increase in operational costs. Hence in order to reduce the operational costs, free cooling with Air side economizer is incorporated, compared to other cooling systems.

Airflow Distribution plays an important role in the Thermal management, if the airflow is less in quantity it may lead to unpredictable thermal performance, while too much airflow may cause the server fans to blow-off or damage to the servers. Numerous research and study has been done on the use of louvers as shading devices for residential purposes but the study on Impact of the louver orientation on Air Flow Distribution and Thermal Management is limited.

The amount of airflow allowed to pass through louvered window is function of its face velocity. The Air-Flow pattern through the louvered window is determined by the louver orientation. These two factors directed us to do a study on the Impact of the Louvers orientation on the Air Flow Distribution and Thermal Management of Data center.

The first half of the thesis will discuss design and modeling of IT equipment's including Power cooling module, Air Plenum, Data centers using commercially available CFD software. It would also segregate there Heat load specifications along with a brief overview of Free Cooling and importance of louvers. The CFD modeling and analysis will include the advantages of using a compact model instead of the detailed model.

The second part will discuss effects on the thermal performance and Air Flow Distribution for 0, 15,25,35,45 Degree Louver angle cases. However on comparing the simulation results for different angle cases, we find with the increase in the Louver angle, re-circulations are incurred which in turn affects the Thermal management inside the IT equipment's. The system is optimized comparing different louver angles.

The study was done in collaboration with an industrial partner and such of the results have been adopted in various cooling systems.

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CHAPTER 1

INTRODUCTION TO MODULAR DATA CENTERS AND LITERATURE REVIEW

1.1 Data Centers

Data Center is "IT Equipment" which can execute functions like store, process, manage and interchange alphanumerical data and information either individually or simultaneously, in order to effect communication. Along with the fast progress in the economies, industries, technologies around the world, there is an epitomic development in the information management systems. In today's world, basic activities like payment of utility bills, shopping, fund transfer, travel booking, etc. happen online. To affect this, IT equipment's are bound to have high computing abilities, fast networking and large storage capacity [1].

A substantial revolution has been seen in data center facilities, over the years. This makeover of the data centers includes, conversion of tedious and of low density site-constructed traditional data centers into flexible, integrated and speedily deployable modular data centers. These modular data centers are built up of integrated, pre-engineered, and pre-fabricated building units along with containerized platforms. As against the traditional data centers, the modular data centers are easy and faster to deploy, needs low operating and capital costs, and can help in achieving higher density and energy redeemable targets.

Modular data centers are 60% faster to deploy as compared to the deployment period of traditional data centers, also they avoid a capital investment of minimum 13% which is the cooling infrastructure and power cost in the traditional data center. As compared to Traditional data centers, modular data centers require low maintenance and are considered to be highly efficient. Thermal condition inside the data center depends on the ambient temperature, humidity, location as well as the conditions inside the data center hall. Servers emit large amount of heat in the surroundings and hence thermal management is important at the device as well as system level [1].

Sun Microsystems, in January 2007 launched the first modular data center in market and was called as “project Black box”.

Fig 1.1 Modular data center by Sun Microsystems [2]

This data center was considered to be a computing powerhouse with a configuration which would place it in the range of top 200 fastest supercomputers in the world. The data center was built in a standard 20-feet shipping container and was packaged with upgradeable, integrated units and equipped with state-of-the-art cooling, monitoring and power distribution systems [2].

1.1.1 Traditional Data Center

The common name for traditional data centers is “site-constructed, fixed structures”, and “brick-and-mortar” buildings. The traditional data centers are generally constructed by the local trade labor and are customized to include various design techniques like, low- and high efficiency architectures and innovative and non-innovative ways for cooling, power distribution and other utilities within the data center [3].

Except the development in the ways of construction of the traditional and modular data centers, there are certain elements which remain common in both the types and they are called as core facility areas (CFAs). These CFAs are as named below:

- Information technology (IT) payload or data hall areas
- Infrastructure or support areas
- Ancillary areas

The data centers are like the rows of the building blocks, these blocks effects smooth operation of the IT equipment's by making available storage and processing capacities. These blocks also provide essential services and capacities to fulfill the needs of the data center itself, of its occupants, of its regulatory units and of various other parts.

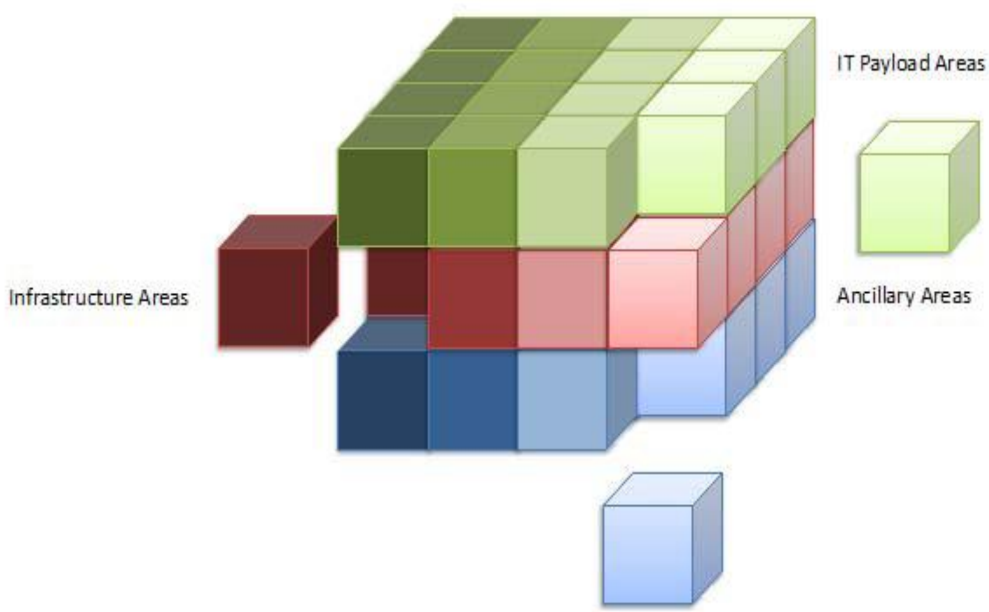


Fig1.2 Many interrelated parts make up a facility's whole

Table1.1 Types of CFAs [3]

Core Facility Area	Definition	Description
Payload/data hall	The portion(s) of the facility that provides the underlying spatial area to house data processing and communications equipment.	• May include: • Whitespace Racks and cabinets (traditional and self-cooling) • Power distribution within, between, and to the racks • Room and rack-level cooling, humidification, • Lighting and other general services • Fire detection and other life-safety services and dehumidification systems
Ancillary areas	The portions of a facility that can be regarded as the spaces that represent the "overhead" required by practice, business need, or code to be able to occupy and operate the facility	May include: • Workspaces, staging areas, and network operations centers (NOCs) • Storage areas and stockrooms • Common areas Bathrooms, break rooms, and kitchens • Reception areas Lifting equipment and people-moving apparatus • Parking facilities • Security and safety equipment and zones (including mantraps and protection layers), blast zones, and other similar capabilities and areas

1.1.2 Modular Data Centers

Modular or Containerized Data Centers as they are widely known, consists of a group or groups of integrated pre-engineered and pre-fabricated modular blocks which can be transported to the customer's site and assembled to provide the requisite payload capacities and equipped with proper cooling and power distribution facilities.

The modular and traditional data centers can be differentiated in simple words as, traditional data center is equivalent to buying the structures and sheets and then fabricating it at backyard while, modular data center can be called as a pre-fabricated shed procured readily and put at backyard which can be made functional within few hours [3].

The pre-fabricated and pre-engineered modular data centers have many undeniable advantages as below:

- The reliability and veracity of the modules can be judged and modified for required efficiency.
- The airflow and cooling infrastructures can be modified for better performance and efficiency.
- Tight management of set point and inlet temperature of the device helps in reducing the energy required for cooling substantially.

Fig1.3 HP Modular data center

Fig shows a HP modular data center similar to Google modular data centers. Modular data centers are designed in such a way that they can be rapidly deployed, high energy efficiency with high density computing to data center capacity as compared to traditional data centers.

1.1.3 Modular Data Centers Vs. Traditional Data Centers

Table 1.2 Traditional and modular data center comparison

Sr. No.	**Factor**	**Traditional data center build out**	**Facility module**
1	Time to deploy	12 to 24 months represents a typical timeframe Can be designed, delivered, installed, and operational within	8 months or less
2	Cost to deploy	High up front capital cost with extensive field assembly, installation, and integration	Allows data center to be built out in large kW building blocks of pre-manufactured power and cooling capacity
3	Regulatory roadblocks	Regulatory approvals on an ad-hoc basis for the various steps of the infrastructure layout. This approach often results in delays that impact the initiation of downstream construction. The end user is responsible for securing approvals.	Data center owners who choose to install facility modules should check with local authorities prior to installation. Permitting processes may vary greatly across different geographies.
4	Security	Physical security is enhanced when assets are located deep within the building, away from the outside perimeter	Location of physical infrastructure assets outside of the building increases exposure to outside physical security and weather threats
5	Installation	From a physical infrastructure perspective, a retrofit can be more complex and more invasive than a build out of a new data center.	Specialized equipment (such as a crane) is needed to maneuver 20 and 40 foot pre-configured facility modules..
6	Tax implications	Recognized as permanent part of the building	Temporary structure which can be more attractive from a tax perspective

Table 1.2- continued

7	Reliability	The solution is assembled on site from various parts and pieces provided by multiple vendors. This increases the need for coordination and therefore, creates more chances for human error.	More predictable performance because components are prewired and are factory acceptance tested before shipping. Smaller modules reduce risks of human error:
8	Efficiency	Existing structures often limit the electrical efficiencies that can be achieved through optimized power and cooling distribution; complex custom configured controls often result in suboptimal cooling operation, reducing efficiency.	Facility modules can utilize standard modular internal components and can be specified to a target PUE.
9	Carbon footprint	Construction materials utilized are high in carbon emissions. Brick, insulation and concrete are all carbon emission intensive materials. Concrete is often used for floors, walls and ceilings.	Steel and aluminum produce about half the carbon emissions of concrete. Concrete is only used to pour a support pad. Significantly less concrete is needed for facility modules as opposed to a comparable "building shell' data center.
10	Serviceability	Traditional data centers have more room for service people to maneuver.	Servicing is more limited with facility modules because of space constraints.

Modular Data Centers have better computing ability at a lower cost than the traditional data centers, are more energy efficient and are deployable faster.

1.2.1 First Generation Modular Data Center

The data centers that need external cooling set ups for the cooling effect are called "first generation" modular data centers. The chilling effect is with the help of cooled water supply or by on-board direct expansion cooling units. The typical data center layout consists of It equipment's stacked in rows over the length of the containers leaving an aisle between the racks and the cooling set ups for manual access. The modular data center by Sun Microsystems, now Oracle had a distinctive layout in which the IT equipment's were stacked with face-to-back on either sides of the central aisle. The air was passed from the back of the racks, through the cooling set ups and then to the face of the stacked It equipment's [2].

Fig 1.4 Oracle Sun Modular Data Center, Featuring a Unique IT Rack Layout [2]

1.2.2 Second Generation Modular Data Center

The second generation modular units have been designed with integral cooling setups. The cooling is achieved by the free cooling techniques such as evaporative cooling, chilled water coils, or DX cooling units. The cooling units are "single pass through", to facilitate intake of outside cold air on one side of the unit and exhaust of hot air on the either side [2].

The single pass through cooling is possible only with linear stacking arrangement of the modular units and this gives plenty accessible areas around the racks. The airflow is continuous and leakage of the air is avoided by placing the racks compactly.

Second generation units are provided with ducts and structures to allow sufficient amount of outside air into the cooling setup. The famous examples of second generation modular data centers are HP's POD's, IBM's PMDC and SGI's ICE Cube.

Fig 1.5 SGI Ice Cube Air Modular Data Center Featuring Air-Side Economizer Cooling [2]

The second generation modular data centers are modified first generation units with a sophisticated cooling technology. The capital cost and the operating cost of the second generation unit is noticeably lower than that of the first generation data centers. The use of free-cooling techniques such as air-side economizers, water-side economizers and miscellaneous units reduces the energy consumption which is otherwise required in the traditional cooling methods. (6)

Table 1.3 Comparison of Primary Attributes [2]

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 Centers Considerations

Various factors like application, efficient cooling setup, power requirement, IT infrastructure and many more are to be thought about before purchasing a modular data.

1.3.1 Cooling Techniques

Apart from traditional cooling systems which involve compression and expansion of the refrigerant, there are many other economical cooling techniques being used today. Techniques like air-side cooling, water side cooling and miscellaneous cooling are widely being preferred over traditional cooling due to substantial low operating cost, as the refrigerants used here are freely available almost throughout the year. But when the atmosphere is not suitable for air-side cooling, other techniques along with conventional cooling are to be used. Water-side cooling and miscellaneous setups like tower chilled water, water-cooled chiller combined with tower chilled water, air-cooled chiller, DX compressor cooling are used when the atmosphere is not favorable for air-side cooling .

Factors like lowest temperature for inlet water in cooling system of an IT equipment, humidity requirements and control, energy requirement for circulation of cooling air in the IT equipment, pumping energy for refrigerant, specifications for heat insulators in modular units, DC power required, and part load energy efficiency and controls are to be concerned while selecting a cooling system for a modular data center [6].

Table 1.4 Five Key Cooling Requirements [7]

Requirement	**Description**
Scalability and adaptability	Cooling system requirements are difficult to predict and are generally oversized in hopes of meeting future demand, since it is difficult to add cooling capacity to an existing space. Loads are frequently changed without knowing if cooling has been affected.
Standardization	Customer engineering is time-consuming, expensive, and a key source of later quality problems partly because of the numerous vendors involved in a typical installation. The planning and unique engineering involved takes 6 to 12 months, which is too long compared to the planning horizon of most organizations. It is difficult to transfer knowledge gained from uniquely engineered systems, as customized solutions lead to customized problems.
Simplification	Complex cooling systems lead to a greater likelihood of downtime due to human error, particularly when repairs are complex and time-consuming. In addition, it is difficult to plan and verify redundancy when dealing with customized cooling solutions.
Intelligence	The temperature from rack top to bottom can vary up to 18ºF (10°C), placing unexpected stress on individual items of IT equipment, which can result in premature failure of equipment.
Management	Traditional cooling management systems rarely provide information that helps in diagnosing faults at the component level, with reported data often bearing little relation to actual symptoms. Cooling performance data is often not summed from separate CRAC units, providing poor insight into overall system performance.

1.3.2 Additional Considerations

- Fire Detection and Suppression

It is a crucial aspect and requires intensive planning while deployment of a modular data center facility. Taking this into consideration, CMFDs are designed to restrain fire, prevent it from spreading, and reduce the damages due to smoke. Refurbishment of these facilities due to fire damage is comparatively easy and takes short time than traditional data centers [3].

- Supply Chain

  Availability of the manpower for various phases of the modular data center lifecycle is an essential parameter while considering a CMFD. The phases include design, delivery, deployment, operation, repair, refit and removal [3].

- Corporate Image

  Owning a data center is can help gaining publicity, but this publicity can be either positive or negative. Being a trend setter can be prestigious but any failure in deployment can ruin an organization’s reputation [3].

- Reliability

  Modular data center’s deployment depends on factors like applications and requirements in an organization, geographic location of installation site, and the atmospheric conditions at the site. Natural factors like temperature range, relative humidity range, rain, wind, and snow exposure, extreme weather such as tornadoes, hurricanes, gales, etc. play an important role [3].

- Transportation Consideration

  Transportation is an important factor in deployment of a modular data center. CMFDs can be built up at a site or can be manufactured at one place and then deployed at different site [3].

- Site-Selection Considerations

  Selecting a geographic location for installation as well as site-placement i.e. total land availability for CMFD has an impact on the operations of a data center [3].

- Environmental and Energy Efficiency Considerations

  Availability of chilled water supply distribution systems, energy supply and backup energy is to be analyzed and if lacking then the suitable infrastructure is to be provided before deployment [3].

1.3.3 Attributes of Modular Data Center

Traditional data centers are huge in size and hence require large amount of energy for cooling as the area to be cooled is big. Conventional techniques of cooling like chilled-water systems are used as free cooling of huge area is not practical. Modular data centers being more compact can be cooled efficiently by free cooling techniques and hence are termed as economical and energy efficient [3].

Benefits of Energy efficient Modular Setups:

- The calculated Power Utilization Effectiveness (PUE) value is low.
- Extremely chilled water supply can be used at intake of cooling systems.
- Fans with variable speeds and effective controlling and monitoring devices are used to check and control the equipment temperatures and air supply requirements.
- The hot aisle/cold aisle is restrained in a better manner which resulted in reduced amount of flow rate and fan power supply.
- Free cooling techniques which are more economical and efficient can be used at stack levels and results in low energy utilization for cooling.

1.4 Literature Review

Nakao et al [8] modeled data center cooling designs in their study. There are four different patterns. They included under floor supply with horizontal exhaust, overhead supply with horizontal exhaust, under floor supply with ceiling exhaust and overhead supply with ceiling exhaust.

Zac Potts [9] studied the different free cooling technologies in the datacenter applications. This review paper compares the four different free cooling technologies. The direct air side economizer, indirect airside economizer, water side economizer, evaporative cooling are the technologies compared. . Power usage efficiency, cost and the suitable applications are being discussed. This paper aims to be a starting point for important free cooling technologies.

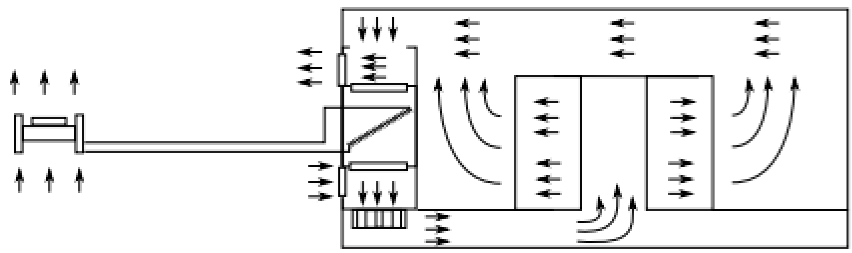


Fig 1.6 Simple Direct air economizer with Supplementary DX [9]

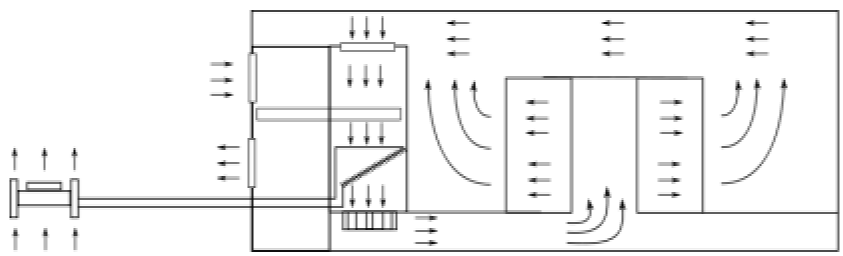


Fig 1.7 Simple representation of a heat wheel based indirect air economizer [9]

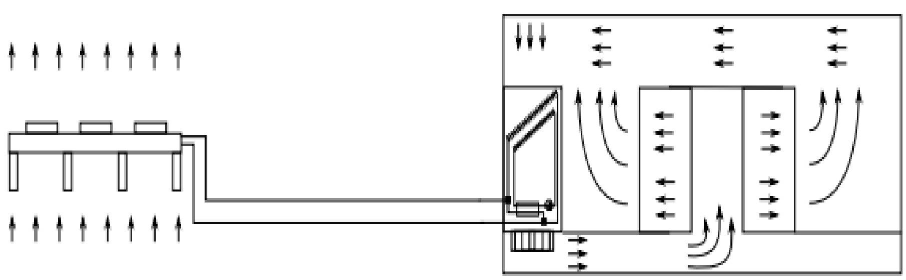


Fig 1.8 Water cooled, free cooling CRAC unit [9]

Water cooled; free cooling CRAC Unit, incorporating the free cooling and DX loop within the CRAC unit and rejecting heat through an external dry cooler.

Shehabi A et al [10] compared the energy implications of conventional datacenters with newer technologies exploiting waterside and air side economizers in his study. The technologies were employed in five different climatic zones in the state of California. The result of the study indicated that performance of the airside economizer is consistently better than the air side economizer in all the climate zones.

Saket karajgikar et al [11] studied the performance of airside economizers in different scenarios. The Numerical models using air side economizer were designed. The first model included the conventional datacenter with CRAC units to supply from under floor plenum. The other three models represented datacenter with airside economizer for bringing in outside air into the datacenter. For all the four models the dimensions of the system, heat load, flow rate, rack layout percentage of open air ratio for the tiles are the same. These models were analyzed at certain operating conditions for their performances. The three models were air side economizer were used indicated better results in terms of energy savings than the conventional model with CRAC unit.

Daniel Kennedy [12] has done a review of the economized datacenter cooling in industries that are prevalent. The paper aims at determining the factor responsible for the free cooling to be implemented. The impact of increased supply water temperature and impact of increased supply air temperature is compared for the waterside and airside economizer respectively for five datacenters. The annual hours of operation in five datacenters namely California, Philadelphia, Phoenix, Illinois, Georgia and New York are monitored and the results denoted that the cooling system is highly dependent on the geographical location.

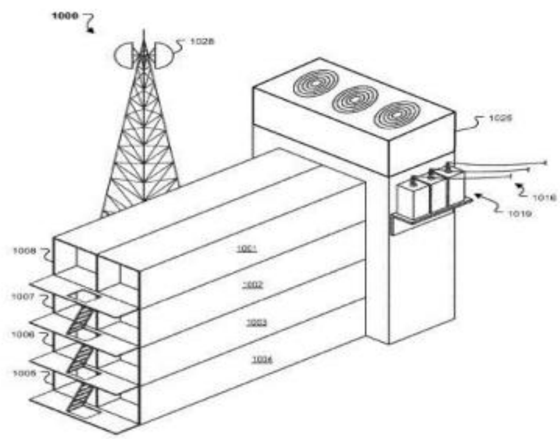


Fig 1.9 Stacked Data centers by Google [13]

Jimmy Clidaras et al [13] developed a model for modular datacenters. This included the shipping containers coupled to each other and stacked one above the other. Each shipping containers would include number of processors or servers. The stacked containers have a separate docking station to which the containers are connected and power. The cooling fluid supply, cooling fluid return, network connectivity is configured according to the containers. The docking stations are power up from a central power spine. The cooling technology comprises of two heat exchange circuit. The primary circuit takes care of the heat transferred from the server to the heat Exchanger and the secondary circuit the cooling fluid supply and cooling fluid return.

Deepa Chandrashekaran et al [14] studied the airflow through the louvered openings. The objective of the research finds the effect of velocity of the air flow on the louvers slats at different angles. A smoke machine was considered to find the airflow angles inside the louvers. The air velocities were tested on four different angles 0, 15, 30 and 45 degree from the horizontal. The results from the experiments were compared to the CFD simulations. There is an accelerating trend in the velocities for the louver angles 0, 15 and 30 degree and slightly slower velocity at 45 degree louver angle. These results denoted that the thermal comfort is higher louver angles.

Atipoang Nuntophan et al [15] have studied the effect of inclination angle on free convection thermal performance of louver finned heat exchanger. A louvered finned heat exchanger exchanges heat between the flowing hot water in the tube side and the heat is transferred to the ambient air by free convection. The ambient temperature has been kept as approximately 27 degree Celsius with three different inlet temperatures for water. The result indicated that the most airflow is directed between the 30 and 45 degree angle of the louvered fins. The results in these particular angles further suggested that the heat transfer performance decreases with increase of the inclination angles.

CHAPTER 2

IMPORTANCE OF FREE COOLING AND LOUVERS

2.1 Free Cooling

Organizations today, are inherently dependent on their information systems for smooth operations. The failure of an IT system may lead the company to deep grievances. Reliability and security of the information in the systems is always a crucial issue for companies. To overcome the difficulties of storage and security of the large volume of data, companies are prominently relying on modular data centers. The performance and processing capacity of the servers in these data centers is a significant issue with many leading companies. Presently, Moore's Law and low cost of manufacturing have relatively reduced the prices of the servers while making them more efficient and robust, but the amount of heat radiated remains the same. Calculations say, after four years the cost of electricity required to cool the servers exceeds the purchase of the server.

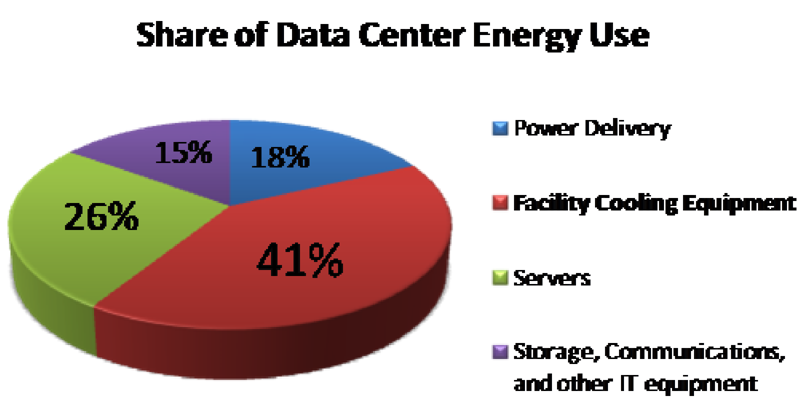


Fig 2.1 Share of Data Centre Energy Usage [16]

To trim down the cost of energy and to reduce its consumption, Free Cooling is considered to be the way out. Free Cooling is brought into effect by drawing in outside cold air and throwing it out, after circulating it through the heated server racks. Free Cooling sidesteps the air conditioner required in Traditional Cooling system [17]. Though economical, but because of the dependence of the free cooling systems on the ambient air temperature, it cannot replace the mechanical cooling systems completely.

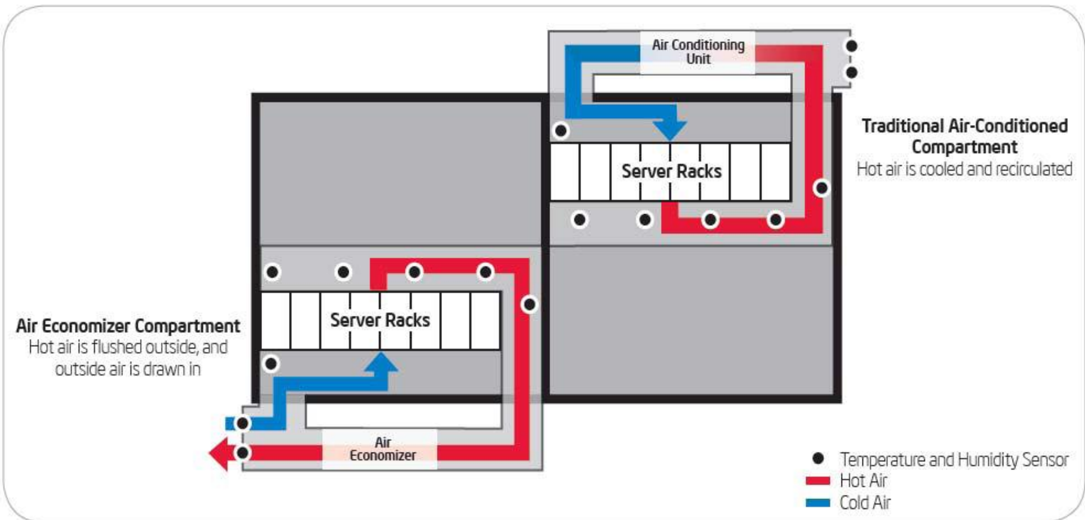


Fig 2.2 Schematic detailing of the difference between Free Cooling and Traditional Cooling [17]

2.1.1 *Types of Free Cooling Systems*

The main types of free cooling systems are air side cooling and water side cooling. Another system called miscellaneous cooling system which consists of ground water cooling and sea water cooling are also being used widely. As shown in Fig 2.2, the air side cooling mechanism includes sucking of the cold atmospheric air and circulated through the heated servers and electronic components and the heat is thrown outside. This process needs large amount of cold air to be taken in and huge ducts to circulate the air, to cool the data centers. Practically, pulling in such a volume of air and filtering it to avoid the entry of impurities like dust, moisture, etc. is pretty difficult. Also it adds to the installation of huge fans to suck in the huge quantity of air and also needs the periodic replacement of the filthy filters to avoid the resistance to air flow into the server racks [18].

2.1.1.1 Air Side Economizer

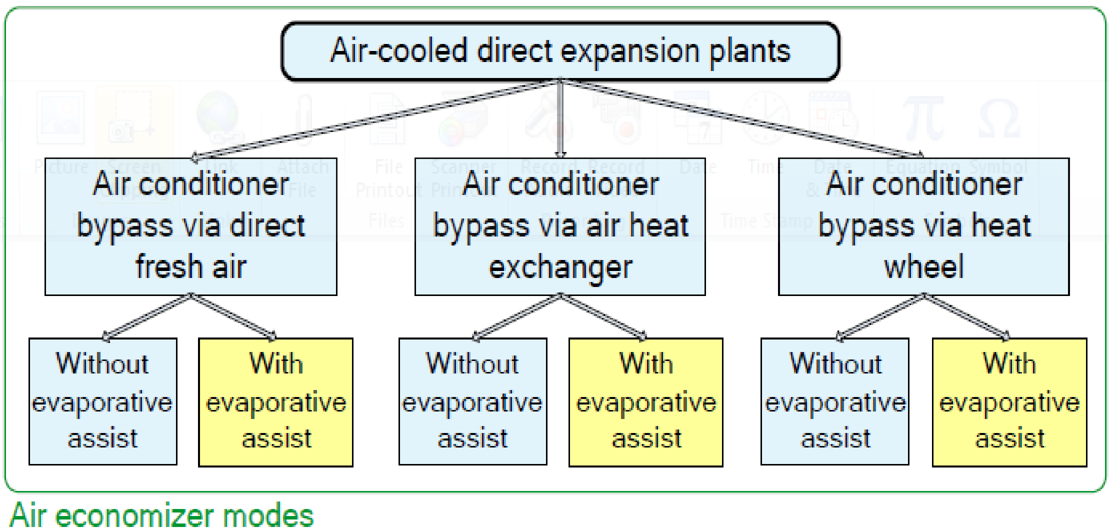


Fig 2.3 Air Side Cooling types [18]

2.1.1.1.1 Air conditioner bypass via direct fresh air

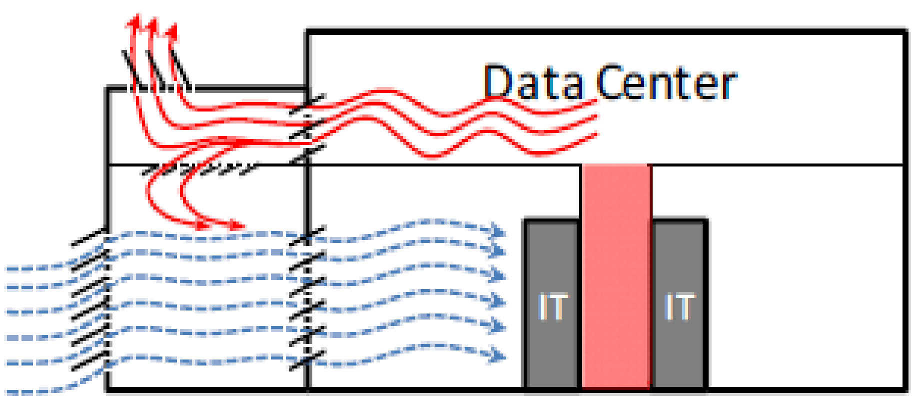


Fig 2.4 Air conditioner bypass via direct fresh air [18]

An air economizer mode draws the cold outside air into the data center through a frame of louvers, filters and fans. When outside air is within the acceptable range, then this cold air is drawn in directly into the data center. The amount of air to be directed into the data center can be controlled by these louvers and dampers. The amount of hot exhaust air, that is exhausted into the atmosphere or the amount of hot air to be mixed to the cold air in order to get the outside cold air within the acceptable range can be done through louvers [18].

When the outside air temperature is hot than the acceptable range, it can be used with the evaporative assist such as cooling pads. In this the dry outside air is passed through the wet cooling pads, which can lower the temperature by up to 19 degree Celsius and this results in increase in economizer mode hours. This type of air side economizer mode is dependent on outdoor humidity [18].

2.1.1.1.2 *Air conditioner bypass via air heat exchanger*

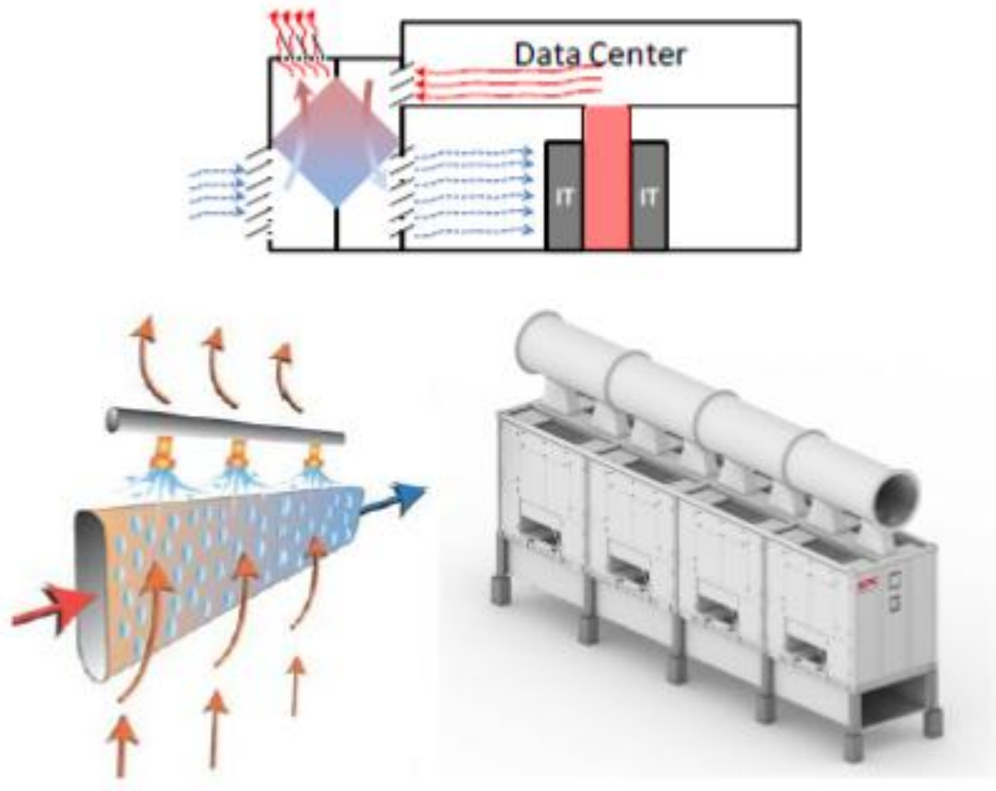


Fig 2.5 Air conditioner bypass via air heat exchanger [18]

This type of economizer mode uses fans, Heat exchange, louvers. In this mode if the outside air temperature is within the recommended range then the outside air is indirectly used to cool the hot data center. In this case, fan draws the cold outside air and in impinges on the plates and cools the data centers on the other side of these plates. This can be used a s a full as well as partial economizer mode. If the outside air temperature is not in recommended range, then it can be used with evaporative cooling. In this case, water is sprayed on the outside of the plates which in turn lowers the outside air temperature [18].

2.1.1.1.3 *Air conditioner bypass via heat wheel*

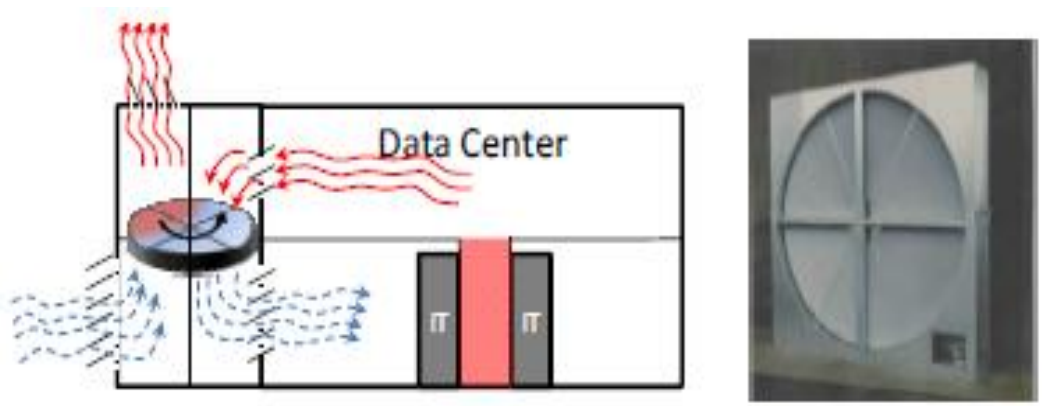


Fig 2.6 Air conditioner bypass via heat wheel [18]

This type of economizer mode uses fans, Heat wheel and pump. If the outside air temperature is within the recommended range, then fans blow this cold outside air directly into data centers. Heat wheel maintains dryer air conditions in data center. This mode can be used with evaporative cooling which in turn can cool the outside air by using a wet media pad. Heat wheels mostly depend on the material that does not allow contaminants to enter in the data center.

2.1.1.2 *Water Side Economizer*

Water side economizer avoids the cooling through compressors. The operation of the water side economizer depends on the ambient conditions. Water side economizer can be classified as follows:

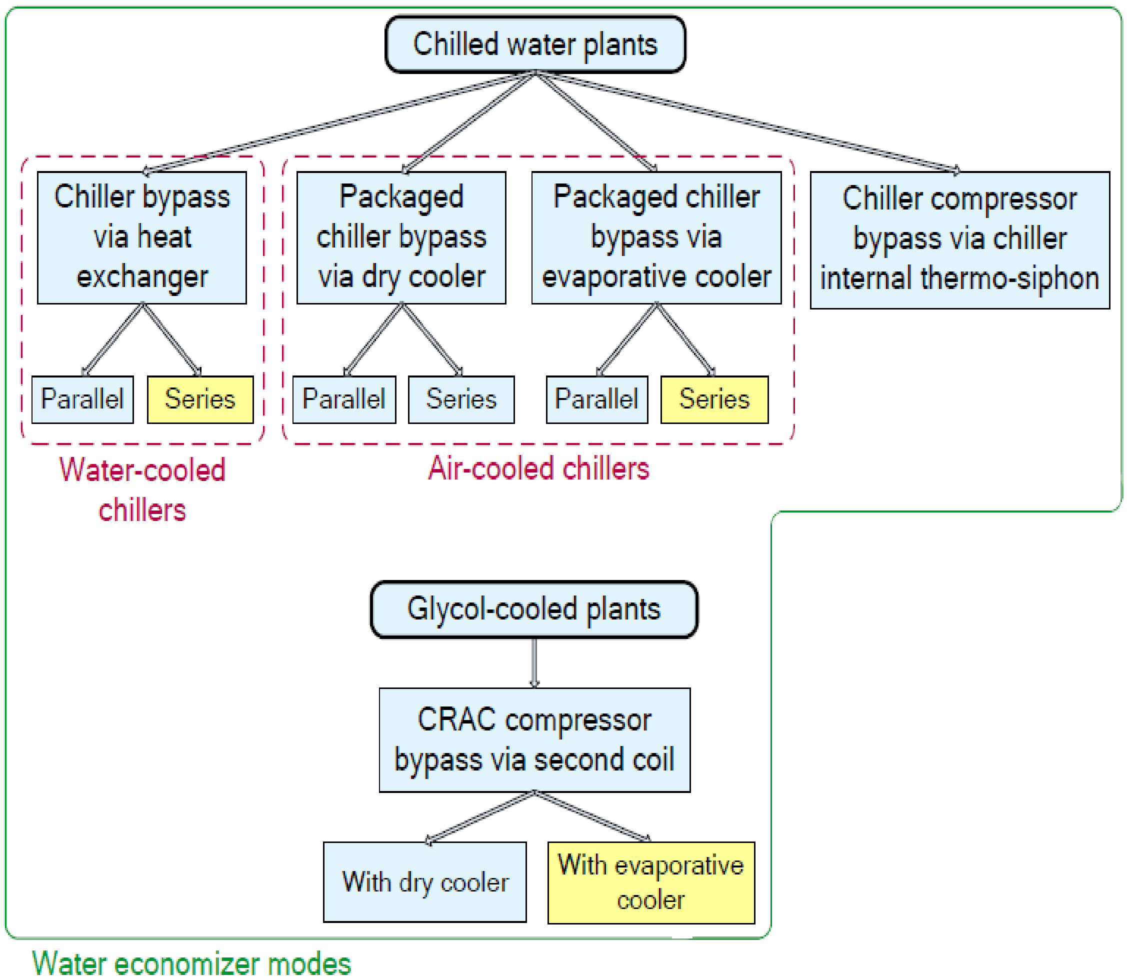


Fig 2.7 Water Side Cooling types [18]

2.1.1.2.1 *Chiller bypass via heat exchanger*

This type of economizer uses cooling towers, pumps, valves, plate and frame heat exchanger, CRAH. Basically, if the outside air temperature is within the recommended range then this type of economizer uses the condenser water to cool the data center chilled water.

Pumps causes the condenser water to move through this plate heat exchanger in order to cool the water used in CRAH unit, without mixing of water streams. Valves allow us to bypass the chiller and in turn allowing us to turn it off depending on the condenser water temperature [18].

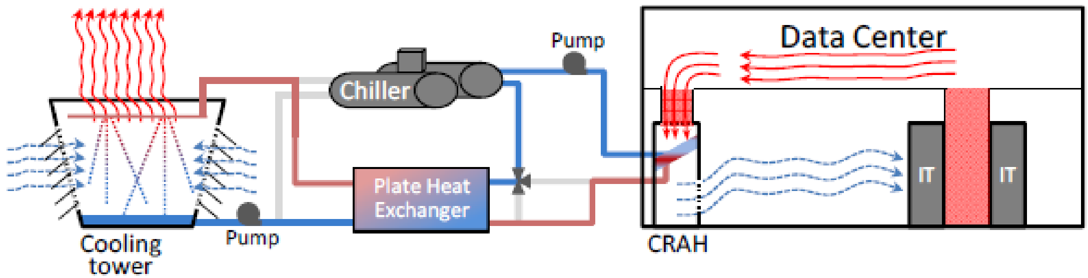


Fig 2.8 Chiller bypass via heat exchanger [18]

2.1.1.2.2 Packaged chiller bypass via dry cooler

In this economizer type, integrated dry cooler is used as a heat exchanger when the outside air is within the acceptable range. This type of economizer mode utilizes dry cooler, pump, CRAC unit with second coil such as wet media pads and valves. It can be also associated with an evaporative cooling. When the outside air is within the acceptable range, pump drives the chilled water into this integrated dry cooler, where it is cooled with the help of outside cold air and is sent back to the second coil (wet media pads) in CRAC unit. If the outside air temperature is as desired then the valves bypass the chiller allowing to turn off and or operate depending on the outside air temperature. It is considered to be more efficient type of economizer mode as compared to other modes [18].

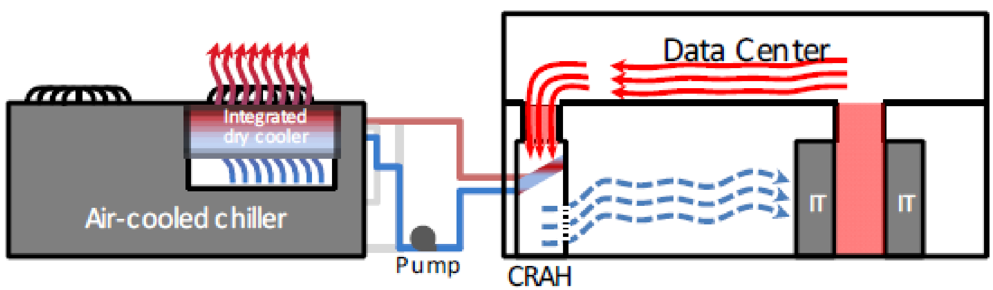


Fig 2.9 Packaged chiller bypass via dry cooler [18]

2.1.1.2.3 *Chiller compressor bypass via chiller internal thermo-siphon*

This type of economizer utilizes dry coolers or cooling towers, chillers with thermo-siphon, pump, valves and CRAH units. Chillers with thermo-siphon acts like a heat exchanger, if outside air conditions are within the desired range. Thermo-siphon helps the hot refrigerant from evaporator coil to flow into cold condenser coil naturally, where it gets cooled off and then under the influence of gravity, it gradually flows to evaporator coil. Again in this evaporator coil, it cools the data center chilled water and this process continues [18]

2.1.1.2.4 *CRAC compressor bypass via second coil*

This type of economizer mode utilizes dry cooler, pump, CRAC unit with second coil such as wet media pads. It can be also associated with an evaporative cooling. When the outside air is within the acceptable range, pump drives the condenser water through this dry cooler, where it is cold with the help of outside cold air. This cold condenser water is then supplied back to the second coil (wet media pads) in CRAC unit. In case of evaporative cooling, dry cooler has to be replaced by cooling tower or so [18]

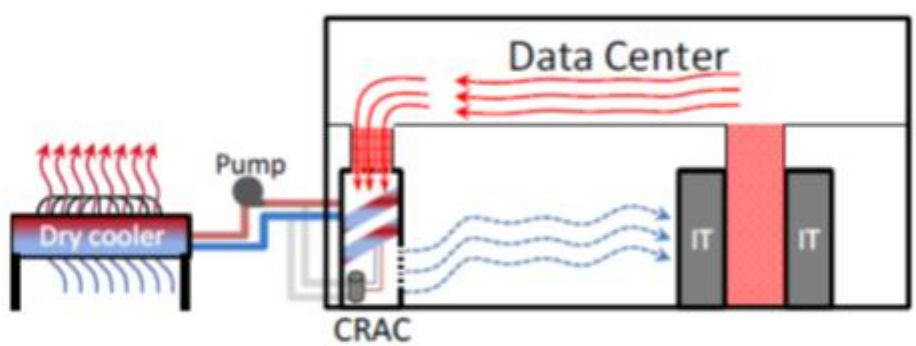


Fig 2.10 CRAC compressor bypass via second coil [18]

2.2 Introduction to Louvers

Louvers were basically developed in olden times to allow light and air in the houses and block undesirable elements like rain water, dirt, snow, debris, etc from entering the house [19]. Today, Louvers are not only used for its functionality but also to add to aesthetics of a building. Louvers of various sizes, colors, shapes and dimensions are available in markets [19]. They can be installed in numerous appearances like line, vertical, horizontal or often with mullions, and can be provided with vertical, horizontal or inverted blades, based on customer's requirements [20]. *2.2.1 Louvers: An Introduction*

Louvers are popularly used in cooling systems of high capacity data centers of IT and telecommunication companies, in compressors, etc. Louvers mounted in the engine section of a vehicle are used to block the cooling air which cools the radiators, compressors, and various components. The Louver's frame reduces the noise in the engine and provides aesthetics and safety. The louver angle is an important parameter and affects the pressure drop in the louvers while cooling the components. Various systems like Wind Tunnel System, CFD (Computational Fluid Dynamics) and LDV (Laser Doppler Velocimetry) are adopted for the measurement of the louver angle so as to increase the efficiency of louver by allowing maximum amount of cooling air in the ducts [21].Louvers are also customized to blend with architectural requirements and to provide sufficient ventilation and light. These are called as Architectural Louvers.

2.2.1.1 *Types of Louvers*

The different types of louvers available to suit the applications are as mentioned:

1) Drainable Blades Louvers: These louvers are developed with drainable blades and drainable head formed by a niche drip lip. These blades facilitate extensive free area and minimum water penetration. Every blade in the louver is equipped with drain gutter to accommodate the water from jambs and sills [20].

Fig 2.11 Drainable Blades Louver [20]

2) Non–Drainable Blades Louver:The blades have slopping sills and header frames to drain the water in jamb gutters and barely allows water penetration [20]

Fig 2.12 Non-Drainable Blades Louver [20]

3) Hurricane Louver:

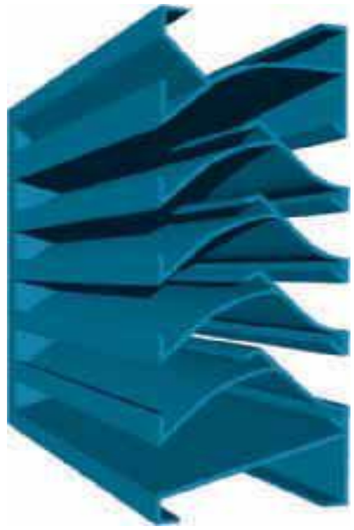


Fig 2.13 Hurricane Louver [20]

4) Acoustical Louver: These louvers consist of air foils and facilitate reduction in sound intensity along with free flow of air.

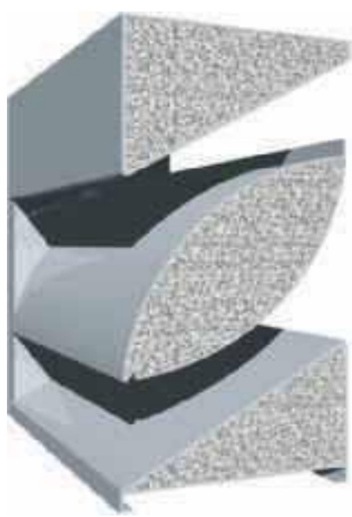


Fig 2.14 Acoustical Louver [20]

5) Adjustable Blades Louver: These louver blades can be adjusted manually, pneumatically, electrically or mechanically according to the requirements of air flow.

Fig 2.15 Adjustable Blades Louver [20]

6) Dual Combination Blades Louver (Drainable): These louvers are designed with both fixed and adjustable blades, to be operated pneumatically, manually or electrically. The blades allow maximum air flow, high resistance to water penetration, protection against weather and bare leakage of air.

Fig 2.16 Dual Combination Blades Louver [20]

7) Sight proof Blades Louver: These louvers are preferred in an application where security is crucial with an option of vertical or horizontal mounting of blades.

Fig 2.17 Sight proof Blades Louver [20]

8) Louvered Penthouse: Penthouses provides huge flow of air to fans and intake units also prevent the entry of undesirable elements. According to customer's requirements blades of various types can be mounted in penthouse louvers.

Fig 2.18 Louvered Penthouse [20]

9) Brick / Block Vents: Such Louvers are prominently used in air conditioning intake units, boilers, compressors, heating rooms, etc.

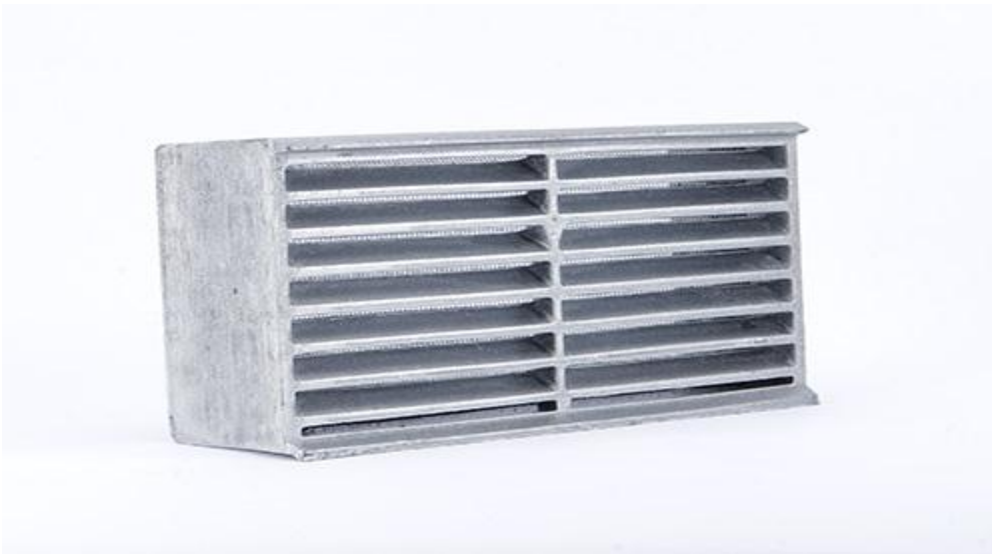


Fig 2.19 Brick/ Block Vents [20]

10) Thinline Louvers: These are designed specifically for the thin wall sections where the standard depth for louvers is not available.

Fig 2.20 Thinline Louver [20]

2.3 Criteria for Selection of Louver

_Considering the functionality of a louver, its selection is based on three requirements namely; Free Area, Water Penetration and Resistance to Airflow.

1) Free Area: A critical parameter for a louver selection, it is the minimum area available for air to flow [22]. The addition of all the unobstructed area between the binds, mullions, bars and corners forms the free area of a louver. In general, the free area of louvers varies between 35% and 60%. A high free area allows maximum air intake but at the same time less obstruction allows penetration of unwanted water. A perfect louver has maximum free area with least water penetration [19].

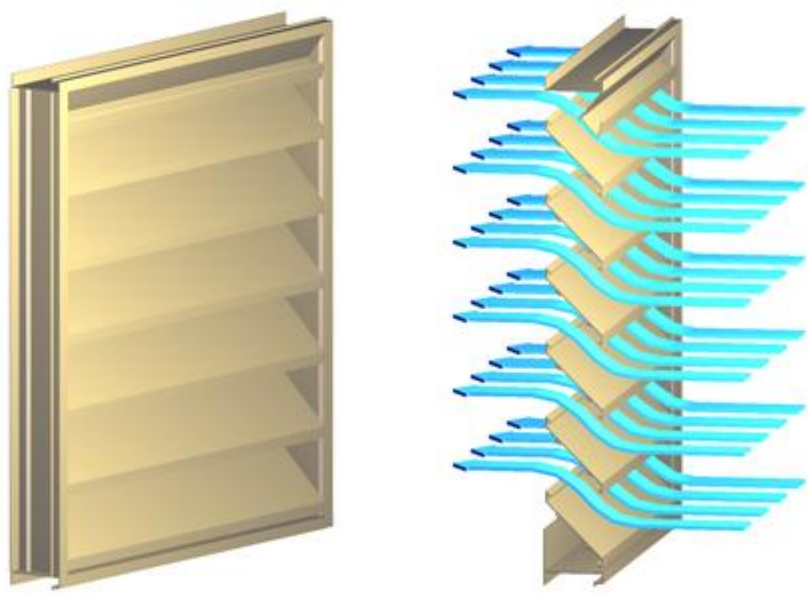


Fig 2.21 Louver Free Area

If the free area of a louver is drastically less than obstruction, then the air intake velocity increases and hence the pressure loss is more [22].

2) Water Penetration: Often water penetrates into the louver at the air intake point, due to winds or rainfalls. An efficient louver should allow minimum water to flow in. Water penetration reduces the air intake velocity through the free area of a louver.

   Traditional Louver: The First Point of Water Penetration Test showed the variation in water entrainment varied from 300fpm to 1250fpm [19].

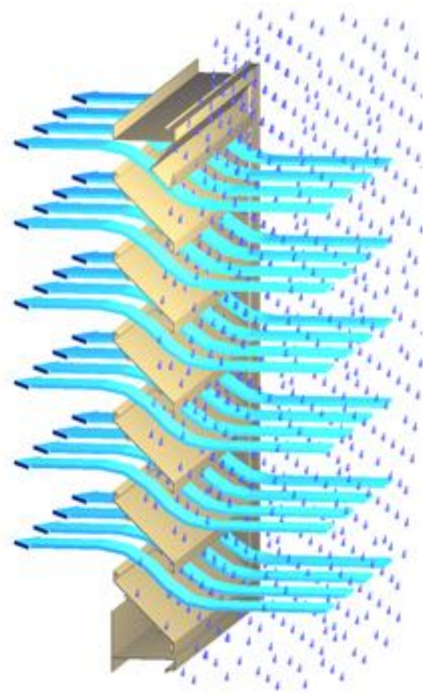


Fig 2.22 Water Penetration in Traditional Louver [19]

Wind Driven Rain Louvers: When wind velocity at a fixed rate was blown on the front of a louver, it prompted that a successful louver could block water penetration to an extent of 99%-100%, whereas failed louvers allowed 15% water entrainment. The tests to measure water penetration have fixed the volume of water and the wind velocities. The popular values are 3"/ hr rainfall for 29mph velocity of wind and 8"/ hr for 50mph speed [19].

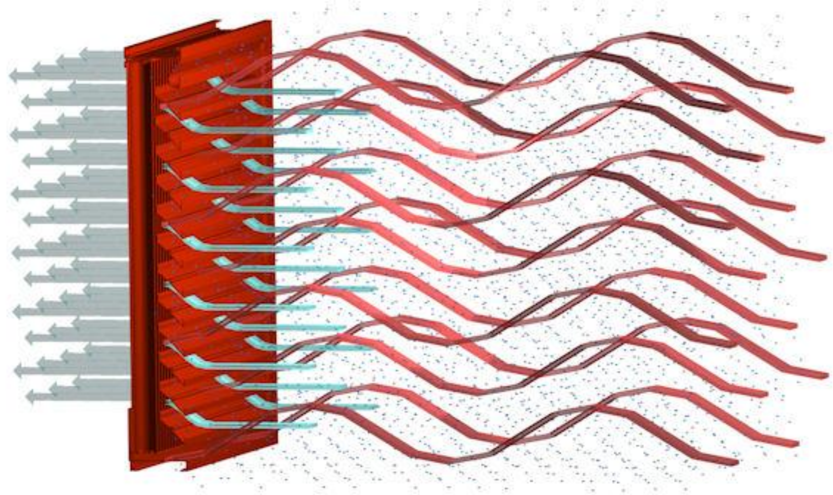


Fig 2.23 Water Penetration in Wind Driven Rain Louvers [19]

3) Resistance to Airflow: The mullions, louvers, ducts, filters, structures, etc. can create hurdle in the flow of air. The simplest way to measure the obstruction is to get the pressure parameter at different velocities in free areas. The hurdles can be reduced by lowering the blade angles or by designing better aerodynamic structures.

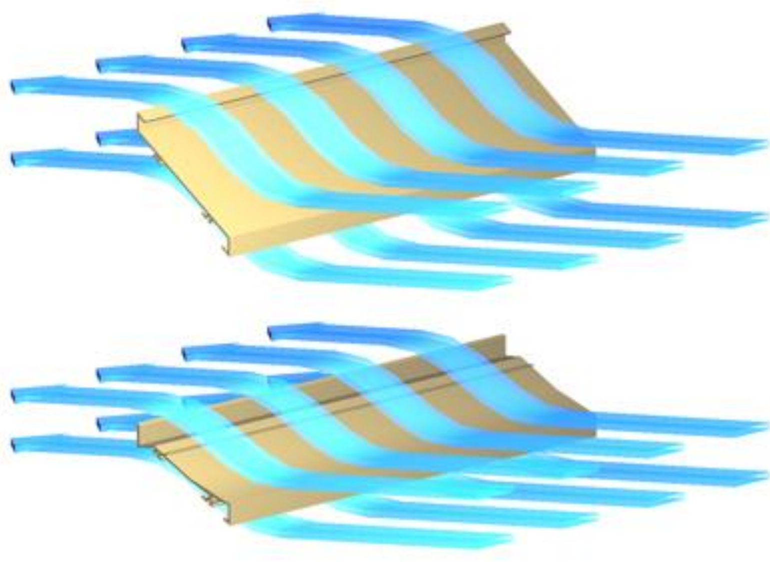


Fig 2.24 Resistance to Airflow in Louver [19]

2.4 Importance of Louvers

In present world, energy has become a basic need for a smooth life. With the increasing consumption of electricity the energy sources are diminishing drastically. Similarly, for the cooling application large amount of power is required to cool the air and components. So it is indeed a perfect way to use louvers in cooling application and save tremendous amount of energy and its cost.

Architectural Louvers have also formed an integral part of building design in many countries. Louvers in various shapes, sizes and colors prominently enhance aesthetics of the building. Eco- friendly louvers are being used efficiently in cooling and refrigerating systems across the world.

CHAPTER 3

CONTAINERIZED DATA CENTER WITH FREE COOLING

3.1 System Configurations of Containerized Data Center

3.1.1 System Configurations

Data centers comprised of racks and corresponding servers form the backbone of today's cloud computing. Continuous operation of large numbers of servers can generate large amounts of heat which in turn requires high capacity cooling systems. These cooling systems can consume a significant portion of the energy required to run a data center and can negatively impact data center efficiency.

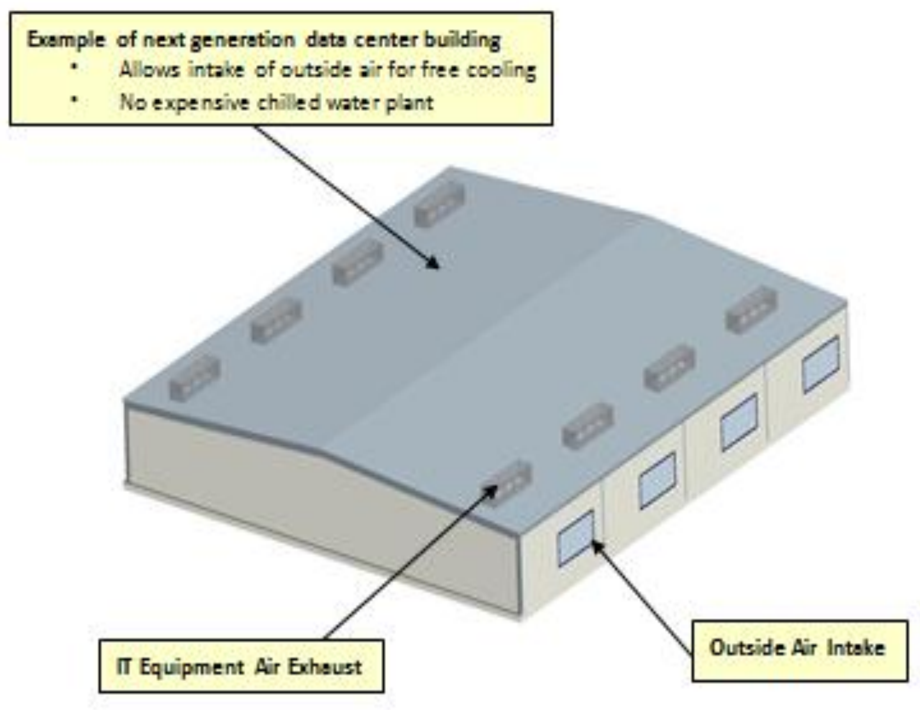


Fig 3.1 System Description with Roof

The following Fig 3.2 shows the overall system which includes the Power Cooling module, Air Plenum, and 2 IT Containers which has all the Data Centers. Fig.1 shows an enclosed building consisting of Data Centers. Since the top is removed in Fig.2, we can see 8 individual systems, with 4 on each side of the hall.

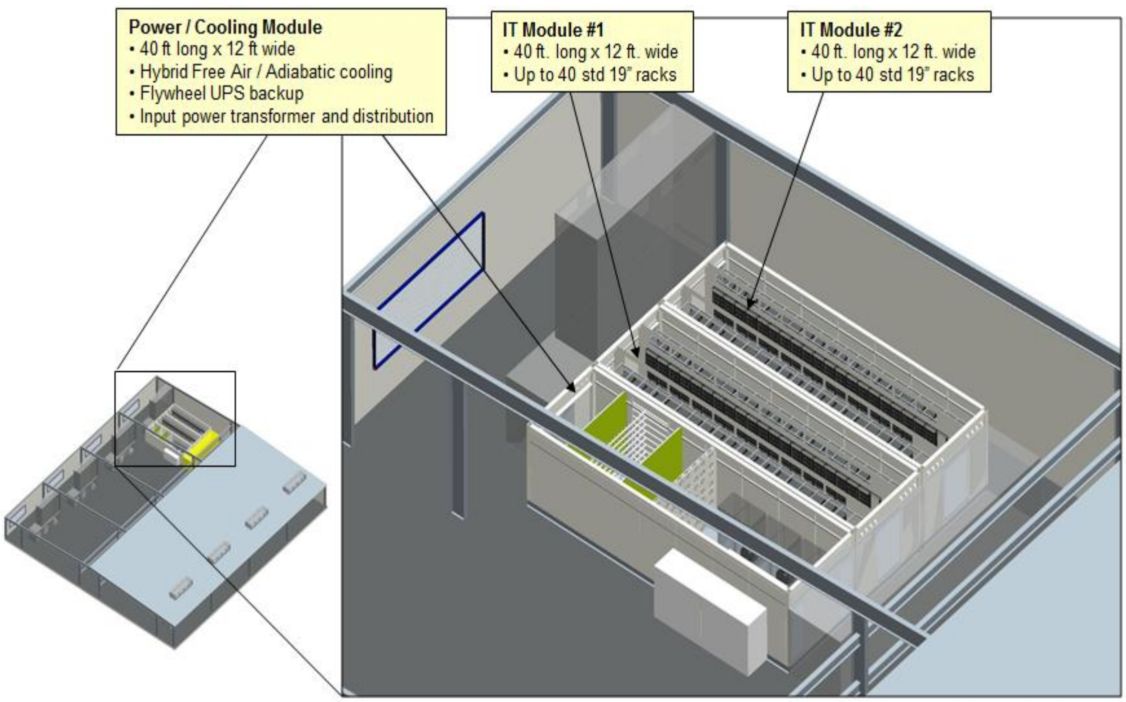


Fig 3.2 Modular Data Center with System Description

The two IT modules contain more than 5000 servers, actuator controlled louvers, and sensors needed for cooling system control. CFD analysis of the modular data center showed the importance of louver angles at the inlet of the IT containers. Air-side economizers use outside air for cooling information technology (IT) equipment completely or part of the time (coupled with traditional computer room air conditioning (CRAC) units). This system is often used in colder climates and requires less energy since it doesn't use compressors for cooling incoming air

3.1.1.1 Availability of the different Cooling Systems in Modular Data Center Model

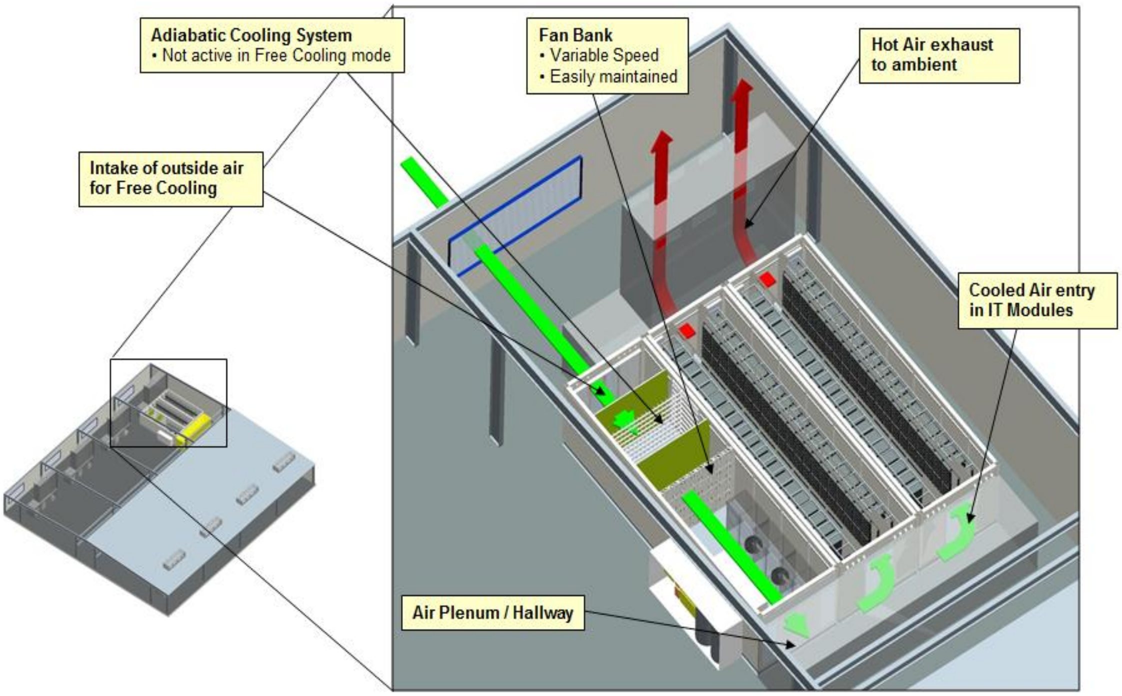


Fig 3.3 System Description with Free Air Cooling

Fig 3.3 shows a Modular data center with a Free Cooling System. In this system, outside air is blown through a frame of filters, blowers into the two IT modules containing all the Servers. The IT modules contain more than 5000 servers. These IT modules are arranged in hot/cold aisle arrangement with a total heat load of 1.2MW.

Significant research has been conducted into alternative methods that reduce cooling energy consumption and improve overall efficiency. Free cooling is one of these alternative methods studied for a particular configuration of power/cooling and IT modules in a modular data center. Free cooling is the most efficient cooling alternative for data center cooling. In this method, ambient air is introduced into the data center through filters, and is then forced by fans equipment. The heated server exhaust air is then vented back out to the ambient. This cooling method is highly effective at reducing energy consumption for data centers in cooler climates where it can be utilized for a significant portion of the year.

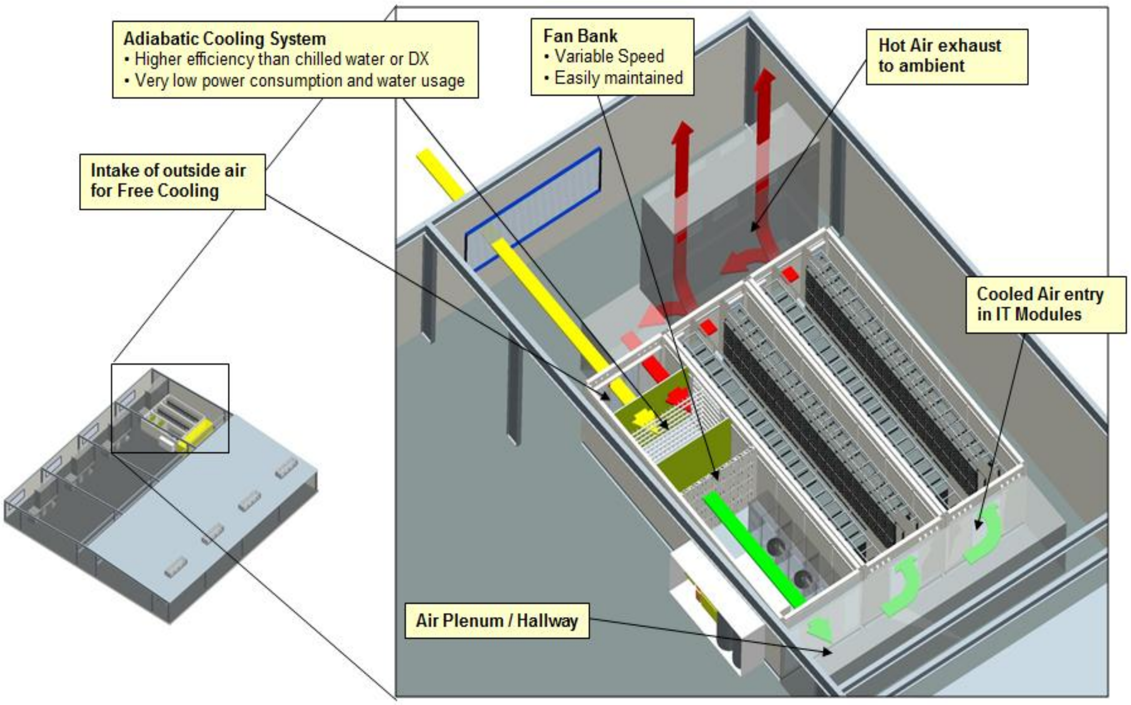


Fig 3.4 System Description with Adiabatic Cooling

Fig 3.4 shows a Modular data center with an Adiabatic cooling system. In this cooling system, the cold ambient air is mixed with the hot exhaust air. Adiabatic cooling system has higher efficiency as compared to chilled water or DX. It has very low power consumption and water usage if evaporative cooling is on. The operational cost of this system is low as it has low power consumption.

Adiabatic cooling is used when the ambient air is below the required inlet temperature. So that this mixing of cold ambient air with the hot exhaust air gets the inlet air temperature in desired range. . 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.

3.1.2 Power Cooling Module

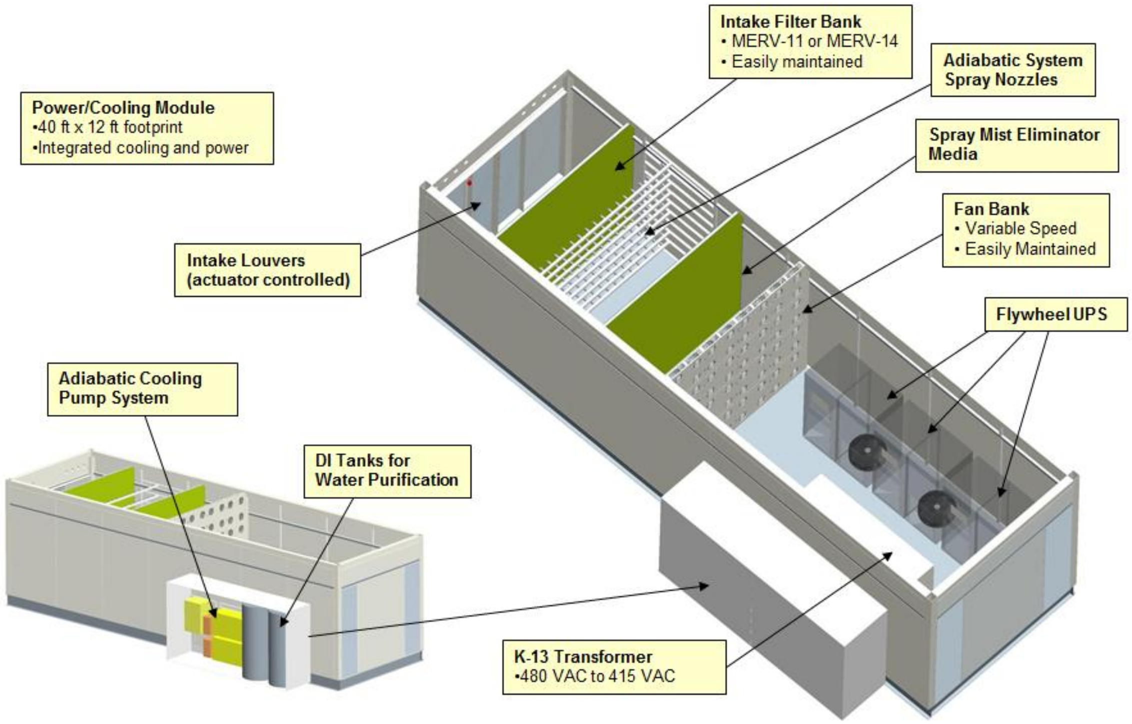


Fig 3.5 Details of Power Cooling Module

The Power cooling module is 40 feet x 12 feet in dimension. It is called as Power cooling module because it is integrated with both power and cooling system in one module. Power cooling module comprises of Intake louvers, Intake Filter Bank, Adiabatic System Spray nozzles, Spray Mist Eliminator media, fan bank, flywheel UPS.

Intake louvers are actuator controlled. The outside ambient air enters through the intake louvers into the power cooling module. This air is then passed through the filter bank to the nozzle assembly (evaporative cooling) and if required may get sprayed by the misting system. Then air passes through mist eliminators or hydrophobic filters to prevent water carryover. Now this cold air pushed through blowers into the inlet of IT modules through Air Plenum. This nozzle assembly is only used when the ambient temperature is hot and requires conditioning by spraying mist. The boundary conditions (ambient temperature and Humidity) in our model are in the desired range and hence there is no need of Evaporative cooling.

The estimated PUE with free air/adiabatic hybrid cooling system is 1.10 or less. Higher power distribution efficiency can be obtained by operating on a three phase 415/240VAC power system and by using a distribution voltage of 240VAC. Flywheel based uninterruptible power supply (UPS) system that provides backup power for up to 52 seconds for 25% loading and a minimum of 14 seconds for 100% loading.

3.1.3 Air Plenum

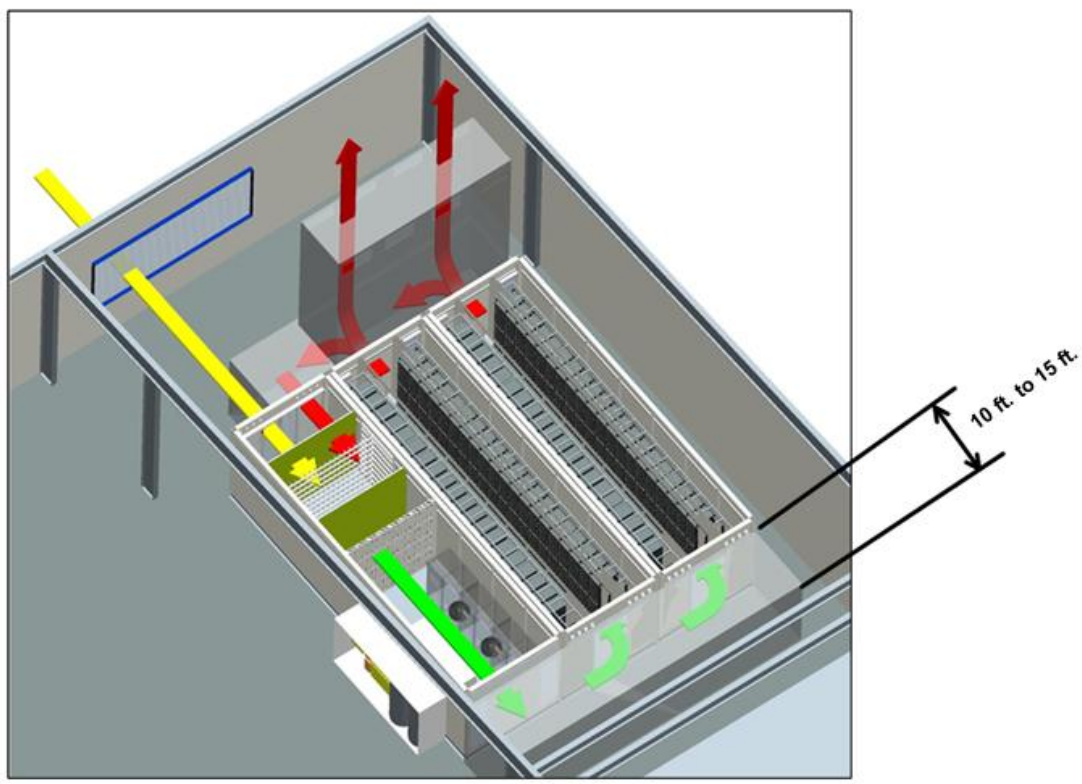


Fig 3.6 Air Plenum Depth

Air Plenum is hollow container which acts as a connecting medium in between the power cooling module and IT modules. The outside air after conditioning comesout of the power cooling module and is pushed into IT modules through Air Plenum.

3.1.4 IT Module

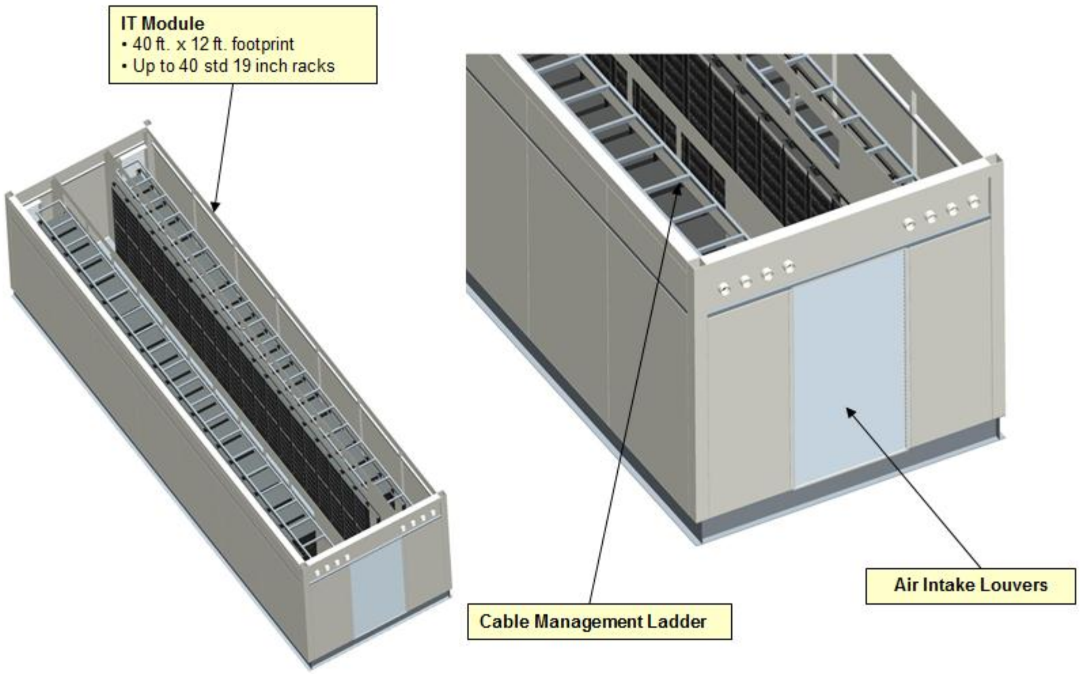


Fig 3.7 IT Module Description with detailed Racks

The modular data center is comprised of two 12 feet x 40 feet (3.66 m x 12.19 m) IT modules. The IT modules are arranged in a hot/cold aisle arrangement with a total heat load of 1.2 MW. As cold aisle and hot aisle are separated hence there is no mixing of hot and cold air. The two IT modules contain more than 5000 servers, actuator controlled louvers, and sensors needed for cooling system control. CFD analysis of the modular data center showed the importance of louver angles at the inlet of the IT containers. Each rack contains four servers system and two operating switches. Each Server consists of server blades, server fans, onboard administrators and power supply.

Fig 3.7 shows a Cable Management ladder at the top of the racks, for the wiring arrangement in order to avoid mixing of wires.

3.1.4.1 Detailed Server system

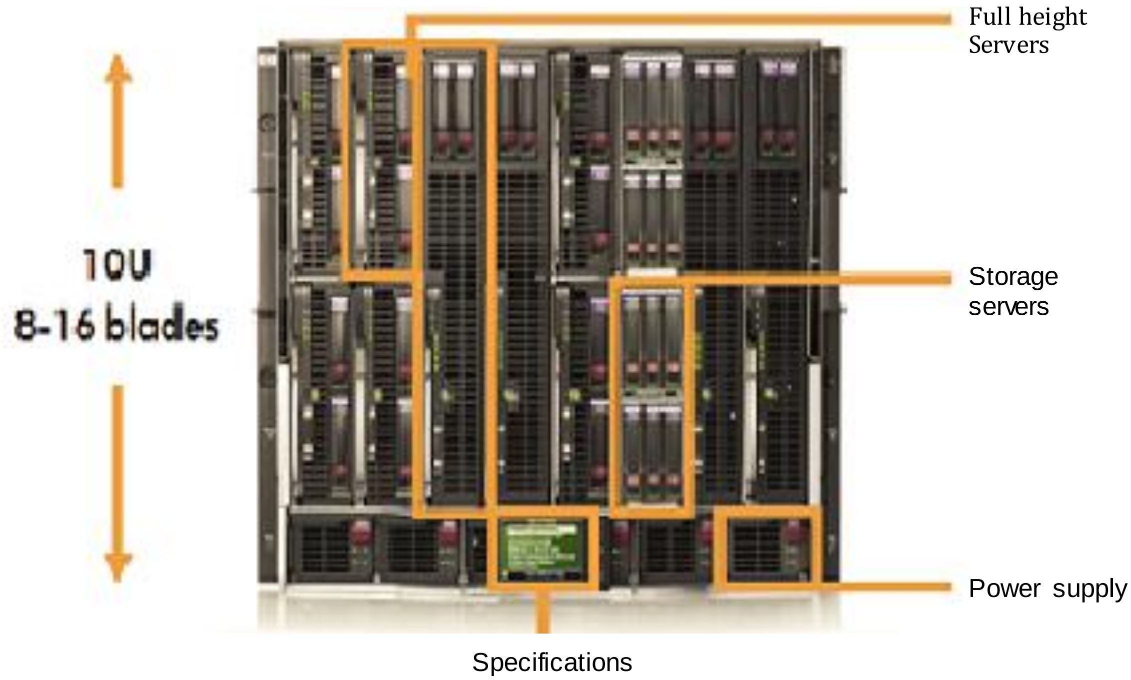


Fig 3.8 Front View of Server system [23]

Fig 3.8 shows the front view of the server system. In front view, we can see sixteen server blades or storage blades. Server blades are divided in two rows with eight servers each. At the bottom, there are five Power supplies. On the sides, there are two openings for air intake into interconnects and onboard administrators. At the back side of the servers or storage blades, there is a signal mid plane followed by a power back plane. The power back plane and signal mid plane are designed in such a way, that the onboard administrators at the rear side get connected to the back of the servers through these planes. In this way data stored in the servers can be taken out through onboard administrators. In the rear view, we can see five fans at the top, underneath there are 8 interconnects and two onboard administrators. Below these we have five server fans followed by five extending power supplies from front. The temperature of the air entering these server systems is 27 degree. The overall heat load of one server system is 2250W.

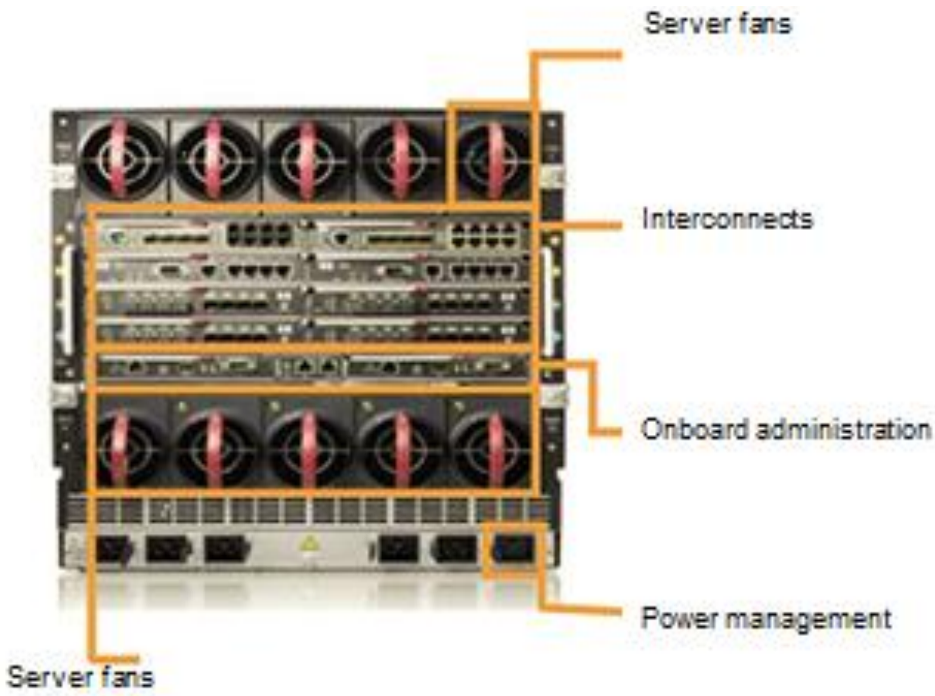


Fig 3.9 Rear View of Server system [23]

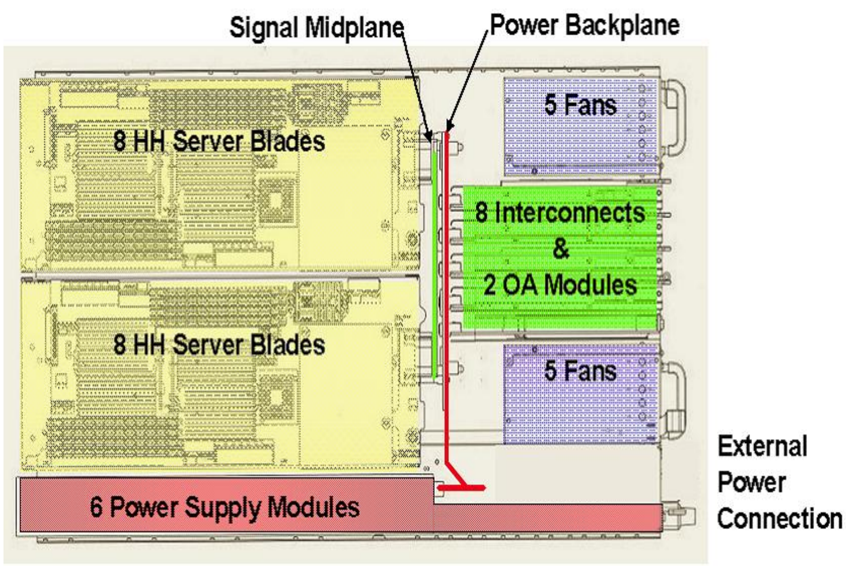


Fig 3.10 Side View of Server system [23]

3.1.4.1.1 Air Flow pattern in Server System

Server/Storage Fig shows the air flow pattern through servers. Air entering the servers from the front side and flowing through these servers flows across the signal midplane and power back plane and is drawn out by server fans.

Power supply ventilation shows the air flow pattern through the power supply located at the bottom of servers and extending to rear side. This air from power supply is drawn out by the server fans.

Interconnects ventilation shows the air flow pattern through interconnect. There are two small openings on the sides of the servers, so that air can enter through these openings into the Onboard administrators and interconnects. This hot air is drawn out by top and bottom row server fans.

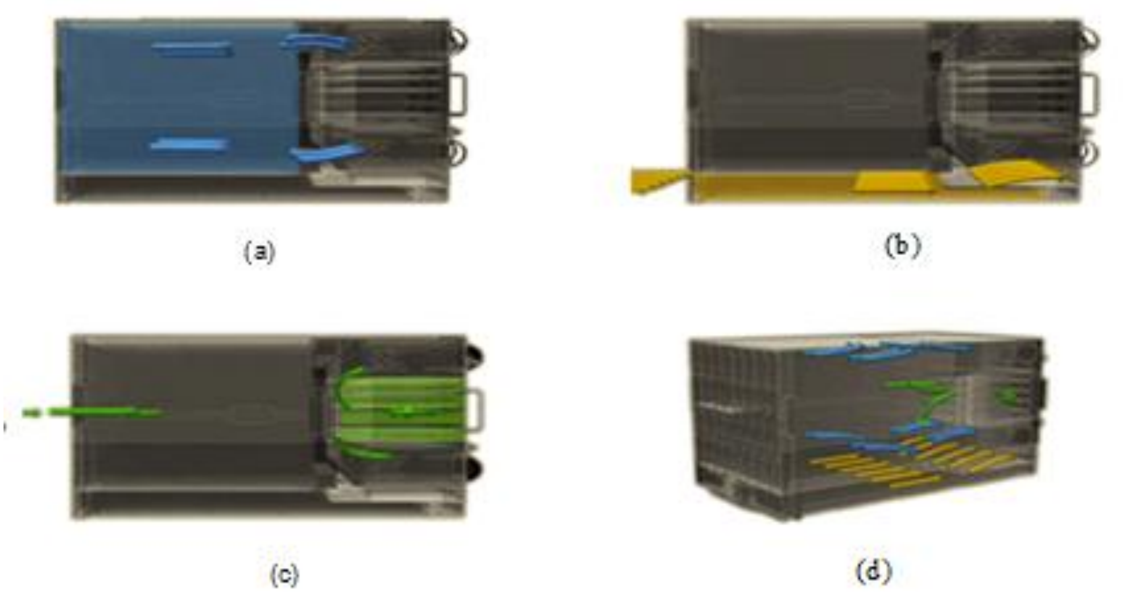


Fig 3.11 Air flow Pattern through the Server system of a) Server/Storage, b) Power supply ventilation, c) Interconnects ventilation d) Combined ventilation path [23]

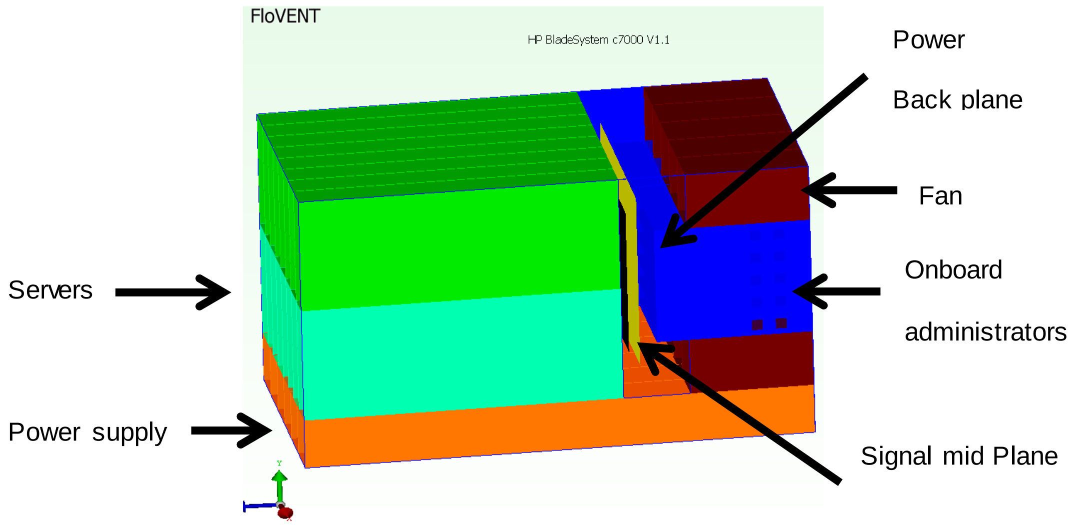


Fig 3.12 Isometric view of a server system using FloVENT

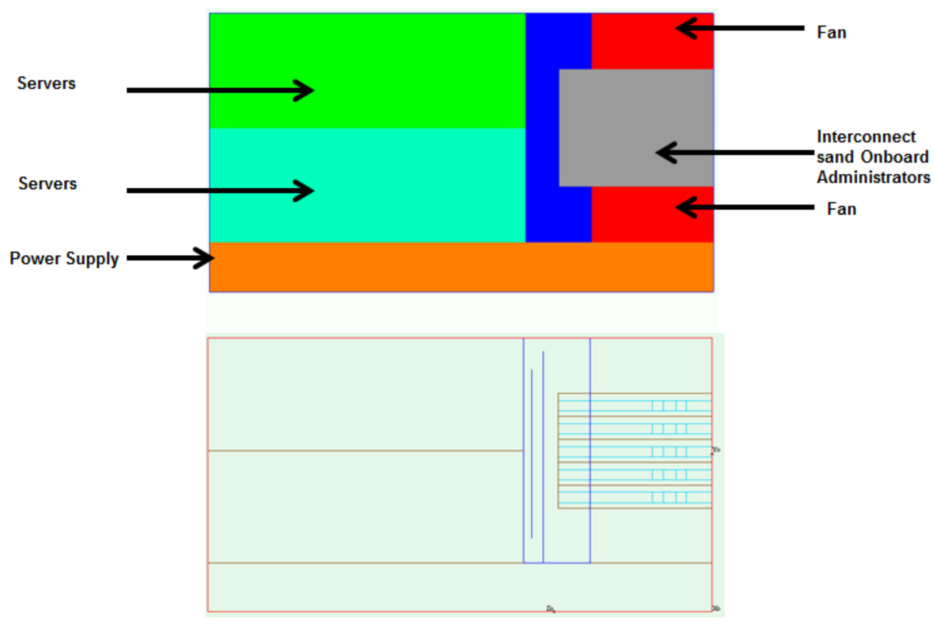


Fig 3.13 Side view and a drawing view of a server system

3.2 Heat load Specifications for the Overall data center:

Table 3.1 Heat Load Description

Number of Item(s)	Item	Heat Load (W)
1	Rack	8970
1	IT module	376,727
2	IT modules	753,454
1	Power Cooling Module	2250
The Entire System (i.e. 1 Power Cooling Module + 2 IT Containers)		755,704

Table represents the overall heat load calculations based on total number of servers, number of racks. There are total 168 server systems in each IT module and each server system contributes 2250W of heat. Each rack has four of these servers systems and eventually each rack contributes 8970W. As each IT module has two rows and each row consists of twenty one racks which gives out a total heat load of 3, 76,727W. Power cooling module contributes a total heat load of 2250W.

CHAPTER 4

COMPUTATIONAL FLUID DYNAMIC (CFD) ANALYSIS

4.1 Introduction to Computational Fluid Dynamics

Computational fluid dynamics, abbreviated as CFD, helps us to understand the fluidic properties by means of numerical methods and mathematical modeling equations. It involves a detail study of heat transfer properties along with pressure characteristics. This numerical simulation of fluid flow helps to design a comfortable and acceptable living environment, depending upon the simulations. CFD analysis does discretization of the problem with the help of numerical methods and achieves a solution. In our case, CFD tool helps us to simulate CFD model including IT modules, power cooling modules along with the server systems, power source, server fans and UPS. CFD provides with a discrete solution with a detailed study of heat transfer, air flow distribution and pressure characteristics in the solution domain [24].

4.2 Governing Equations

The fundamental governing equations of fluid dynamics are mass, momentum and energy equation [25]. Fluid dynamics is solely dependent on basic physics principles. These principles are stated as follows:

Mass is conserved, Force equals to product of mass and acceleration and lastly energy is conserved. CFD is used for modeling electronic packaging and hence temperature and fluid flow properties are solved. These solutions solve Navier Stokes equation with a combination of turbulence model [26].

Conversation of Mass

$$\frac{\partial \rho}{\partial t} + \frac{\partial \rho \tilde{u}_i}{\partial x_i} = 0 \qquad (1)$$

Conservation of momentum

$$\frac{\partial \rho \widetilde{u}_i}{\partial \tau} + \frac{\partial \rho \widetilde{u}_j \widetilde{u}_i}{\partial x_j} = \frac{\partial}{\partial x_j}\left(\mu \frac{\partial \widetilde{u}_i}{\partial x_j} \right) - \frac{\partial \widetilde{\rho}}{\partial x_i} + \rho g_i + \widetilde{s}_{ui} \qquad (2)$$

Conservation of passive scalars

$$\frac{\partial \rho c_p \widetilde{T}}{\partial \tau} + \frac{\partial \rho c_p \widetilde{u}_j \widetilde{T}}{\partial x_j} = \frac{\partial}{\partial x_j}\left(k \frac{\partial \widetilde{T}}{\partial x_j} \right) + \widetilde{s}_t \qquad (3)$$

4.3 Computational Solution Domain

A computational solution domain is a defined volume for which thermodynamics equations are solved. A solution domain encloses the overall model and the conservation of mass, momentum and energy equations are solved within this specified domain. Specific boundary conditions are to be provided to this domain such as ambient properties such as temperature, solar radiation, humidity along with the fluidic properties such as conductivity, density, viscosity and so on. The conservation equations and associated boundary conditions are solved by means of numerical integration. First step is to discretize the solution domain with finite volume grid cells. More the grids, more accurate are the result but eventually it takes long time to calculate the solution.

The finite volume method for solving the governing equations is more easy and advantageous as compared than 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.

4.4 Turbulence Modeling

A turbulent flow is a considerate combination of velocity fluctuations in all directions and infinite number of degrees of freedom. This flow is a three dimensional flow. FloVENT commonly uses two turbulent models named as LVEL turbulence model and K-Epsilon turbulence model. Fluid flow with higher Reynolds number is considered as turbulent flow whereas fluid flow is lower Reynolds number is considered as Laminar flow.

4.3.1 LVEL Turbulence Model

LVEL is the simplest algebraic turbulence model which does not require solution of any partial differential equations. Basically this model is based on the distance calculation to the nearest distance wall, local velocity and laminar viscosity in order to determine effective viscosity. LVEL model name originates from the calculation of effective viscosity, for which we need distance from the nearest wall (L), local velocity (VEL), laminar viscosity [27].

$\nabla\phi = -1$ Were $\phi = 0$ at the wall

ϕ is the dependent variable.

$$D = \sqrt{|\nabla\phi|^2 + 2\phi} \tag{4}$$

$$L = D - |\nabla\phi| \tag{5}$$

4.3.2 K-Epsilon Turbulence Model

K-Epsilon turbulence model is the most commonly used and validated model for turbulent fluid dynamics. The drawback of this model is that, it is designed for high Reynolds number whereas if it's used for electronic purposes results in inaccurate results as the fluid flow over small electronic boards has small velocity and which in turn has low Reynolds's number.

K-Epsilon Turbulence model consists of two transport equations as follows:

Equation 6 is the transport equation to describe kinetic energy of turbulence.

$$\frac{\partial\rho k}{\partial t} + div(\rho uk) = div\left(\left(\mu_1 + \frac{\rho\upsilon_t}{\sigma_k}\right) gradk\right) + \rho\nu_t G - \rho\varepsilon \tag{6}$$

Equation 7 is another transport equation to describe rate of turbulent dissipation.

$$\frac{\partial\rho\varepsilon}{\partial t} + div(\rho \underline{u}\, \varepsilon) = div\left(\left(\mu_1 + \frac{\rho\upsilon_t}{\sigma_\varepsilon}\right) grad\varepsilon\right) + C_{1\varepsilon}\rho\nu_t G\frac{\varepsilon}{k} - C_{2\varepsilon}\rho\frac{\varepsilon^2}{k} \tag{7}$$

This model calculates viscosity depending on the grid cells rather than viscosity calculations based on walls.

4.5 FloVENT Smart Parts

4.4.1 Enclosure: Enclosures are useful in order to model electronic equipment's such as servers, PCB's, server racks, cabinets and several more. The size of the enclosure created in the project manager represents the solution domain. If this enclosure smart part is used for modeling small internal objects where there is no internal flow, then it would unnecessarily increase the number of cells and the solution time. Enclosure consists of a cuboid with six walls and depending on the requirement, a hole for ventilation or for using louver can be done on the either of the walls [24].

4.4.2 Cuboid: Cuboid is one of the most commonly used smart part in FloVENT. It is modeled as a solid block with six sides and depending upon the requirement, one can create holes or model recirculation device, heat source, fan assembly to this cuboid. Material and thermal properties can be attached to cuboid [24].

4.4.3 Sloping Blocks: Sloping blocks represents cuboids, with a cross section on through diagonals. They can be modeled as smooth and non-conducting solids. Surface exchange, radiation, grid constraints, material and thermal properties can be attached to the Sloping blocks. While allocating grids, it is important to ensure the availability of grids on the cut sections [24].

4.4.4 Fans: Fans can be classified as Centrifugal and axial fans. This classification depends upon the air flow path through fans. There is a wide variation in efficiency of the fans depending upon their designs. They vary from 40 to 80 percent [24].

Centrifugal fans are also called as “squirrel cage” or “utility fans”. These fans consist of an impeller, which rotates and hence increases the air velocity. When this high velocity air flows through the fans blades, it gains kinetic energy and when this air is allowed to flow through the fans, this kinetic energy gets converted to static pressure [24].

Axial fans are also called as propeller fans and are directly connected to the motor. These fans direct a straight air flow. Axial fans can be classified into three ways: propeller fans, tube-axial fans, vane-axial fans. Vane-axial fans are considered to the most efficient fans out of the three with an efficiency of high 80s.

4.4.5 System or Impedance curve:

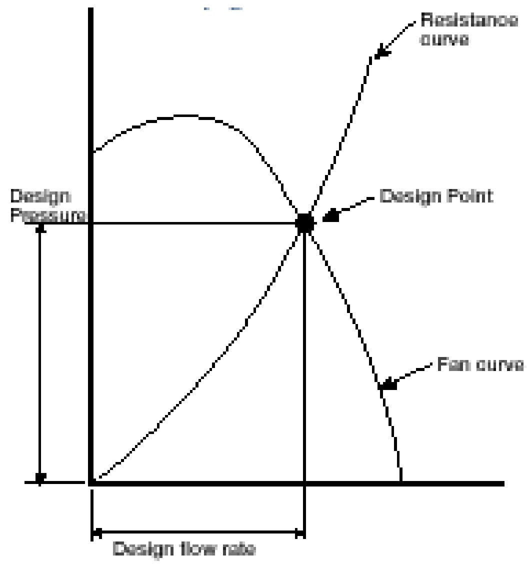


Fig 4.1 System curve

System curve is the relationship between the pressure drop and volume flow rate. On x-axis is flow rate whereas on y-axis is pressure drop. The point of intersection of resistance curve with the fan curve is known as Operating point. Resistance curve remains constant if the geometry of the system remains the same. Resistance curve changes with a change in the geometry of the system. In our particular case, the resistance curve for 0degree louver angle case is different from resistance curve for 45 degree louver case.

We can see the increase or decrease in the resistance curve depending on the change in the geometry inside the system.

4.4.6 Fan curve:

Fan curve is a relationship between static pressure and volume flow rate. Along x-axis is the volume flow rate whereas on y-axis is static pressure.

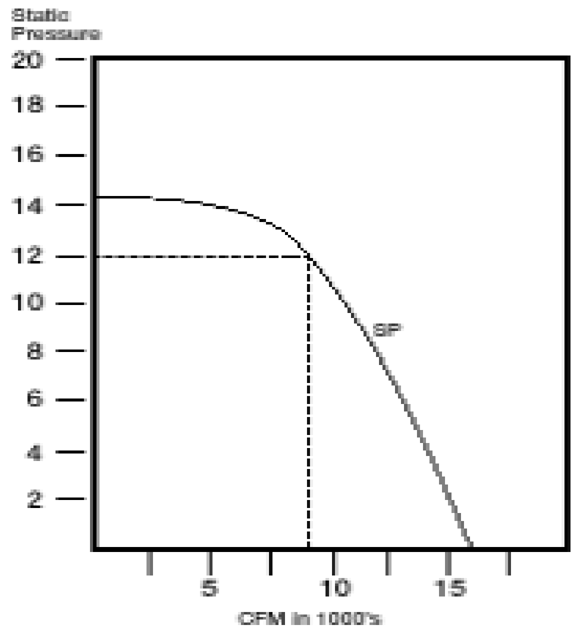


Fig 4.2 Fan curve

A maximum pressure drop is observed with a zero flow rate when fan is shut off whereas zero pressure drops at maximum flow rate also called as free delivery position of fan [29].

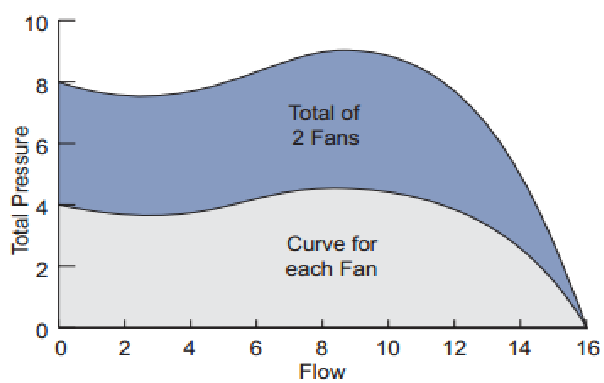


Fig 4.3 Fans in Series [29]

Fans in series are used where the higher pressure drop is required by the system for the same amount of air flow.

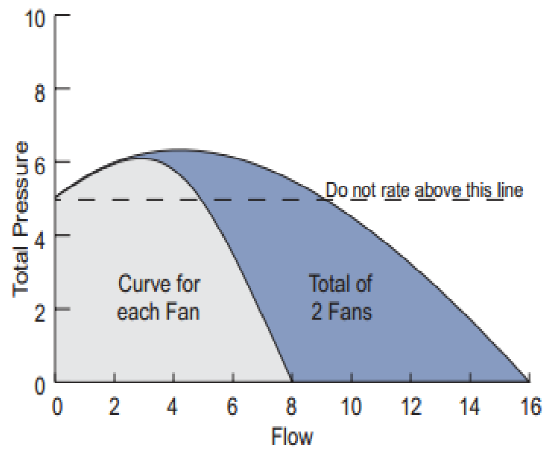


Fig 4.4 Fans in Parallel [29]

Fans in Parallel are used where the higher volume flow rate is required for the same amount of pressure drop.

4.4.7 Rack:

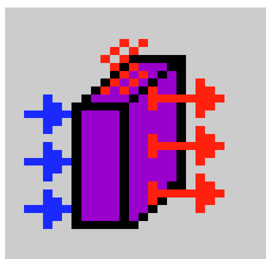


Fig 4.5 Smart part Rack

This smart part consists of extract and supply as the main components [24]. Grid constraints can be attached to this smart part. Power dissipation of the rack and volume flow rate of air through this rack can be defined to this smart part. Power dissipation of rack can be specified in units of W, KW, Btu/hr., and Btu/s. Amount of air flow passing through this rack can be defined in four ways as follow:

Volume flow rate/ Power: This refers to the volumetric flow rate as a function of power.

Temperature change: Airflow rate as a function of change in temperature.

$$\dot{m} = \frac{Q}{c_p * \Delta T}$$

Where Q= power dissipation

ΔT = change in temperature

Volume flow rate: A specified default volume flow rate value can be given.

Curve: A fan curve can be provided at the supply side, so depending upon the system impedance and requirement fans can operate at particular operating point.

4.4.8 Monitor points: Monitor points help us to measure temperature, pressure, and flow properties at the critical areas. They also help us to analyze the results and allow us to track whether system is running efficiently or not.

4.4.9 Command center: Command center in FloVENT is also known as a post processing tool. It is used for parametric study and mesh sensitivity analysis. Model can be run with change in the number of cells and hence the change in the results for different grid size can be analyzed using Visual Editor. Parametric analysis has been done is with the change in the louver angles. It gets us an access to Graphical inputs, scenario table and solution monitoring.

4.4.10 Visual Editor: Visual editor helps us to visualize the model with different planes such as Temperature and velocity. Visual editor allows us to get a wireframe as well as solid view. Temperature, Velocity and pressure planes can be viewed using Visual Editor.

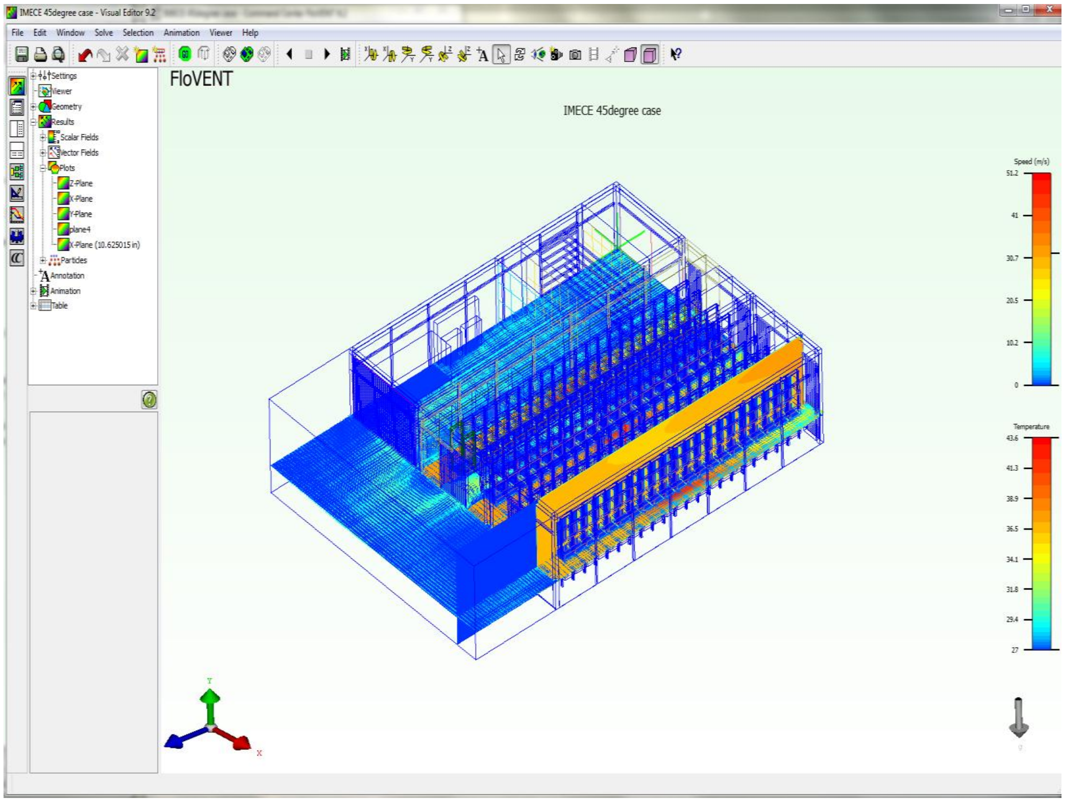


Fig 4.6 Visual Editor

CHAPTER 5

AIR FLOW DISTRIBUTION AND THERMAL ANALYSIS OF DATA CENTER

5.1 CFD Modeling of Containerized data center

A containerized data center consists of server racks. Each rack consists of four server systems. Server system can be modeled in a detailed way with the detail parts such as servers, onboard administrators and fans, signal mid-plane and power back-plane. Detail model increases the complexities in the model. In order to get accurate outputs, the number of cells as well as grids in the solution domain increases and hence solution time increases. In order to avoid these complexities, a smart part called as "Rack" is being used. Rack is an exact prototype of a detail server system. This smart part consists of two basic attributes as extract and supply. Along with volumetric heat load, a fan curve is attached to this smart part "Rack".

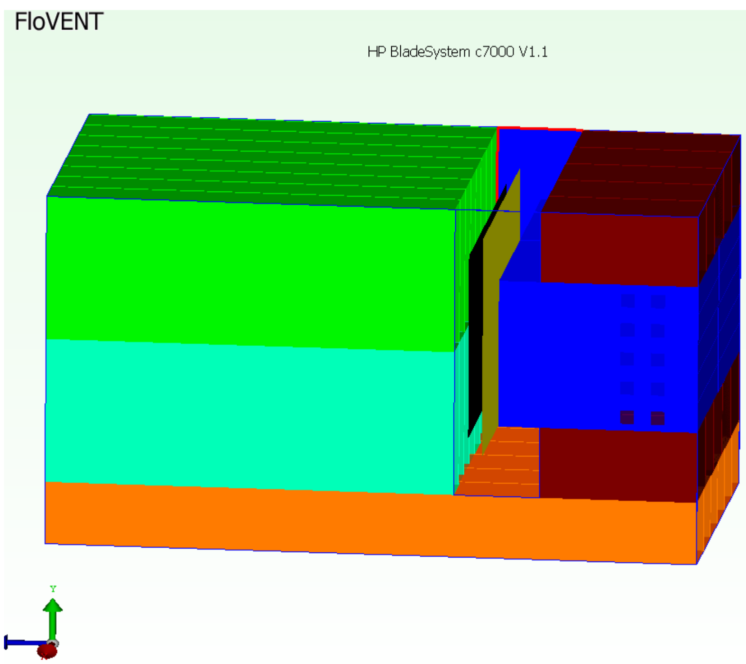


Fig 5.1 Detail Server system

Fig 5.1 illustrates a Detail Server model, modeled using a CFD tool named FloVENT. Fig 5.2 shows the grid view of one detail server system. Each detail server system constitutes around 66,000 numbers of cells and hence the time required to solve detail model is more compared to compact model.

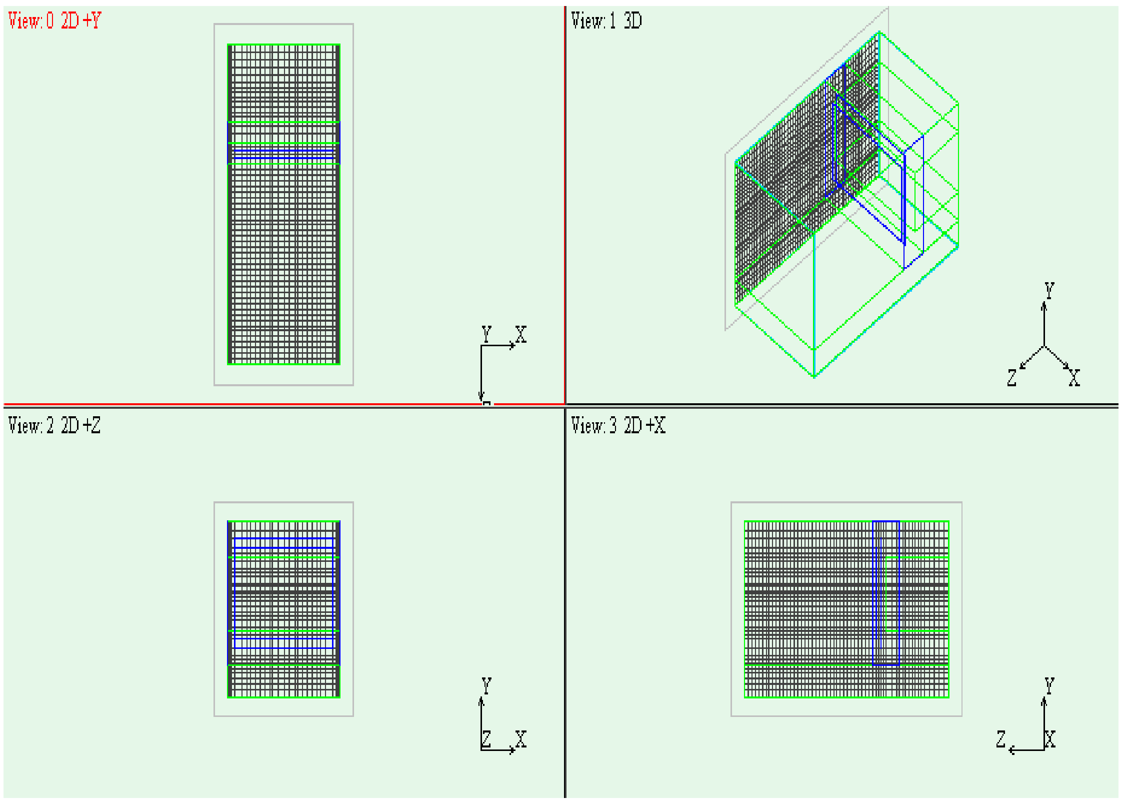


Fig 5.2 Grid view of Detail server system

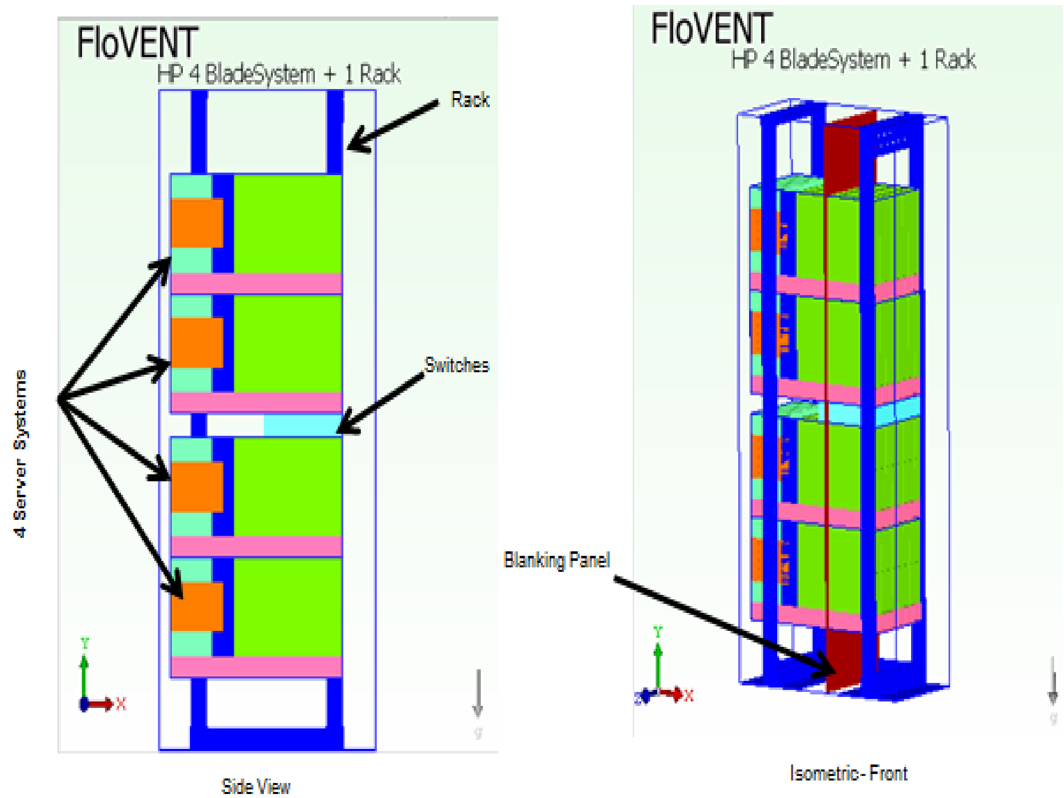


Fig 5.3 Rack with Detail Server systems

Fig 5.3 represents a rack with detail server systems. The total numbers of cells per rack are around 1.09 million. Fig 5.4 shows a grid view of an entire rack in X, Y and Z views.

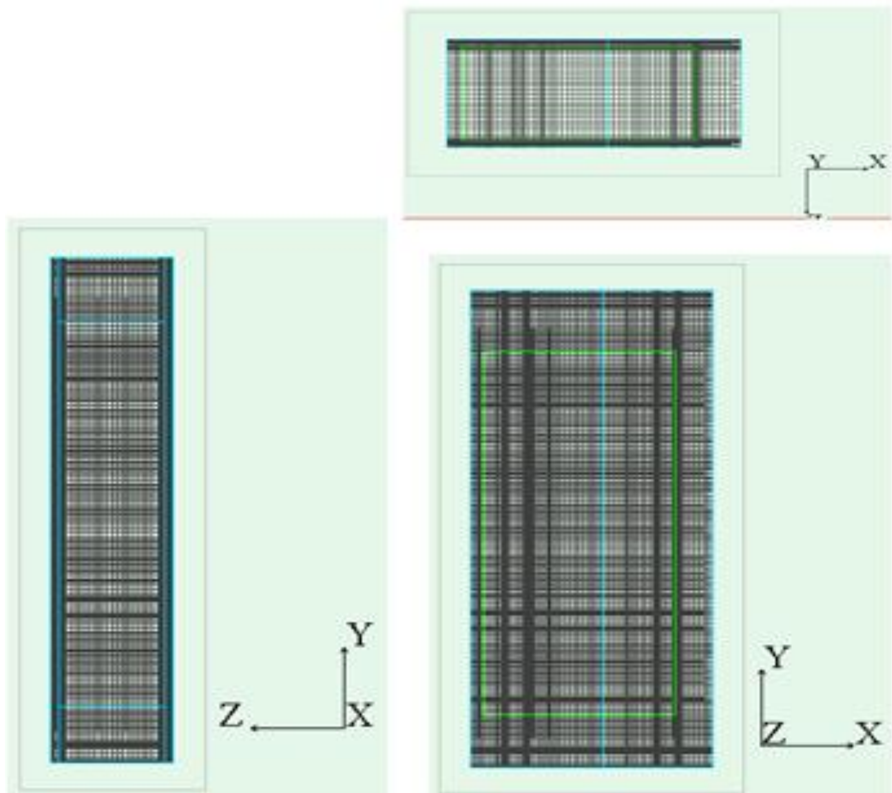
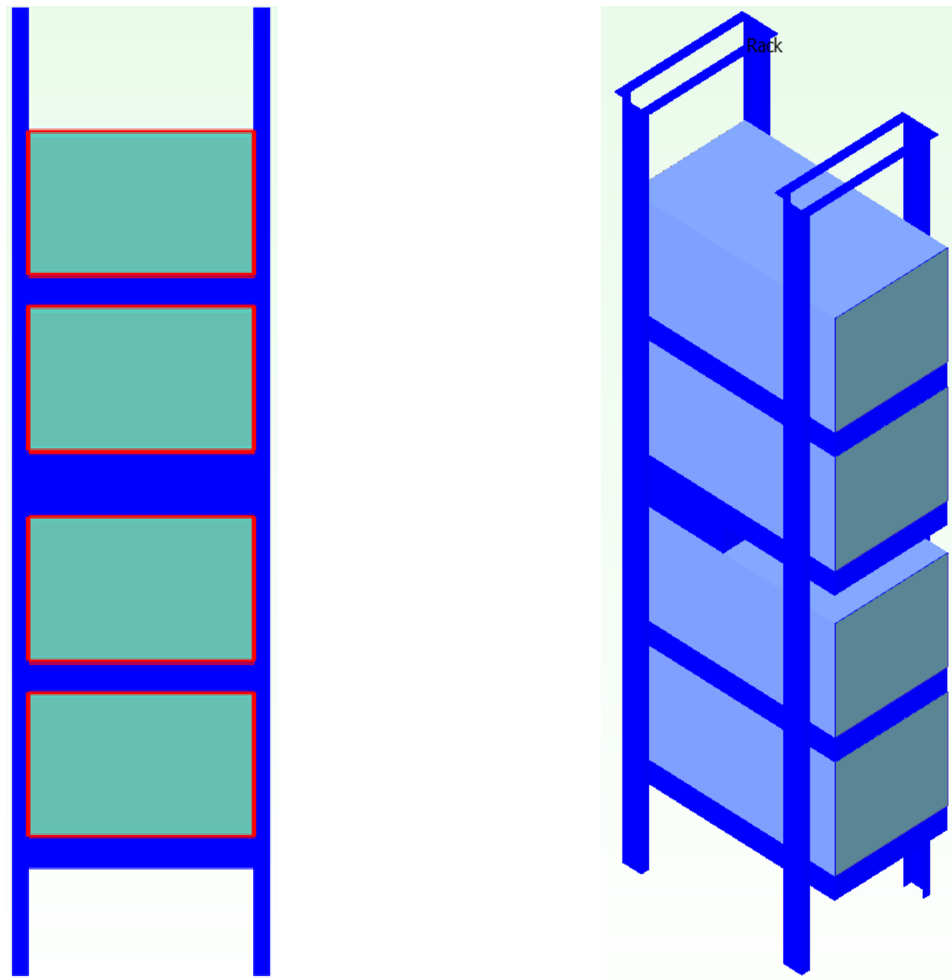


Fig 5.4 Grid view of a Rack

In compact modeling, two attributes as extract and supply are attached to the smart part. Extract side is on the front side which represents the intake to the server system whereas the supply side represents the rear side of the server system and hence acts as the exhaust of the server system. A volumetric heat load is provided to the model. A fan curve is attached to the supply side of server system. This compact model has less complexity and hence constitutes less number of cells. Compact model is modeled as a hollow block with a supply and extract on front and rear sides respectively. So the number of cells for a compact model is less as compared to the number of cells for a detail rack.



(a) (b)

Fig 5.5 (a) Front view of Compact model (b) Isometric view of compact model

Fig 5.5(a) shows a front view of a compact rack model and Fig 5.5(b) shows an isometric view of compact rack model. Each IT module contains two sets of 21 racks placed to the left and right hand side of the cold aisle. The two hot aisles in each IT container are located opposite the cold aisle across each set of 21 racks. As the geometrical and boundary conditions are similar for these racks inside the IT module, we can pattern the racks in rows.

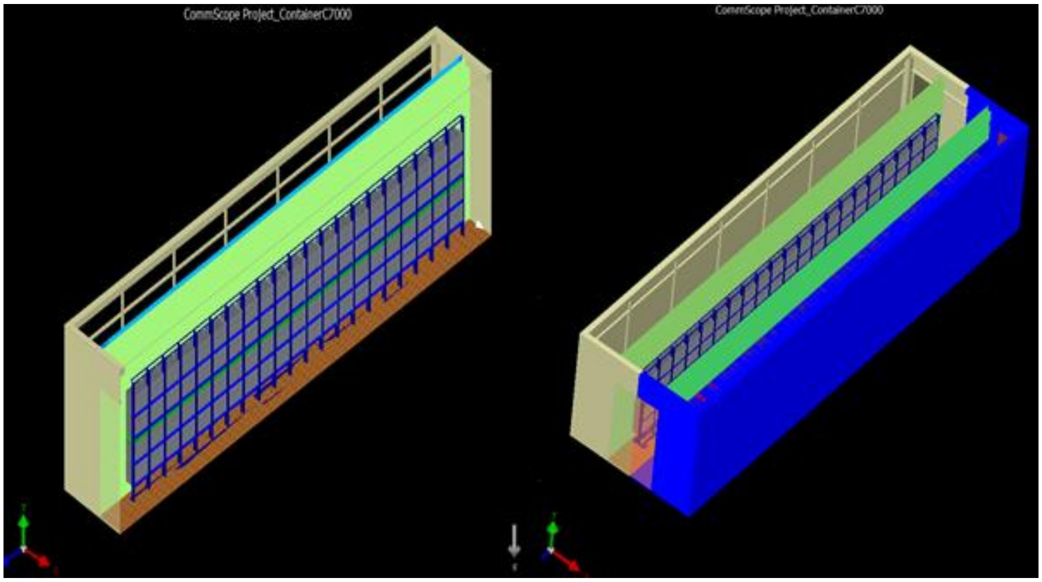


Fig 5.6 Patterning of Racks

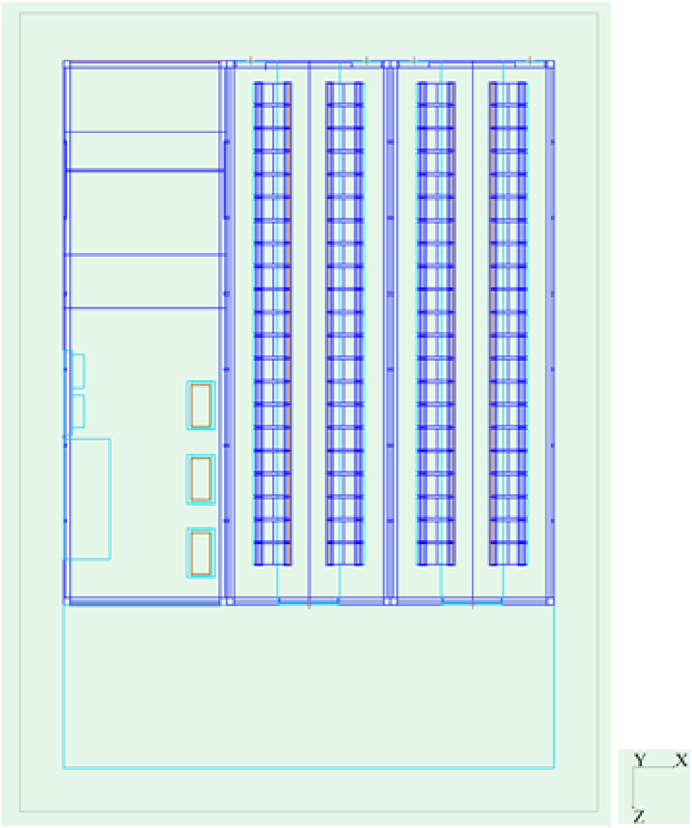


Fig 5.7 Wire frame diagram of Containerized data center from top view

Fig 5.7 shows a top view of the containerized data center. Fig 5.8 shows Power cooling module with a frame of MERV-11 filter, Nozzle assembly, hydrophobic filters and blowers along with UPS. It also shows two IT modules with louvers at the inlet of the IT modules with the server racks inside the IT module. The model has two openings at the exhaust of the hot aisle side.

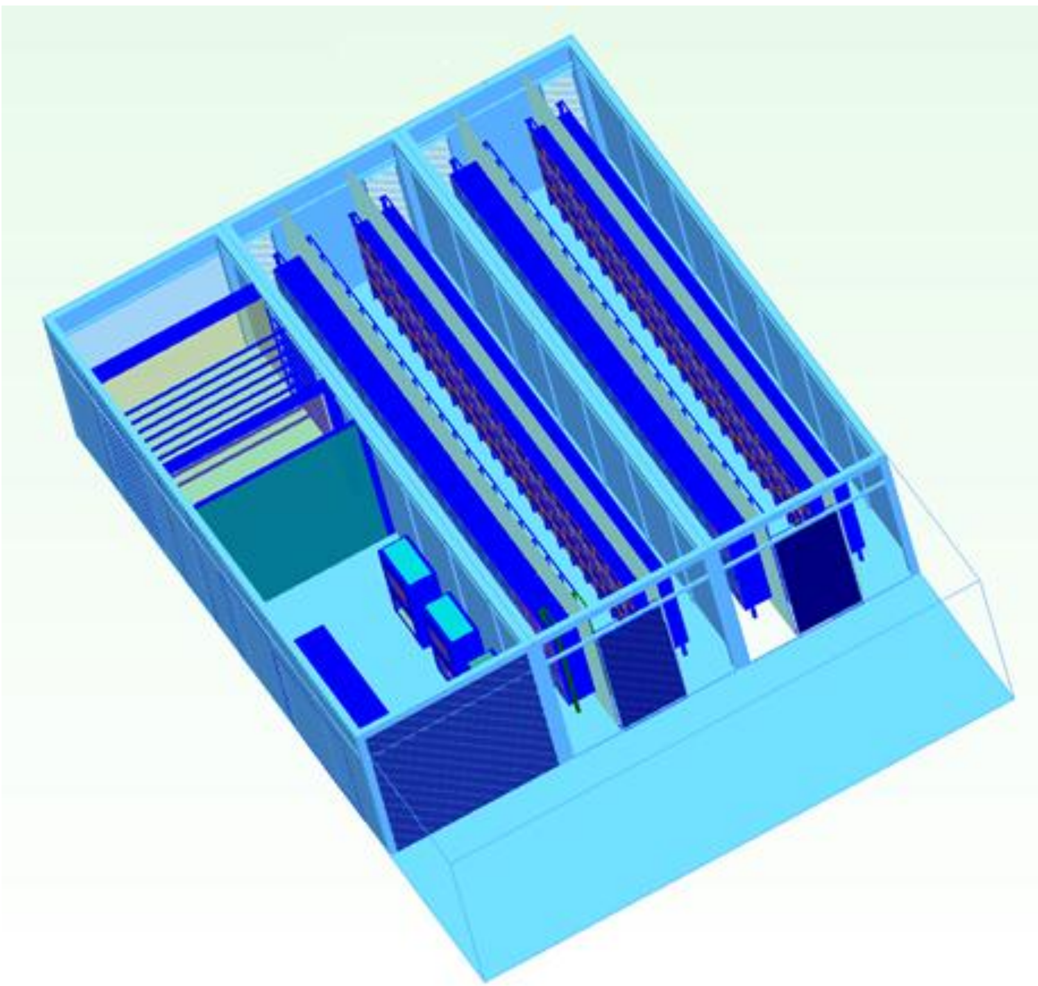


Fig 5.8 Isometric View of Containerized data center using Visual Editor

5.2 Thermal Analysis and Air flow Distribution

Case 5.2.1 Case Study I: 0 Degree Louver angle (Baseline)

0 degree louver angle case is considered to be the baseline case. In this case, inlet louver angles are at 0 degrees for both IT modules. In this section particularly, the impact on blowers in power cooling module, thermal contour and air flow distribution in IT modules is studied using a CFD tool FloVENT. Fig 5.9 shows a isometric view of the inlet louvers at 0 degree.

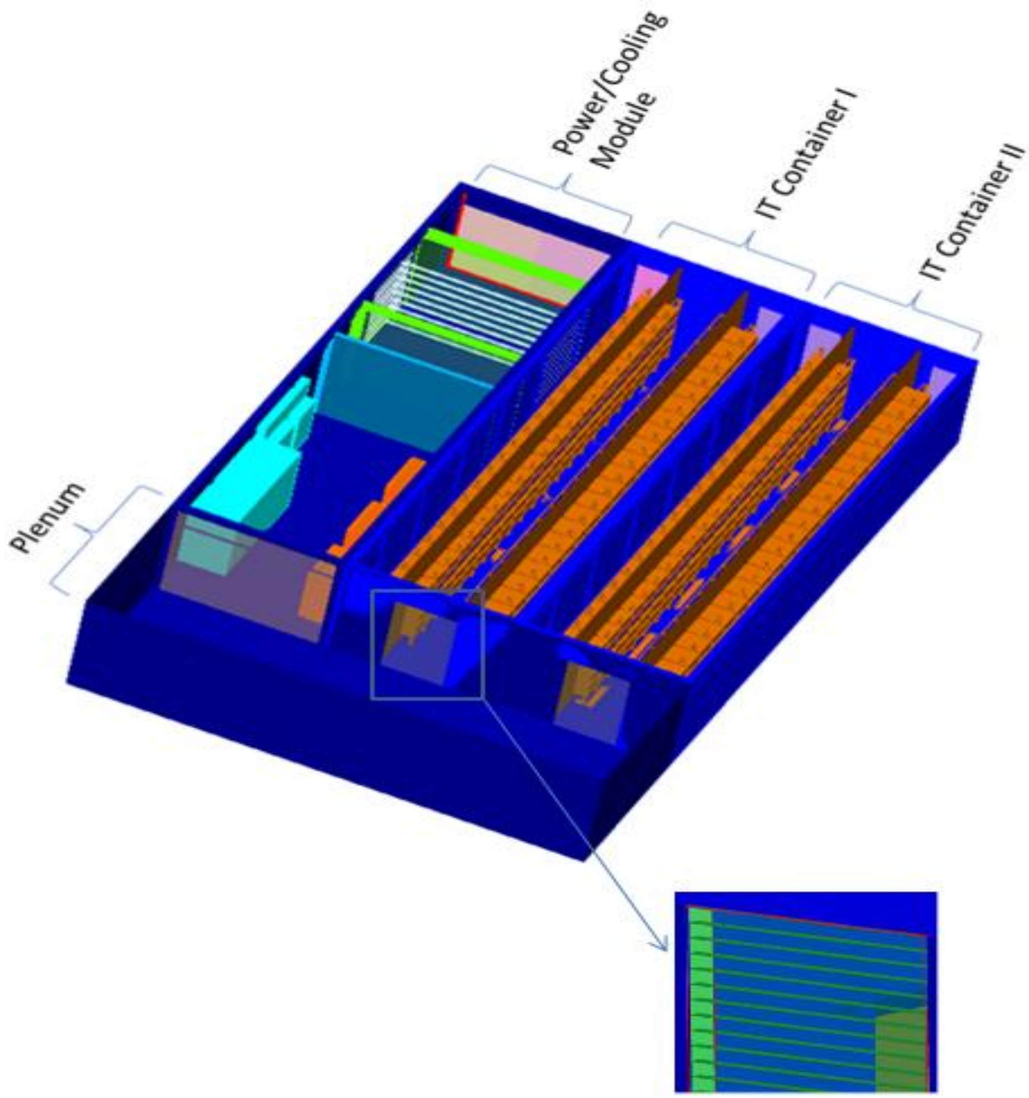


Fig 5.9 Inlet Louver with 0 Degree angle case

5.2.1.1 Thermal contour of Containerized data center

The thermal profile on a horizontal cut plane passing through the modular data center is own in Fig 5.4. The maximum temperature in the modular data center is 37.9°C that is 12°C above the inlet temperature, 27°C.

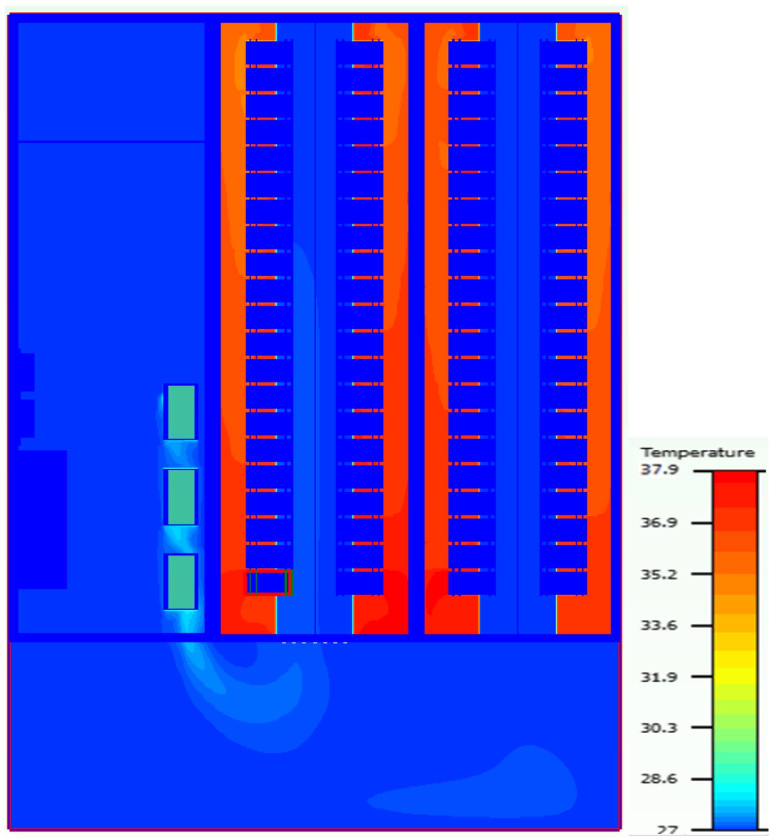


Fig 5.10 Thermal contour for 0 degree louver angle case

An increase in the temperature in the power cooling module is observed above the ambient 27°C, as a power source of 750W is attached to the three Flywheel UPS in the power cooling module. The temperature on the hot aisle sides of the IT modules is observed as a diverging as we move from rack 1 to rack no 21. This concludes that the racks at the end of the IT modules are getting sufficient air as compared to the racks in front.

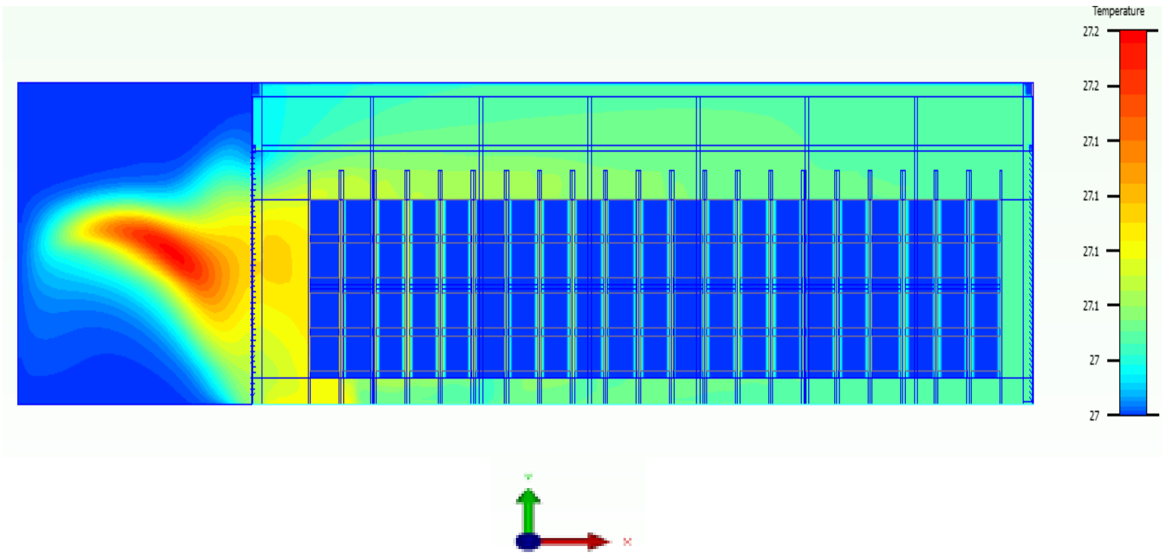


Fig 5.11 Thermal contour of a Containerized data center

Fig 5.11 illustrates a cross sectional plot at x= 1.31 meters from the reference. This section is in the hot aisle of IT module I. An increase in temperature is observed at the inlet of the IT module I before inlet louvers, because of the air circulations. It can be seen that as we move towards the end of the racks, temperature goes on reducing because velocity of air reduces and hence more air goes into the Server racks, whereas air gushes at the front of the racks resulting in high exhaust temperature at the initial.

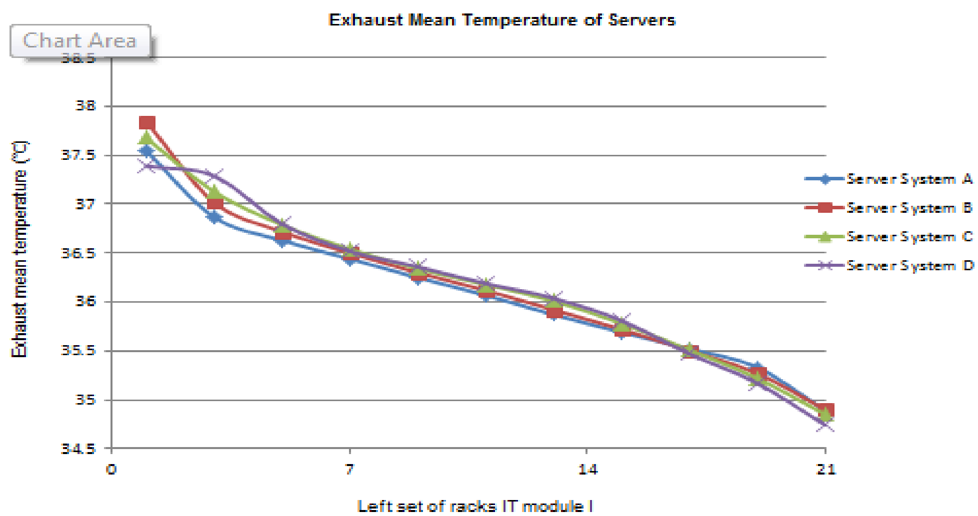


Fig 5.12 Temperature distribution across Left set of Racks in IT module I

Fig 5.12 illustrates the exhaust temperatures of the server systems A, B, C and D with respect to their corresponding racks. It can be seen that the exhaust temperature of the server systems reduces at the end of the IT module that is a decrease in temperature is observed from rack no.1 to rack no.21. The maximum temperature of 37.9°C is observed at rack no.1 because the air at the inlet has high velocity and hence less amount of air is drawn by server fans at the initial racks.

5.2.1.2 Air flow Distribution in Containerized data center

Fig 5.13 and Fig 5.14 show airflow patterns in the cold aisle of IT module I with inlet louvers inclined at 0°. Louvers at 0 degrees of inclination are shown in Fig 5.9. In Fig 5.14 no air circulation around mid-length of the cold aisle is observed. Comparison of Fig 5.14 can be used for the comparison with the effect of change in the inlet louvers angles on airflow distribution in the cold aisle.

Air circulation forms a low pressure region at its center. Thus server fans which have to draw air from regions of strong circulation in the cold aisle will have to overcome higher differential pressure as long as the pressure in the hot aisle is relatively uniform. Overcoming higher pressure differential means less air flow passing through the fans which in turn results in high temperature at the servers. This observation is seen in Fig 5.14 which shows mean exhaust temperatures at the exhaust of sets of servers numbered in increasing order starting from the rack closest to the inlet louvers.

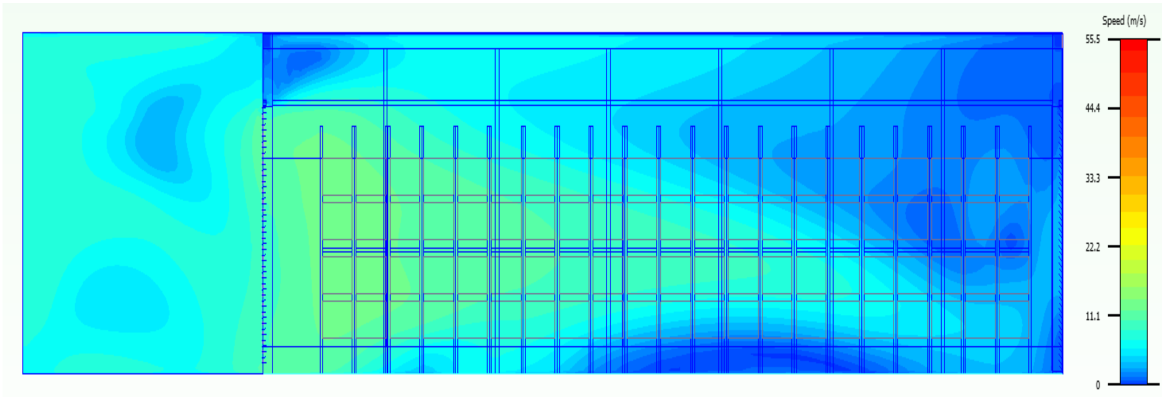


Fig 5.13 Scalar view of the air flow distribution in cold aisle side of IT module I

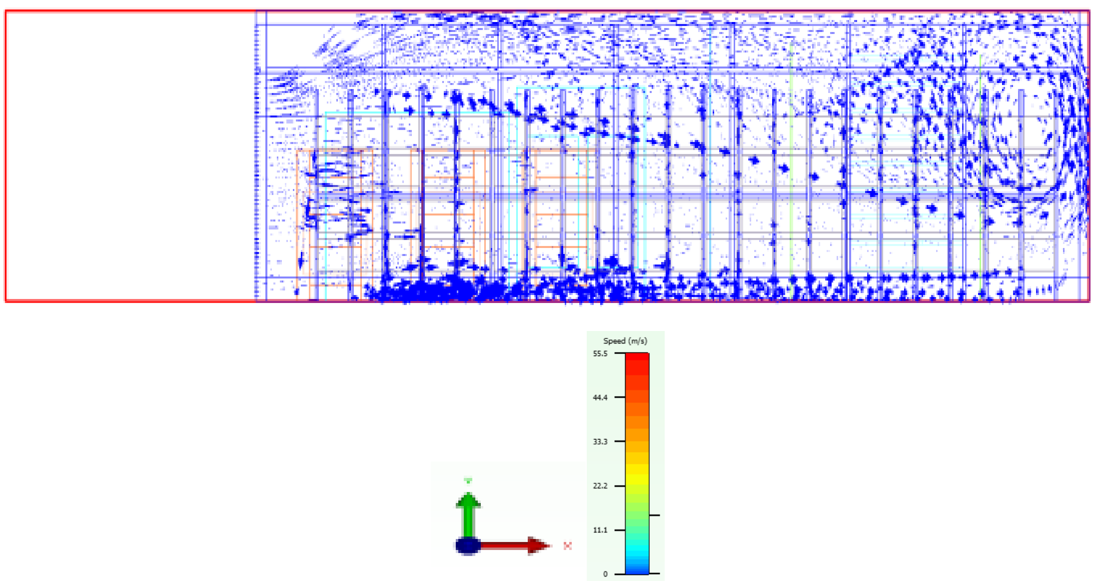


Fig 5.14 Vector Plot indicating Air flow pattern for 0 Degree Louver angle (Baseline)

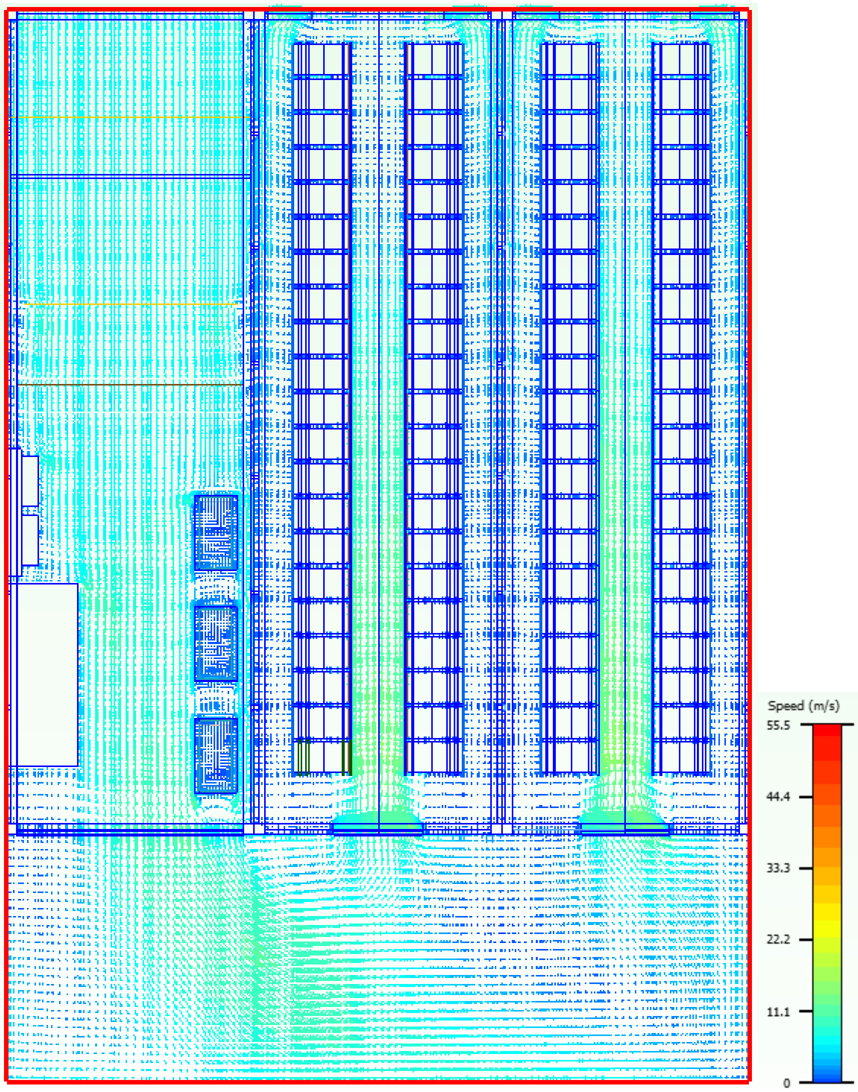


Fig 5.15 Air flow pattern in containerized data center from Top View

Fig 5.16 shows that the Volumetric flow rate of air drawn into each server rack in IT module I with respect to their respective racks. As the velocity of air reduces at the rear side of the IT module hence it can be seen that more amount of air is drawn inside the server systems by the server fans. The total of 134,600 CFM of air from the ambient is drawn by the server fans inside the system. IT module I draws 66,900 CFM whereas IT module II draws 67,700 CFM.

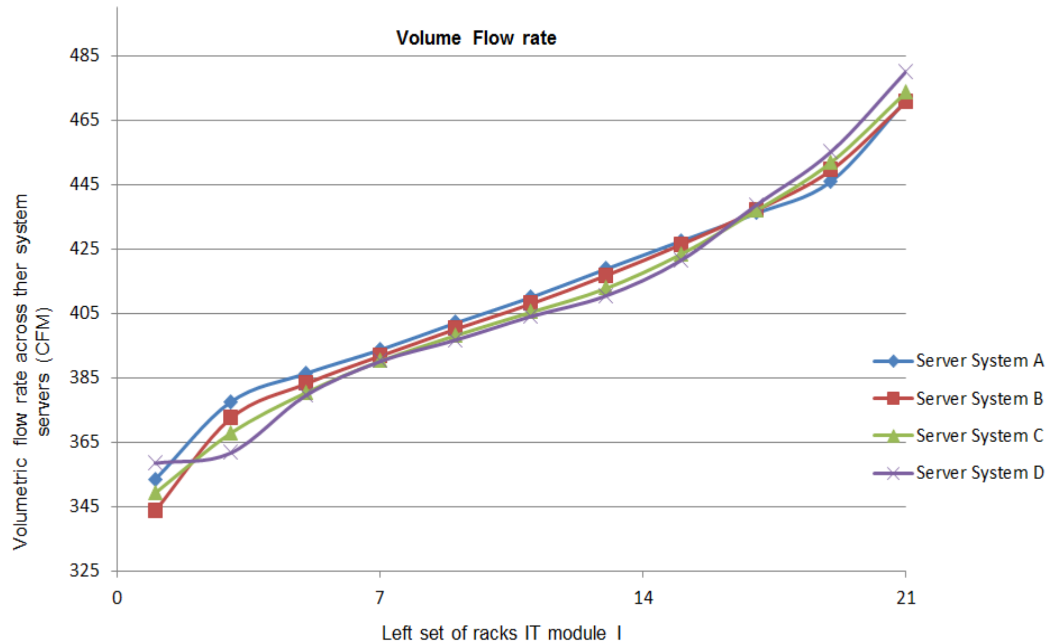


Fig 5.16 Volume Flow rate across Left set of Racks in IT module I

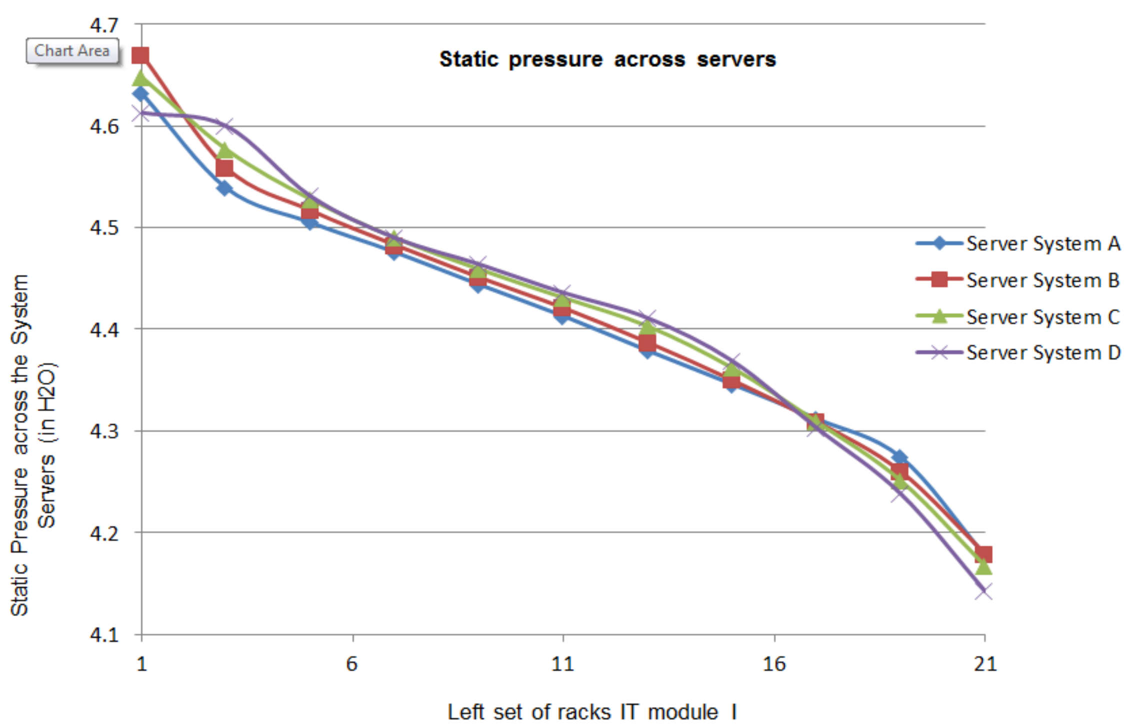


Fig 5.17 Static Pressure across Left set of Racks in IT module I

5.2.1.3 Impact of 0 Degree louver angle on Blowers in Power cooling module:

Table 5.1 Volume flow rate in IT modules

Item	Item Details	m^3/s	CFM
IT-I	Inlet	141824670	66,900
IT-II	Inlet	143519870	67,700

Table 5.2 Blower data for 0 degree louver angle case

Item	Item Details	CFM	in H2O	m^3/s	Pa
Blowers	Fan 1	11340888	0.011473	5352	2.854
	Fan 2	11501932	0.011176	5428	2.78
	Fan 3	11535836	0.011111	5444	2.764
	Fan 4	11510408	0.01116	5432	2.776
	Fan 5	11395982	0.011373	5378	2.829
	Fan 6	11343007	0.011469	5353	2.853
	Fan 7	11506170	0.011168	5430	2.778
	Fan 8	11542193	0.011103	5447	2.762
	Fan 9	11518884	0.011143	5436	2.772
	Fan 10	11404458	0.011357	5382	2.825
	Fan 11	11349364	0.011457	5356	2.85
	Fan 12	11506170	0.011168	5430	2.778
	Fan 13	11540074	0.011107	5446	2.763
	Fan 14	11521003	0.011139	5437	2.771
	Fan 15	11410815	0.011344	5385	2.822
	Fan 16	11351483	0.011453	5357	2.849
	Fan 17	11491337	0.011196	5423	2.785
	Fan 18	11512527	0.011156	5433	2.775
	Fan 19	11506170	0.011168	5430	2.778
	Fan 20	11402339	0.011361	5381	2.826
	Fan 21	11213748	0.01171	5292	2.913
	Fan 22	11347245	0.011461	5355	2.851
	Fan 23	11368435	0.011421	5365	2.841
	Fan 24	11359959	0.011437	5361	2.845
	Fan 25	11249771	0.011642	5309	2.896

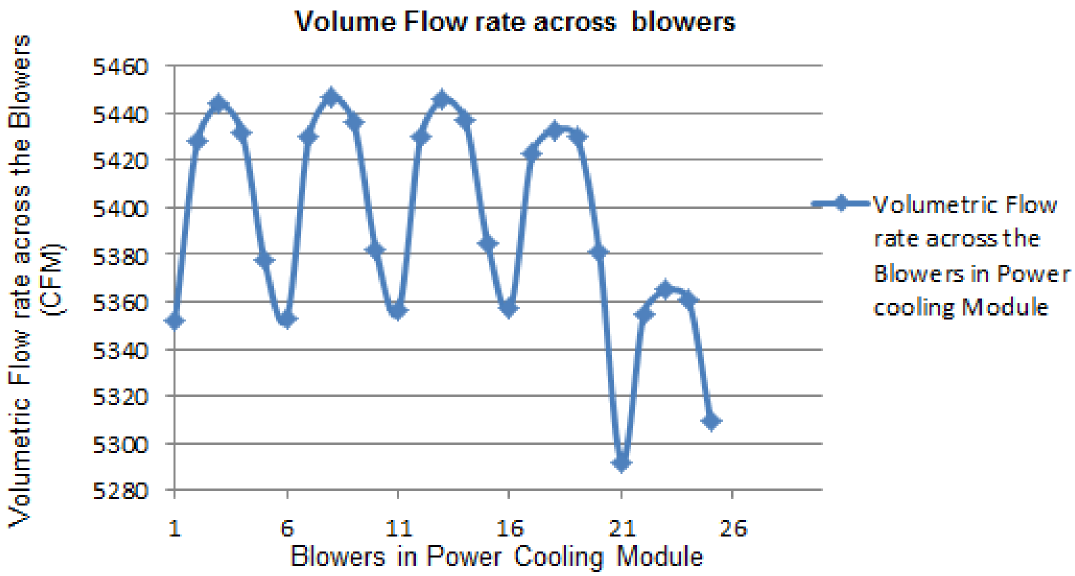


Fig 5.18 Volume flow rate across Blowers for Baseline case

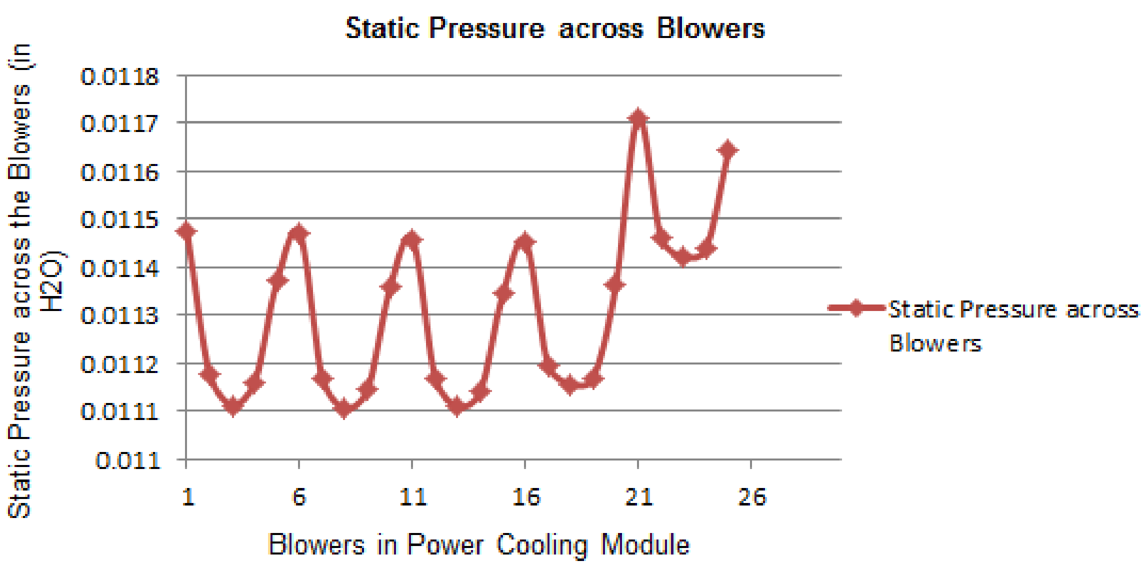


Fig 5.19 Static pressure across Blowers for Baseline case

Fig 5.20 and Fig 5.21 shows the volumetric air flow and Static pressure across the blowers respectively. Fig 5.22 illustrates the blower curve with a blue line representing the system curve. In our model there are 25 blowers. Fig 5.23 represents the server fan curve. This fan curve provides a maximum of 1550 CFM of air. Depending upon the system impedance or the resistance of the system, server fans operate at a particular operating point as shown in Fig 5.23.

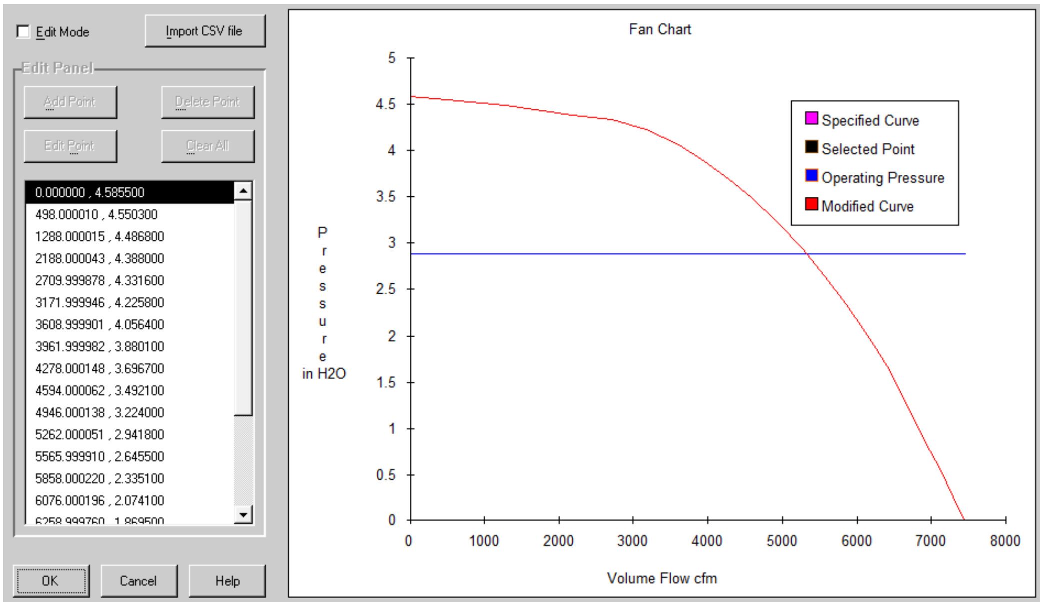


Fig 5.20 Blower curve for 0 Degree louver angle case

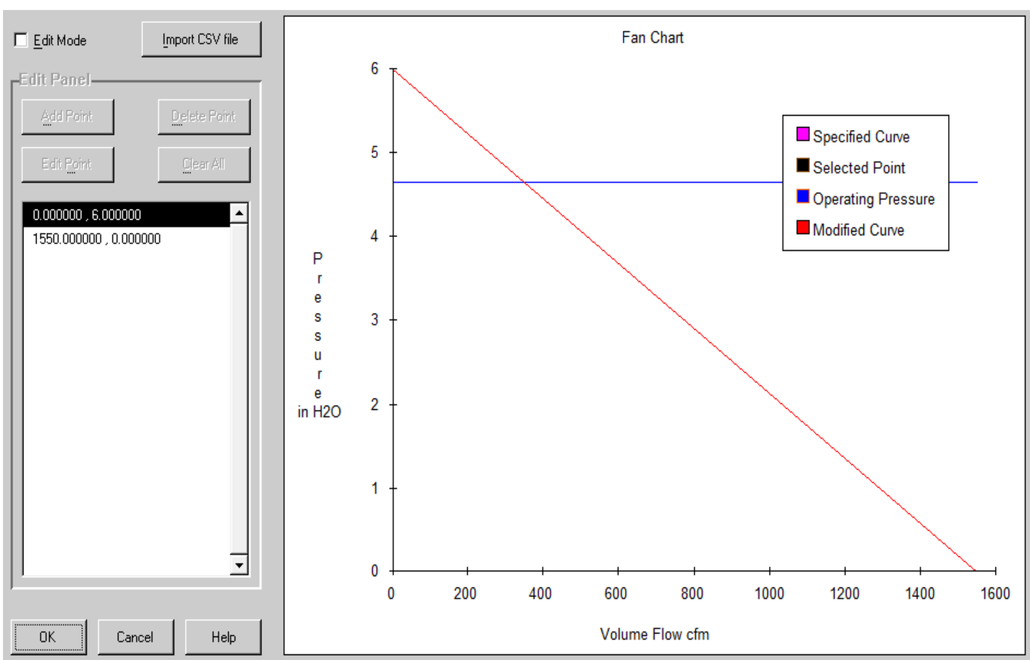


Fig 5.21 Server Fan curve for 0 Degree louver angle case

Case 5.2.2 Case Study 2: 15 Degree Louver angle

In this case, the inlet louver is inclined at 15°C to horizontal. This section particularly concentrates on the impacts of change in louver angle from 0 to 15 degree on air flow distribution in the cold aisle sides of the IT modules and thermal performance. Fig 5.23 shows the orientation of the louvers at 15°C.

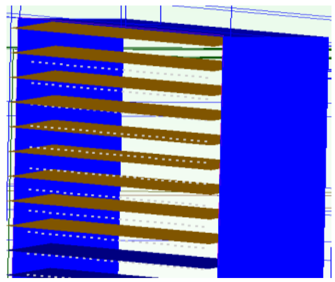


Fig 5.22 Inlet louvers with 15 degree angle case

5.2.2.1 Thermal contour of Containerized data center

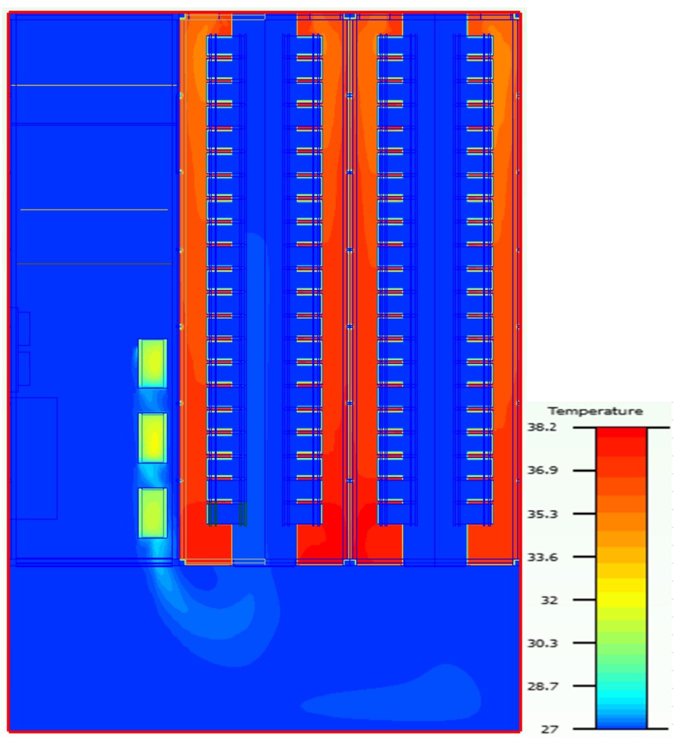


Fig 5.23 Thermal contour for 15 Degree Louver angle case

Fig 5.24 illustrates the temperature profile of the containerized data center from top view. The maximum temperature is obtained at the left set initial racks in IT module I. The cold ambient air is drawn into the system at 27°C. The maximum temperature in the containerized data center is 12°C above the inlet temperature, 27°C.

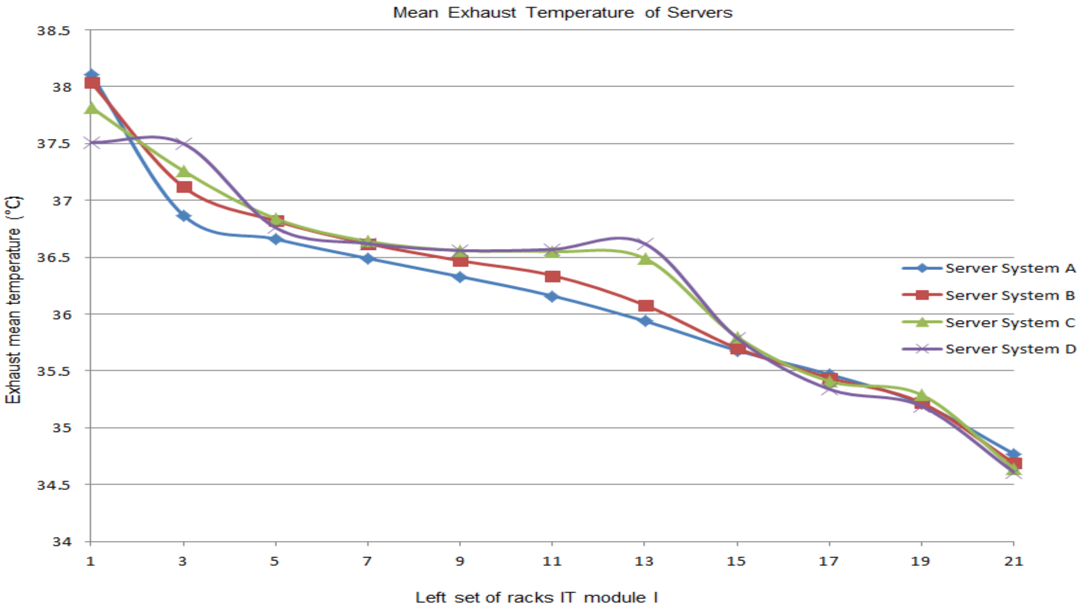


Fig 5.24 Temperature distribution across Left set of Racks in IT module I

Fig 5.25 represents the thermal performance of the left set server racks in IT module I. The maximum temperature is observed as 38.2°C at the initial left set of racks whereas this exhaust temperature reduces to about 34.5°C at the last set of racks. As compared to 0 degree louvers, there is an increase in exhaust temperature.

5.2.2.2 Air flow Distribution with 15 Degree louver angle

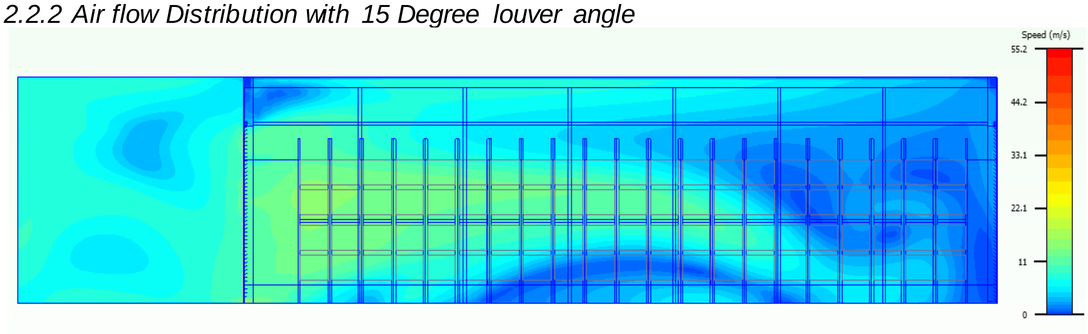


Fig 5.25 Scalar view of air flow distribution in cold aisle side of IT module I

Air circulations are observed in the cold aisle side of both the IT modules as compared to baseline case. These air circulations are because of the orientation of the inlet louvers. In baseline case, louvers direct the air flow with a 0 degree inclination and hence less air circulation is obtained, whereas with 15 degree inlet louvers, louvers direct the air with 15 degree inclination and hence causing air circulations in the cold aisle. Fig 5.26 shows a cross sectional view of the containerized data center at x=1.73meters from the reference.

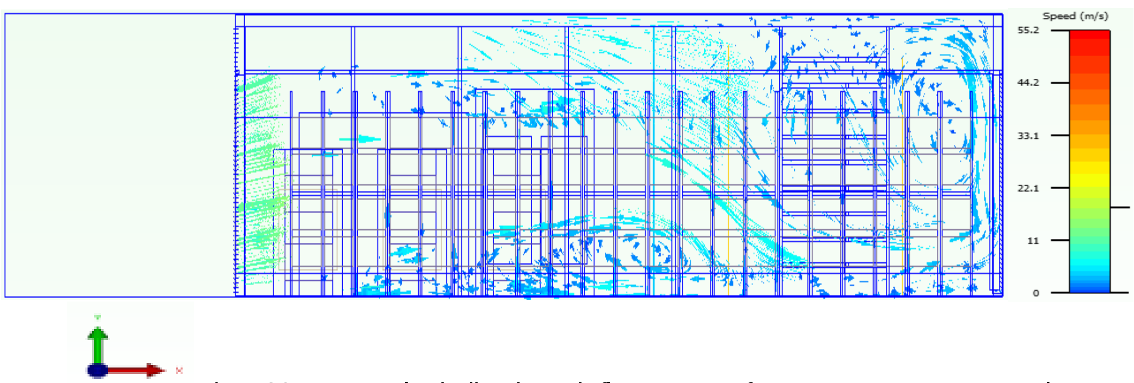


Fig 5.26 Vector Plot indicating Air flow pattern for 15 Degree Louver angle

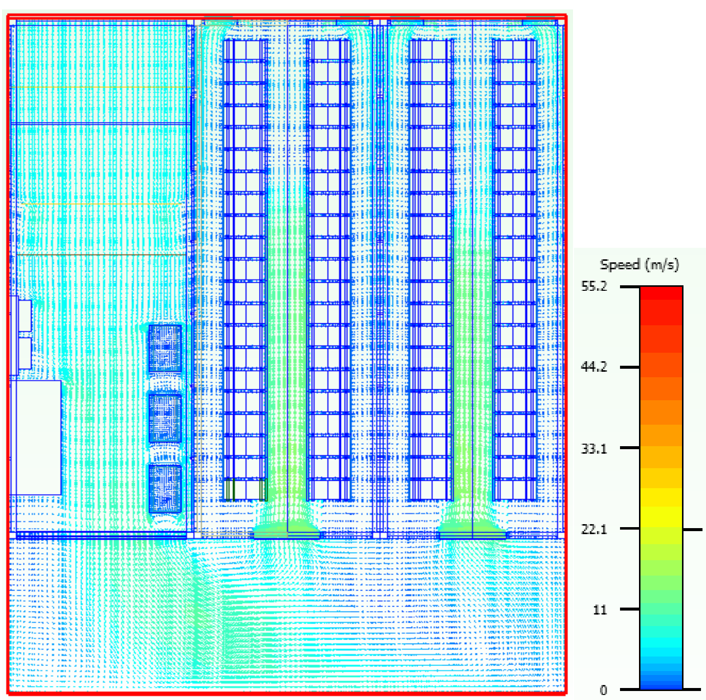


Fig 5.27 Air flow pattern in containerized data center from Top View

Table 5.3 Volume flow rate in IT modules

Item	Item Details	m^3/s	CFM
IT-1	Inlet	140680410	66,400
IT-2	Inlet	142651080	67,300

Table 5.3 shows the segregation of volume flow rate going into the IT modules I and II. The total amount of air flow passing through the blowers is 133,800CFM. Out of this total amount of air, 66,400CFM goes into IT module-I and 67,300CFM go into IT module-II

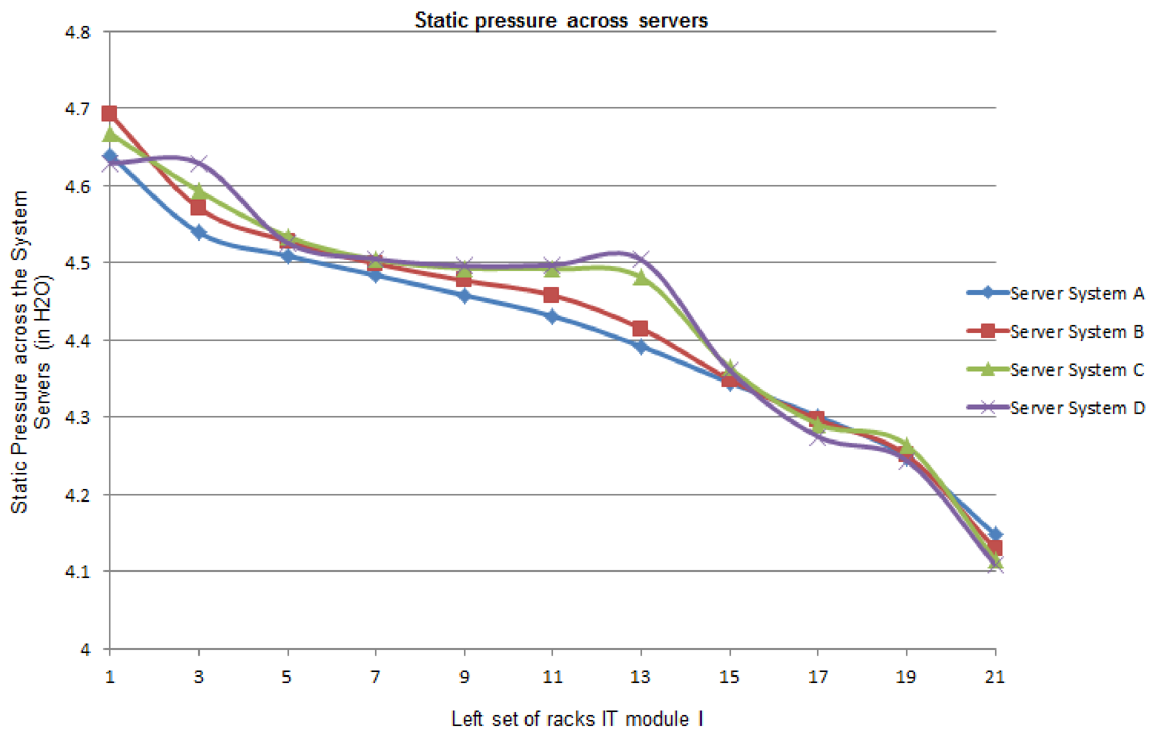


Fig 5.28 Static Pressure across Left set of Racks in IT module I

Fig 5.29 and Fig 5.30 illustrates the static pressure and the volumetric flow rate across the left set of racks in IT module-I. We can see from Fig 5.30 that the racks in mid area from 10 to 14 get less amount of air because of the air circulations in the cold aisle. Air circulation forms a low pressure region at its center. Thus server fans which have to draw air from regions of strong circulation in the cold aisle will have to overcome higher differential pressure as long as the pressure in the hot aisle is relatively uniform. Overcoming higher pressure differential means less air flow passing through the fans which in turn results in high temperature at the servers.

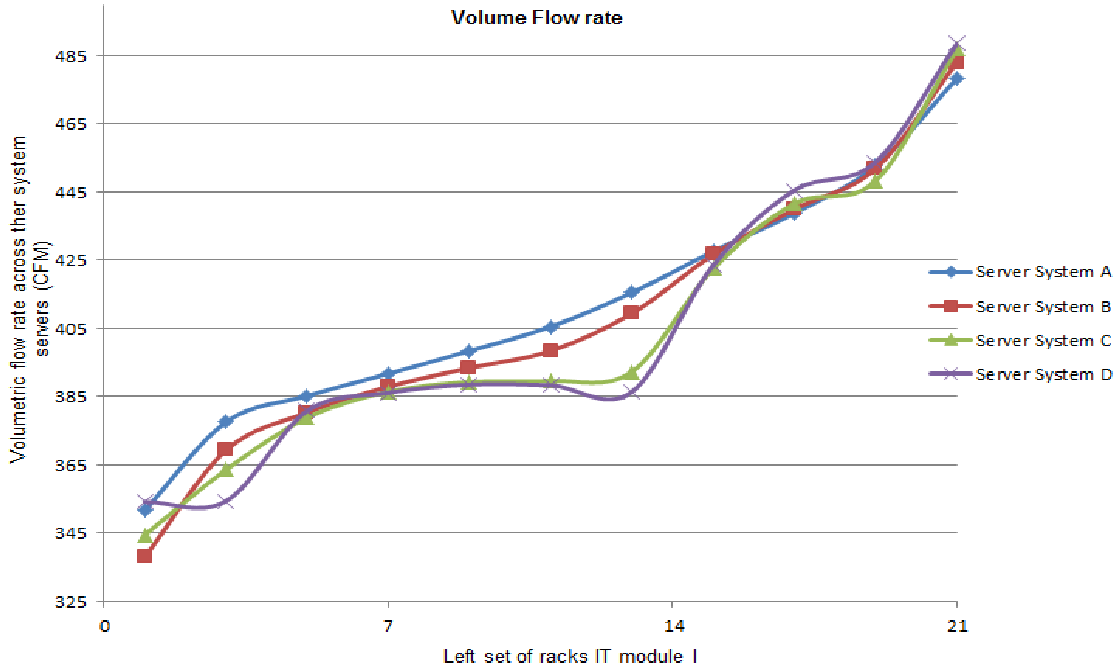


Fig 5.29 Volume flow rate across Left set of Racks in IT module I

Case 5.2.3 Case Study 3: 25 Degree Louver angle

In this case, louvers are placed at 25 degree angle. More air circulations are expected with the increase in the inlet louver angle as compared to 0 and 15 degree louvers. The open area ratio has been reduced as compared to 0 and 15 louver cases and hence the operating point of the blowers is changed.

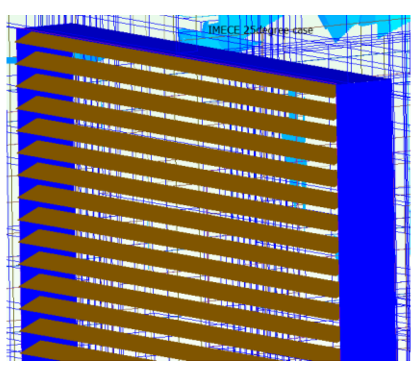


Fig 5.30 Inlet louvers with 25 degree angle

5.2.3.1 Thermal contour of Containerized Data center

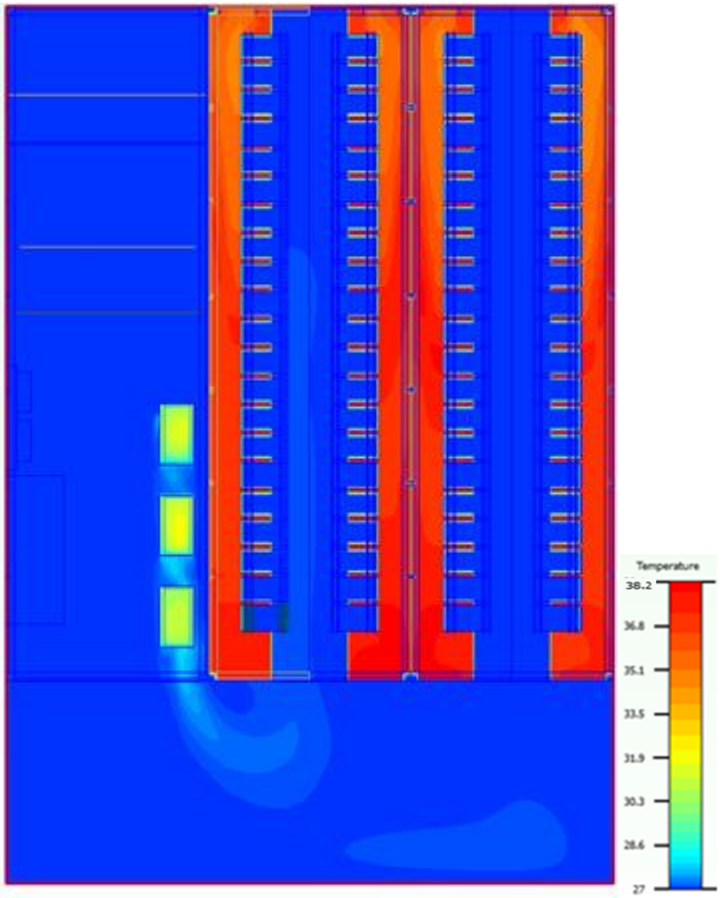


Fig 5.31 Thermal contour for 25 degree louver angle case

The thermal profile on a horizontal cut plane passing through the containerized data center is shown in Fig 5.32. The maximum temperature of 38.3°C is observed in the containerized data center.

5.2.3.2 Air flow Distribution with 25 Degree louver angle

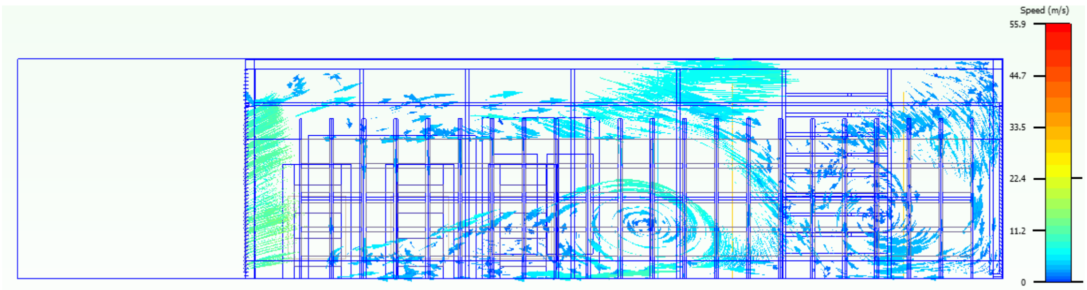


Fig 5.32 Vector Plot indicating Air flow pattern for 25 Degree Louver angle

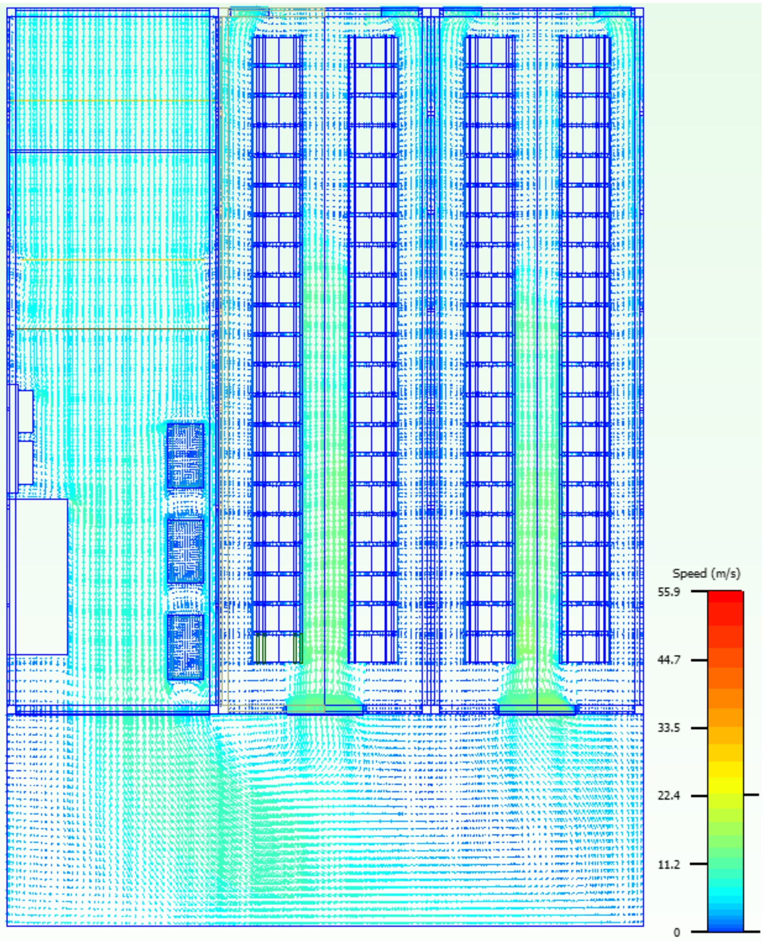


Fig 5.33 Air flow pattern in containerized data center from Top View

The total volume of air going into the system is 133040 CFM. This volume of air gets into two IT modules. IT module gets around 66,090CFM of total air whereas IT module II gets 66950CFM of total air.

Table 5.4 Volume flow rate in IT modules

Item	Item Details	m^3/s	CFM
IT-1	Inlet	140044710	66,090
IT-2	Inlet	141867050	66,950

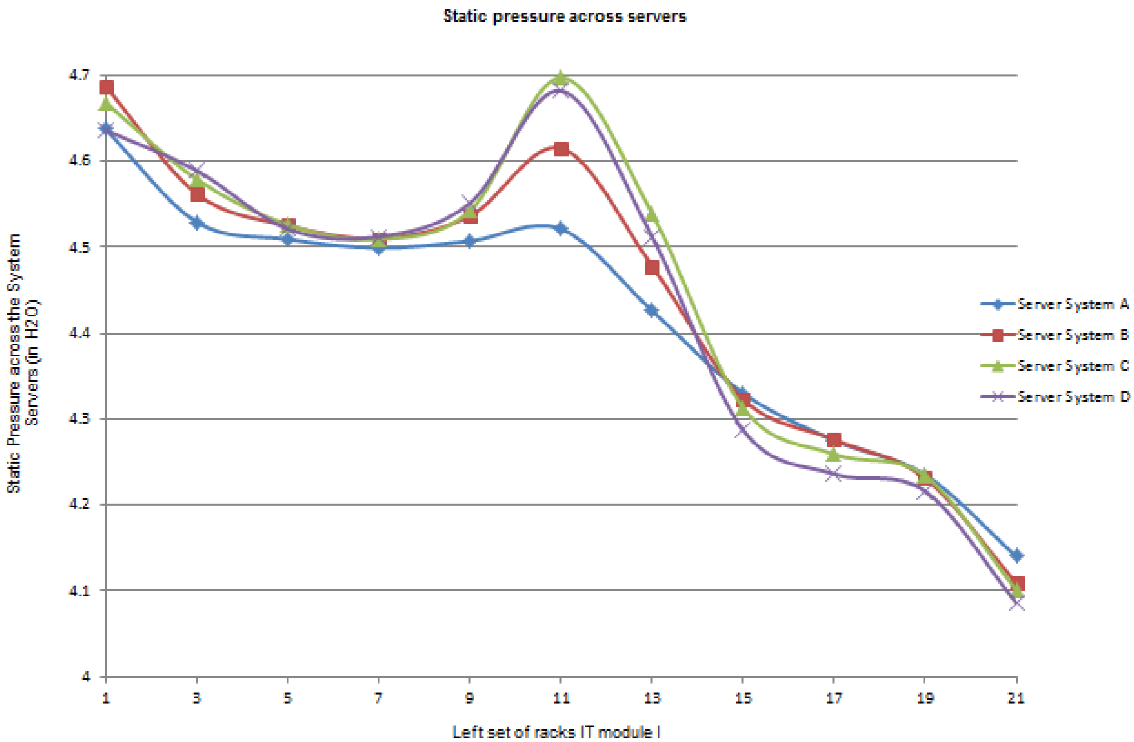


Fig 5.34 Static Pressure across Left set of Racks in IT module I

Fig 5.35 illustrates the static pressure across the left set of racks in IT module I. It can be seen that the mid area racks from 8 to 12, there is an increase in the static pressure which in turn corresponds to the lack of air in that area because of air circulations. Because of this increase in static, a fissure is observed in Fig 5.37 and hence increases in the exhaust temperatures of the racks.

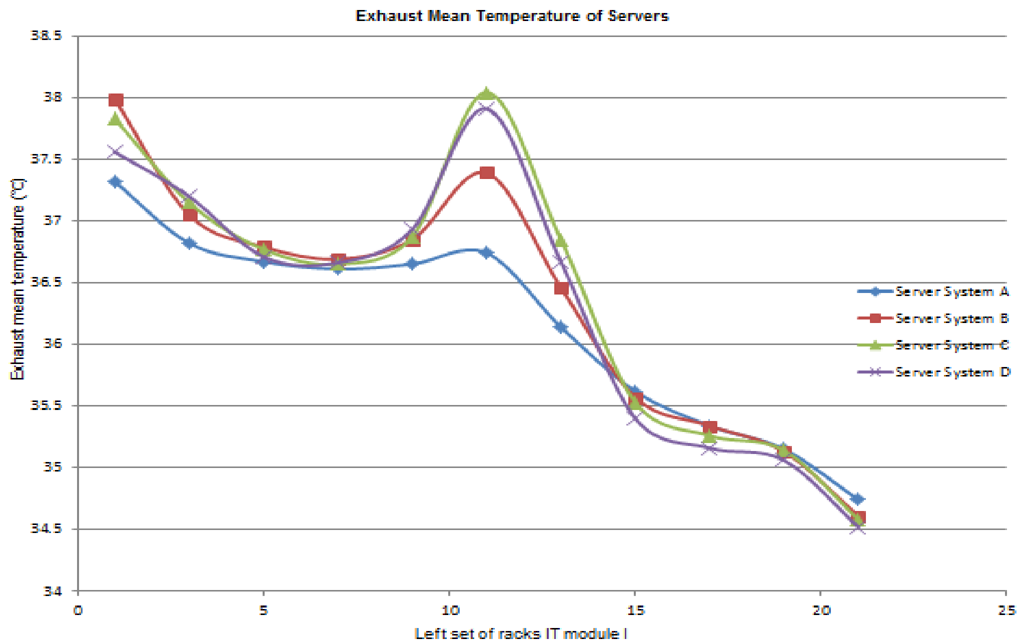


Fig 5.35 Temperature across Left set of Racks in IT module I

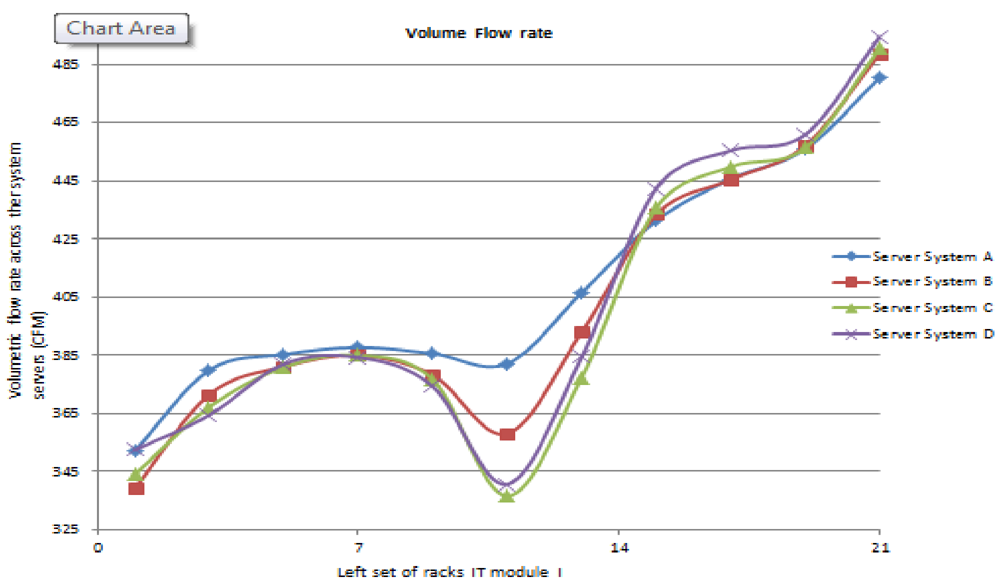


Fig 5.36 Volume flow rate across Left set of Racks in IT module I

Case 5.2.4 Case Study 4: 35 Degree Louver angle

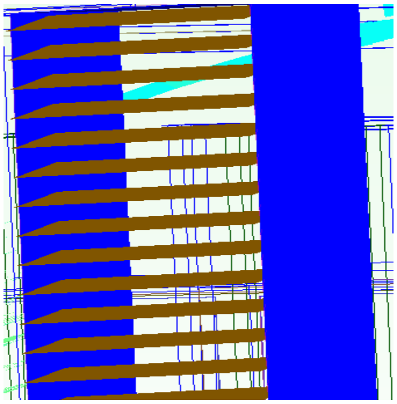


Fig 5.37 Louvers at 35 degree angle

5.2.4.1 Thermal contour of Containerized data center

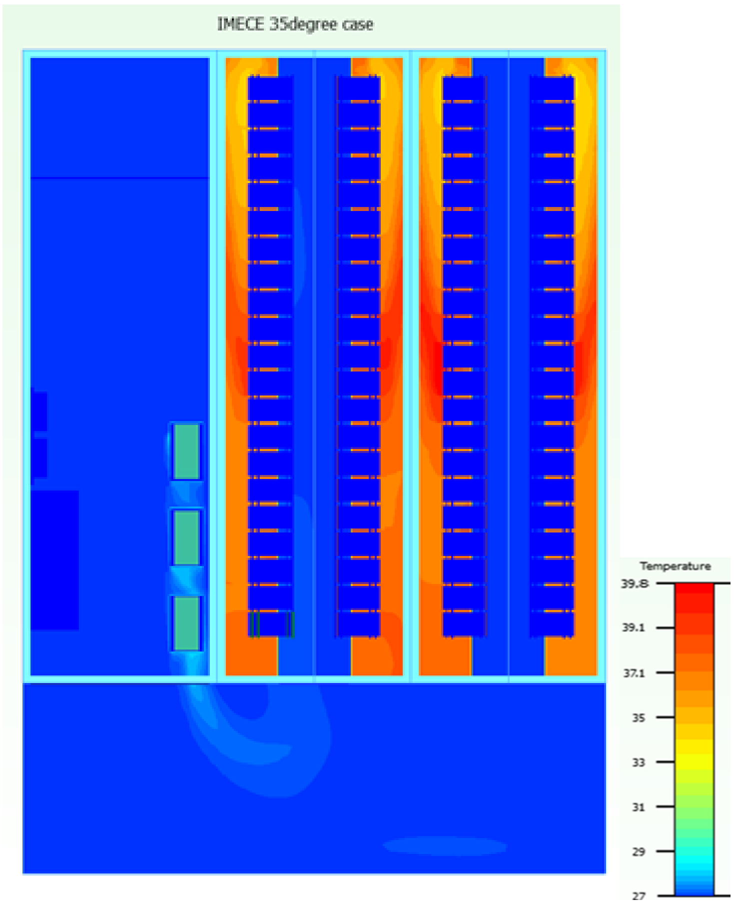


Fig 5.38 Temperature contour for 35 Degree Louver angle case

Fig 5.38 shows a temperature profile of containerized data center with 35 degree inlet louver. The maximum temperature observed is to be 39.8°C on the hot aisle side of the IT modules. It can be seen that this maximum temperature lies in the mid area racks as there is a strong air circulation observed in Fig 5.40. Because of the formation of this air circulation, it forms a low pressure region at its center. Thus server fans which have to draw air from these regions of strong circulation in the cold aisle will have to overcome higher differential pressure as long as the pressure in the hot aisle is relatively uniform. As the server fans operate at higher static pressure, that means less amount of air flows through the servers leading into increase in the exhaust temperature.

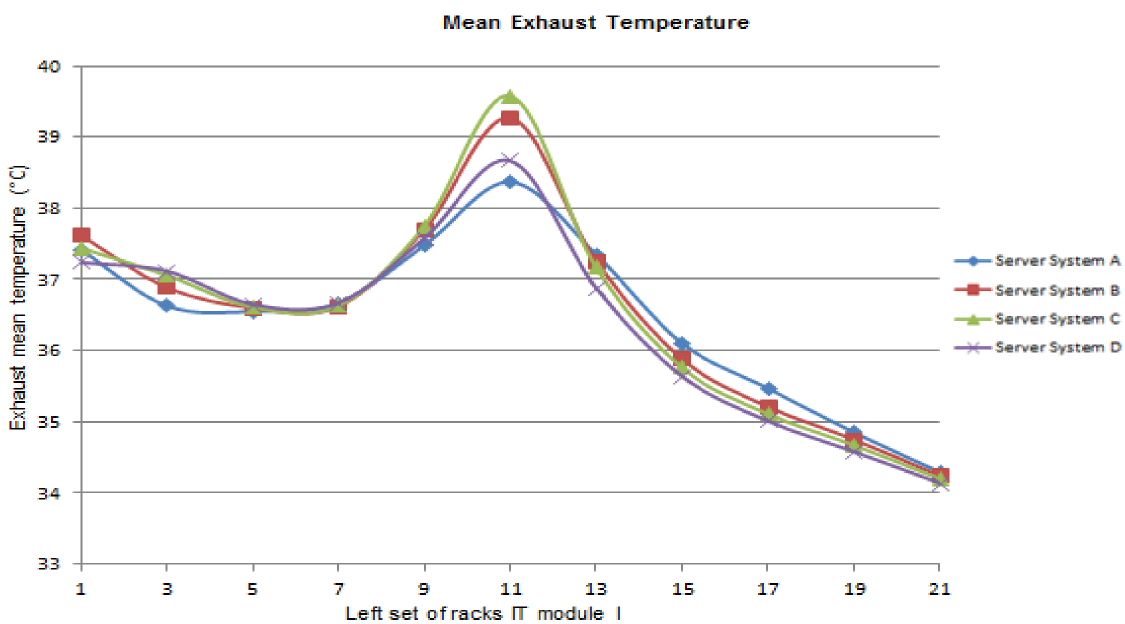


Fig 5.39 Temperature distribution across Left set of Racks in IT module I

As in the mid area left set of racks are not getting sufficient air, the exhaust mean temperature increases with an increase in the static pressure.

5.2.4.2 Air flow Distribution in containerized data center

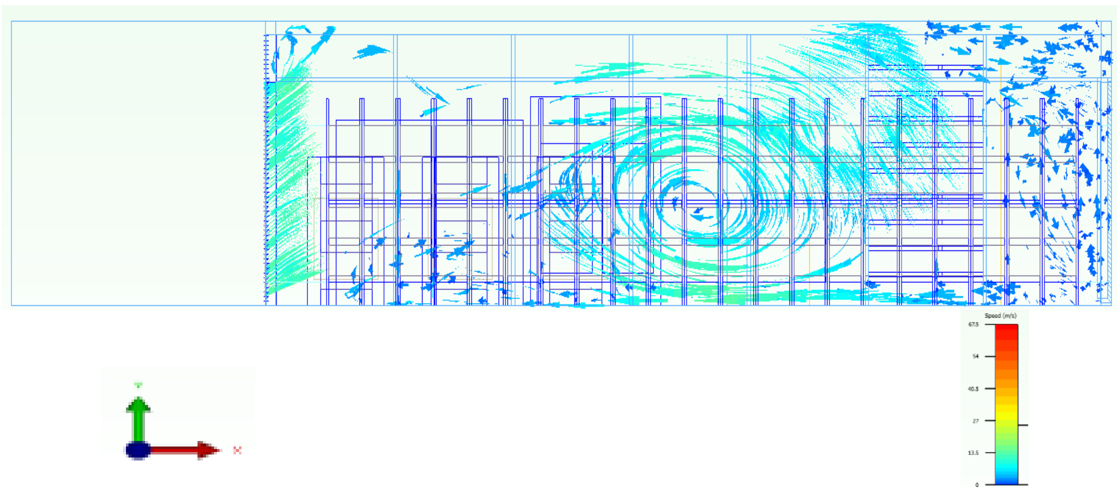


Fig 5.40 Vector Plot indicating Air flow pattern for 35 Degree Louver angle

Fig 5.34 illustrates the air flow pattern in the containerized data center from top view.

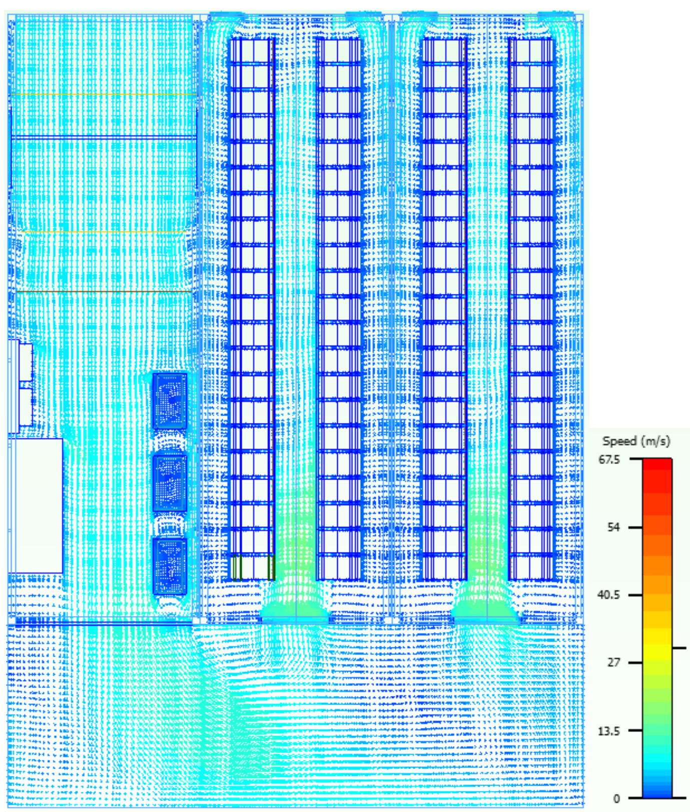


Fig 5.41 Air flow pattern in containerized data center from Top View

Table below illustrates the total volume flow for the overall system, 131400CFM. Out of this total volume of air, 65290CFM is drawn by IT module I and 66050CFM is drawn in IT module II.

Table 5.5 Volume flow rate in IT modules

Item	Item Details	m^3/s	CFM
IT-1	Inlet	138349510	65,290
IT-2	Inlet	-139959950	66,050

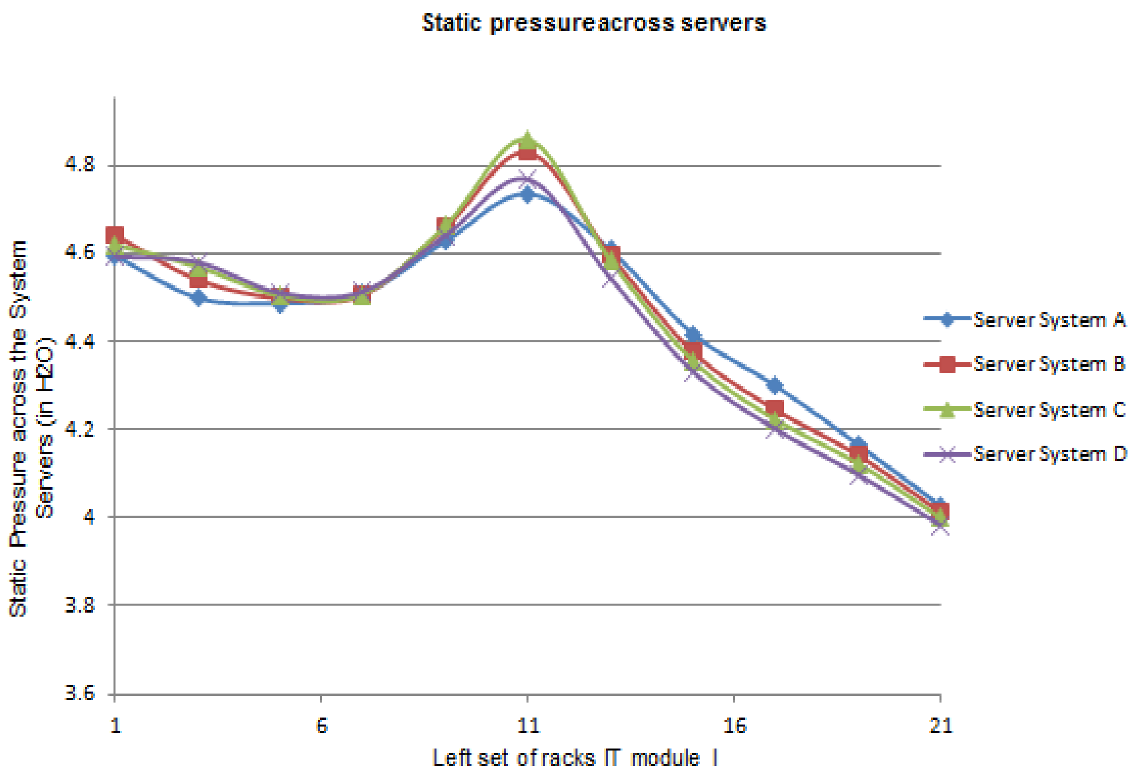


Fig 5.42 Static Pressure across Left set of Racks in IT module I

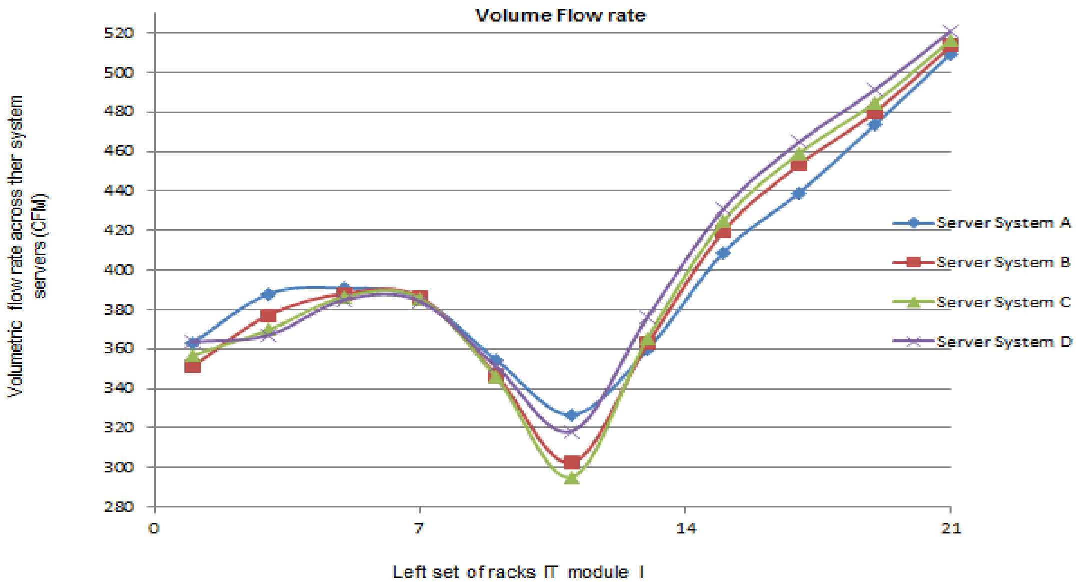


Fig 5.43 Volume Flow rate across Left set of Racks in IT module I

Case 5.2.5 Case Study I: 45 Degree Louver angle

In this case inlet louver angles are inclined at 45 degrees in both IT modules. This case has the least free area ratio as compared to other cases. The impact on blowers in power cooling module, thermal contour and air flow distribution in IT modules is studied using a CFD tool FloVENT. Fig 5.44 shows an isometric view of the inlet louvers with 45 degree.

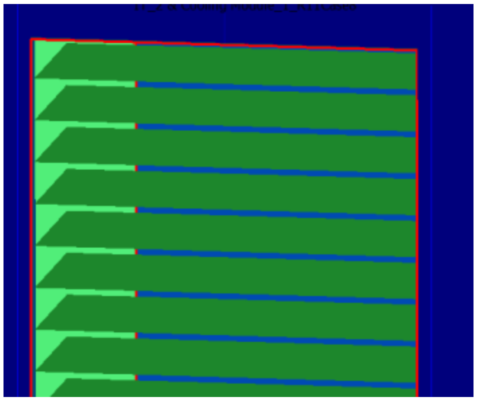


Fig 5.44 Inlet Louver with 45 Degree angle case

5.2.5.1 Thermal contour of server rack

The thermal profile on a horizontal cut plane passing through the modular data center is shown in Fig 5.45. The maximum temperature in the modular data center is 43.6°C that is 16°C above the inlet temperature, 27°C. This maximum temperature is observed at the rack from 8 to 15 and this is because the insufficient air in this region. This increase in temperature is because of the irregularity of air flow in the cold aisle of both IT modules.

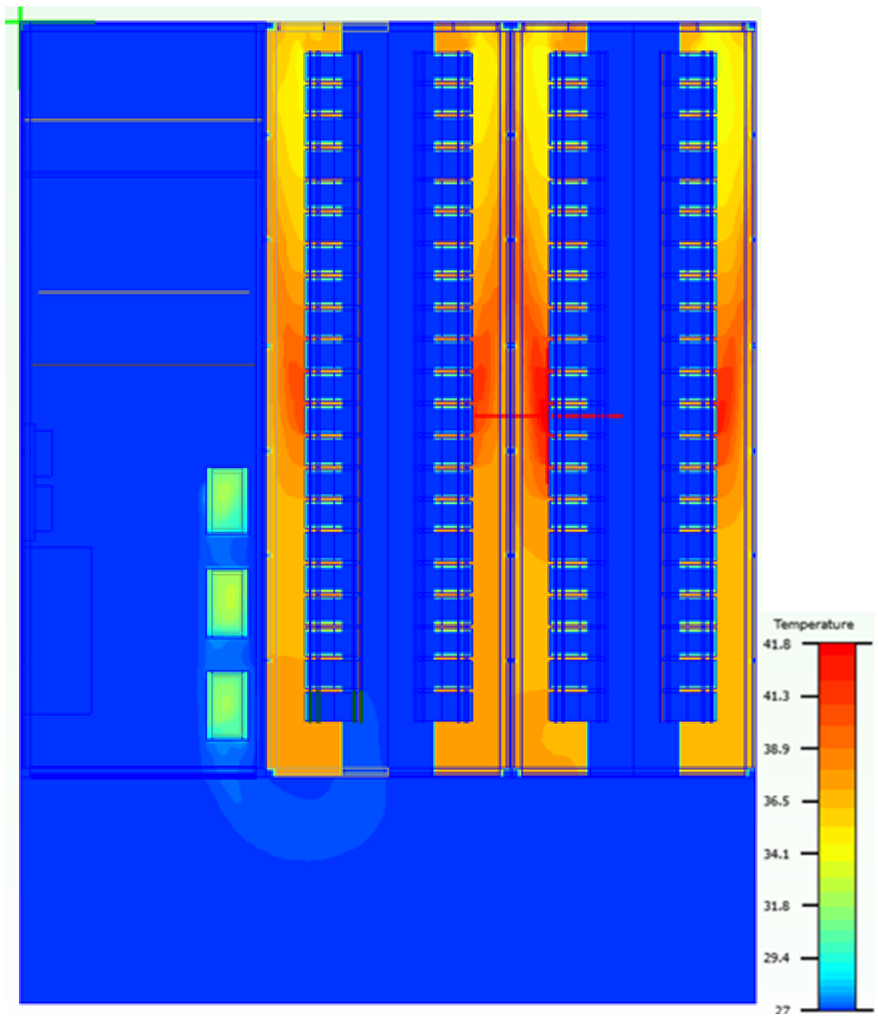


Fig 5.45 Thermal contour for 45 degree louver angle case

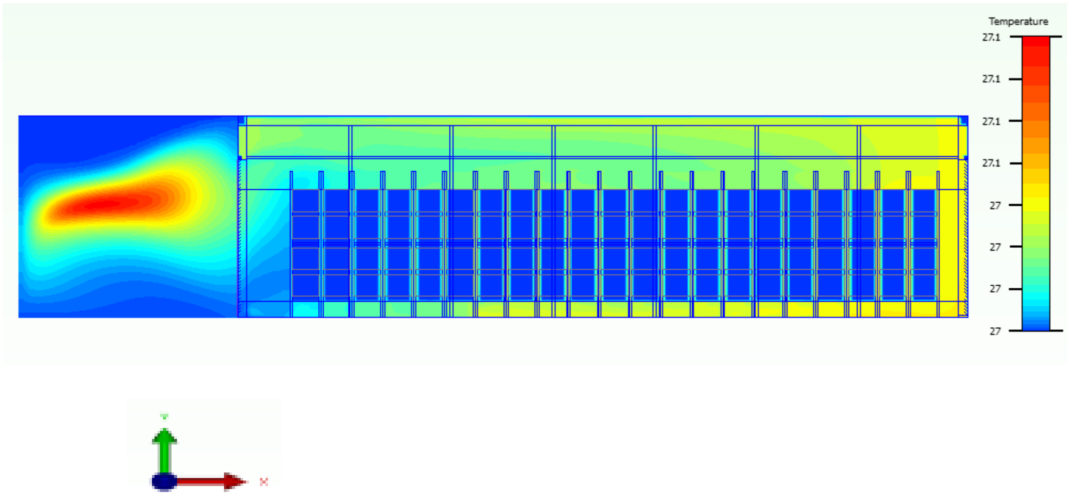


Fig 5.46 Thermal contour of a Containerized data center

Fig 5.46 illustrates a cross sectional plot at x= 1.31 meters from the reference. This section is in the hot aisle of IT module I. An increase in temperature is observed at the inlet of the IT module I because of the air circulations. In this case, there is a malfunctioning of air distribution in the cold aisle of the containers. At the end of the container, it can be seen that strong air circulation is formed which might restrict the sufficient air flowing into the system and increase in server temperatures.

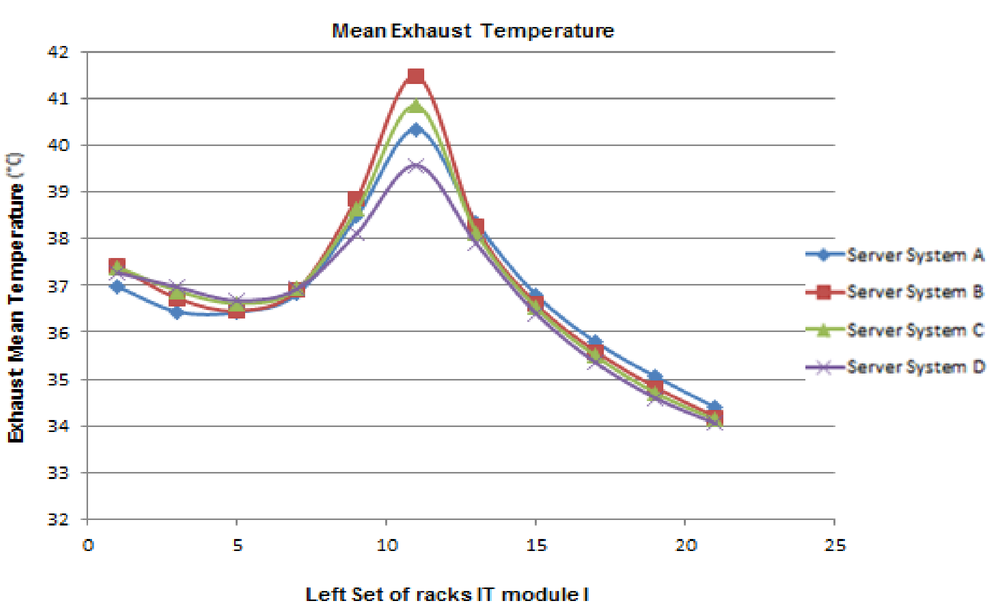


Fig 5.47 Temperature distribution across Left set of Racks in IT module I

Fig 5.47 illustrates the exhaust temperatures of the server systems A, B, C and D with respect to their corresponding racks. It can be seen that the exhaust temperature of the server systems reduces at the end of the IT module that is a decrease in temperature is observed from rack no.1 to rack no.21. The maximum temperature of 41.8°C is observed at rack no.13 because of the air circulations causing into higher differential pressures. Hence the operating point of the server reduces to cope up with this high static pressure with a lower volumetric air flow.

5.2.5.2 Air flow Distribution in Containerized data center

Fig 5.48 show scalar view of the airflow patterns in the cold aisle of IT module I with inlet louvers inclined at 45° to horizontal. Fig 5.49 shows strong air circulation around mid-length of the cold aisle.

Air circulation forms a low pressure region at its center. Thus server fans which have to draw air from regions of strong circulation in the cold aisle will have to overcome higher differential pressure as long as the pressure in the hot aisle is relatively uniform. Overcoming higher pressure differential means less air flow passing through the fans which in turn results in high temperature at the servers. This observation is seen in Fig 5.10 which shows mean exhaust temperatures at the exhaust of sets of servers numbered in increasing order starting from the rack closest to the inlet louvers.

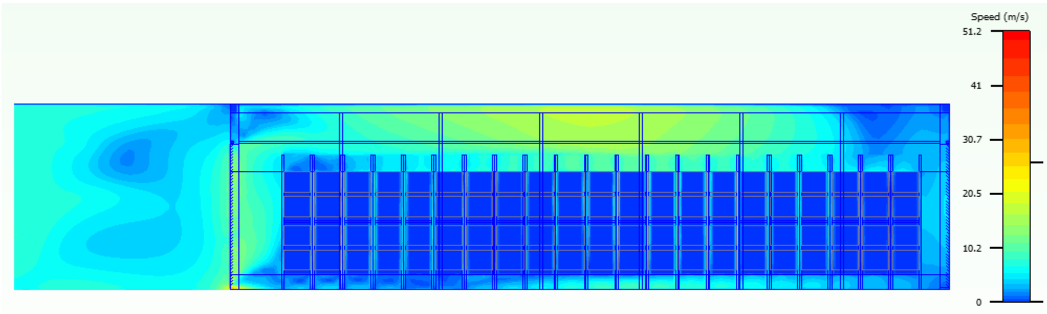


Fig 5.48 Scalar view of the air flow distribution in cold aisle side of IT module I

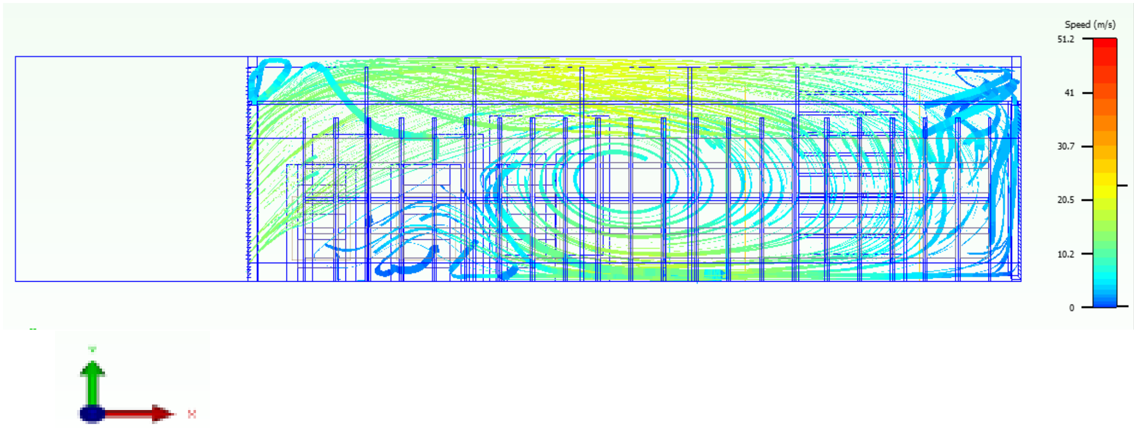


Fig 5.49 Vector Plot indicating Air flow pattern for 45 Degree Louver angle

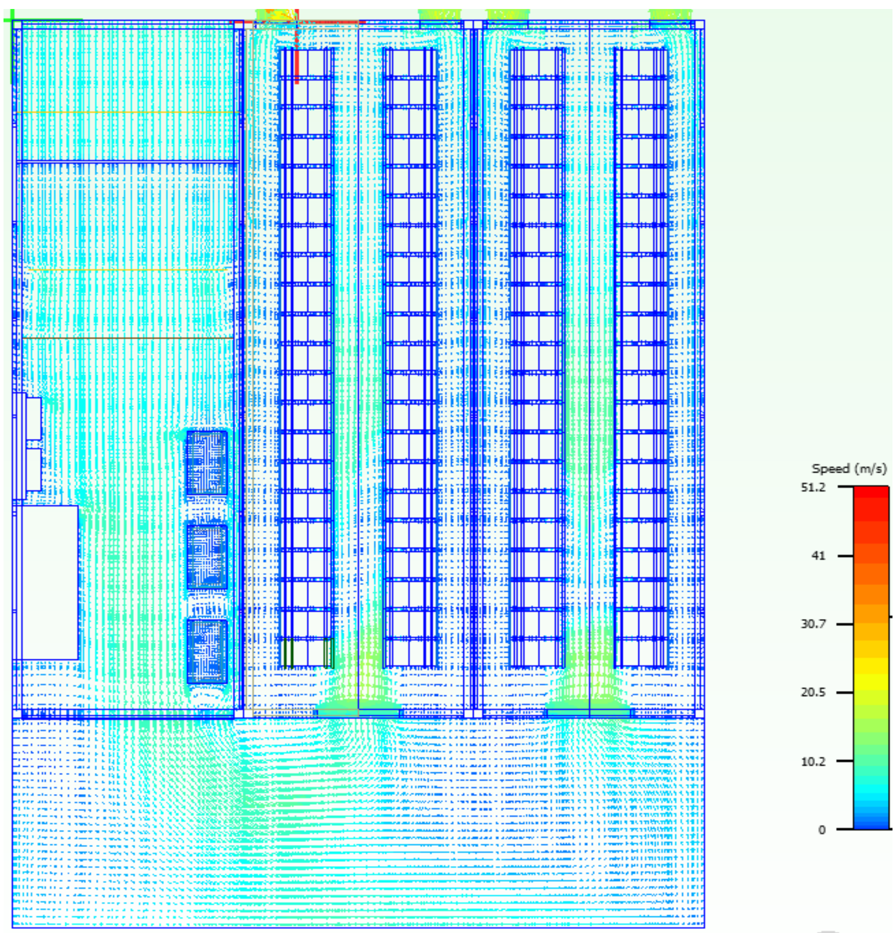


Fig 5.50 Air flow pattern in containerized data center from Top View

Fig 5.51 shows that the Volumetric flow rate of air drawn into each server rack in IT module I with respect to number of racks. As the velocity of air reduces at the rear side of the IT module hence it can be seen that more amount of air is drawn inside the server systems by the server fans. The total of 126,300 CFM of air from the ambient is drawn by the server fans inside the system. IT module I draws 63,000 CFM whereas IT module II draws 63,300 CFM.

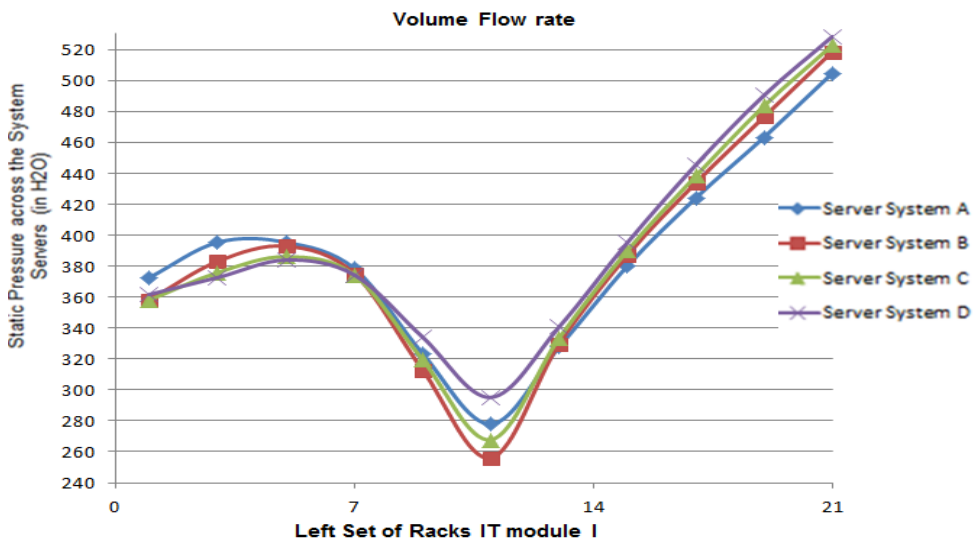


Fig 5.51 Volume Flow rate across Left set of Racks in IT module I

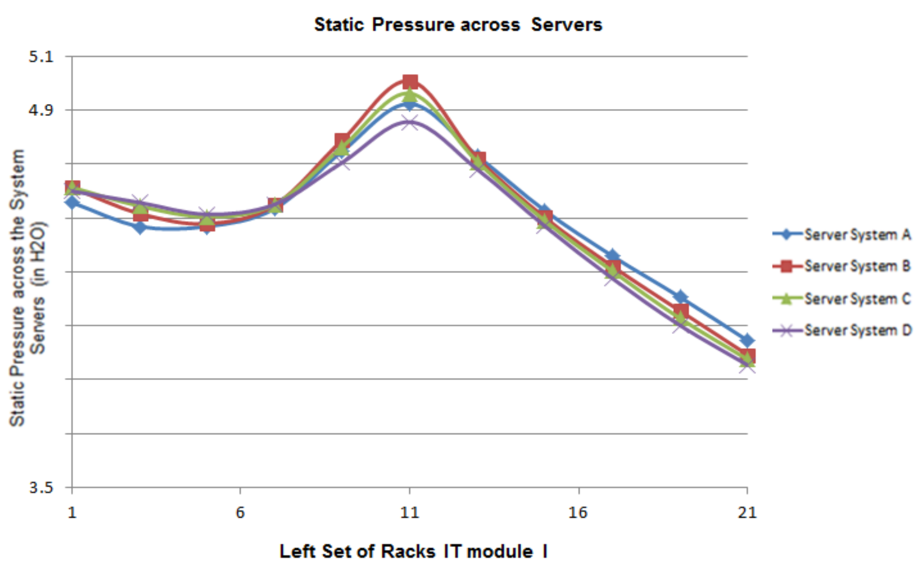


Fig 5.52 Static Pressure across Left set of Racks in IT module I

5.2.5.3 Impact of 0 Degree louver angle on Blowers in Power cooling module:

Table 5.6 Volume flow rate in IT modules

Item	Item Details	m^3/s	CFM
IT-I	Inlet	133497000	66,300
IT-II	Inlet	134175080	63,320

Table 5.7 Blower data for 45 degree louver angle

Item	Item Details	CFM	in H2O	m^3/s	Pa
Blowers	Fan 1	10631023	0.012707	5017	3.161
	Fan 2	10785710	0.012446	5090	3.096
	Fan 3	10817495	0.01239	5105	3.082
	Fan 4	10792067	0.01243	5093	3.092
	Fan 5	10679760	0.012623	5040	3.14
	Fan 6	10633142	0.012703	5018	3.16
	Fan 7	10789948	0.012438	5092	3.094
	Fan 8	10823852	0.012382	5108	3.08
	Fan 9	10800543	0.012418	5097	3.089
	Fan 10	10688236	0.012611	5044	3.137
	Fan 11	10639499	0.012691	5021	3.157
	Fan 12	10789948	0.012438	5092	3.094
	Fan 13	10821733	0.012386	5107	3.081
	Fan 14	10802662	0.012414	5098	3.088
	Fan 15	10696712	0.012595	5048	3.133
	Fan 16	10641618	0.012687	5022	3.156
	Fan 17	10775115	0.012462	5085	3.1
	Fan 18	10796305	0.012426	5095	3.091
	Fan 19	10787829	0.012442	5091	3.095
	Fan 20	10688236	0.012611	5044	3.137
	Fan 21	10508121	0.012912	4959	3.212
	Fan 22	10637380	0.012695	5020	3.158
	Fan 23	10656451	0.012663	5029	3.15
	Fan 24	10647975	0.012675	5025	3.153
	Fan 25	10542025	0.012856	4975	3.198

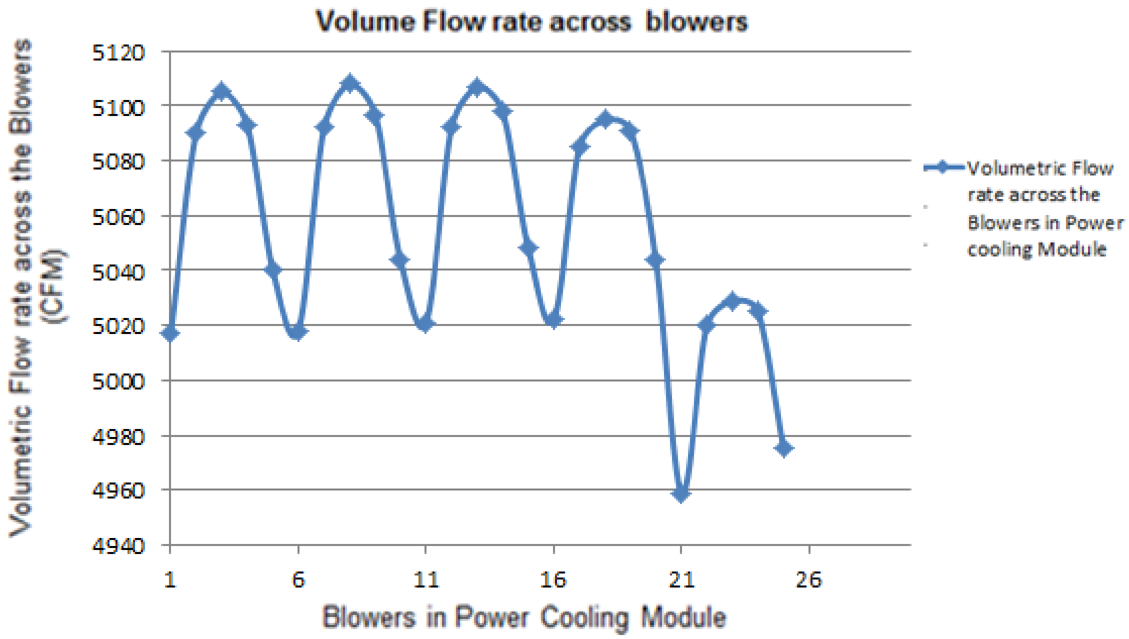


Fig 5.53 Volume flow rate across Blowers for 45 Degree case

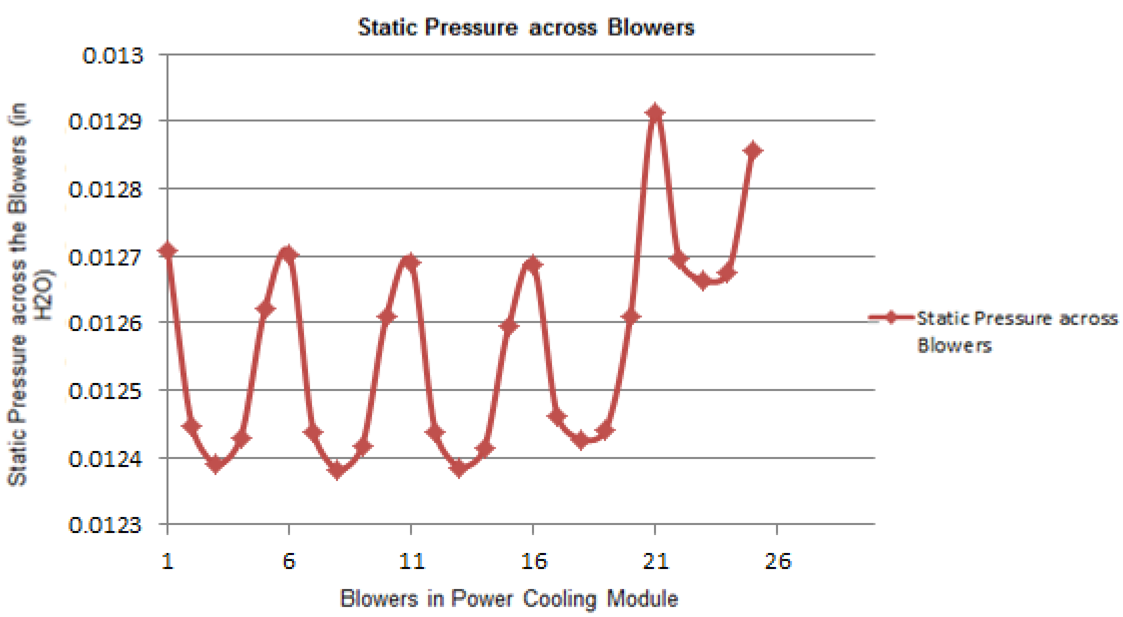


Fig 5.54 Static pressure across Blowers for 45 Degree case

Table 5.6 and Table 5.7 show the volumetric air flow and Static pressure across the blowers respectively. Fig 5.55 illustrates the blower curve with a blue line representing the system curve. In our model there are 25 blowers. Fig 5.56 represents the server fan curve. This fan curve provides a maximum of 1550 CFM of air.

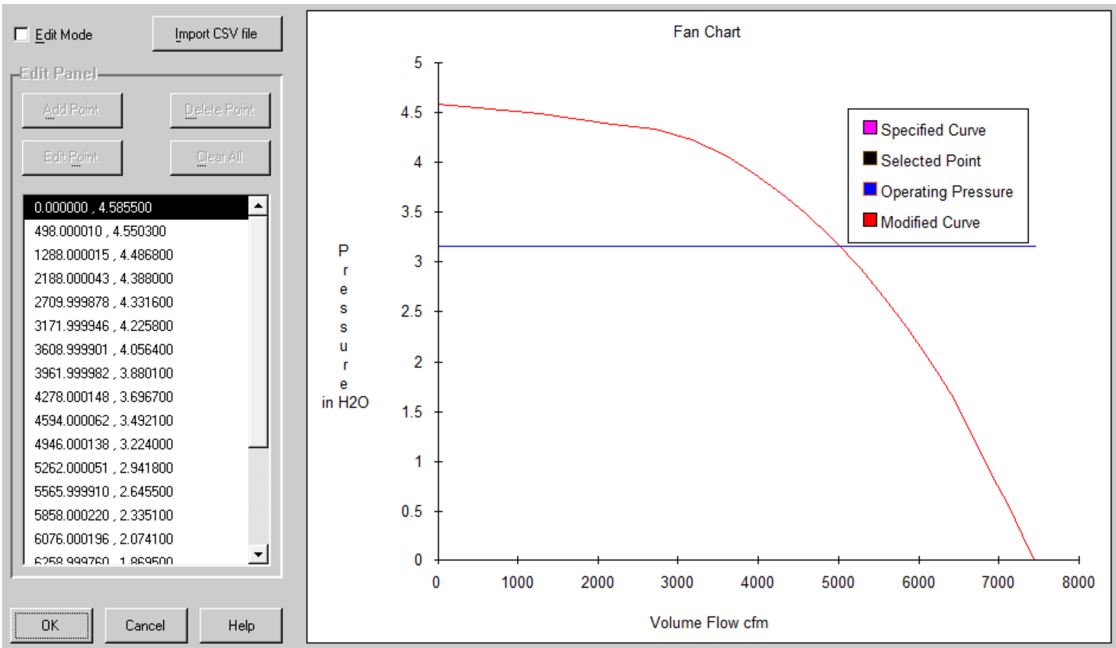


Fig 5.55 Blower curve for 45 Degree louver angle case

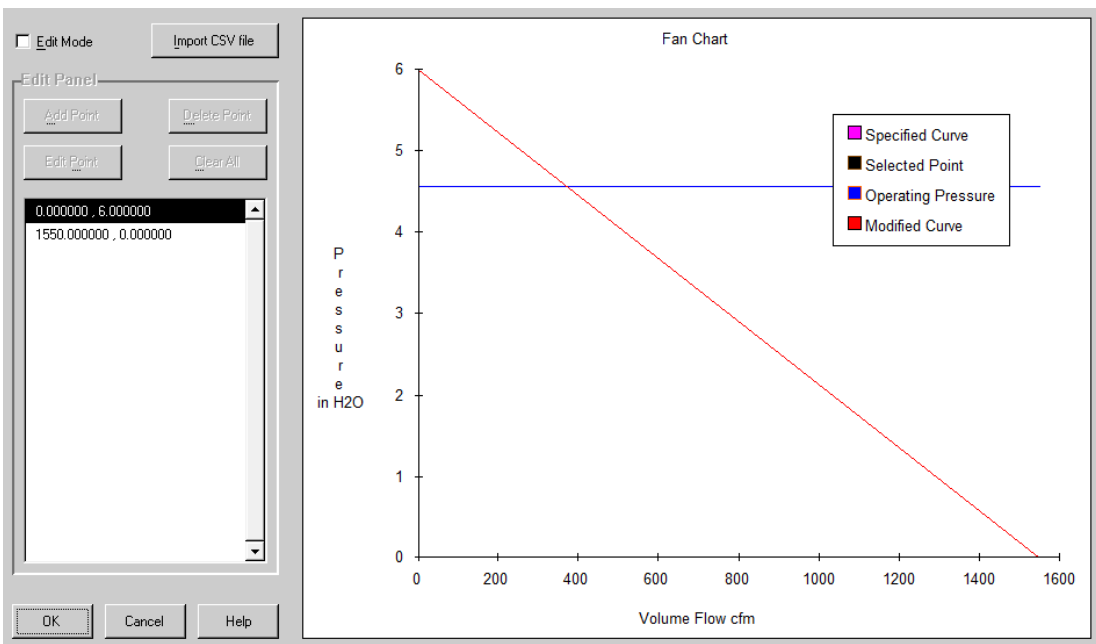


Fig 5.56 Server Fan curve for 45 Degree louver angle case

5.3 Results and Conclusion

5.3.1 Exhaust temperature comparison between 0 and 45 degree case:

Fig below shows the graphical representation of the exhaust temperatures for both 0 and 45 degree louver angle case. For 0 degree louver angle case (baseline), it can be seen that the maximum temperature is about 38°C and as we move from rack no.1 to rack no. 21, the temperature reduces to 35°C. For 45 degree louver angle case, it can be seen that the exhaust temperature at the initial set of racks is about 37.5°C and for racks in mid area this value rises to 41.5°C whereas the exhaust temperature of racks at the end of the container reduces to a significant value of 33.75°C. This increase in exhaust temperature at the mid area is because insufficient amount of air is going into the server fans because of air circulations. These air circulations are because of the change in the orientation of the inlet louvers.

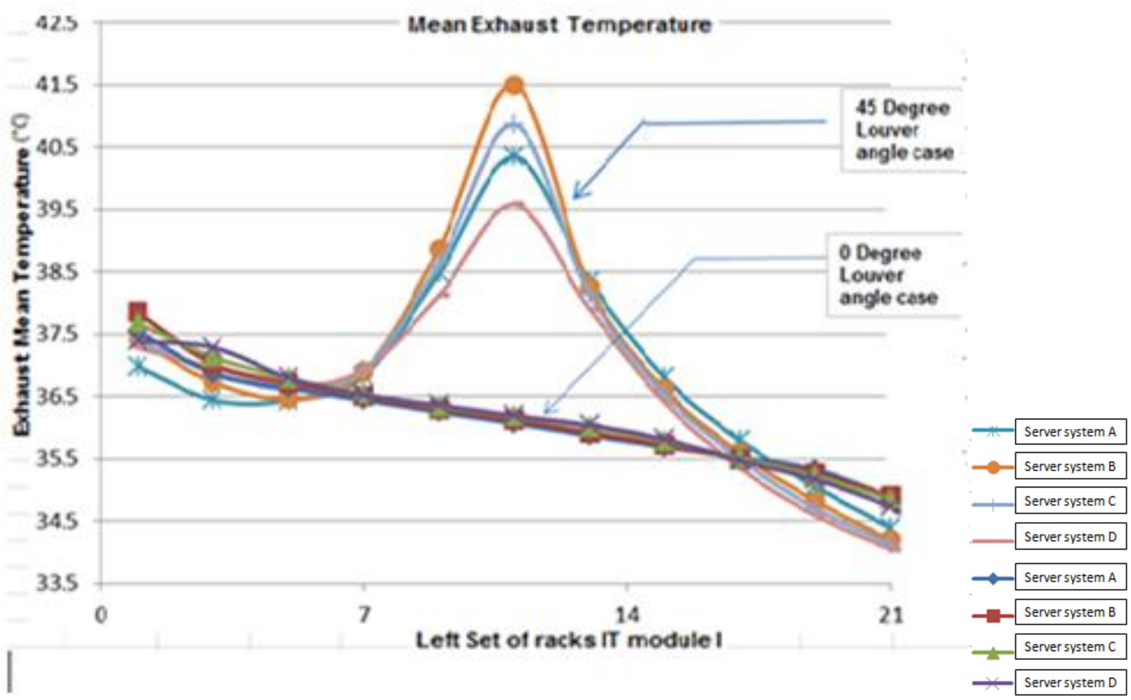


Fig 5.57 Thermal Performance of 0 and 45 Degree louver angle case

For 0 degree louver angle case (baseline), the volume air flow going into the containerized data center is 134,700CFM whereas in 45 degree louver angle case, the value is 126,300CFM. This decrease in the total volume flow rate is because with the change in the louver angle, the resistance in the system is being changed and hence a change in the operating point of the blowers in power cooling module is observed. From Fig 5.57, we can conclude that the louver orientation plays an important role in Air flow distribution and thermal management in data centers.

Fig 5.58 illustrates a Blower curve and Server Fan curve for 0 degree inlet louvers. The total volume of air drawn into the containerized data center is varied by the resistance inside the system. The amount of air blown through each Blower is 5500CFM with a Static pressure of 2.8 in H2O whereas the volume flow through each server fan is around 400 CFM with a Static Pressure of 4.8 in H2O. So corresponding to this air flow and total static pressure across the blowers and server fans, Pumping power can be calculated. Therefore the pumping power can be calculated for this configuration with 0 degree inlet louver angles as follows.

$$(Pumping\ \ Power\ )_{Overall\ \ System} = (Pumping\ \ Power\ )_{Blowers} + (Pumping\ \ Power\ )_{ServerFans}$$
$$= (\text{Total}\ \ \text{S.P}\ * \text{Volume}\ \ \text{Flow}\ \ \text{Rate})_{\text{Blowers}\ +\ \text{Servr}\ \ \text{Fans}}$$
$$= (1806\ \ * 25)\,\text{W} + (201.03\ \ * 336)\text{W}\ = 112.5\ KW$$

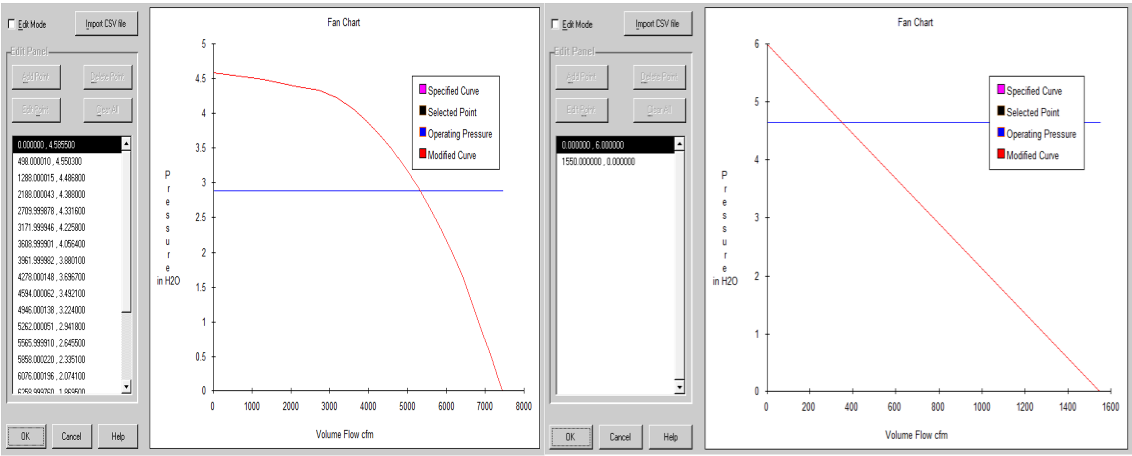


Fig 5.58 Blower & Fan curve for Baseline case

Fig 5.59 illustrates a Blower and Server curve for 45 degree inlet louvers. As the angle has increased from 0 to 45 the free area ratio has been reduced. The amount of air flow reduces from 134,700CFM to 126,400 CFM. The amount of air flow through each Blower is 5100CFM with a Static pressure of 3.1 in H2O whereas the volume flow through each server fan is around 380 CFM with a Static Pressure of 4.5 in H2O. So corresponding to this air flow and total static pressure across the blowers and server fans, Pumping power can be calculated. In our particular system, there are 25 blowers and 336 Server systems.

Therefore the pumping power can be calculated for this configuration with 45 degree inlet louver angles as follows.

$$(Pumping\ \ Power)_{Overall\ \ System} = (Pumping\ \ Power)_{Blowers} + (Pumping\ \ Power)_{ServerFans}$$

$$= (\mathrm{Total\ \ S.P\ * Volume\ \ Flow\ \ Rate})_{\mathrm{Blowers\ + Server\ Fans}}$$

$$= (1888.714\ * 25)\,\mathrm{W} + (225.8\ * 336)\mathrm{W}\ = 128.3\ KW$$

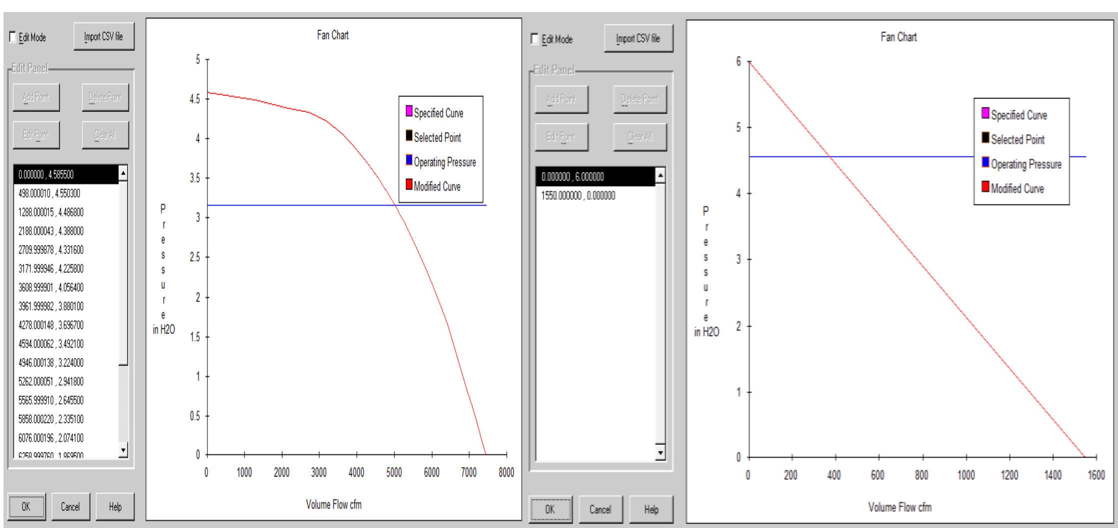


Fig 5.59 Blower & Fan curve for 45 Degree louver angle case

5.4 Partial PUE Calculations

Power usage effectiveness is abbreviated as PUE and is used to compare data center designs. The PUE's that does not take into account all the infrastructure components in order to concentrate on a particular portion of data center is known as Partial PUE. Partial PUE is abbreviated as "pPUE". Partial PUE refers to components within a boundary. PUE is important in order to control and manage data center power [30].

Partial PUE can be calculated as follow;

$$\textit{Partial}\ \text{Power Usage (pPUE)} = \frac{\text{Total Energy within a boundary}}{\text{IT Equipment Energy within that boundary}}$$

$$= 1 + \frac{25 * 1806}{336(201.03 + \textit{Heat load}\ \text{for each server system})}$$

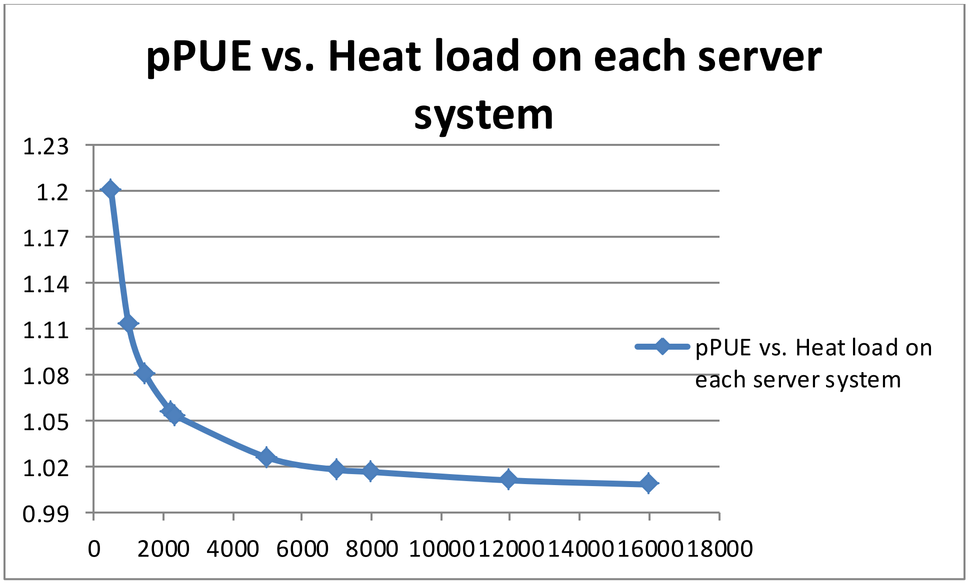


Fig 5.60 pPUE vs Heat load on each server

5.5 Mesh Sensitivity Analysis with 0 Degree Louver angle Case Model

A mesh sensitivity analysis is performed with 0 degree louver angle case. A mesh sensitivity analysis is carried out in order to insure the grid independence of the output variables. The number of cells is changed keeping the critical areas into mind for this particular case. The trials with change in the number of mesh count range approximately between 2.2 million, 4.1 million, 5.7 million, 6.7 million, and 7.7 million.

Table 5.8 Mesh Sensitivity analysis with 0 Degree angle case

Trials	Number of Mesh Counts	Temperature (°C)
1	2291633	37.3
2	4145117	37.5
3	5676977	37.6
4	6725650	37.9
5	7750488	37.9

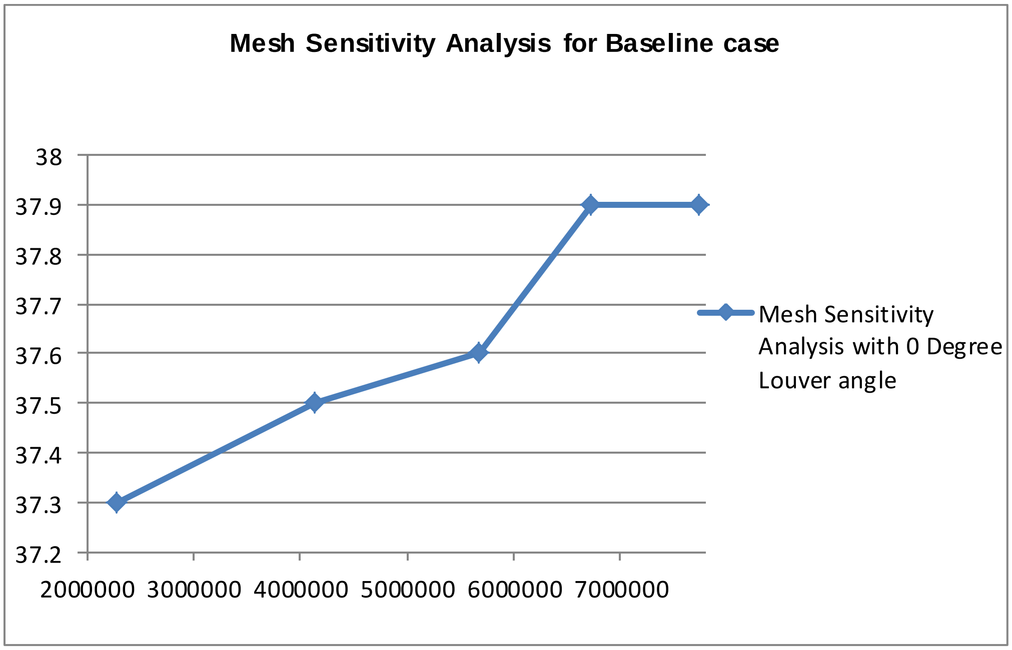


Fig 5.61 Mesh Sensitivity Analysis for Baseline Case

5.6 Future Work

Future work will include, optimizing the Server fans and analyzing the effect on pressure distribution, and thermal performance with a change in server fans. Also different louver combination will be modeled and thermal performance and air flow distribution will be studied. Also future work will include free cooling with water side economizer and its impact on the thermal performance of the system with a study of contaminants in data center.

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BIOGRAPHICAL INFORMATION

Kushal Aurangabadkar received his Bachelor's Degree in Mechanical Engineering from Yeshwantrao Chavan College of Engineering, Hingna Road, Nagpur, India in June 2009. He completed his Master of Science degree in Mechanical Engineering at the University of Texas at Arlington in December 2012.

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

He has handled a number of projects such as thermal analysis of AT&T Dual DAS Cabinets for stadium applications; air side economization with free cooling; filter characterization to determine system impedance curves; CFD analysis of direct evaporative cooling for modular data centers and impact of louver orientation on air flow distribution and thermal analysis in data center. He has worked on several industry projects during his research at the UTA.

Kushal also worked as a co-op at Lennox International. During the course of the co-op, he primarily focused on computational as well as experimental simulations on roof op air conditioning units. He is a member of ASHRAE, and Surface Mount Technology Association (SMTA).