EXPERIMENTAL AND COMPUTATIONAL ANALYSIS OF AN IT POD AND ITS COOLING SYSTEM

by

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ABSTRACT

EXPERIMENTAL AND COMPUTATIONAL ANALYSIS OF AN IT POD AND ITS COOLING SYSTEM

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Conventional data centers are extremely large buildings that have complex power distribution and cooling systems. These data centers employ relatively expensive cooling systems which are inefficient. These inefficiencies of traditional data centers can be overcome by partitioning the server load into modular sections which can be deployed, powered and cooled depending on availability and requirement. Modular data centers are increasingly being developed instead of using large data centers to save huge amount of capital investment. High energy efficiency is a priority and measures have been taken to increase it. Cooling techniques such as air-side economization and evaporative cooling are proving to be some of those very effective measures.

An IT pod cooled by an indirect and direct evaporative cooling unit is the prime focus of my research. Computational fluid dynamics analysis is performed

to study the airflow pattern, temperature distribution and the effect of solar loading inside the IT pod and the Aztec cooling unit. Both steady state and transient analysis are performed during the study by modeling the IT pod and the cooling system using a commercially available tool, FloTHERM. The temperature distribution inside the IT pod is validated by obtaining the temperature measurements through thermocouples and sensors at different locations. The study also reveals location of the servers which get cooled efficiently than the others.

The study was done in collaboration with an industrial partner and as such most of the results of this study have been continuously or being implemented.

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NOMENCLATURE

ρ	Density (kg/m^3)
k	Thermal Conductivity (W/m-K)
ε	Kinematic Rate of Dissipation (m^2/s^3)
v	Velocity (m/s)
μ	Viscosity (N/m^2 s)
$\dot{m}$	Mass flow rate (kg/s)
q	Heat load (W)
P	Power (W)
$\dot{v}$	Volumetric Flow Rate (cfm)
IT	Information Technology
ASHRAE	American Society of Heating, Refrigeration and Air Conditioning Engineers
R_e	Reynolds number
C_p	Specific Heat capacity (J/kg K)
p	Pressure (in of H_2O)
DEC	Direct Evaporative Cooling Unit
IEC	Indirect Evaporative Cooling Unit
BTU	British Thermal Unit (1 BTU/hr = 0.29307107 Watts)

CHAPTER 1

INTRODUCTION TO MODULAR DATA CENTERS

1.1 Introduction to Data Centers

1.1.1 Data Centers: An introduction

Data centers are facilities where servers, switches and other electronic equipment for data processing, communication and storage are housed. These centers are used by industries with data processing needs such as telecommunications, banking, stock markets, social networks, educational institutions, search engines, etc. Due to increase in networking and internet usage, the number of data centers have increased considerably. The size of the data centers and the power utilization have also increased. These large power dissipations are mainly dissipated as heat inside the data centers. Therefore, better thermal management of the data center environment is highly recommended. Along with maintaining safety, operating these facilities with optimal energy efficiency while securing power supply to the electronic equipment at all times [1].

Figure 1.1- Inside a Google data center [2]

1.1.2 Power trends in Data Centers

The Information Technology industry has been improving the performance of microprocessors by reducing the size of the transistors and using multiple cores on single chips, resulting in high power chips. Packaging these high powered chips into a server and stacking them into a rack, results in a dangerous concentration of rack power [1].

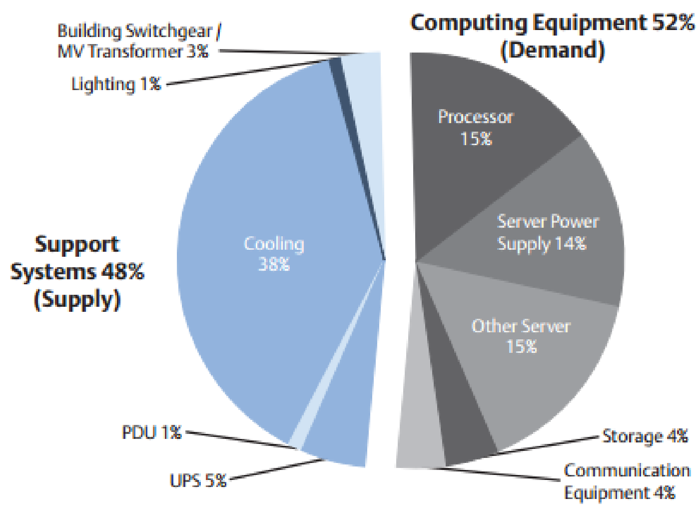

Figure 1.2- Energy Consumption in a data center [3]

The continuing rise in heat loads of data processing equipment poses concerns for data centers which house large numbers of servers and require a lot of cooling, to provide adequate airflow through the equipment at a temperature that meets the manufacturers' requirements [4].

The above figure shows a typical data center energy consumption chart. It is clear that IT equipment consume more than 50% of the total power consumed in a data center and cooling consumes around 38% of the total power consumed. This is more than half of what the IT equipment consume as useful power.

1.2 ASHRAE Recommendations

The ASHRAE Technical Committee (TC) 9.9 has been responsible for providing the thermal guidelines for the safe operation of IT equipment in data centers. Prior to their existence, each IT manufacturer provided recommendations on the operation of their products in a data center environment which is not practical given the diversity of the equipment typically used in data centers [1].

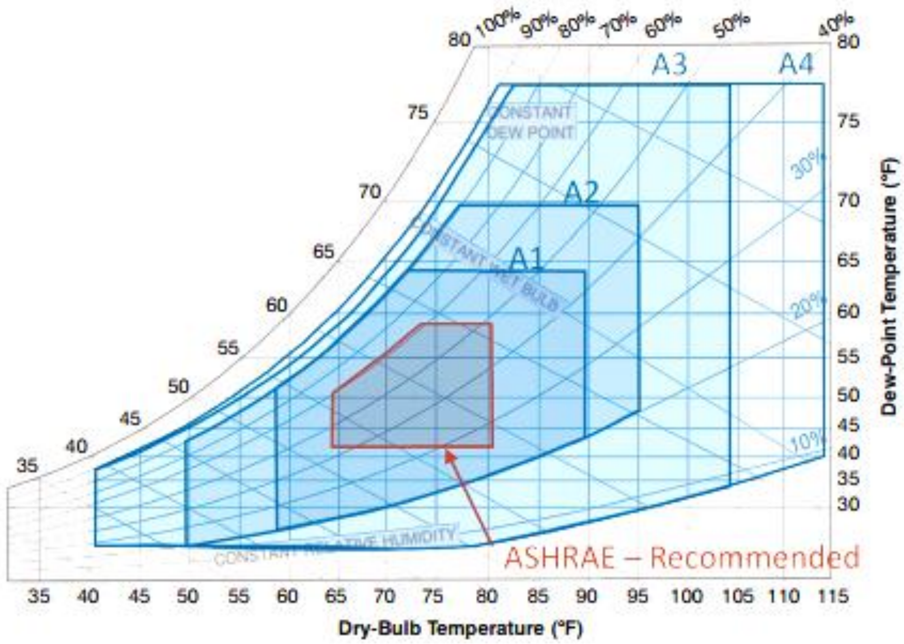

Figure 1.1- Psychrometric chart showing the various recommended regions by ASHRAE [5]

Table 1.1- ASHRAE environmental classes for data center applications [5]

Range	Class	Dry-Bulb Temperature	Humidity Range, Non-Condensing	Maximum Dew Point
Recommended	All A	64.4°F to 80.6°F	41.9°F DP to 60% RH and 59°F DP	59°F
Allowable	A1	59°F to 89.6°F	20% to 80% RH	62.6°F
	A2	50°F to 95°F	20% to 80% RH	69.8°F
	A3	41°F to 104°F	10.4°F DP and 8% RH to 85% RH	75.2°F
	A4	41°F to 113°F	10.4°F DP & 8% RH to 90% RH	75.2°F
	B	41°F to 95°F	8% RH to 80% RH	82.4°F
	C	41°F to 104°F	8% RH to 80% RH	82.4°F

As awareness rose regarding the energy required to run data centers, the TC 9.9 expanded the environmental range in order to allow data center operators to operate in the most energy efficient mode and still achieve the reliability necessary as required by their business. This enables many more data centers to take advantage of operating with more hours of economizer usage. The expanded envelope is captured in two new data center classes (A3 and A4) created to achieve the most flexibility in the operation of the data center and are shown in the psychometric chart in Figure 1.2 along with the two old classes [1].

ASHRAE Class A3 expands the temperature range to 41°F to 104°F while also expanding the moisture range from 8% RH and 10.4°F dew point to 85 % relative humidity.

ASHRAE Class A4 expands the allowable temperature and moisture range even further than A3. The temperature range is expanded to 41°F to 113°F while the moisture range extends from 8% RH and 10.4°F dew point to 90 % RH.

The Recommended class extends from dry-bulb temperatures 64.4°F to 80.6°F, with humidity range from 41.9°F dew point to 60%RH and 59°F dew point.

1.3 Modular Data Centers

1.3.1 Modular data centers: An Introduction

Data centers are large facilities which perform more than one functions like store, process, manage and exchange data. The servers which do the above mentioned functions, along with power conversion equipment and environmental control equipment to maintain operating conditions are all termed as "IT equipment" collectively [6].

The data centers are expanding in terms of size and power density with rapid advancement of technology and networking. Therefore, the investment to set up high capacity data centers has also increased, so as the additional costs for construction and maintenance. Expansion of traditional, large data centers is difficult unless it is accounted earlier before construction. Expansion in terms of capacity is also considerably difficult as systems have to be ordered, shipped and delivered to the data center where they must be racked and installed. The process would require skilled labor in addition to cost of shipping and delivering the systems [7].

Modular data centers are containerized data centers or portable self-contained environment designed for rapid deployment, energy efficiency and better computing density. They are portable and can be deployed faster compared to a traditional one, at any given location in the world. They are self sufficient modules consisting of thousands of systems built within a shipping container which houses all the necessary equipment, configured and shipped as a fully operational unit ready to be powered up. It requires power supply, internet access and chilled water supply upon delivery [7].

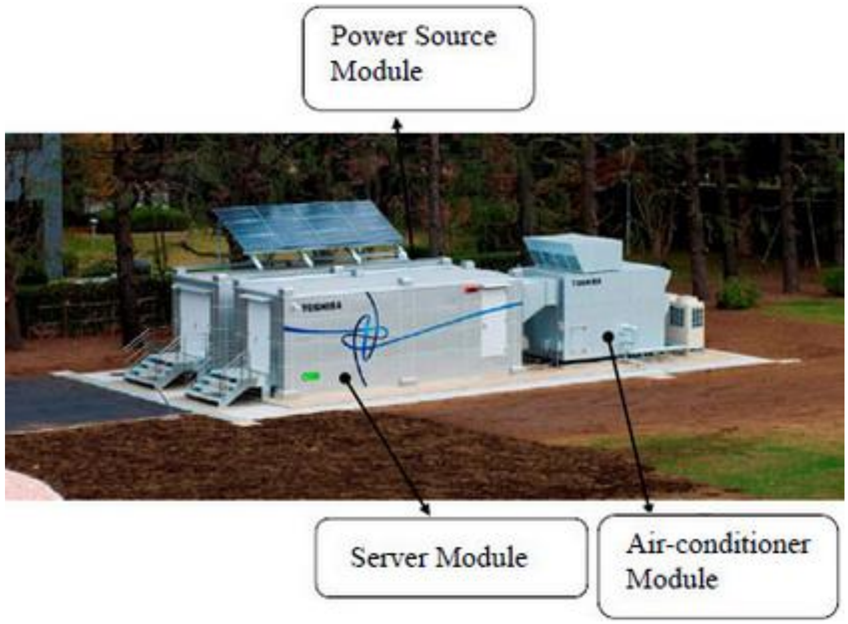

Figure 1.2- Toshiba's Modular data center attached to an air-conditioning unit and a power unit [8].

The first modular data center known as "Project Black box" was introduced by Sun Microsystems (currently owned by Oracle Corporation). It was a portable data center built into a standard 20 feet shipping container and required power supply and an external chiller to be operated. It housed around 280 servers. Since then, many companies have developed containerized data centers featuring state of the art technologies [7].

1.3.2 Importance of Modular Data centers and the need for cooling [7]

Modular Data Centers have gained great importance in recent years in the Data Center world because of their simplicity and the ease at which they can be quickly deployed to expand the existing IT infrastructure. They are energy efficient and require less maintenance as opposed to the large, traditional data centers.

Interestingly, these modular data center facilities can be located anywhere from onsite facilities to warehouses, garages or even in parking lot areas. These facilities can be used during the intermediate stage when there is construction or expansion seen on the large data centers with rapidly growing IT requirements.

These modular facilities exist in various sizes. It can range from 20 to 50 feet and the capacity to house several servers in the unit with provision of large amounts of power. Tremendous amount of heat is generated by these IT equipment inside the modular facilities. It is very necessary to ensure that the temperature of the air is cooler and within the prescribed limits in order to avoid hot spots. Formation of hot spots and the thermal stresses lead to equipment failure, short term reliability and so on. Factors such as ambient temperature, humidity, location, flow rate and solar radiation (solar loading) play an important role as thermal conditions are based on ambient conditions, along with conditions existing inside the modular data center. Reduction in chip sizes and high chip utilization rates has led to an increase in heat density of the chips at a higher rate. Hence it is necessary to pay attention on the thermal management at the server, rack and room level, in order to maintain optimum performance of the IT equipment and other devices.

1.3.3 Differences between traditional and modular data centers [7]

1.3.3.1 First generation modular data centers

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

1.3.3.2 Second generation modular data centers

Second generation modular data centers eliminate the need for chilled water supply or direct expansion cooling. These systems use free cooling, chilled water or direct expansion methods. Evaporative cooling, another highly efficient technique, is sometimes paired with free cooling when ambient air temperature reduction is needed. These systems may also include chilled water or direct expansion cooling units as backup when outside air temperatures dictate that use of economizers may not be favorable [7].

Table 1.1- Comparison between Traditional data centers, first generation and second generation modular data centers [9]

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.

1.3.4 Modular data centers considerations and requirements

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

Selection of cooling technology is very important and varies primarily depending on the location, geography, humidity, other environmental conditions and availability of existing resources in the vicinity where modular data centers are set up. The selection of cooling systems can be divided into air side systems, water side systems and other miscellaneous systems. Air side systems are preferred for free cooling systems. When environmental conditions are not favorable for operation of air side systems, water side systems and miscellaneous systems such as evaporative coolers and dry coolers can be utilized. These systems can be used in combination with conventional cooling systems such as water cooled chillers, chilled water towers and direct expansion units to support IT equipment depending on outdoor conditions [7].

Additional requirements such as availability of maintenance and service are crucial. It should be determined if backup power is available for the unit. The orientation of the modular unit with respect to the direction of wind is also important for those units with air-side economization, to improve free cooling and energy efficiency [9].

1.3.5 Energy efficiency in modular data centers

Energy efficiency and high performance is the most important attribute to design a modular data center. Since modular data centers are small in size compared to the traditional ones, better performance and energy efficiency is expected . Conventional cooling systems such as chilled water systems are used in the traditional data centers since free cooling on such a large scale is very difficult to provide for [7].

Advantages of energy efficient modular data centers are [9]:

i. Lower Power utilization effectiveness (PUE) value.

ii. The ability to use higher chilled water supply.

iii. Variable speed fans used in cooling systems and effective control systems that monitor device temperatures and air flow requirements.

iv. Use of air side economizers and other free cooling systems such as evaporative coolers which are cost effective and can improve efficiency.

v. Improved hot aisle/cold aisle containment. By doing so, this can reduce the amount of flow rate and the fan power required to supply it.

Power usage effectiveness (PUE) is a standard/metric developed by The Green Grid consortium in order to determine energy efficiency within a data center. Since power and cooling are two of the biggest challenges in data centers, companies require different solutions to reduce costs and maximize energy efficiency. By doing so, companies can increase computing; achieve lower energy costs and reduce the total cost of ownership (TCO) [10].

Power usage effectiveness (PUE) is defined as the ratio of the total power used by a data center facility to the IT equipment power supplied [11]. The ideal PUE value is 1.0 which would indicate 100 percent efficiency. This means all the power is being used up by the IT power only. PUE values are generally between 2.0 to 3.0 for data centers, but can be brought down significantly by designing them much more efficiently.

PUE = Total Facility Power/IT Equipment Power [11]

Total facility power includes all the components which support the IT equipment load such as power systems like generators, UPS systems and batteries and power distribution units, cooling systems such as chillers, cooling towers, computer room air handling units (CRAHs), mechanical components such as compressors and condensers, pumps and direct expansion systems [12].

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1.4 Free Air Cooling for Air-Side Economization

1.4.1 Introduction to Free Cooling

Servers have become an integral part of today's computational world since they are the source for data storage and enormous computational power. Data centers now, houses a large volume of servers. Until recently, the performance of processors and servers in terms of energy and power utilization has been of less concern compared to their computational performance. Although the initial capital for these powerful servers has become comparatively cheaper due to Moore's law and lower manufacturing costs, operating these devices for continuous and longer durations require the use of large amounts of energy [13]. Consumers are demanding higher server performance due to increased computing power at the chip level. Although these devices have become extremely efficient in terms of computational output per watt, however due to high performance, it has led to an increase in power density. Continuous operation of these devices leads to the generation of a large amount of heat.

One of the major goals is to reduce the power usage effectiveness in order to improve efficiency of data centers. Cooling systems play a very important role in removing heat from server racks, but require significant amount of power. This has caused an increase in consumption of electricity [7].

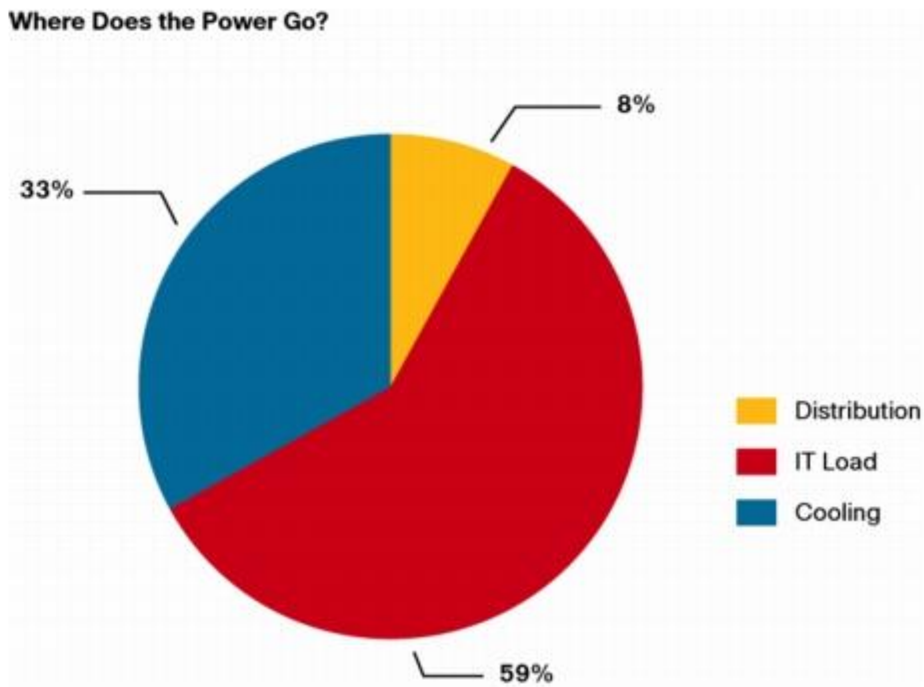

Figure 1.3- Operating Expense Contributions by Infrastructure Components in the Data Center [14]

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

1.4.2 Types of Free Cooling systems

Usually Air-side cooling systems and water-side cooling systems are the two types of free cooling systems but miscellaneous systems such as sea water cooling and ground water cooling are also used. Air-side cooling involves outside air being pulled in and circulated around the IT equipment to cool them whereas circulating water or a mixture of glycol water is used in case of water-side cooling systems.

Water side cooling is the most commonly adopted form of cooling. Water is an effective medium for transferring heat compared to air because of its high thermal conductivity, density and specific heat capacity. Water can transport heat over longer distances with a reduced temperature difference. Water side cooling is achieved using chilled water systems, cooling or evaporative towers, and dry coolers. Water side cooling systems are classified into direct water side systems and indirect water side systems [7].

Free cooling using ground water and sea water are being considered by a number of data center industries. This form of cooling is an innovative approach to completely avoid any mechanical components such as compressors and expensive refrigerants. But, cooling using ground water or sea water is based on several factors such as location, surplus availability of these natural resources, existing infrastructure and environmental conditions [7].

Evaporative cooling differs from typical air conditioning systems. Evaporative coolers take advantage of water's large enthalpy of vaporization. An evaporative cooler cools air through evaporation of water by absorbing the latent heat during the evaporation process. Evaporative coolers draw fresh outside air through a large fan mounted with moist pads. As the warm air passes through the moist pads, it absorbs the water through the process of evaporation and the fan blows the cool air outside. Evaporative cooling is a very simple free cooling technique which is widely used in data centers.

1.4.3 Air-side Economizers

Air side economizers are used as a control mechanism to regulate the use of outside ambient air for cooling. They are the most commonly used air side cooling systems. These economizers are interconnected by ducts to allow the entry of fresh outside air and drive out hot exhaust air. Air side economizers utilize a system of dampers and sensors to allow desired quantity of air for cooling purposes. The sensors are used for monitoring outside and inside air conditions and temperature. If external conditions are suitable for use of fresh outside air for cooling purposes, the economizer adjusts the position of dampers through a control system for the introduction of fresh outside air making it the primary source of cooling. As air passes through the ducts, it is filtered to remove contaminants. The filtered air is circulated across the portion that has to be cooled and heated air is exhausted out. In case large volumes of outside air are introduced into the system, exhaust dampers maintain the pressure by driving out unnecessary air. If external conditions are cooler than required, then the dampers allow a portion of the return air to mix with cold outside air which is either recirculated or exhausted back outside. Therefore, air side economizers significantly reduce the use of air conditioning units and chilled water systems [7].

Control systems are very crucial to operate an air-side economizer. Excessive humidity control can cut into the savings achieved by the economizer. In certain geographic locations, for example, air can be very cool but very dry, and the system may spend excessive energy humidifying the air. Users will need to consider ASHRAE's recommendations, studies of their ambient climate, and their humidity preferences before considering implementation. If desired humidity ranges are too restrictive, net energy savings from an economizer can be limited. Proper management and controls are imperative to ensure that correct air volume, temperature and humidity are introduced [15].

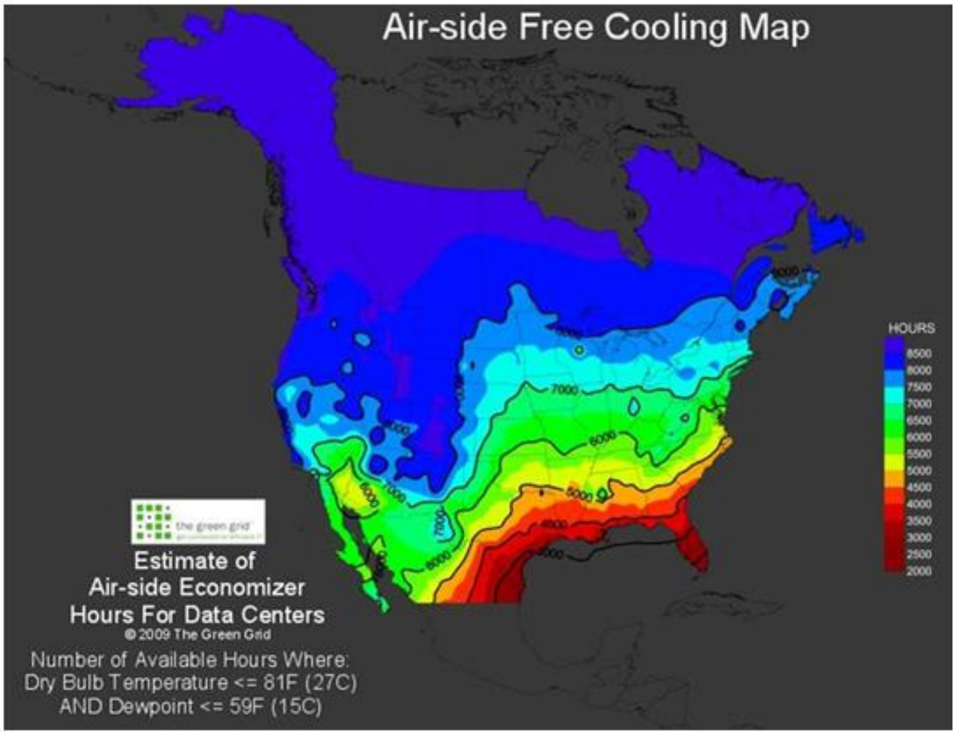

Figure 1.4- Hours with ideal conditions for an air-side economizer [15]

CHAPTER 2

EVAPORATIVE COOLING AND LITERATURE REVIEW

2.1 Evaporative Cooling

2.1.1 Introduction to Evaporative Cooling

Conventional cooling systems operate on a refrigeration cycle, and they can be used in any part of the world. But they have a high initial and operating cost. In desert (hot and dry) climates, we can avoid the high cost of cooling by using evaporative technique, also known as mist cooling, spray cooling or evaporative cooling. Evaporation is a type of vaporization of a liquid that occurs only on the surface of a liquid. The other type of vaporization is boiling, which, instead, occurs on the entire mass of the liquid [16].

Evaporative cooling differs from typical air conditioning systems which use vapor-compression or absorption refrigeration cycles. For molecules of a liquid to evaporate, they must be located near the surface, be moving in the proper direction, and have sufficient kinetic energy to overcome liquid-phase intermolecular forces. Only a small proportion of the molecules meet these criteria, so the rate of evaporation is limited. Since the kinetic energy of a molecule is proportional to its temperature, evaporation proceeds more quickly at higher temperatures. As the faster-moving molecules escape, the remaining molecules have lower average kinetic energy, and the temperature of the liquid, thus, decreases. This phenomenon is also called evaporative cooling [17].

Evaporative cooling occurs: when air comes into contact with water, some of the water evaporates. This happens because the temperature and the vapor pressure of the air attempt to equalize. As the water molecules become a gas (evaporate), they “absorb” heat from the surrounding air and lower temperature of dry air significantly through the phase transition of liquid water to water vapor, which requires much less energy than refrigeration. The heat is still present; however, it has just been “captured” in the form water vapor within the air. This phenomenon is also known as adiabatic cooling. When considering water evaporating into air, the wet-bulb temperature, as compared to the air's dry-bulb temperature, is a measure of the potential for evaporative cooling. The greater the difference between the two temperatures, more the evaporative cooling effect. When the temperatures are the same, no net evaporation of water in air occurs, thus there is no cooling effect. The effectiveness of evaporative cooling depends upon the humidity or amount of water vapor in the air.

Evaporative cooling is a common form of cooling buildings for thermal comfort since it is relatively cheap and requires less energy than other forms of cooling. Evaporative cooling is a reliable and energy efficient system than refrigeration system. Here are some pros and cons of evaporative cooling system [16].

Evaporative Cooling Pros [7]:

i. Consumes less energy than cooling with a refrigerant-based AC system
ii. Adds moisture to dry air (an advantage in dry climates)
iii. Well-suited for use in hot, dry climates

Evaporative Cooling Cons [7]:

i. Continually consumes water while operating
ii. Adds humidity to indoor air, rather than dehumidifying it
iii. Requires regular maintenance
iv. Not suited for use in hot, humid climates

2.1.2 Types of Evaporative Cooling

There are two basic types of evaporative cooling systems, direct evaporative cooling and indirect evaporative cooling.

2.1.2.1 Direct Evaporative Cooling

With traditional direct evaporative cooling, outside air is blown through a water-saturated medium (usually cellulose) and cooled by evaporation. The cooled air is circulated by a blower. Direct evaporative cooling adds moisture to the air stream until the air stream is close to saturation. The dry bulb temperature is reduced, while the wet bulb temperature stays the same. These systems are relatively simple and are widely used to provide comfort cooling for mobile homes, single-family housing, and industrial warehouses. Direct evaporative cooling systems generally cost about half as much as traditional vapor-compression systems and consume only about a fourth of the energy. Evaporative coolers would work best in the dry climates. However, in the eastern parts of the country, other types of air conditioners should be used.

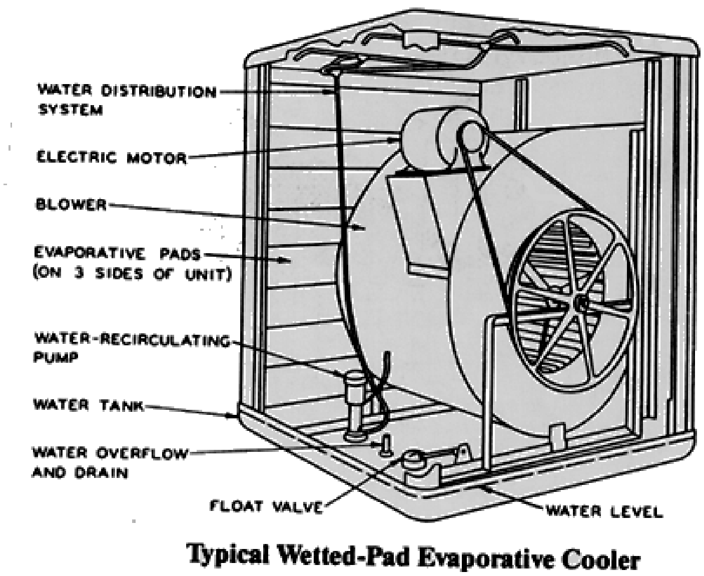

Figure 2.1- Illustration of a Direct Evaporative Cooler

The presence of a media type evaporative cooler inherently creates a pressure drop and this will create a drop in blower output. Increases in inlet duct differential pressure will cause a reduction of blower mass flow and also operating pressure. This factor is important when considering the application of any inlet technology such as evaporative cooling system, refrigeration etc [18].

Direct inlet fogging is a method of cooling where demineralized water is converted into a fog by means of special atomizing nozzles operating at 1000-3000 psi. This fog then provides cooling when it evaporates in the air inlet of containerized data center. This technique allows 100% effectiveness in terms of attaining required percentage of relative humidity at the blower inlet and there by gives the lowest temperature possible without refrigeration. This system can install either upstream or downstream of the filters.

2.1.2.2 Indirect Evaporative Cooling

Indirect evaporative cooling works on the same principle as direct evaporative cooling: lowering air temperature by causing water to evaporate. Both the dry bulb and wet bulb temperatures are reduced. During the heating season, an indirect system's heat exchanger can preheat outside air if exhaust air is used as the secondary air stream. The main difference with an indirect system is that a heat exchanger is used to cool the air supplied to the living space.

Here is sequential explanation of indirect evaporative cooling system [7].

i. Hot outside air is blown through a heat exchanger that is supplied with water. One design for this type of heat exchanger features a series of metal tubes that are kept wet on their outside surfaces. As hot air passes over these tubes, the water evaporates and the tubes are cooled. After passing over the tubes, the cool, moist air is exhausted to the outside.

ii. As cooling happens on the heat exchanger's exterior surfaces, hot exterior air is drawn through the tube interiors. This air is cooled, but without gaining any extra humidity, before it is blown through ductwork to the building interior.

Indirect evaporative cooling provides cool air to interior spaces without as much humidity as direct evaporative cooling. This, cooling method is more suitable for areas where additional humidity is not desirable for interior air. Because indirect evaporative cooling requires two fans rather than one, it consumes more electricity than direct evaporative cooling. Thus, direct inlet fogging technique is selected for this analysis.

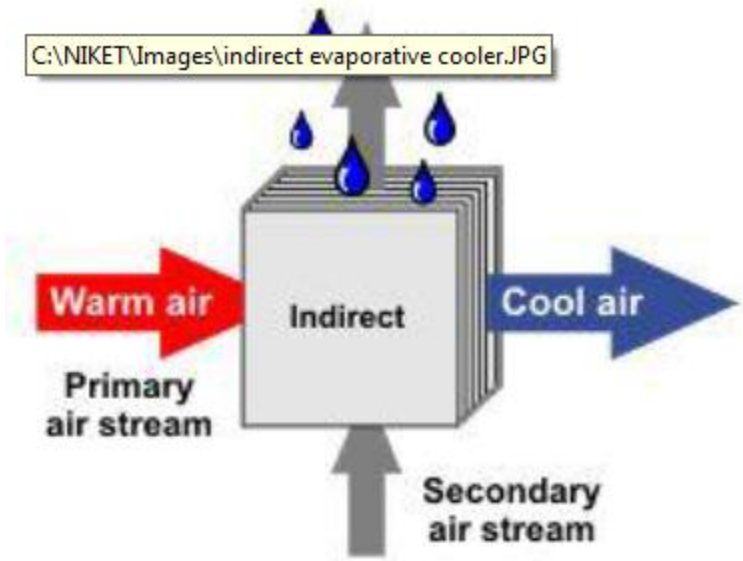

Figure 2.2- Illustration of an Indirect Cooling system

2.2 Literature Review

Arghode et al [19] conducted room level air flow field investigation for open, partially and fully contained cold aisles in an air cooled data center. Since his previous investigation for rack level modeling had shown that consideration of momentum rise, above the tile surface, due to acceleration of air through the pores, significantly improved the predictive capability, as compared to the generally used porous jump model. In his work, a modified body force model was used to artificially specify the momentum rise above the tile surface. The modified body force model was validated against the experimental data as well as with the model resolving the tile pore geometry at the rack level and then implemented at the room level. With the modified body force model, much higher hot air entrainment and higher server inlet temperatures were predicted as compared to the porous jump model. Even when the rack air flow requirement was matched with the tile air flow supply, considerable hot air recirculation was predicted. With partial containment, where only a curtain at the top of the cold aisle was deployed and side doors were opened, improved cold air delivery was suggested.

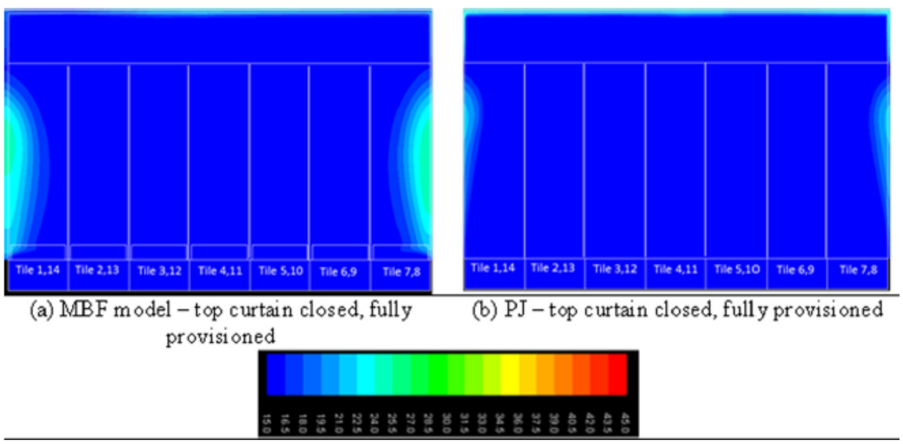

Figure 2.3- Comparison of (a) MBF (b) PJM

Ibrahim et al [20] conducted tests on a server to obtain thermal mass information which is proposed to be used in CFD simulations. The study presents set of experiments to experimentally characterize the thermal mass of a 2U server. Assuming a typical range of specific heat capacity for the components inside the server, the contribution of each component is considered as the ratio of the component weight to the overall server weight. Based on the weight information and temperature measurements of each component inside the server (i.e. HDD, memory modules, power supply, CPU assembly, chassis) a unit temperature for the server can be obtained which is part of the time-dependent energy balance equation for the server. Putting aside the value of the extensive testing on the inner components of the server, this approach does not seem to be practical.

With the ever increasing heat loads dissipated by computer hardware, the ability to accurately characterize the cooling requirements in data centers is becoming crucial. Ibrahim et al [21] explains that Computational fluid dynamics modeling has proven in many cases to be adequate in providing a general understanding of the thermal environment in data centers. However, almost all analyses of data centers to this day are conducted in steady state. The effect of changes in hardware configurations and cooling resources on server rack inlet temperatures and airflow through servers has not been adequately investigated. His work introduces transient modeling of data centers with changing power dissipations and computer room air-conditioning (CRAC) airflow rates. Transient modeling proves advantageous in monitoring temperature fluctuations due to airflow changes, which in some cases leads to insufficient cooling. In addition, modeling server thermal mass is shown to be important for transient analysis, as it can lead to overshoots in temperatures. Another segment of his work looks at the effect of introducing thermal characteristics curves into CRAC modeling on server inlet temperature. All the cases he conducted, show that fixed CRAC supply temperature is a non valid assumption.

Alkharabsheh et al [22] conducted a transient analysis on a contained-cold-aisle data center using CFD modeling. He said containing the cold aisle reduced the inherent challenge of predictability and energy consumption of data center cooling systems by separating the hot and cold air streams. He investigated the effect of variable power and flow rate in time on a raised-floor data center with specific geometry. He established a base case numerical model and later, conducted a transient analysis for the uncontained base case and three containment configurations namely, ceiling-only, doors-only and a fully contained cold aisle. He compared the different geometrical configurations of the containment system under certain transient operating conditions. The transient analysis showed overshoots of cabinet inlet air temperatures beyond the final steady state, which could not predict through a simple through a simple steady state analysis. The temperature distribution in the cold aisle changed with time.

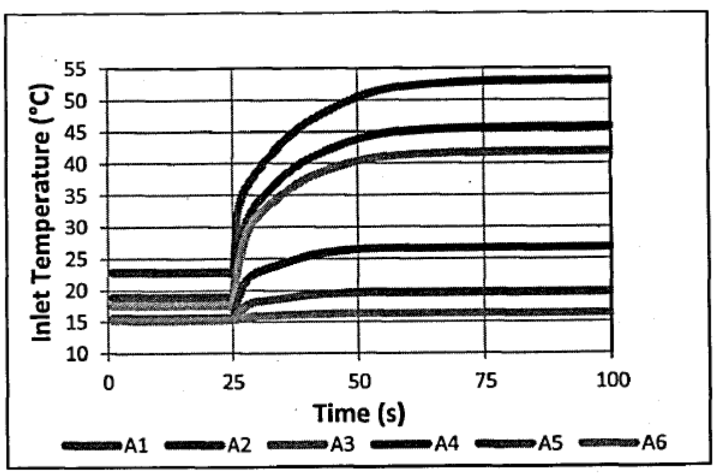

Figure 2.4- Inlet temperatures with time for doors-only configuration

These inefficiencies of traditional data centers can be overcome by partitioning the server load into modular sections which can be deployed, powered and cooled depending on availability and requirement. Furthermore, improvements in efficiency and operational costs can be achieved by employing “free cooling” to cool the IT equipment through use of air-side economization. Air-side economizers bring in large amounts of ambient air to cool internal heat loads when weather conditions are favorable and result in substantial savings from the cost of running cooling resources. However, if ambient air properties are not suitable to cool information technology (IT) equipment directly, ambient air needs to be conditioned before entering IT equipment. One method of conditioning outside air is to use direct evaporative cooling which sprays atomized water as air passes through an evaporative cooling zone. Atomized water vaporizes and conditions air passing through the cooling zone by adding moisture and reducing its temperature, thus foregoing expensive computer air conditioning units (CRACs).

Shah [7], in his thesis, discussed various cooling techniques available for air-side economizer. He studied the effect of various ambient environment conditions corresponding to different controls and/or environmental conditioning are required to optimize energy efficiency. ASHRAE recommended Psychrometric chart for the operating environment was used to determine the water requirements for direct evaporative zone. In the second phase, computational fluid dynamics (CFD) analysis was performed using commercially available CFD tool, Fluent, to determine the performance of direct evaporative cooling in an air-side economizer. He investigated and studied various factors that affected the performance of evaporative cooling, such as particle sizes of atomized water, ambient air temperature and humidity, water temperature.

Kannan [23] on the other hand, discussed the design and thermal analysis of IT telecommunication switches using commercially available CFD software, FloTHERM. Network switches are the central core of the network infrastructure. The CFD modeling and analysis included the study of side breathing network switches which were classified based on their air flow pattern. The issues addressed were cooling performance differential between 6 and 12 inch wide vertical cable managers located between two alternating side breathing switches; even and odd number of side breathing switches; and even and odd number of side breathing switches with and without top blanking panels. These network switches drew cold air in through one side of the chassis and released hot air out of the opposite side. Kannan also discussed the CFD modeling and analysis of a modular data center. Free cooling was adopted for cooling the data center. He then, analyzed the thermal performance of the system. The study was done in collaboration with an industrial partner and as such most of the results of his study were adopted in an actual telecommunication system.

CHAPTER 3

COMPUTATIONAL FLUID DYNAMICS (CFD) ANALYSIS

3.1 Introduction to CFD Analysis

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

The objective of CFD is to provide the engineer with a computer-based predictive tool that enables the analysis of the air-flow processes occurring within and around the electronic equipment. CFD analysis is very important for various applications such as data center industries, systems with high heat loads, telecommunication industry, and several more [24].

3.2 Governing Equations

The numerical solution for heat transfer and fluid flow based problems is obtained by solving a series of three differential equations. These three differential equations are the conservation of mass, conservation of momentum and conservation of energy. They are very commonly known as the governing differential equations [25].

For a generalized case,

The conservation of mass is given by:

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

The conservation of momentum is given by:

$$\frac{\partial}{\partial t}(\rho u) + \nabla.(\rho u u) = \nabla.(\mu \mathrm{grad} u) - \frac{\partial p}{\partial x} + B_x + V_x$$

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

$$\nabla.(\rho u h) = \nabla.(k \mathrm{gra\ d} T) + S_h$$

3.3 Global Computational

The computational domain or the solution domain is the region or space within which the governing differential equations are solved. The solutions to these equations are obtained by fixing the boundary conditions for the solution domain. The boundary conditions for most computational problems include the external ambient temperature, solar loading, wind conditions, other environmental conditions and. It depends on the type of heat transfer such as conduction or convection and also any radiation factors. In addition, the conditions at the domain wall also need to be specified whether they are open, closed (adiabatic) or symmetrical in nature. The fluid properties namely conductivity, density, expansivity, diffusivity and specific heat need to be specified

[24].The governing equations for many complex problems can be solved by using various numerical techniques such as Finite Element Method where the elements are varied and approximated by a function; Finite Volume Method where the governing equations are integrated around the mesh elements whose volumes are considered for the solution and Finite Difference Method where the differential terms are discretized for each element.

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

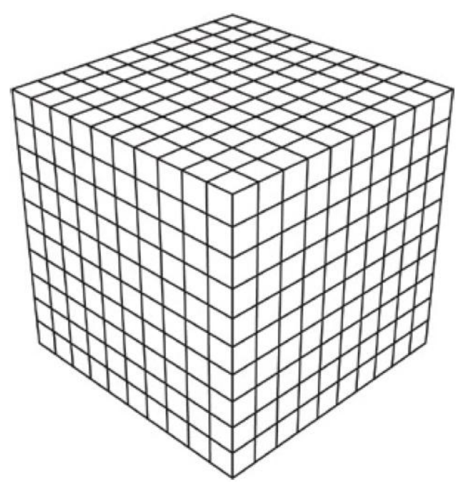

Figure 3.1- Representation of a 3-D grid

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

$$T = \frac{C_0T_0 + C_1T_1 + C_2T_2 +..CnTn + S}{C_0 + C_1 + C_2+..Cn}$$

Where T_0 represents the temperature value within the initial cell; T_1, T_2, ... T_n are the temperature values in the neighboring cells; C_0, C_1, C_2,... C_n represent the coefficients that connect each cell value to each of its neighboring cell values; and S denotes the source term. These algebraic equations are solved for the field variables T, u, v, w and density ρ. This implies that if 'n' cells are present in the domain, then a total of '5n' equations are solved.

3.4 Turbulence Modeling

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

3.4.1 LVEL Turbulence Model

LVEL turbulence model is a simple algebraic turbulence model which does not require the solution of any partial differential equations. The model requires calculation of the nearest wall distance (L), the local velocity (VEL) and the laminar viscosity to determine the effective viscosity [26]. In LVEL turbulence model, Poisson's equation is solved initially to calculate the maximum local length scale and local distance to the nearest wall.

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

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

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

$\emptyset$ is a dependent variable. The length and velocity scales are also computed for each cell in addition to the boundary layer wall functions to determine the turbulent viscosities for each cell [27].

3.4.2 K-Epsilon Turbulence Model

This model solves using two variables; the kinetic energy of turbulence (k) and the dissipation rate of kinetic energy of turbulence (ε) [28]. K-Epsilon turbulence model is also commonly known as two equation model and is widely used for turbulent flow modeling. The two equation model computes viscosity depending on the grid cells rather than calculating the viscosity due to the walls. The K-Epsilon model is applicable for problems with thin shear layers and recirculating flows. Two transport equations namely kinetic energy of turbulence (k) and dissipation rate of kinetic energy of turbulence (ε) are solved [28].

The following are the transport equations:

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

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

3.5 Grid Constants and Meshing

Grid constraints are used for specifying minimum and maximum number of cells across the geometry. As discussed before, FloTHERM uses a Cartesian grid and the value for pressure and temperature is calculated at each cell center. Grid keypoints appear when components are created in FloTHERM. These keypoints are object associated. Grid lines may be classified as hard, coarse or fine grids. Localized grid cells can be created which are smaller cells used for meshing around an object. In localized meshing, the gridlines meet the edges of the object and truncate along the edges and disappear. Meshing is an important feature since a mesh sensitivity analysis can determine when a solution reaches grid independence. Grid independence is defined as the point at which the addition of a large number of grid cells no longer significantly affects the solution. Grid independence can significantly reduce computational time [24].

3.6 Smart Parts in FloTHERM

3.6.1 Cuboid

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

3.6.2 Enclosure

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

3.6.3 Resistance

The resistance smart part is used to define a region of resistance to flow. It can either be collapsed, non-collapsed or angled. Collapsed resistances or planar resistances are used to define planar objects such as vents or any porous media. The free area ratio and loss coefficient must be defined in order to calculate the pressure drop. Non-collapsed resistances or volumetric flow resistances are used when thickness of an object has to be specified. They are mostly used for modeling filters. Perforated plates can also be used for creating holes. Filters are devices which are used for trapping air contaminants such as dust particles, pollen etc. They are used for supplying and controlling the amount of clean air entering into a system. Filters are located at the inlet of various HVAC and telecommunication systems. Filters can arranged either in series or parallel configuration. Dirty filters have a higher resistance and increase the total static pressure. Clean and dirty filters can be compared by determining the system impedance curve for both filters and computing the increase in pressure drop across the filters. In doing so, the approximate life of a filter can be estimated. MERV (Minimum efficiency rating value) filters and pre filters are typically used for data centers and HVAC systems. Hydrophobic filters can be used for controlling the amount of humidity in air when it enters into a system.

3.6.4 Source

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

3.6.5 Monitor Points

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

3.6.6 Region

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

3.6.7 Fans and Blowers

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

The distinguishing characteristics that differentiate fans and blowers are the method used to move the air and the system pressure they must operate against [29]. The most commonly used fans in cooling applications are axial flow fans and centrifugal blowers. Axial flow fans deliver air flow in the direction parallel to the fan blade axis. These fans can deliver very high flow rates. They produce air flows with high volume and low pressure. They are used for cooling IT equipment and several other electronic devices. Axial fans can be classified into propeller fans, tube-axial fans and vane-axial fans [39]. On the other hand, centrifugal blowers deliver air flow in the direction perpendicular to the blower axis. They are used for moving air through large systems. These devices are used for delivering lower flow rates since they are designed for working against high pressure.

Table 3.1- Difference between fans and blowers

Equipment	Specific Ratio	Pressure Rise (mm WG)
Fan	Up to 1.11	1136
Blower	1.11 to 1.2	1136-2066

3.6.7.1 System Curve Characteristics

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

3.6.7.2 Fan Curve Characteristics

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

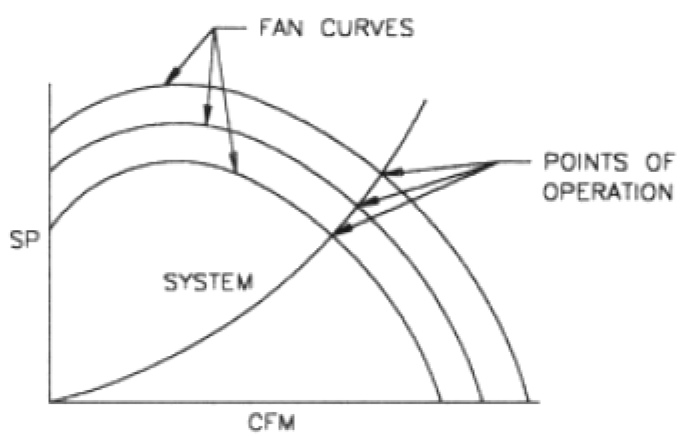

Figure 3.2- System Resistance curve and Fan Curve super-imposed [30]

3.6.8 FloTHERM Command Center

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

CHAPTER 4

DESCRIPTION OF THE CFD MODEL

The Computational Fluid Dynamics (CFD) model is based on an actual cooling system connected to an Information Technology (IT) pod. CFD analysis of different modular data centers has been extensively studied. Gebrehiwot et al. [31] suggested different design changes such as changing the orientation of dampers and placing blanking panels inside the mixing chamber of the cooling unit which affected the lifespan of the filters. Based on simulation results, Gebrehiwot et al. [32] made improvements to the model by adjusting the angle of the louvers which showed significant improvements in the mean exhaust temperature at the servers.

Figure 4.1- Actual IT pod and the cooling system

4.1 Description of the Indirect/ Direct Evaporative Cooling Unit

The IT pod is cooled by an Indirect/ Direct Evaporative Cooling (IDEC) unit. It is called as Indirect/ Direct Evaporative cooling system since it consists of both the Indirect Evaporative Cooling Unit and the Direct Evaporative Cooling Unit within the system.

This cooling unit comprises of two sub-units, the cooling tower and the indirect/direct evaporative cooling chamber.

4.1.1 Cooling Tower

The Cooling Tower (CT) is a part of the cooling system used to cool the water flowing through the coils of the Indirect Evaporative Cooling Unit. This section comprises of two cooling pad media at opposite sides. The media is wetted by water dripping from the top of the media, through the pads and is collected by the sump at the bottom which is then distributed to the cooling coils in the Indirect Cooling section. A fan is present at the top of the cooling tower, which pulls the outside ambient air through the pad. This air passes over water, the heat from the air is quickly picked up by the water and vaporize. Thus the water that falls down into the sump becomes cooler and this chilled water. The cool air is then sent out.

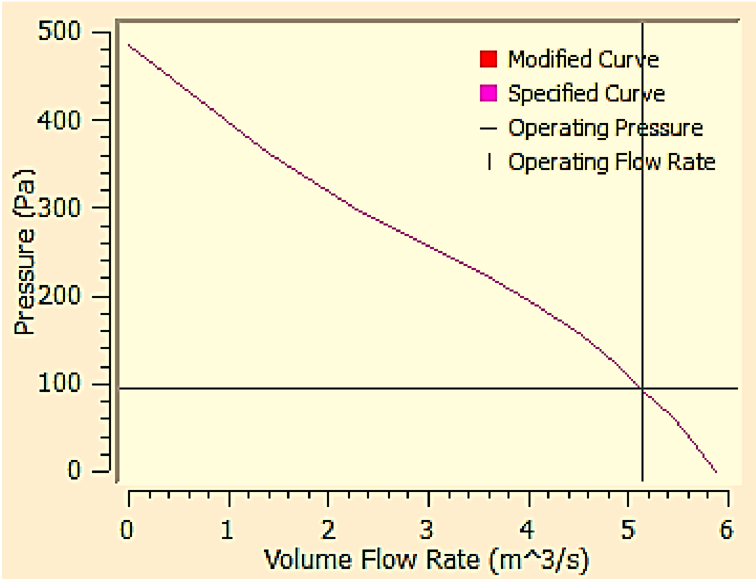

Figure 4.2- Cooling Tower Fan performance curve

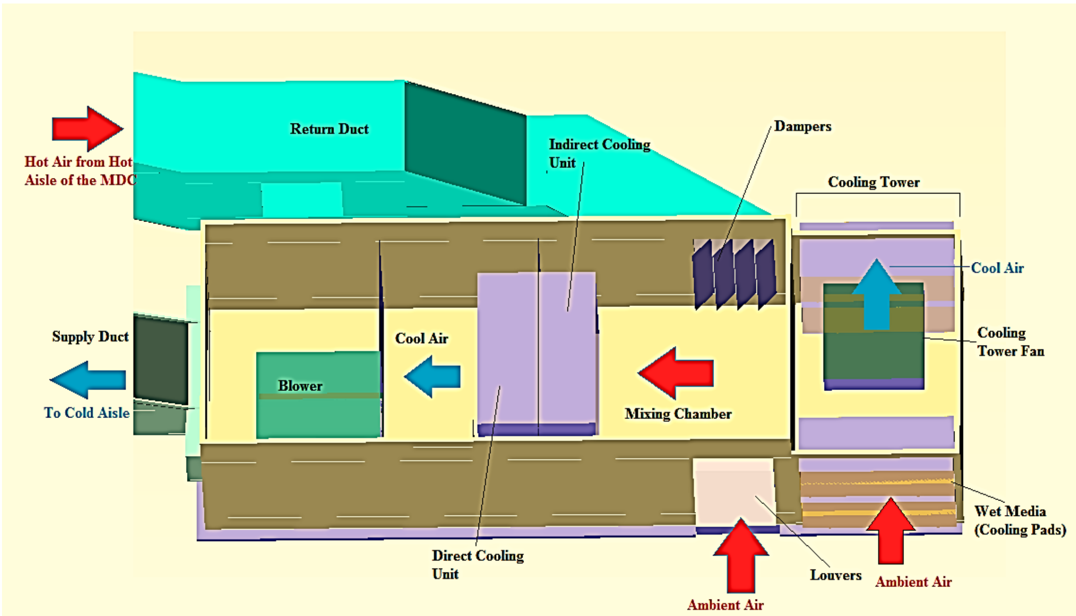

Figure 4.3- CFD model of the Indirect/ Direct Cooling Unit

Figure 4.2 shows the fan performance curve of the cooling tower fan. From the figure, operating pressure and operating flow rate is known. These performance characteristics are calculated based on manufacturer's specs.

4.1.2 Indirect/ Direct Evaporative Cooling section

Figure 4.3 shows the indirect/ direct evaporative cooling section. This section consists of different parts. The outside ambient air enters this section through Louvers. There are seven louver section which lets in the ambient air. The dampers direct the air towards the Indirect evaporative cooling unit. The louvers and dampers are present on either side of the section.

This air in turn passes through the indirect evaporative cooling unit. There are several coils inside the indirect unit which carry the chilled water from the cooling tower. As the outside air passes over these coils, the water in the coils absorb all the heat from the outside air thereby leaving the exiting air to be cooler.

This air now, passes through a section of direct evaporative cooling unit. Like the cooling pad media in the cooling tower, this section also consists of a wet media where the water drips from the top over the pads. As air enters, the water picks up the heat from the air and the exiting air is much cooler and humid.

Both the Indirect and the Direct evaporative cooling unit are modeled as Smart parts, where the amount of heat absorbed by the water is calculated using the following equations:

$$q = \dot{m} C_p \Delta T$$

$$\eta = 100 \times \frac{(T_{dbi} - T_{dbo})}{(T_{dbi} - T_{wbi})}$$

where q is the amount of heat absorbed by water or rejected by air, $\dot{m}$ is the mass flow rate of air, C_p is the specific heat capacity of air and ΔT is the dry-bulb temperature difference between the air before and after a cooling unit, η is the cooling efficiency, T_{dbi} is the dry-bulb inlet temperature, T_{dbo} is the dry-bulb outlet temperature, T_{wbi} is the inlet wet-bulb temperature.

The cooling efficiency of the wet media and the coils are known and the outlet temperature is calculated. Using the outlet temperature, the heat rejected by the air is then calculated.

The saturation efficiency of the Direct Evaporative Cooling unit is assumed to be 88% and the Evaporative efficiency of the Indirect Evaporative cooling unit is assumed to be 80%.

Item	Number of Items	Heat Load in each item (W)
Cooling Unit		
Cooling Tower Wet Media	2	21647
Indirect Cooling Unit in the Mixing Chamber	1	23980
Direct Cooling Unit in the Mixing Chamber	1	13058

Figure 4.4- Heat load at different locations inside the cooling unit

4.1.3 Blower section

The air from the direct evaporative cooling unit is now pulled by the blowers and sent to the IT pod through a supply duct. The blowers are modeled as Fan smart parts taking in account of its performance curve through manufacturer's supplied data.

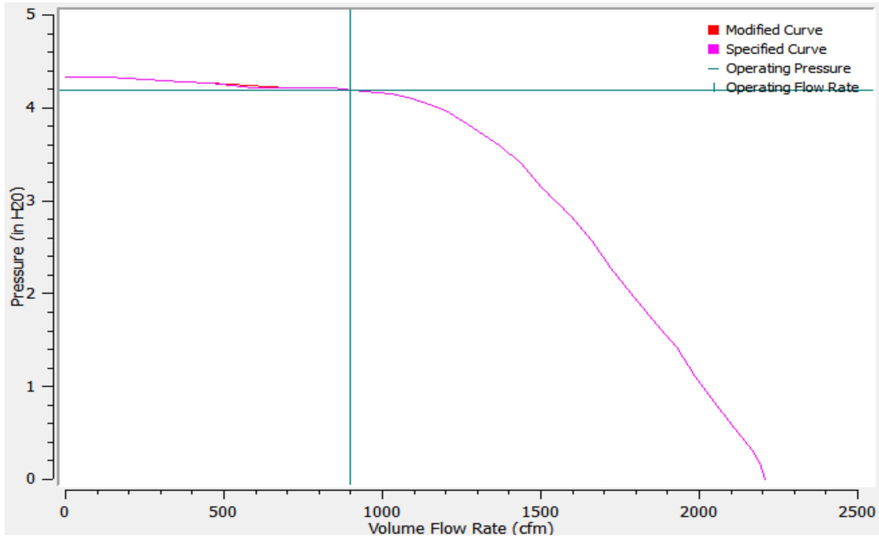

Figure 4.5- Blower Performance Curve

The following are the manufacturer's specifications:

i. Cooling tower fan: Model is LL924, 2HP, 1720 rpm, 208-230/460 V

ii. Cooling tower filters: Filter Perm MVEZ Kleen, (4) 20x20x2, (4) 20x25x2

iii. Glasdek media: 12” depth

iv. Filters in the IEC/ DEC Unit: Filter Z-line, (6) 16X25X2

v. Indirect coil: 58W 45” FH x 48” FL, 6 rows, 12 fins per inch

vi. Louvers: 26W x 46 H, Arrow

vii. Dampers: 26W x 46H, Arrow

viii. Direct evaporative section media: Glasdek, 12” depth

ix. Thickness of the insulation on the Cooling unit: 1" (One inch)

4.2 Description of the IT pod

The cooling system and the IT pod is connected through a duct called as the Supply duct to necessitate the supply of cold air from the cooling unit to the IT pod with the help of the blowers. This supply duct is a stainless steel duct with 1" thick insulation. The duct is modeled with thickness and material properties included along with thermal conductivity of the insulation.

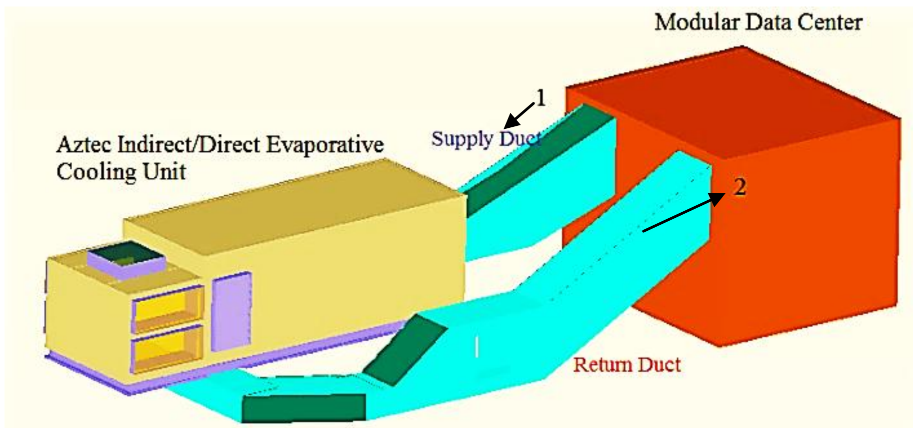

Figure 4.6- CFD model of the IT pod and its cooling system

The IT pod is a concrete structure This container is 8.22 m (323.75 in) long, 3.21 m (126.5 in) wide and 2.71 m (106.5 in) high. The IT pod is divided into two sections, Section 1 and Section 2. Section 1 is used as a work space to monitor different parameters of the data center such as ambient dry-bulb temperature, wet-bulb temperature, relative humidity, cold aisle temperature, total water consumption by the cooling unit, total power usage, PUE, etc. Section 2 is a server room which is divided into a hot and a cold aisle by curtains and containment panels. There are four cabinets which hold 120 servers in this section.

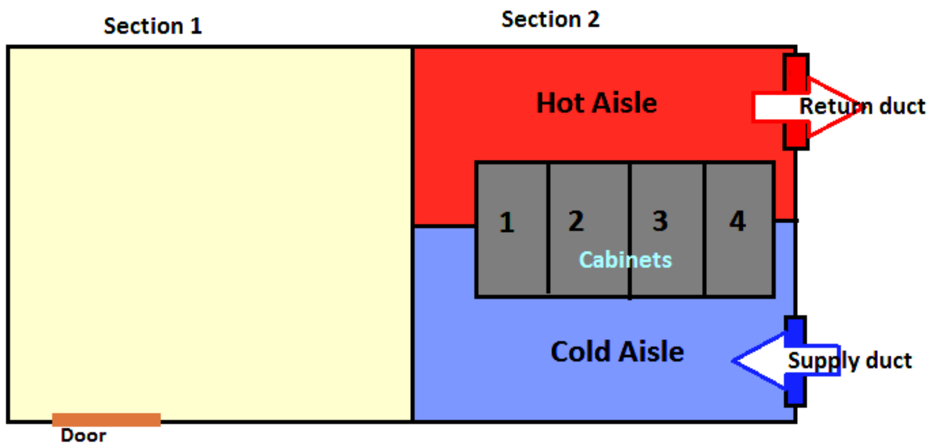

Figure 4.7- Schematic representation of the IT pod

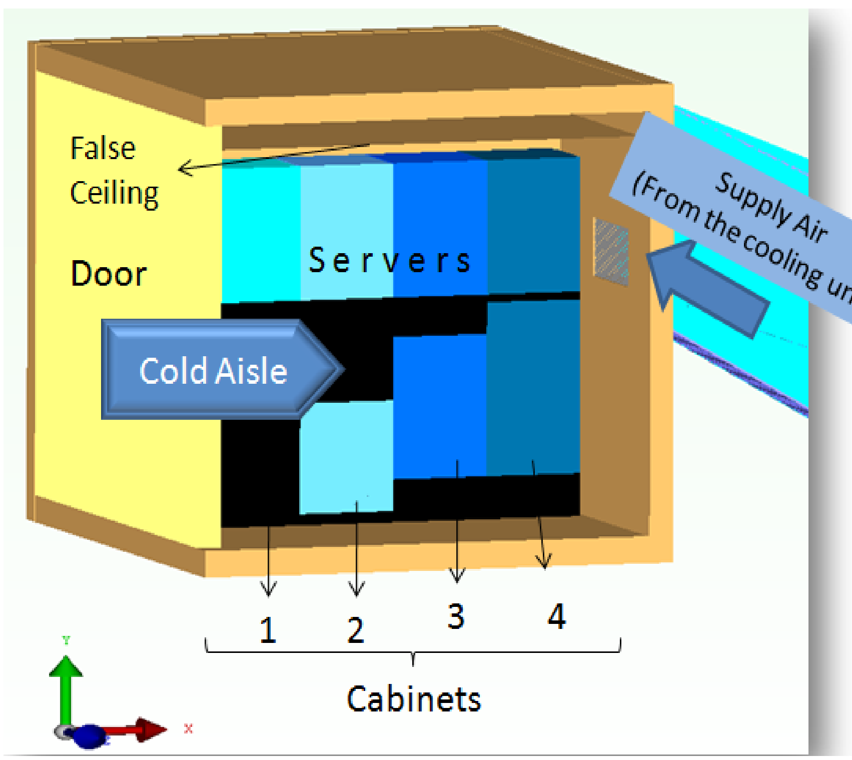

Figure 4.8- Schematic representation of the Cold Aisle

Inside Section 2 of the IT pod, There are four Panduit 42U cabinets (numbered as 1, 2, 3 and 4 away from the inlet and outlet). All cabinets have certain number of HP 1102SE servers. Cabinet 1 has 17 from the top; Cabinet 2 has 17 from the top and 14 from the bottom with the space in between being blocked; Cabinet 3 has 17 from the top and 17 servers after some gap; and Cabinet 4 having the maximum number of servers, with 38 servers. All the gaps between the servers are blocked. The curtains divide this section into a Hot Aisle and a Cold Aisle.

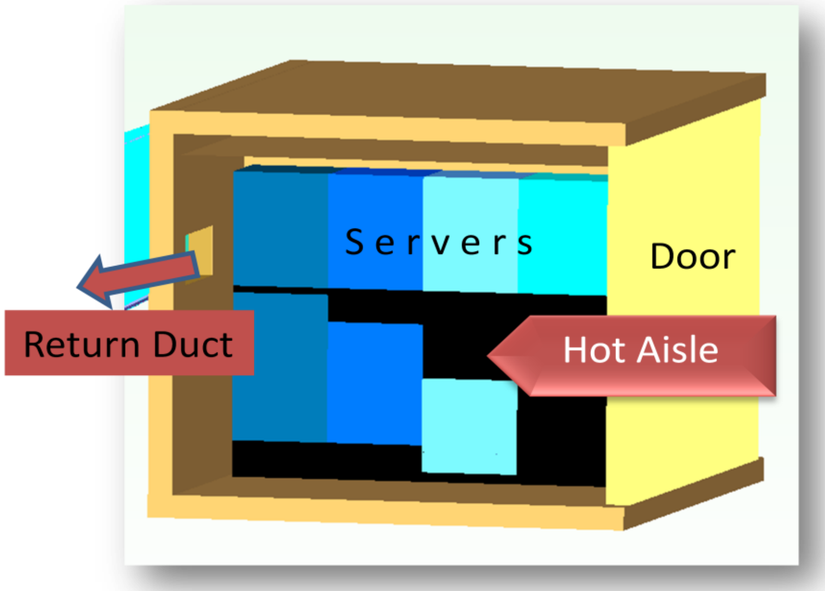

Figure 4.9- Schematic representation of the Hot Aisle

The cold air arriving from the cooling unit through the supply duct enters the Cold Aisle through the diffusers. This air cools the servers and other IT equipment like Power Distribution Unit, CPU and Switches. The heat from the IT equipment is released out into the Hot Aisle which is either returned to the cooling system if the Air-Side Economization is turned 'on' or the hot air is simply let out into the atmosphere.

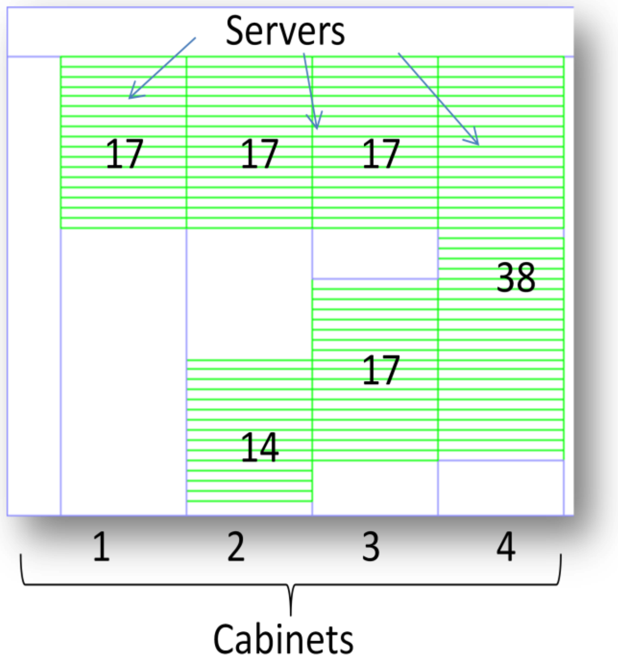

Figure 4.10- Location of the servers inside the cabinets

The servers are modeled using smart parts, Extract and Supply. The server fan performance curve is introduced into the model along with the system resistance curve.

There are various sensors and thermocouples placed in the cold and the hot aisle. These sensors record the various changes occurring in terms of dry-bulb temperature, relative humidity, pressure differential, etc.

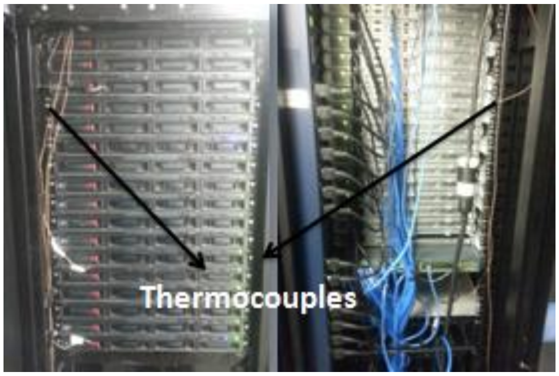

Figure 4.11- Thermocouples inside the Cold and the Hot Aisle

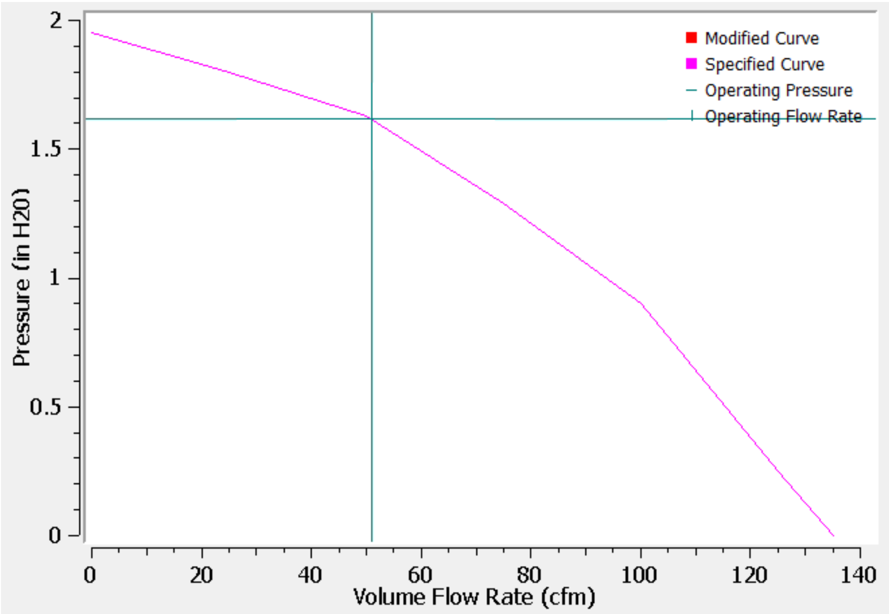

Figure 4.12- Server Fan Performance Curve

The amount of power utilized by the server was experimentally calculated and the was added on to the model [33]. The power consumed by each server were calculated to be around 200 watts.

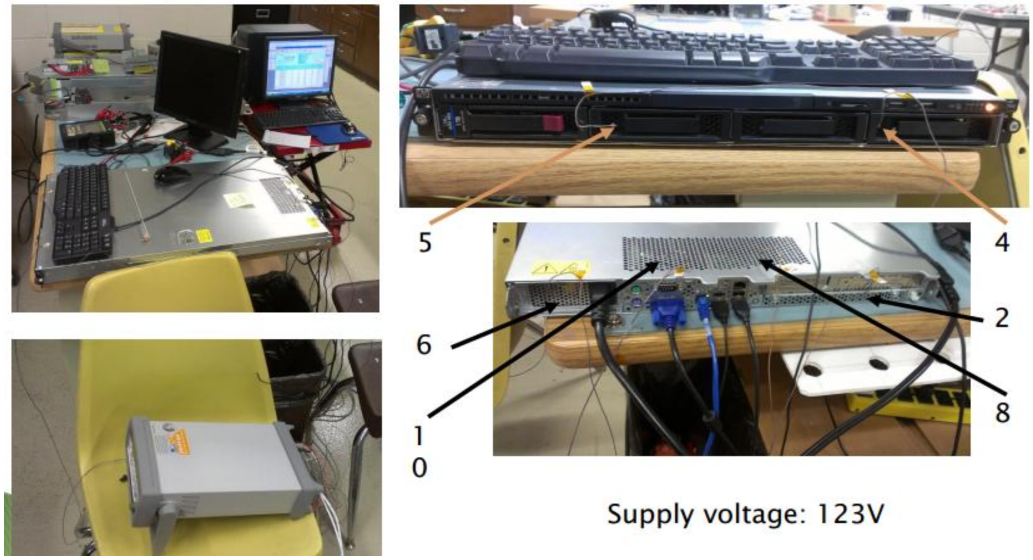

Figure 4.13- Server: Stress test setup with thermocouples numbered

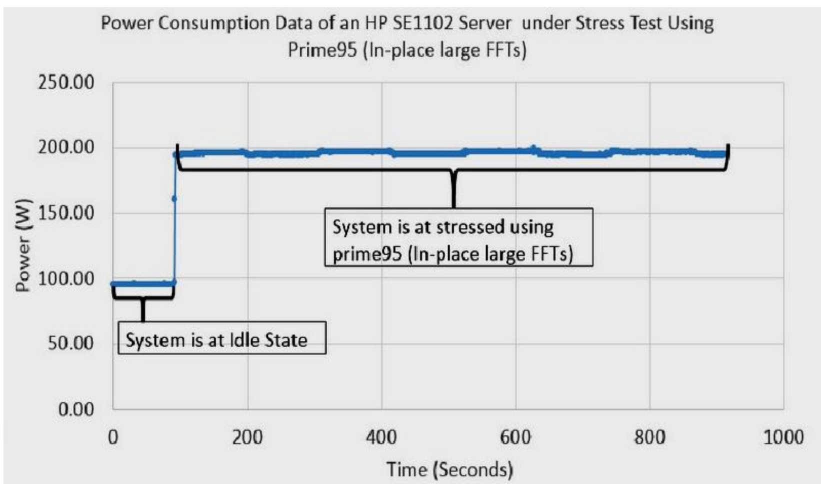

Figure 4.14- Power consumption data from the stress test on the servers

Thermocouples were placed at different locations in all the four cabinets, both in the cold aisle and the hot aisle to record the server inlet and outlet temperature. This is very essential to validate the CFD model.

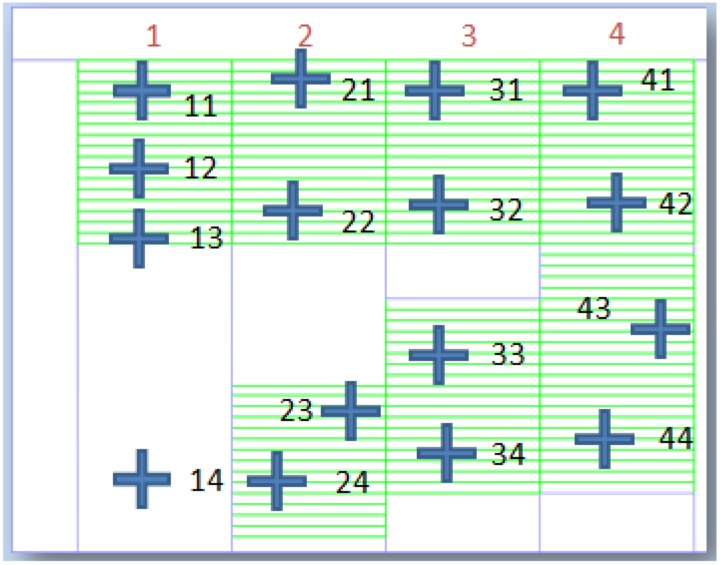

Figure 4.15- Location of the thermocouples in the Cold Aisle

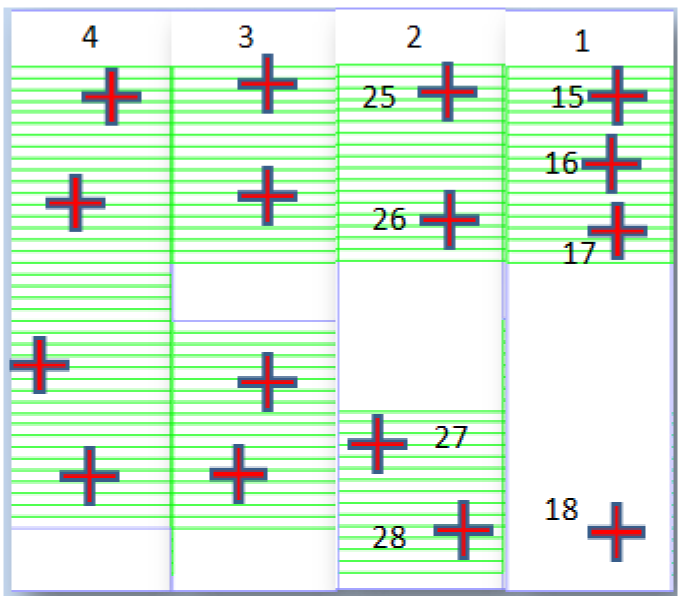

Figure 4.16- Location of the thermocouples in the Hot Aisle

4.4 Description of the CFD model

4.4.1 Ambient properties

Table 4.1- Ambient Properties

Property	Value
Temperature of the ambient air	85.2˚F
Conductivity of air	0.01515 Btu/(hr ft °F
Viscosity	3.3416 lbf s/ft^2
Density	0.07304 lb/ft^3
Specific Heat	0.241 Btu/(lb °F)
Expansivity	0.00183 1/°F
Pressure	404.5523 in H_2O
Gravity	32.18 ft/s^2

4.4.2 Meshing

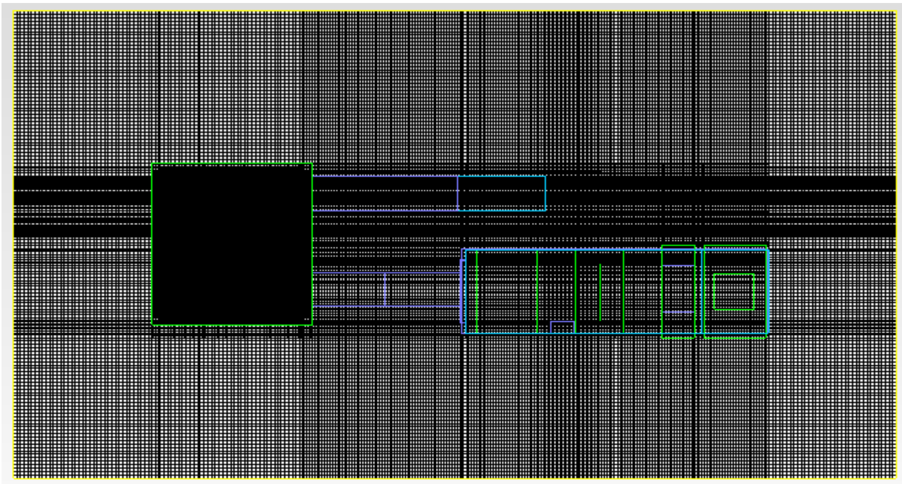

Figure 4.17- Mesh of the CFD model

The meshing is dense. There are around 11 million cells and the maximum aspect ratio of the model is 6.

The computation time is high since the meshing is refined. There are complex geometries in the model of different height and thickness. Hence it was essential to refine the mesh and thereby increase the computation time.

CHAPTER 5

RESULTS AND DISCUSSIONS

5.1 Velocity Profiles

The following are the velocity profiles taken at different positions of the IT pod and the cooling system.

5.1.1 Velocity profile of the IT pod

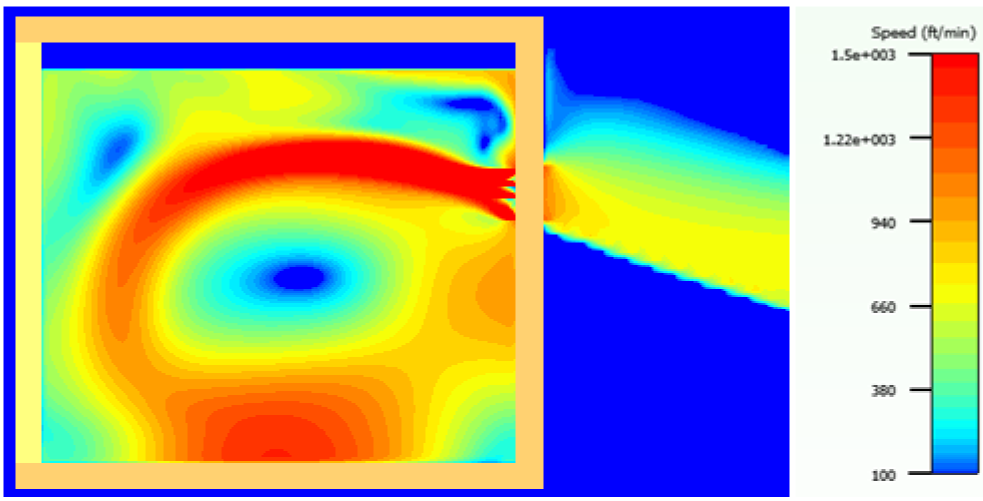

Figure 5.1- Velocity profile of the IT pod on the cold aisle

In the above profile, it can be seen that high speed air gushes into the cold aisle and circulates closely at the center. This is due to the presence of diffusers at the inlet which guides the incoming cold air downwards.

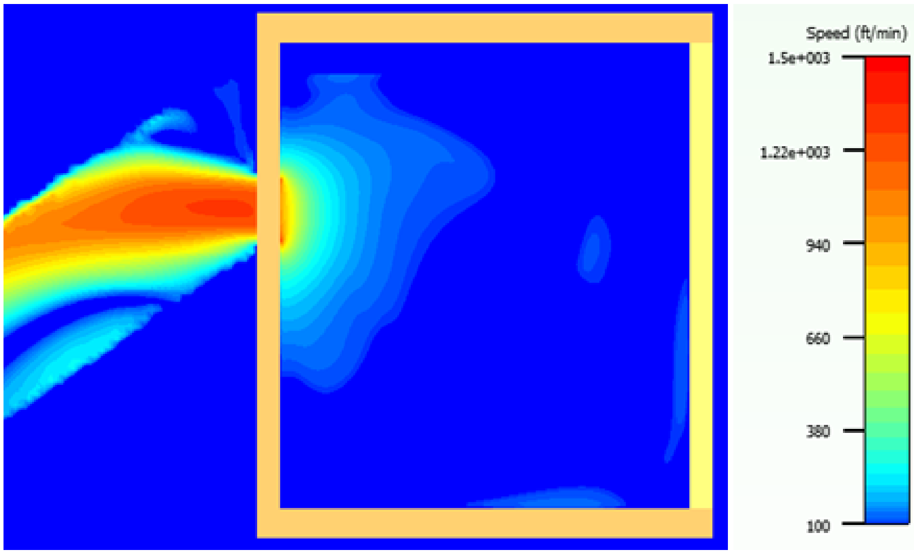

Figure 5.2- Velocity profile of the IT pod at the hot aisle section

The hot air from the backend of the servers are let out and due to a small opening at the outlet, the speed of the air at that location again increases before it is let down to the return duct.

5.1.2 Velocity profiles of the cooling system

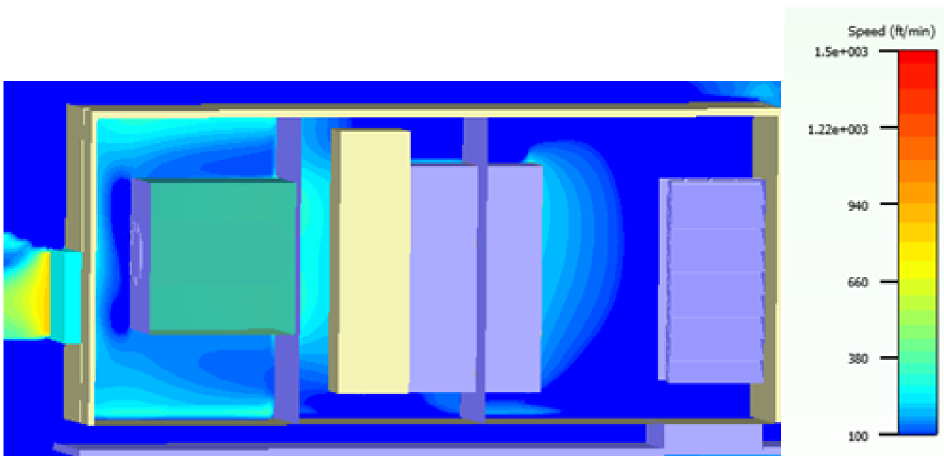

Figure 5.3- Velocity profile at the cooling unit

The previous profile shows the speed of the air as it enters the indirect cooling unit on the right, then from the direct cooling unit towards the blowers, where it is sent out to the IT pod through the supply duct.

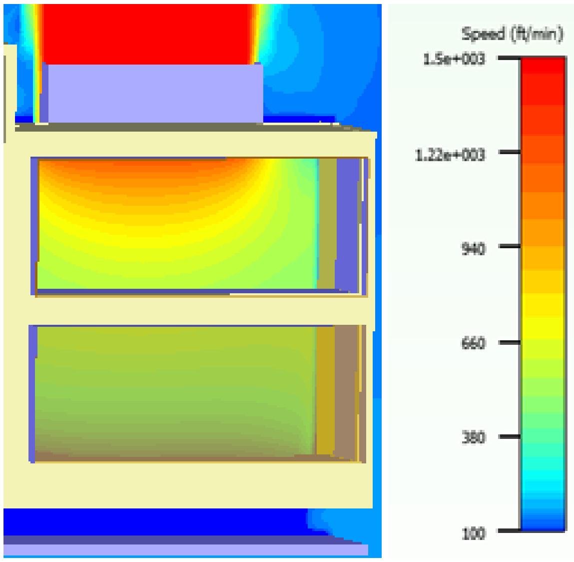

Figure 5.4- Velocity profile at the cooling tower

Due to the cooling tower fan at the top of the cooling tower, there is high speed of air seen gushing out of the tower.

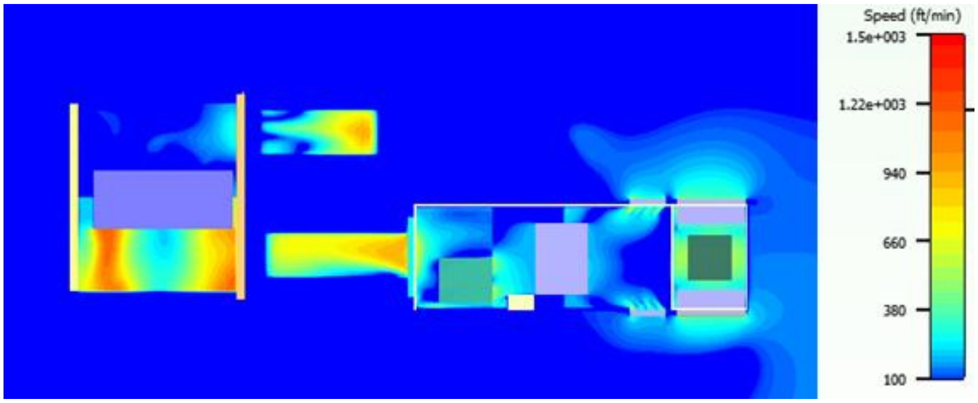

Figure 5.5- Velocity profile of the entire system with a top view

5.2 Temperature Profiles

5.2.1 Temperature profiles of the IT pod

The following profiles were obtained from the CFD analysis:

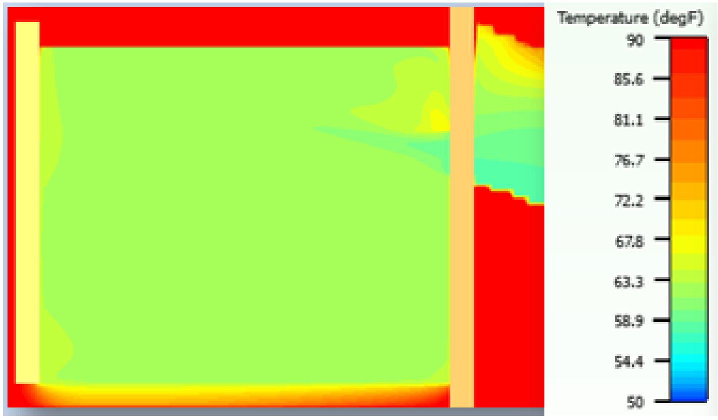

Figure 5.6- Temperature profile of the IT pod in the cold aisle

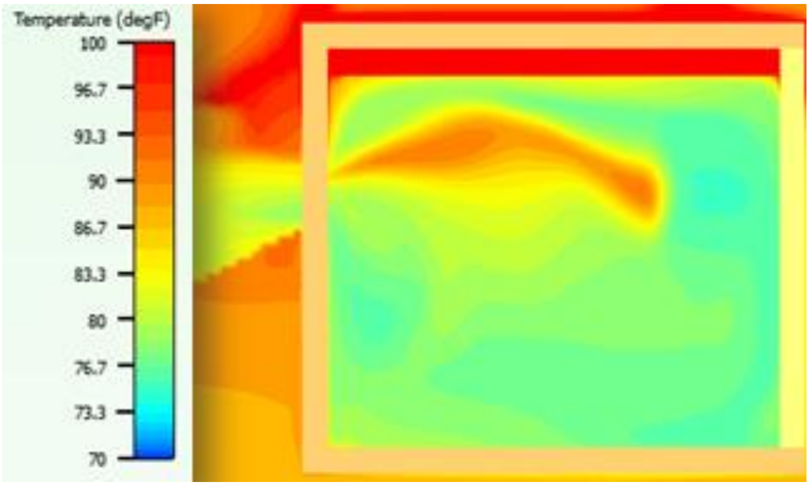

Figure 5.7- Temperature profile of the IT pod on the hot aisle

We can see the accumulation of hot air near the outlet region and mostly on the first few servers from the top of the cabinets.

Figure 5.8- Temperature profile of the cooling unit

From the previous figure, the temperature of air inside the cooling system can be clearly visualized. The air near the louvers and dampers have the ambient outside temperature and as it passes through the indirect and direct evaporative cooling sections, the temperature drastically reduces.

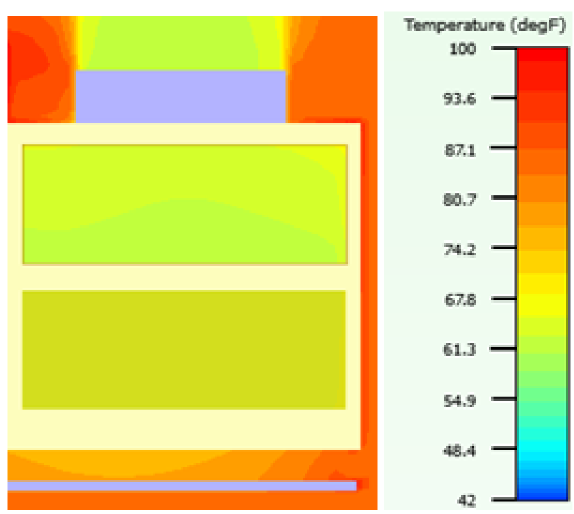

Figure 5.9- Temperature profile of the cooling tower

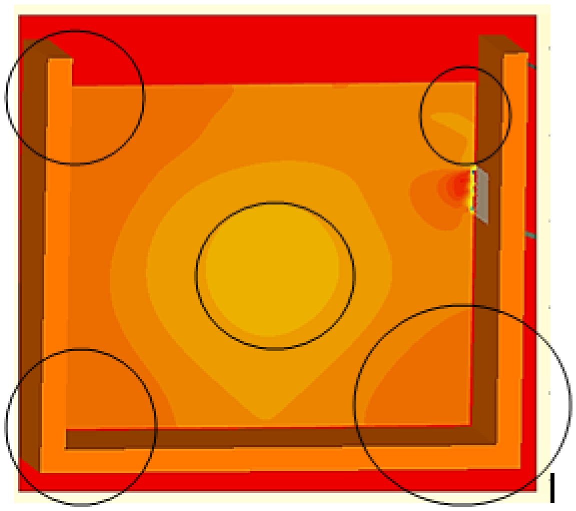

Figure 5.10- Location of the hot spots in the cold aisle circled

The above picture shows the various locations where hot spots are created. Due to the circulation seen in the cold aisle, there are several low pressure areas created at the corners, mostly above the inlet diffusers and at the center of the cold aisle. From this, we are able to predict where the temperatures would be slightly higher than the surrounding areas.

These hot spots are fatal to the IT equipment since they would result in failure. It is highly recommended to get rid of these hotspots by implementing good design techniques.

5.3 Effect of Solar Loading

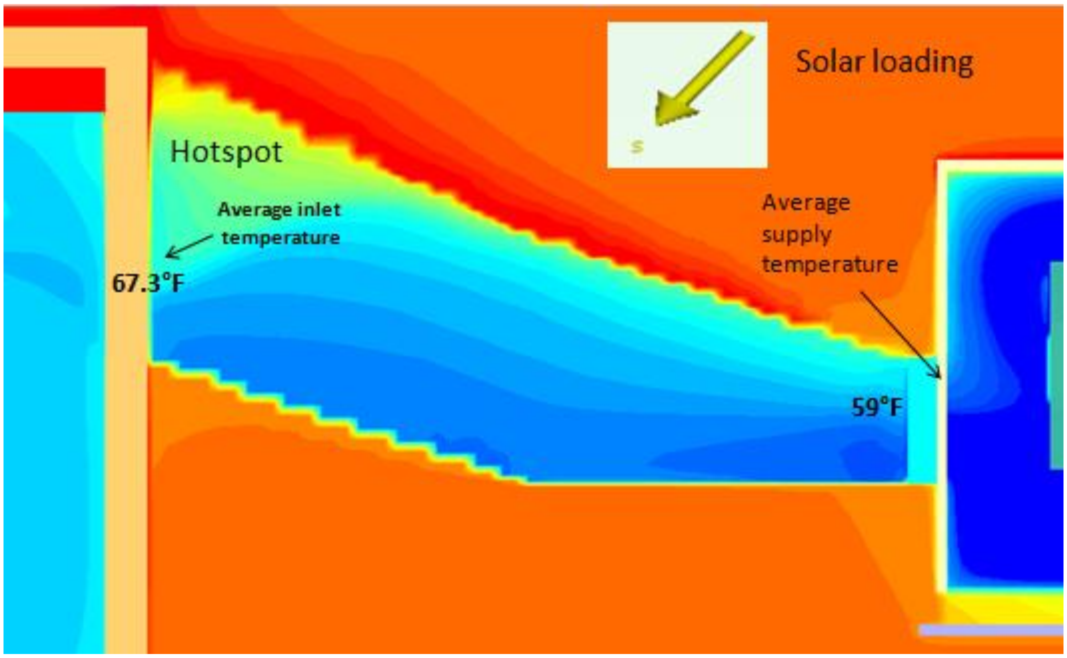

Figure 5.11- Effect of Solar Loading

It is highly important to consider the effect of solar loading on the CFD model since the actual unit is placed in sunlight throughout the day. From the analysis conducted, the average temperature leaving the cooling unit was 59˚F and the average temperature entering the cold aisle from the supply duct was close to 67˚F. There is a large difference of temperature of around 8˚F. This observation can be visualized with the above figure where the pointed arrow shows the direction of the solar loading on the model.

Hotspots in the supply duct and continuous accumulation of hot air inside the top most area of the supply duct has increased the temperature of the supply temperature drastically, though the supply duct was insulated with 1 inch thick insulation.

5.4 Server Temperatures

On conducting a steady state analysis with an earlier model, the following results were obtained:

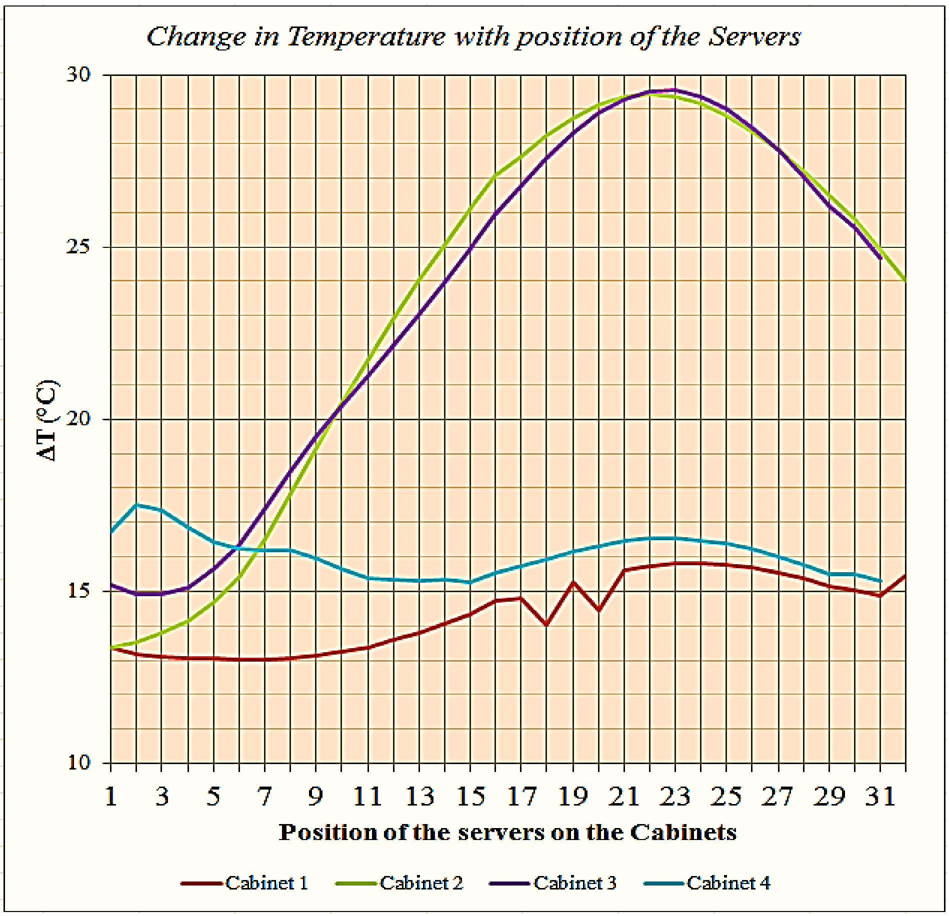

Figure 5.12- Change in the temperature of the servers with respect to their position

From the figure, it was observed that the servers on the second and the third cabinet saw higher temperature rise as compared to the servers on the first and the fourth cabinets. This is due to the low pressure region created at the center of the cold aisle.

5.5 Thermocouple data

The thermocouple data were obtained from the cold and the hot aisle and then compared with the monitor points placed in the cold and hot aisle of the CFD model.

5.5.1 Thermocouple readings for the Cold Aisle

Table 5.1- Thermocouple readings for Cabinet 1 in the Cold Aisle

	Thermocouple	Temperature (Experimental) in ˚F	Temperature (Modeling) in ˚F	Error %
Cabinet 1	1	65.30	61.78	5.39
	2	65.32	61.4	6.00
	3	63.29	62	2.04
	4	64.24	63.44	1.25

Table 5.2- Thermocouple readings for Cabinet 2 in the Cold Aisle

	Thermocouple	Temperature (Experimental) in ˚F	Temperature (Modeling) in ˚F	Error %
Cabinet 2	1	65.30	60.1	7.97
	2	62.27	58.9	5.42
	3	59.34	56.2	5.29
	4	58.42	57.5	1.57

Table 5.3- Thermocouple readings for Cabinet 3 in the Cold Aisle

	Thermocouple	Temperature (Experimental) in ˚F	Temperature (Modeling) in ˚F	Error %
Cabinet 3	1	64.20	60.1	6.38
	2	68.32	62	9.25
	3	62.30	59.8	4.01
	4	65.25	61	6.51

Table 5.4- Thermocouple readings for Cabinet 4 in the Cold Aisle

	Thermocouple	Temperature (Experimental) in ˚F	Temperature (Modeling) in ˚F	Error %
Cabinet 4	1	N/A	65.4	0.00
	2	65.17	64.8	0.57
	3	65.85	64.1	2.65
	4	69.18	68.7	0.69

5.5.2 Thermocouple readings for the Hot Aisle

Table 5.5- Thermocouple readings for Cabinet 1 in the Hot Aisle

	Thermocouple	Temperature (Experimental) in ˚F	Temperature (Modeling) in ˚F	Error %
Cabinet 1	1.00	85.21	80.40	5.65
	2.00	80.21	75.60	5.74
	3.00	80.29	76.20	5.10
	4.00	81.41	77.30	5.05

Table 5.6- Thermocouple readings for Cabinet 2 in the Hot Aisle

	Thermocouple	Temperature (Experimental) in ˚F	Temperature (Modeling) in ˚F	Error %
Cabinet 2	1.00	86.07	81.50	5.31
	2.00	87.21	81.80	6.20
	3.00	80.29	76.20	5.10
	4.00	76.41	72.40	5.25

Table 5.7- Thermocouple readings for Cabinet 3 in the Hot Aisle

	Thermocouple	Temperature (Experimental) in ˚F	Temperature (Modeling) in ˚F	Error %
Cabinet 3	1.00	95.31	89.30	6.30
	2.00	93.53	88.20	5.69
	3.00	85.33	80.00	6.25
	4.00	80.82	76.40	5.47

Table 5.8- Thermocouple readings for Cabinet 4 in the Hot Aisle

	Thermocouple	Temperature (Experimental) in deg F	Temperature (Modeling) in deg F	Error %
Cabinet 4	1.00	96.25	90.50	5.98
	2.00	98.29	91.80	6.61
	3.00	82.30	77.10	6.32
	4.00	77.35	72.70	6.02

5.6 Conclusion

The following conclusions could be drawn out from the analysis:

- The steady state analysis was conducted and the airflow pattern and the temperature distribution were observed. Any variation in the temperature and speed of air inside the IT pod can easily be predicted using the CFD model.
- Server inlet temperatures inside each of the cabinets were found out.
- From the CFD analysis conducted, high circulation of the cool air inside the cold aisle was observed. This was due to the orientation of the diffusers at the inlet.
- It was also observed that the servers inside cabinets 2 and 3 see higher temperature rise than the other cabinets. This was because of the low pressure region created in front of cabinets 2 and 3 in the cold aisle.
- CFD model could be well validated with the thermocouple readings; which had an average error of 5%-7%
- Solar loading does play an important role. It was a major factor which increased the supply temperature by approximately 8°F

5.7 Future Work

A steady state analysis is quite not enough to predict or analyze the dynamics involved in the process. A transient analysis is perhaps the best way to explain some of the rapid changes that occur within the system.

By providing the transient attributes in the model on various parameters, such as ambient temperature, solar loading, relative humidity, heat rejected by the air at the indirect evaporative cooling unit and the direct evaporative cooling unit.

A mesh sensitivity analysis can be conducted on the model. Computational time and meshing are few parameters that could determine a good model. Steps must be taken to ensure all the necessary conditions are met before modeling. More experimental data could be obtained to verify the compatibility of the CFD model with the real life scenario.

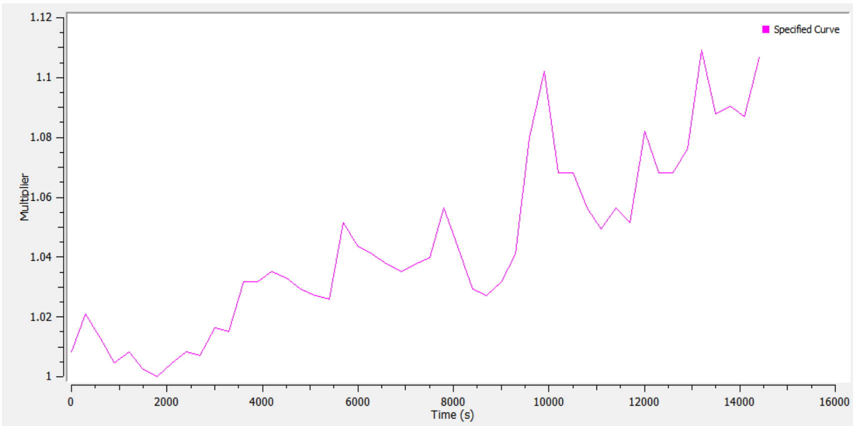

Figure 5.13- Example of a transient attribute

REFERENCES

1. M. I. Ibrahim, "Dynamic Thermal Management of Data Centers," ProQuest LLC, Binghampton, 2012.
2. Daily Mail, "Inside the internet: Google allows first ever look at the eight vast data centres that power the online world," 17 October 2012. [Online]. Available: http://www.dailymail.co.uk/sciencetech/article-2219188/Inside-Google-pictures-gives-look-8-vast-data-centres.html.
3. Emerson Network Power, "Energy Logic: Reducing Data Center Energy Consumption by Creating Savings that Cascade Across Systems," Emerson Electric Co., Columbus, Ohio, 2009.
4. M. Ibrahim, S. Bhopte, B. Sammakia, B. Murray, M. Iyengar and R. Schmidt, "Effect of Thermal Characteristics of Electronic Enclosures on Dynamic Data Center Performance," in *(IMECE) ASME International Mechanical Engineering Congress & Exposition*, Vancouver, British Columbia, Canada, 2010.
5. R. A. Steinbrecher and R. Schmidt, "Data Center Environments-ASHRAE's Evolving Thermal Guidelines," *ASHRAE Journal*, pp. 42-49, 2011.
6. V. Mulay, "Analysis of Data Center Cooling Strategies and the Impact of The Dynamic Thermal Management on the Data Center Energy Efficiency," December, 2009.
7. N. Shah, "CFD Analysis of Direct Evaporative Cooling Zone of Air-side Economizer for Containerized Data Center," May 2012.

8. Data Center Knowledge, "Toshiba Offers Modular Data Center Design," November 2010. [Online]. Available: http://www.datacenterknowledge.com/archives/2010/11/23/toshiba-offers-modular-data-center-design/.
9. Bramfit, M.; Coles, H., "Modular/Container Data Centers Procurement Guide: Optimizing for Energy Efficiency and Quick Deployment," February, 2011.
10. M. K. Patterson, D. G. G. P. F. Costello and L. M., *Data Center TCO: A Comparison of High-Density and Low-Density Spaces*, Santa Fe: THERMES 2007, January 2007.
11. The Green Grid, "PUE: A Comprehensive Examination of the Metric," 2012.
12. C. Belady, A. Rawson, J. Pflueger and T. Cader, *Green Grid Data Center Power Efficiency Metrics: PUE and DCIE*, 2008.
13. Z. Potts, "Free Cooling technologies in Data Center Applications," February 2011.
14. Cisco Systems Inc., "Power Management in the Cisco Unified Computing System: An Integral Approach," 2011.
15. Energy Star, "Air-Side Economizer," [Online]. Available: https://www.energystar.gov/index.cfm?c=power_mgt.datacenter_efficiency_economizer_airside.
16. B. L. Capehart, in *Encyclopedia of Energy Engineering and Technology*, CRC Press, 2008, pp. 633, Vol.2-3.

17. Dr. Energy Saver, [Online]. Available: http://www.drenergysaver.com/heating-cooling/cooling-systems/evaporative-cooling/indirect-evaporative-cooling.html.

18. J. Park, in *Open Compute Project Data Center V 1.0,* 2011, p. 10.

19. V. K. Arghode and Y. Joshi, "Room Level Modeling of Air Flow in a Contained Data Center Aisle," *Journal of Electronic Packaging, ASME,* vol. 136, pp. 01101-(1-10), 14 February 2014.

20. M. Ibrahim, S. Shrivastava, B. Sammakia and K. Ghose, "Thermal Mass Characterization of a Server at Different Fan Speeds," *13th IEEE Intersociety Conference on Termal and Thermomechanical Phenomena in Electronic Systems (ITherm),* pp. 457-465, 2012.

21. M. Ibrahim, S. Bhopte and B. Sammakia, "Effect of Transient Boundary Conditions and Detailed Thermal Modeling of Data Center Rooms," *IEEE TRANSACTIONS ON COMPONENTS, PACKAGING AND MANUFACTURING TECHNOLOGY,* vol. 2, no. 2, pp. 300-310, February 2012.

22. S. A. Alkharabsheh, M. Ibrahim, S. Shrivastava, R. Schmidt and B. Sammakia, "Transient Analysis for Contained-Cold-Aisle Data Center," *Proceedings of the ASME International Mechanical Engineering Congress and Exposition (IMECE),* vol. 9, pp. 1167-1174, 2012.

23. N. Kannan, "Design and Modeling Techniques for Cooling of Telecommunication Systems," December 2011.

24. Mentor Graphics, *FloTHERM 10.0 User Guide.*

25. S. V. Patankar, Numerical Heat Transfer and Fluid Flow, New York: Mc Graw Hill Book Company, 1980.

26. K. K. Dhinsa, C. J. Balley and K. A. Pericleous, "Turbulence Modeling and its impact on CFD Predictions for Cooling of Electronic Components," *Thermal and Thermomechanical Phenomena in Electronic Systems, I-THERM,* pp. 487-494, 2004.

27. D. Agonafer, L. Gan-Li and D. B. Spalding, "The LVEL Turbulence Model for Conjugate Heat Transfer at Low Reynolds Numbers," *Application of CAE/CAD Electronic Systems, ASME,* vol. 18, 1996.

28. B. E. Launder and D. B. Spalding, "The Numerical Computation of Turbulent Flows," in *Computer Methods in Applied Mechanics and Engineering*, 1974, pp. 269-289 (Appendix D).

29. Energy Efficiency Guide for Industry in Asia, "Electrical Energy Equipment: Fans and Blowers," UNEP, 2006. [Online]. Available: www.energyefficiencyasia.org.

30. The New York Blower Company, "Fan Laws and System Curves," [Online]. Available: http://www.nyb.com/Catalog/Letters/EL-02.pdf.

31. B. Gebrehiwot, N. Dhiman, K. Rajagopalan, D. Agonafer, N. Kannan, J. Hoverson and M. Kaler, "CFD Modeling of Indirect/Direct Evaporative Cooling Unit for Modular Data Center Applications," *ASME International Technical Conference and Exhibition on Packaging and Integration of Electronic and Photonic Microsystems,* 2013.

32. B. Gebrehiwot, K. Aurangabadkar, N. Kannan, D. Agonafer, D. Sivanandan and M. Hendrix, "CFD Analysis of free cooling of Modular data centers," *28th Annual IEEE Semiconductor Thermal Measurement and Mangement Symposium (SEMI-THERM),* 2012.

33. B. Gebrehiwot, N. Dhiman, K. Rajagopalan, D. Agonafer, N. Kannan, J. Hoverson and M. Kaler, "CFD Modeling of Indirect/Direct Evaporative Cooling Unit for Modular Data Center Applications," in *ASME 2013 International Technical Conference and Exhibition on Packaging and Integration of Electronic and Photonic Microsystems,* Burlingame, California, USA, 2013.

34. B. Gebrehiwot, K. Aurangabadkar, N. Kannan, D. Agonafer, D. Sivanandan and M. Hendrix, "CFD analysis of free cooling of modular data centers," in *28th Annual IEEE Semiconductor Thermal Measurement and Management Symposium, SEMI-THERM 2012*, San Jose, CA, United states, 2012.

35. Based on experiments conducted in the laboratory by setting up the server on an airflow bench and conducting a stress test on the server. Assisted by Betsegaw Gebrehiwot and Vishnu Sreeram.

BIOGRAPHICAL INFORMATION

Suhas Sathyanarayan received his Bachelor’s Degree in Mechanical Engineering from Sapthagiri College of Engineering, an institution affiliated to the Visvesvaraya Technological University, Bangalore, India in May 2012. He completed his Master of Science degree in Mechanical Engineering at the University of Texas at Arlington in December 2014.

Suhas has been involved in a number of projects in UTA with the industry especially with room level cooling. His research areas include, cooling of IT pods, Modular Data Centers, Evaporative cooling where he has worked on different kinds of systems such as Direct evaporative, Indirect evaporative and Indirect/ Direct evaporative cooling systems.

He has extensively modeled both steady state and transient conditions on the IT pod and cooling systems and has an experience of two years, working with the industry.