COMPUTATIONAL STUDY OF DATA CENTER HOTSPOT MITIGATION WITH SNORKELS AS AN ALTERNATIVE RACK-LEVEL CONTAINMENT STRATEGY

by

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Presented to the Faculty of the Graduate School of

The University of Texas at Arlington in Partial Fulfillment

of the Requirements

for the Degree of

MASTER OF SCIENCE IN MECHANICAL ENGINEERING

THE UNIVERSITY OF TEXAS AT ARLINGTON

May 2014

Acknowledgements

I cannot express enough thanks to Dr. Dereje Agonafer, my graduate advisor and committee chair for his guidance throughout the period of my research with the EMNSPC team. The support, motivation and opportunities he offered were enough to keep me working hard. I offer my sincere gratitude to Dr. Haji-Sheikh and Dr. Hyejin Moon for consenting to participate as committee members at my thesis presentation. My many thanks also go to Sally Thompson for always being ready with helpful information, as well as remaining a good friend.

My completion of this project could not have been accomplished without the support and contributions of my partner and friend, Richard Eiland. His consistency and patience with reviewing every detail and proffering useful tips and suggestions always came in handy. I also would like to appreciate the members of the EMNSPC team, mostly those who are my friends and have offered one word of encouragement or another.

To my loving and caring family that have always filled in the gaps, my heartfelt love and thanks. Finally, all thanks and glory is ascribed to God Almighty, in whom I move and live and have my being.

March 25, 2014

Abstract

COMPUTATIONAL STUDY OF DATA CENTER HOTSPOT MITIGATION WITH, SNORKELS AS AN ALTERNATIVE RACK-LEVEL CONTAINMENT STRATEGY

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One of the major concerns of companies around the world is business continuity and with that comes the need to prevent operational dysfunction by keeping their information systems available and functional. IT professionals therefore, are constantly striving towards network sustainability by boosting the cooling cycle and infrastructure in data centers, while also reducing overall energy consumption. The combination of increasing IT workloads and packaging densities place stringent requirements on data center cooling systems and so, various traditional airflow management technologies have been implemented that propose significant energy savings and potential reduction in net annual cost for running data centers.

In this work, a parametric study of a 1008 ft^2 baseline data center with 161kW of IT load is used as an example for CFD analysis and the concept of using rack-level containment with snorkels has been explored as an alternative airflow management strategy. Snorkels minimize rack inlet temperatures by directing and aiming cool air from the sub-floor plenum to individual racks/cabinets, hence removing hotspots. Over 40 CFD cases were analyzed to compare different such strategies. Two different designs of snorkels, the flat-top and the angle-top were specifically examined to determine the

design with the optimal performance. Test models include the baseline case, separate cases with hot-aisle and cold-aisle containment as well as separate cases with the two snorkel designs. Other models were built for different simultaneous combinations of cold aisle containment with the two snorkel designs for the purpose of comparison. A comparative metric based on industrial thermal guidelines as specified by ASHRAE was used to measure the efficacy of rack cooling at increasing supply temperatures for all the cases compared, and the snorkels especially ones with the flat-top design showed a significant inlet temperature modulation and improvement along the height of the racks, maintaining a rack cooling index-high of 100%. Other performance metrics like the return temperature index and supply heat index were also used to analyze and compare the models.

In the later part of this work, it was needful to see the effectiveness of snorkels at elevated rack density. Heat load was increased from 4kW/rack to 10kW/rack for a selected row of cabinets, and cooling improvements starting from over 13% were achieved at the different set-points monitored by temperature sensors.

These results present the feasibility of this strategy as a preliminary review and give an initial guideline on where this concept can be implemented, depending on the respective data center layout and design.

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Chapter 1

Introduction

1.1 An Overview of Data Centers

One of the main concerns of companies around the world is business continuity and with that comes the need to keep their information systems up and running, which otherwise could reflect in seriously impaired or dysfunctional operations. It becomes therefore, necessary to have their data centers equipped with reliable infrastructure for IT operations, in order to prevent or minimize any chance of service disruption.

A data center is a facility or a dedicated portion of a facility whose primary function is to house computer systems and associated components that store, process, manage and exchange digital information. These components are known as IT Equipment and include the compute servers that respond to requests across a computer network to provide network service, the storage systems used for data storage and network equipment used for communication. Asides redundant power supplies and communications connections, data centers are also equipped with environmental controls (e.g. Air Conditioning Units ACU, fire suppression tools), various security devices and power conversion equipment in order to maintain operating conditions.

Traditionally data centers were either built for the sole use of one large company or as Carrier Hotels/Network-neutral Data Centers which are essentially data centers that allow interconnection between multiple telecommunication carriers and/or colocation providers [1]. These facilities act as regional fiber hubs serving local businesses in addition to hosting content servers. These kinds of data centers exist worldwide and vary in size and power. Today a lot of data centers are run by Internet Service Providers, ISPs for hosting their own and third party servers.

1.1.1 ASHRAE IT Equipment Thermal Envelope

Data centers are typically within buildings that are locked in without windows and very minimal fresh air, and most of them with a lot of servers have them generate very large amount of heat, by consuming a substantial amount of energy. Since data centers are designed for IT equipment, it is therefore imperative that the operating conditions maintained within these facilities by the cooling systems are kept within certain prescribed limits. The ASHRAE guidelines for data center operation suggest thermal ranges of operation for IT equipment that are commonly accepted by many data center facility managers and administrators. The current and previous editions of ASHRAE's Thermal Guidelines for Data Center Processing Environments clearly define a set of "Allowable" temperature envelopes that provide IT equipment manufacturers and data center designers with simple ways to define product specification limits [2].

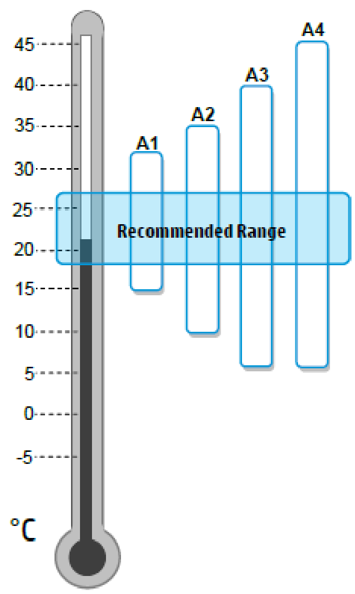

Figure 1-1 ASHRAE Recommended and Allowable Temperature Ranges for Data Centers [2]

These four operational classes suggested by ASHRAE for IT equipment in data centers are designated by A1 through A4 with recommended and allowable temperature envelopes for maintaining high equipment reliability across a broad spectrum of businesses and conditions. While classes 1 and 2, corresponding to the A1 and A2 ranges represent the 2008 guidelines edition, the 2011 ASHRAE guidelines include the A3 and A4 ranges which have been added with expanded (allowable) operating ranges - such as encourage the use of ‘no-chillers’, free cooled facilities.

Table 1-1 2011 ASHRAE Thermal Guidelines for Data Centers [2]

Class	IT Equipment Type	Recommended Operating Range	Allowable Operating Range	Maximum Dew Point	Environmental Control
A1	Enterprise Servers, Storage Products	18º to 27º C	15º to 32º C	17º C	Tightly controlled
A2	Volume servers, Storage Products, Personal computers, workstations	Same as above	10º to 35º C	21º C	Some control
A3	Same as above	Same as above	5 to 40º C	24º C	Some control
A4	Same as above	Same as above	5 to 45º C	24º C	Some control

1.2 Data Center Energy Trends

Increased power costs and pressure from environmental groups will lead data center professionals to minimize their traditional energy needs. The heat load per square feet of data center footprint has increased as a result of substantial increase in chip and module heat flux, and with that comes the increase in energy costs. Energy costs now sit close to the top of the list, accounting for about 25% of total operating costs for running data centers, besides expenditures in hardware purchases and labor for operation.

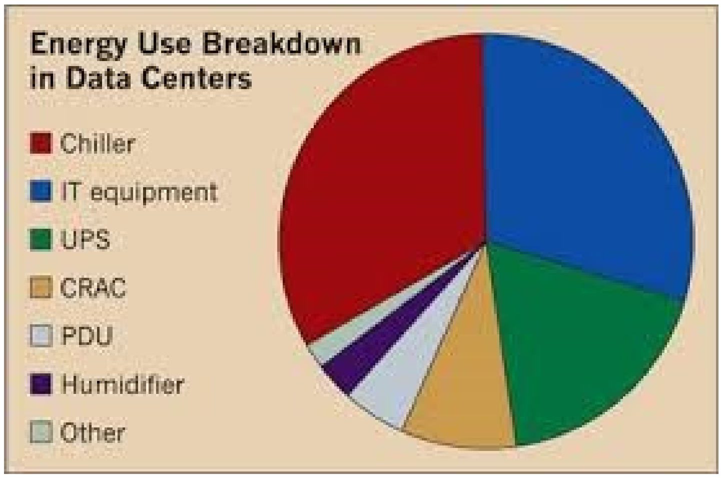

Figure 1-2 Typical Data Center Energy End Use [4]

With data center professionals striving to cut down the amount of power consumed per unit of computing executed, the unbridled growth of computing continues to come off as a wasteful contributor to global warming – a typical traditional data center uses almost twice as much electricity as it needs to do the actual computing, while the extra amount is used for cooling, lighting and sustaining the data center.

The Power Usage Effectiveness, PUE which is essentially the ratio of the total facility energy (lighting, cooling, etc.) to the IT equipment energy (computing) gives a measure of how efficiently a data center uses its energy, with an ideal value of 1.0. Google showed how close it could get to a perfect PUE by building data centers that had decreasing PUEs from 1.16 (2010) to 1.14 (2011) [3]. Facebook, by building an energy-efficient data center at Prineville close to cheap hydropower and using misting technique with ambient air also showed how selecting the right location for a data center can drive energy consumption lower – with a record PUE of 1.09.

The type of energy to use is another issue being considered an economical importance in running data centers. With an oversupply of natural gas drilled from underground shale formations in South Dakota, Pennsylvania and other Appalachian states and low price of gas over the years, some companies would resort to using onsite generators to power their data center facilities. In fact, Datagryd in Manhattan boasts of a certain cogeneration facility that employs waste heat reuse of hot gases from the generators' exhaust to drive their data center cooling system. This is coupled with the ability of Datagryd to generate electricity from fuel supplied through underground pipeline and keep delivering services to its customers in New York and New Jersey during Hurricane Sandy. This pattern shows promise for use by future data centers, especially as other states allow for the possibility of drilling for natural gas.

Another current trend would be AOL's remotely managed micro-module data centers known as Port-A-Data-Centers. They are typically integrated with weather-tight server racks, storage, and switching, as well as plugged-in power, water and network service. With this system employing a closed-loop piping structure where hot exhaust air from the server is used to warm the water in the heat exchanger and subsequently cooled by ambient air, the cooling system is still efficient despite the temperature rise to as high as 85 degrees Fahrenheit. This cooling system requires less energy than CRAC units and the concept is definitely more cost effective since there is no need for lights or electrical locking mechanisms. A PUE rating of 1.1 was achieved from using these units [3].

Renewable sources of power generation ranging from wind, solar, hydroelectric or geothermal energy will soon take the center stage as prime candidates for data center energy use. Modern data centers will not only be made to consume less power per unit of computing done but will also be built next to self-renewing sources of local energy, yielding a net zero of carbon fuel consumption. As opposed to the practice of bringing power to the data, such facilities, often micro-data centers would be designed and equipped to take the data they are working with to the sites of self-renewing energy sources. Early prototypes of these data centers are already being built by the likes of Microsoft (data centers fueled by biogas from a waste-water treatment facility), Google and cloud service providers as well as Facebook.

1.3 Cooling in Data Centers

Data center cooling is driven by increasing power densities and heat levels and as such, has experienced a dramatic change over time. The traditional cooling methodology has always been the cooling scheme where a perimeter CRAC unit pumped out a large volume of air at high pressure into the cold aisles to cool the IT equipment and subsequently push out hot exhaust air back to its return duct through the hot aisles of the facility.

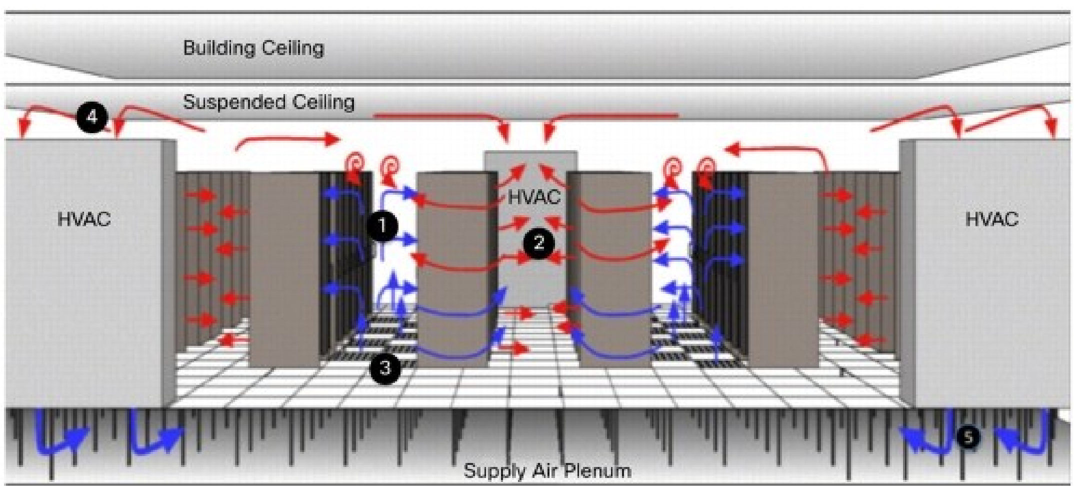

Figure 1-3 Raised Floor Air Supply Configuration [5]

This system of air delivery has often been perceived as chaos air distribution due to the inherent inefficiencies and limitations that come with it. Some of those include certain phenomena that data center operators have to deal with in order to sustain the temperature requirements of their facilities. Some of these include:

- Cold air bypass – A situation where the cold air stream from the plenum shoots beyond the face of the racks/cabinets without initiating enough cooling. This occurs when the velocity of the air stream exceeds the ability of the fans to draw in the cool air.
- Hot Air Recirculation – This instance describes the situation when some of the exhaust air stream from the IT equipment in the hot-aisle mix with and effectively increase the temperature the cool air from the plenum. Hot spots are created when this occurs and temperatures too high for the IT equipment can develop at the inlet of the racks.
- Air stratification - This refers to the natural tendency of air to mass in different temperature-based layers according to their densities in an attempt to provide cooler air at the top of the face of the rack, thereby forcing set points on precision cooling equipment to be lower than recommended. Often in an attempt to remediate this situation, technicians tune up the CRAC unit fan speeds in order to provide more cool air to the room; a practice that results in bypass air.

1.3.1 The Evolution of Containment Cooling Solutions

Businesses have sought ways to combat these inefficiencies in their data centers and some have adopted the hot aisle/cold aisle rack orientation arrangements, in which only hot air exhausts and cold air intakes face each other in a given row of server racks. With convection currents that are generated by these configurations, airflow and temperature distribution in data centers are marginally improved – both hot aisle and cold aisle containment share the same fatal flaw of allowing air to move freely around the data center.

Rack containment cooling strategies are now being introduced and are designed to organize and control air streams. They do this by enclosing racks in sealed structures that capture hot exhaust air, vent it to the air cooling units and deliver chilled air directly to the IT equipment. Some others like the snorkel (a technique reviewed in this work) are placed in front of racks, completely isolating the cool inlet air (through the floor tiles) from the ambient air effectively reducing the inlet temperatures and improving cooling efficiency. These techniques by eliminating re-circulation of hot air, increase reliability - servers are spared from exposure to potentially dangerous warm air that can result in thermal stress which decreases IT equipment life.

1.4 Energy Consumption by Data Centers

By design, most data centers consume a vast amount of energy in an incredibly wasteful manner. Online companies for instance, typically run their data centers at full capacity around the clock regardless of the demand, sometimes wasting about 90% or more of the electricity they pull off the grid [The Times]. More so, they further rely on banks of generators that emit diesel exhaust. Worldwide, the digital warehouses use about 30 billion watts of electricity of which data centers in the United States account for about 25% to 33% of that load [The Times].

A certain energy use analysis of data centers conducted by McKinsey & Company in the same edition of the New York Times reveals that they literally use only 6% to 12% of the electricity powering their servers to perform computation while the rest was merely used to keep the servers idling and prepared for unexpected surges in activity that could slow or potentially crash their operations [7]. This study significantly portrays the huge energy expenditure and inefficient use of power by companies in running their data centers, which can mostly be attributed to the customers' irrepressible demand for high-speed, instantaneous response to the click of a mouse. EMC and the International Data Corporation estimated that about 75% of the more than 1.8 trillion gigabytes of digital information created in 2011 was created by ordinary consumers in sending huge data files back and forth. During the creation of a 3-D animated movie, roughly a million gigabytes are processed and stored in a data center. Besides the huge electricity-at-full-throttle usage, large data centers still own generators, thousands of lead acid batteries, and banks of huge spinning flywheels to take care of unexpected grid failures.

Despite this huge energy consumption, a few companies like Facebook and Google strive to minimize wasted power by redesigning their hardware and using some extensively re-engineered software and cooling systems. This nonetheless, did not prevent Google's data centers from consuming nearly 300 million watts and Facebook about 60 million watts of electricity in 2012 [7]. As the amount of data and energy use continue to rise, it becomes almost inevitable that companies may have to alter their practices in order to permit the restructuring that will ensure better energy management.

1.5 Energy Consumption in Data Centers

In data centers, cooling contributes primarily to the overall energy consumption and accounts for about 30% to 50% of total energy used [4']. According to the US Department of Energy, less than half of the power used by a typical data center powers its IT equipment while the remaining energy is used to support infrastructure, including cooling systems, UPS inefficiencies, power distribution losses and lighting. From a study [8], the principal contributors of cooling energy consumption in data centers include those from the facility side - chiller compressors (41.2%), CRAC units (27.6%), cooling tower (13%), and pumps for building chilled water (4%) as well as that from the IT side - server fans (14%), as shown in figure 1.5. Therefore, a data center looking to reduce cooling energy consumption would better consider the chiller operations, followed by the CRACs.

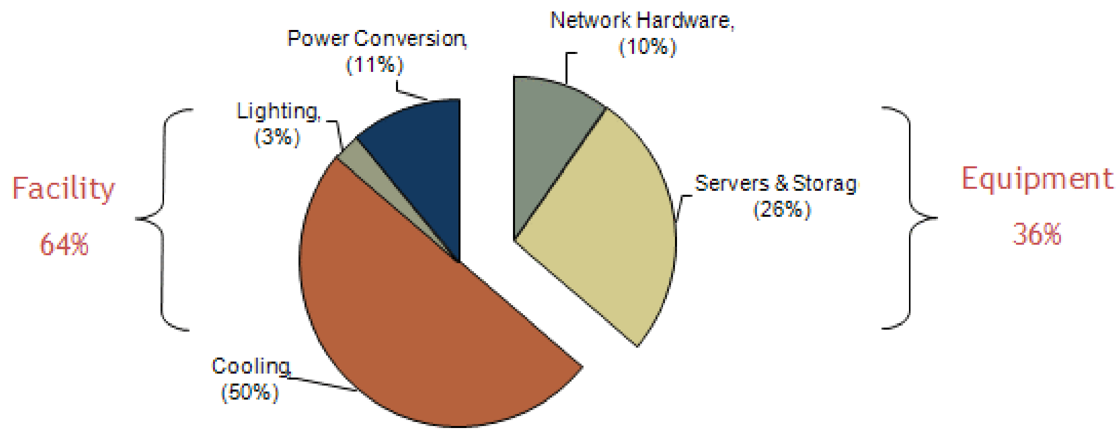

Figure 1-4 Breakdown of Total Energy Consumption [6]

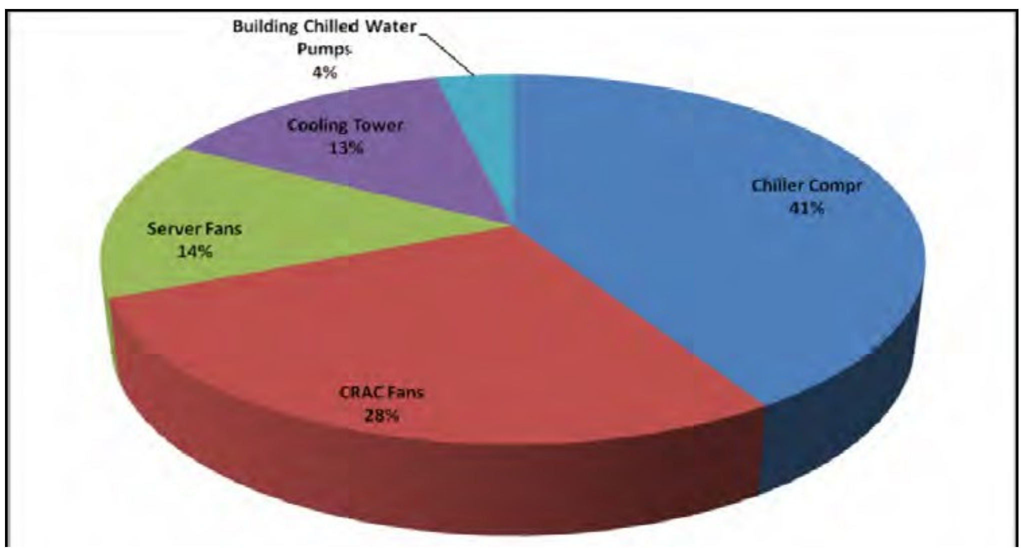

Figure 1-5 Breakdown of Cooling Energy Consumption [8]

IT equipment, cooling systems and PDUs (Power Distribution units) are the three principal components that require energy in data center facilities. Electricity from the utility grid is split into two broad streams, the uninterruptible loads (IT equipment) and other loads (such as can withstand temporary interruption). The UPS (Uninterruptible Power Supply) receives the electricity for the IT equipment first hand, absorbs any fluctuations in power supply and provides a more uniform supply. AC power from the grid is converted to DC power to be used in charging up the UPS batteries and afterwards is converted back to AC before leaving the UPS. Once out of the UPS, the electricity is received by the PDUs to feed into the racks. Another round of power conversion from AC to low voltage DC is performed by the server PSUs (Power Supply Units) for use by the electronic components (CPU, chipset, memory, disk drives, fans etc.) in the server motherboards.

Chapter 2

Literature Review

2.1 Data Center Cooling Scheme Design

Due to the explosion of digital information and the proliferation of digital infrastructure, IT equipment continues to increase the amount of heat dissipated and exhausted to the data center rooms housing them. Customers faced with the challenge of increasing rack heat loads are required by equipment manufacturers to keep their equipment maintained within certain temperature and humidity specifications. A lot of research has gone into data center cooling design aimed at tackling this issue and this chapter seeks to address some of the works that have been done previously as well as collect some of the best ideas that have been proposed [9]. Certain basic cooling concepts that need to be evaluated before building a new data center will include some of the following:

2.1.1. Ventilation Design

Representative geometries for four different data center ventilation schemes were modeled by Nakao et al.[10] with a heat flux of 660 W/m^2 (61 W/ft^2) and chilled air supply fractions (of total rack flow rate) of 80% to 220% and were as follows:

- Under-floor supply (raised floor) with ceiling exhaust
- Under-floor supply with horizontal exhaust
- Over-head supply with under-floor exhaust
- Over-head supply with horizontal exhaust

Similarly, Noh et al. [11] used computational modeling to compare three different designs as follows:

- Over-head supply with under-floor exhaust
- Over-head supply with horizontal (wall) exhaust

- Under-floor supply (raised-floor) with ceiling exhaust

of a data center for telecommunications application, with racks (5 to 6 kW) with heat fluxes of 400 W/m^2 (37.2 W/ft^2). They both (Noh et al. and Nakao et al) reported that the best ventilation scheme is that of a raised floor chilled air supply with exhaust hot air removal from the ceiling vents or venting through the CRAC units.

With numerical CFD modeling, Shrivasta et al. [12] characterized and contrasted thermal performance of seven distinct ventilation schemes of different data center configurations based on average region rack inlet temperatures and mean region rack inlet temperatures to determine the effectiveness. They established that the location of the CRAC unit return vent and ceiling height had the most influence on rack inlet temperature amongst the supply air flow fraction. They also reported the under-floor (raised floor) design as being more effective than the other configurations considered and agreed with Nakao et al. that the worst ventilation scheme was with overhead chilled air supply and under-floor return.

In a similar vein, Sorell et al. [13], Herrlin and Belady [14] and Schmidt and Iyengar [15] with CFD analyses, have all compared under-floor and over-head supply designs. Sorell et al. and Herrlin and Belady also showed that the typical under-floor configuration can set off recirculation patterns at the top part of the rack inlet, leading to hot-spots and that over-head supply design eliminates that set back as a result of supplying air from the top to provide good mixing. Also, steep temperature gradients can develop at the front of the racks (Schmidt and Iyengar [15]; Sorell et al. [13]) for high server density layout with under-floor, chilled-air supply but can be less pronounced with an overhead configuration.

2.1.2. Plenum Depth

Some guidelines have been proposed that offer the best overall airflow in data centers while also making provisions to accommodate modifications to the airflow distribution that correspond to the IT equipment layout within data centers. A principal objective has always been to balance chilled air distribution in such a way that the data processing units with the highest heat loads receive more than those with lower density. Therefore, a good consideration will be the depth or height of the sub-floor plenum but even that in itself is not as important as the particular height that will allow for the best possibility of making changes when IT equipment are moved back and forth from a data center – for instance, when lower-density racks are replaced with higher-density racks.

Analytically, Bernoulli's principle shows that with a higher plenum height, there is more flow uniformity and better distribution because lower velocities of chilled air molecules will produce a reduced, more uniform sub-floor pressure. Karki et al. [16] with an analysis carried out on a base configuration with 25% open perforated tiles, showed the possibility of reverse flow occurring through the perforated tiles nearest the CRAC unit when the plenum height is not very high (0.5 to 1 ft) due to very low or insufficient flow. This same study shows that flow distribution across tiles becomes more uniform as the raised floor height increases up to 30 inches, and the reverse flow effect is eliminated. A plenum depth with obstruction-free height of 2 ft was suggested by Patankar and Karki [17], Beaty and Davidson [18] as was agreed upon by VanGilder and Schmidt [19].

2.1.3. Ceiling Height

The type of ventilation scheme determines the height of the ceiling to be designed. According to a study performed by Schmidt [20], increasing the ceiling height from 8ft to 10ft for a data center with underfloor air distribution would cause an inlet temperature increase to the datacom equipment. This study also showed that hot-spots developed at the top of the racks for cases where the flow through the tile facing the rack either exceeded or did not match the rack flow rate. Sorell et al. [21] conducted a similar study on three ventilation schemes:

- Overhead air distribution without ceiling
- Under-floor air distribution without ceiling
- Under-floor air distribution with ceiling

They reported that with flow from the CRAC unit set at 110% of the total datacom equipment flow, an improvement was observed in the performance of the three configurations when the ceiling heights were increased from 12ft to 16ft, but however cautioned that increased building cost could be a major factor with increasing the ceiling height.

2.1.4. Perforated Floor Tile Layout and Configuration: Raised Floor Data Centers

Schmidt and Iyengar [22] and VanGilder and Schmidt [19] examined the a few different parameters on various different raised floor data center configurations, among which were leakage flow through perforated tiles, airflow exiting perforated tiles, under-floor blockages, tile layout and total airflow rate etc. Bhopte et al. [23] showed with CFD, the impact of under-floor blockages on rack inlet temperatures and tile flow rates by identifying best possible locations for installing blockages with minimal impact on data center performance.

The numerical and experimental study carried out by Redmehr et al [24] was focused on the procedure to estimate the amount of airflow through cable cut-outs and trays, seams between panels and other gaps. The data obtained was used to show the relationship between leakage area and leakage flow, which was estimated to be about 5-

15% of the available cooling air, if the seams in the panels are sealed. Summarily, authors present guidelines on how to achieve the best performance.

2.1.5. CRAC Unit Placement

The configuration and location of a CRAC unit has been shown from studies to impact cooling in data centers in so many ways. Some recommendations have been made:

- CRAC units should be positioned to discharge chilled air in the same direction. According to the study by Schmidt et al. [27], airflow rate distribution through perforated tiles has been found to be uniform with this concept as well as non-uniform distribution has been observed for airflow discharge in collision with each other. They also established that it was preferable to not use turning vanes in CRAC units, since it appeared to reduce airflow rate by 15% or otherwise, set such CRAC units (with vanes) facing each other, such that the airflow produced is in the same direction.
- CRAC units should be placed in front of hot aisles rather than in front of cold aisles in order to minimize the under-floor velocity pressure and provisions should be made for racks to have a clear path of hot air back to the CRAC units returns/intakes because that way, they show reduced rack inlet temperatures (Beaty and Davidson [18]; Schmidt and Iyengar [25])
- CRAC units on the raised floor (under-floor) configuration and aligned on parallel rows should not exhaust chilled air in a direction that makes their plumes to collide, thereby reducing static pressure but rather in such a direction that increases their static pressure. Koplin [26].

Chapter 3

Airflow Distribution and Management Strategies

3.1 Airflow Management Best Practices

In order to ensure that the air conditioning system in a data center is efficient and effective, the path, temperature and quantity of cooling air delivered to the IT equipment; have to be properly conditioned to eliminate mixing with the hot exhaust air from the racks. Several approaches therefore have been developed over the years to properly manage and mitigate certain airflow-related and thermal challenges in data centers such as hot air recirculation, existence of hot-spots, cold air bypass, and reverse flow. Some other related issues that present serious airflow inefficiencies and limitations include unintended leakage and airflow obstructions. Excess flow from over-provisioning of CRAC units also leads to significant energy waste, thus justifying the need for data center sustainability.

As such, airflow management best practices and cooling strategies are often implemented towards data center optimization, which mostly involves containing the air in the data center. Some of the common best practices adopted in data centers today include, but are not limited to blanking panels, containment systems – CAC (Cold Aisle Containment), HAC (Hold Aisle Containment) and snorkels (a rack-containment technique under study in this work), VED (Vertical Exhaust Duct) or cabinet chimneys, VFD (Variable Frequency Drives) in CRAC/CRAH units. These airflow isolation techniques are either applied independently or in combination with others to maximize airflow and cooling efficiency in data centers.

3.1.1. Aisle Containment Systems

Critical IT equipment functionality, energy efficiency and uptime can be improved with aisle containment which allows equipment to operate within ASHRAE TC 9.9

guidelines. ASHRAE TC 9.9 sets recommended environmental envelopes in which IT equipment should operate. For the most stringing requirements, this is between 18.0°C (64.4°F) to 27.0°C (80.6°F) for the recommended inlet temperature to the IT equipment, a 60% relative humidity and a dew point of 15.0°C (59.0°F) [40]. Table 1-1 also shows a set of “Allowable” operating temperature ranges, as defined by ASHRAE for the various operational classes, the underlying goal being to provide a larger operating range in order to achieve more energy savings.

Both hot aisle and cold aisle containment improve the predictability and performance efficiency of data center cooling systems. The study by Saurabh et al. [35] shows that separation of hot and cold air by deploying a containment system allowed for improvements in system scalability, operational reliability and efficiency. By effectively isolating hot and cold air, the CRAC units can do less work in supplying cooling air at cabinet server inlets. Therefore, with proper selection of containment systems, high heat density issues can be addressed, as well as efficient hot-spot removal and lower rack inlet temperatures may also be achieved. While CAC systems offer some improvement in a traditional room-based perimeter cooling layout, HAC with a row-based cooling architecture very easily addresses the higher IT density requirements without compromising the temperature distribution in a data center.

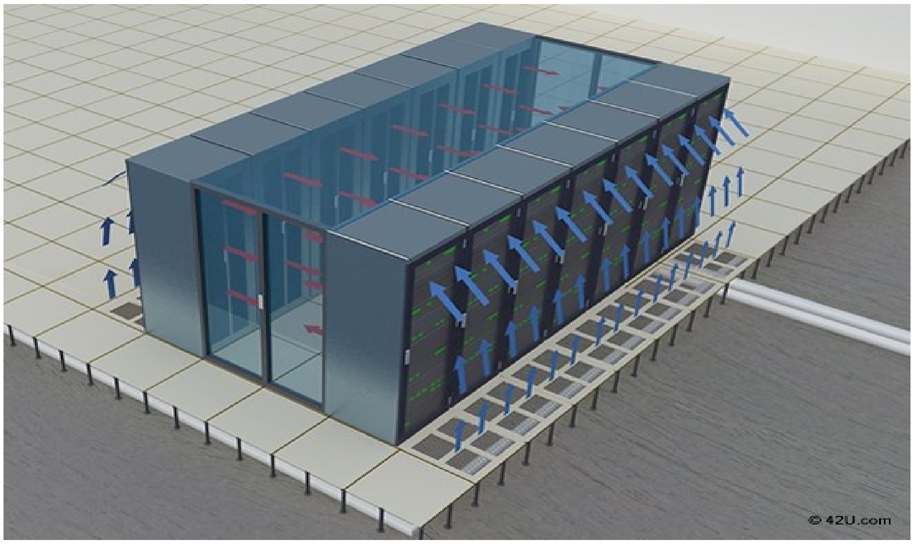

Figure 3-1 Hot Aisle Containment (HAC) [43]

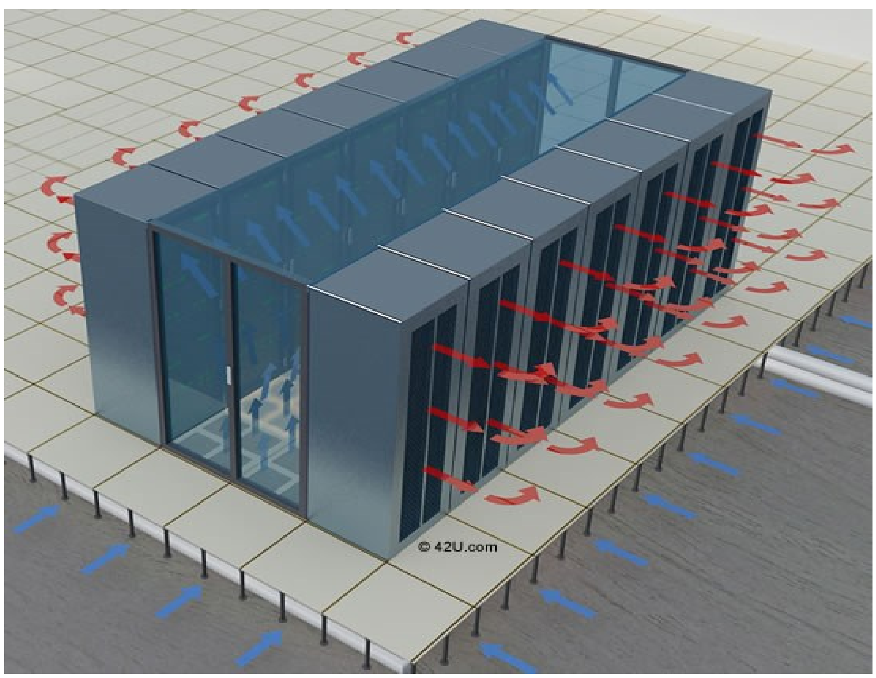

Figure 3-2 Cold Aisle Containment (CAC) [43]

3.1.2. Blanking Panels

Blanking panels are useful in maintaining proper airflow in data centers by sealing off unused rack spaces between rack mount equipment. Change in airflow through and across the rack can be controlled and overheating which happens sometimes as a result of exhaust air recirculation is highly minimized. With such a feat achieved, the resulting reduction of inlet temperatures can lead to energy savings. In fact, adding a single 12-inch blanking panel to the middle of a server rack can yield 1% to 2% energy savings [45]

Figure 3-3 Use of Blanking Panels [44]

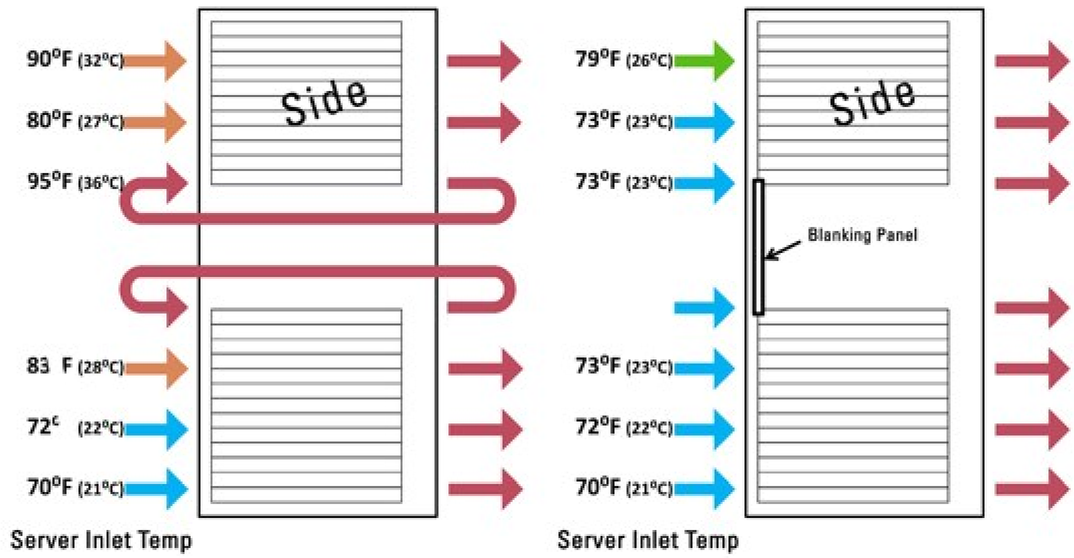

Figure 3-4 Impact of Blanking Panels [44]

3.1.3. Vertical Exhaust Ducts(VEDs)/Cabinet Chimneys

Cabinet chimneys, also known as VEDs (Vertical Exhaust Ducts), function primarily to provide isolated containment of cabinet exhaust air. They ensure passive cooling by effectively enclosing the hot air from the cabinet, channeling it to a drop ceiling plenum and returning it directly to the cooling unit without letting it mix with the cool air in the room. For this approach, a solid rear door and exhaust duct that connects to a drop ceiling plenum (or that opens up high above the cabinet inlet) are required for the cabinet. This setup, as opposed to CAC and similar to HAC, helps keep the ambient temperature of the room as close enough as possible to the supply air temperature [35].

Figure 3-5 Cabinets equipped with CPI's VEDs [46]

3.1.4. Snorkels

Snorkels are Plexiglas casings installed directly on less-densely populated racks to direct and aim cool air coming from the under-floor plenum to individual racks. When pressurized supply air from the CRAC unit is introduced from the sub-plenum through the perforated floor grilles/tiles into the cold aisle, snorkels have been shown to be capable of channeling the streamline along the length of the rack, inhibiting mixing with the ambient air in the cold aisle, or recirculated air from the hot aisle to a reasonable extent. Experiments conducted at the IBM Thomas J. Watson Research Center demonstrated a significant drop in the rack inlet temperatures, using snorkels. With half rack-height snorkels, a 5°F drop in rack inlet temperatures was achieved. However, with full rack-height snorkels, an additional 15°F drop in rack inlet temperatures was recorded due to the significant temperature gradient midway between 3 and 5 feet above the data center floor (Figure [28]). Snorkels, when used on less densely-populated racks, especially requiring spot cooling, show some promise of reducing or maintaining rack inlet temperatures and may prove to be a cost-effective alternative to aisle containment systems.

Figure 3-6 IBM Racks equipped with Snorkels [28]

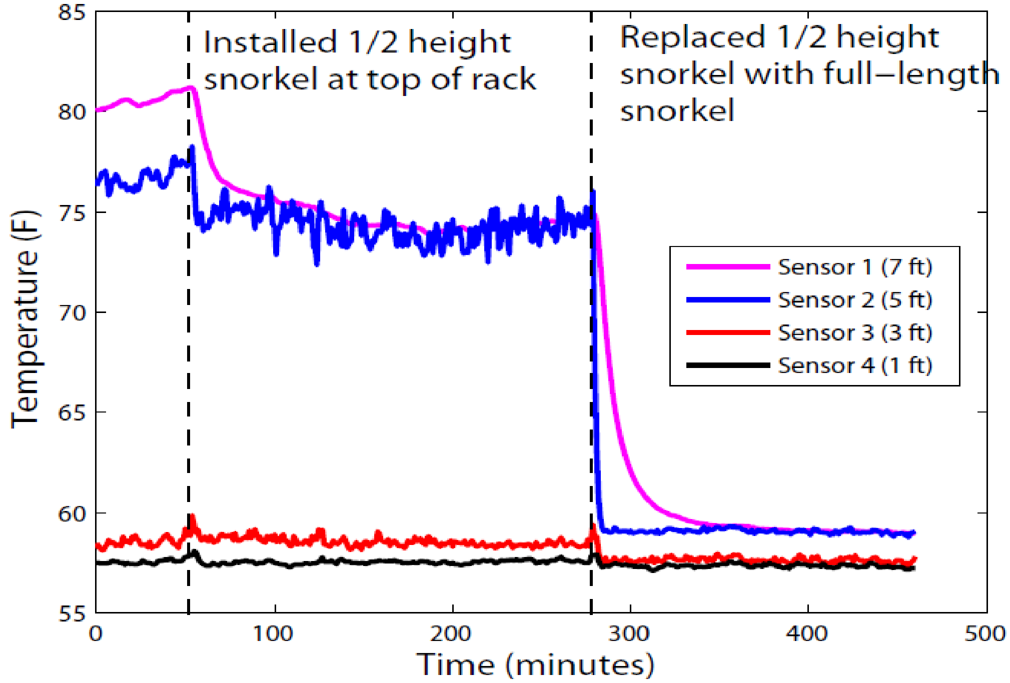

Figure 3-7 Impact of Snorkels upon Rack Inlet Temperature [28]

Chapter 4

CFD Analysis

4.1 Introduction to CFD

In computational fluid dynamics, computer programs perform calculations that simulate the interaction of fluids (liquids, gases etc.) and surfaces defined by boundary conditions, hence CFD is a branch of fluid mechanics that uses numerical methods and algorithms to analyze and solve problems that involve fluid flow. These methods involve the simulation of variables like velocity, temperature, pressure, kinetic energy, and potential energy etc. and their distribution throughout a computational domain. The results from such simulations help to analyze designs and explore design process in order to make necessary optimizations to a product or condition of interest. High speed supercomputers generally yield accurate and better simulations.

The Navier-Stokes equations define single-phase (gas or liquid, but not both) fluid flow and form the fundamental basis of almost all CFD problems. These equations technically undergo several stages of simplification and linearization: the first, to yield Euler equations by removing the viscosity terms; further simplification yields the full potential equations by eliminating the vorticity terms and finally, the linearization for small perturbations in subsonic and supersonic flows to yield the linearized potential equations [47]. CFD was used initially used in automobiles and aircrafts – two dimensional methods using conformal transformations of the flow about a cylinder to the flow about an airfoil were developed in the 1930s. But its applications today have been extended to telecommunication and data center industries as well as systems with high heat loads.

CFD establishes a connection between experimental work and pure theory and this can be viewed as an advantage because it helps to clearly understand certain theoretical principles and see them come to play before experimental work is done. This significantly saves costs from running experiments repeatedly for any required design optimization. Other advantages include that design problems can be discretized based on a set of numerical parameters and solved; it saves time because as many complex cases can be solved within a specific time frame that may not be possible with experimentation.

Typically, a mathematical model is generated by a numerical prediction and represents the domain to be solved and analyzed. Simulation tools are equipped with features for grid generation, mesh sensitivity analysis (or grid-independence Study), batch solving etc. When system level electronics like server chassis and electronic equipment (PSU, hard disk etc.) or room level structures like datacenters and telecommunication centers are modeled with commercially available software, airflow processes and temperature distribution patterns occurring within and around them are analyzed and as such, provision can be made to optimize existing design. This study focuses on the later, and several different components that are modeled separately (but are essentially enclosed in the structure), specifically the snorkels which is a rack-level component under review in this work.

4.2 Governing Equations

The governing differential equations are solved for problems involving heat transfer and fluid flow and are for conservation of mass, conservation of momentum and conservation of energy [47]. The generalized cases for the conservation of mass, momentum and energy are given respectively below:

$$\frac{\delta \rho}{\delta x} + div(\rho \mathrm{u}) = 0 \tag{1}$$

$$\frac{\delta}{\delta t}(\rho \mathrm{u}) + div(\rho \mathrm{uu}) = div(\mu \; grad \; u) - \frac{\delta \rho}{\delta x} + \mathrm{B_x} + \mathrm{V_x} \tag{2}$$

$$div(\rho u h) = div \; (\; k \; grad \; T) + \mathrm{S_h} \tag{3}$$

4.3 Global Computational Domain

The governing equations with the boundary conditions are generally solved by means of numerical integration in a region or space denoted as the domain of integration. This is usually a closed volume within a finite region of flow known as a control volume and this may be fixed in space or may be moving along with the fluid [48]. The boundary condition for fluid properties in most computational domains such as the density, conductivity, expansivity, mass flow rate, viscosity, pressure, temperature, external/internal ambient temperature, thermal conductivity and specific heat, as well as the conditions at the enclosure of the domain (open, closed/adiabatic, or symmetrical) have to be specified prior to solving.

The series of steps to solving these equations include defining the geometry of the problem, discretization of the integration domain into contiguous finite volumes or grid cells - process also known as meshing. This involves converting differential equations to algebraic equations. The few methods of problem discretization include Finite Difference Method (transformation of differential terms into series of grid points suitable for numerical computing – difficult when equation coefficients become discontinuous), Finite Element Method (finding approximate solutions of partial differential equations and integral equations by dividing up geometry into discrete elements and solving with respect to each other) and Finite Volume Method (Integration of the governing equations around the mesh elements – fluid and solid structure analysis) [49]. The CFD code for the computational study in this work, 6SigmaRoom [37] uses finite volume method and involved the integration of the governing equations over the several control volume regions obtained from the discretization of the solution domain. The calculated variables are located at the centroid of the grid cells. Next up, the discretized results can be obtained from a set of algebraic equations, each relating the value of a variable in a cell to the value of that in a neighboring cell. The algebraic equation below shows how the pressure variable, P can be calculated:

$$T = \frac{C_0P_0 + C_1P_1 + C_2P_2 + C_3P_3 + \cdots C_nP_n + S}{C_0 + C_1 + C_2 + C_3 + C_n} \tag{4}$$

Where P_0 represents the pressure value in the prior/initial step; P_1, P_2, P_3,…P_n represent the pressure values in neighboring cells. C_0, C_1, C_2, C_3, C_4, C_n represent the coefficients connecting each cell value.

Five variables are obtained from solving the algebraic equation: u, v, w, T and ρ. So, depending on the number of cells n, 5n number of equations are solved (ex. For 1 million grid cells, 5 million equations will be solved). The coefficients above are functions of the field variables and as such, the equations are actually non-linear even though they appear to be linear because of the iterative number of solution steps in which coefficient values are solved once for outer iteration and considered constant afterwards, while the equations are solved by inner iteration.

The higher the number of grid cells (finer meshing), the better the approximation of the governing equations and the more accurate the solution gets. For this reason, the regions in some solution domains with high variable gradients are usually solved with more grid cells. Contrary to common belief, more than just grid independence is needed to guarantee the accuracy of a simulation (how closely it predicts a real world situation); boundary condition accuracy and turbulence model also dictate the solution outcome and accuracy.

4.4 Turbulence Modeling

Turbulence modeling is essentially the construction and use of a model to predict the effects of turbulence and it is the key issue in most CFD simulations because virtually all engineering applications are turbulent and hence require a turbulent model [50]. A turbulence model is a computational procedure to close the system of mean flow equations. These models allow the calculation of the mean flow without first calculating the full time-dependent flow field. The priority in using a turbulent model relies on how turbulence affected a mean flow. For a turbulence model to be useful, it must be simple enough, accurate, have a wide applicability and be economical to run [51]. A turbulent flow is described as being three dimensional (diffusive, dissipative and intermittent) and with rapid changes in pressure and velocity. It is a flow regime with an infinite number of degrees of freedom as well as irregular velocity fluctuations in all directions.

Navier Stokes equations cannot be solved for a turbulent flow due to the fact that they are coupled with temperature, pressure, velocity and are also non-linear and elliptical. Thus it becomes necessary to develop new partial differential equations for each term in the Navier Stokes equations. The equations below are solved for variables:

- Conservation of mass

$$\frac{\delta\rho}{\delta\tau} + \frac{\delta\rho U_i}{\delta x_i} = 0 \tag{5}$$

- Conservation of momentum

$$\frac{\delta\rho U_i}{\delta\tau} + \frac{\delta\rho U_i}{\delta x_i} = \frac{\delta}{\delta x_j}\left[\mu\frac{\delta U_j}{\delta x_j} - \overline{\rho u_i\, u_j}\right] - \frac{\delta P}{\delta x_j} + S_{ui} \tag{6}$$

- Conservation of passive scalar

$$\frac{\delta\rho C_p T}{\delta\tau} + \frac{\delta\rho C_p U_j T}{\delta x_j} = \frac{\delta}{\delta x_j}\left[K\frac{\delta T}{\delta x_j} - \overline{\rho C_p u_j t}\right] + S_t \tag{7}$$

Where T is a scalar

Partial differential equations are developed for turbulent stresses and fluxes to aid modeling. The different models used are as follows [52]

- Algebraic or zero equation models
- One equation models: k-model or μ_ε first order model
- Two equation models: k- $\mathcal{E}$, k-kl, k-w2, low Re k- $\mathcal{E}$ first order model
- Algebraic stress modes or ASM second order models
- Reynolds stress models or RSM second order models

Eddy viscosity on a cell can normally be predicted by solving two differential transport equations using the two-equation model.

4.4.1 K-Epsilon Turbulence Model

6SigmaRoom uses the K- Epsilon turbulence model which is also known as the two equation model. This model is preferable for free air streams like data centers and telecommunication shelters as well as for problems with thin shear layers. The two variables solved for in the transport equations for this model are the kinetic energy of turbulence (k) and the dissipation rate of kinetic energy of turbulence ($\mathcal{E}$) [53]. Here, viscosity computed is that on the grid cell rather than that on the walls. The transport equations are as follows [54]:

$$\frac{\delta(\rho\mathcal{E})}{\delta t} + \frac{\delta(\rho\mathcal{E}\mathrm{Ui})}{\delta x_{\mathrm{i}}} = \frac{\delta}{\delta x_{\mathrm{j}}}\left[\left(\mu + \frac{\mu_{\mathrm{t}}}{\sigma_{\mathrm{k}}}\right)\frac{\delta \mathrm{K}}{\delta x_{\mathrm{i}}}\right] + G_{\mathrm{k}} + G_{\mathrm{b}} - \rho\mathcal{E} \tag{8}$$

$$\frac{\delta(\rho\mathcal{E})}{\delta t} + \frac{\delta(\rho\mathcal{E}\mathrm{U_i})}{\delta x_{\mathrm{i}}} = \frac{\delta}{\delta x_{\mathrm{j}}}\left[\left(\mu + \frac{\mu_{\mathrm{t}}}{\sigma_{\mathrm{k}}}\right)\frac{\delta \mathcal{E}}{\delta x_{\mathrm{i}}}\right] + C_{1\mathrm{z}}\frac{\mathcal{E}}{K}(G_{\mathrm{k}} + C_{3\mathrm{z}}G_{\mathrm{b}}) - C_{2\mathrm{z}}\,\rho\frac{\mathcal{E}\char`^2}{K} \tag{9}$$

4.5 6SigmaRoom Components

The 6SigmaRoom software by Future Facilities is specifically designed for use in creating 3D virtual models of data centers. Fundamentally it can be used by data center professionals to assess and compare new designs as well as model and troubleshoot existing facilities. The models creatable with 6SigmaRoom are full-scale models that are calibrated using field measurements and that accurately reflect the environmental conditions present in actual data centers. This calibration ensures the capacity to accurately predict the real life effects of any subsequent changes effected on a virtual model. Some of the features include:

- The architecture: This describes the geometry of the data center facility

- Ventilation: This system provides the cooling ex. The CRAC units (denoted as the Air Cooling Units (ACUs)
- The Power distribution system/equipment: This system includes the PDUs and provides power to the facility.
- Power and data cabling
- Cabinets, rack-mounted equipment and other equipment
- Miscellaneous items: For example, personnel, lighting etc.

The Version Tree tool enables the user to create multiple versions of a virtual facility for easy modification and comparison of models.

4.5.1 The Facility Model

The default mode for a facility contains a rectangular room with a raised floor that houses all the other components. The room is the overall envelope for the data center and cannot be created outside of a facility. The walls are solid with no airflow or heat transfer (i.e. assuming the conditions on the outside of the room are similar to those on the inside). The floor is 65ft (20m) across with a floor void or raised floor of 2ft (600mm) depth. The room height from the floor to the ceiling is 11.3ft (3.44m) and 9ft (2.8m) from the raised floor to the ceiling.

4.5.2 Cabinets/Racks

Cabinets are equipment racks or frames with doors and sides to it that can be removed (in which case they are called open racks/frames). They are designed to contain the rack-mounted equipment/servers. By default, the cabinet front and rear faces are assumed to be perforated and the sides and doors are present except the bottom. They require a certain minimum amount of airflow through the perforated tiles, depending on the capacity load they contain.

4.5.3 Servers

The generic server (IT Equipment) used in this study is a simplified representation of a server, representing the overall physical geometry and the power (heat) and airflow interactions with their surroundings. Some of the default physical attributes and boundary conditions are thus:

- Height - 4U
- Width and Depth – 450mm and 600mm
- Temperature Limit – 32°C
- Ventilation Mode – Forced
- Flow Rate Ratio – 56.6cfm/kW
- Input Power (per server) – 0.8kW
- Flow In – 96cfm
- Flow Out – 96cfm

4.5.4 Air Cooling Units (ACUs)/CRAC units

The CRAC units are known as ACUs or Air Cooling Units in 6SigmaRoom are used to circulate air throughout the room in order to control the room air temperature and humidity. The software is decked with the capacity to control the airflow and heat transfer, reflecting the control settings for the ACU. There are basically three types of cooling which the ACU can provide: Overhead Cooling, in which ACUs are designed to be attached to the ceiling or mounted on top of cabinets, In-row Cooling in which they are placed within the cabinet rows to provided localized high cooling areas and Perimeter Cooling, in which they are placed in a corridor external to the data hall or against the perimeter of the room being cooled. The later has been used for the purpose of this study.

Four CRAC units were used for this study. Some of the default boundary conditions are listed thus:

- Input Power – 2.25 kW
- Minimum Supply Temperature - 10°C
- Cooling Type – Chilled Water
- Coil Heat Capacity – 100kJ/C
- Inertial Resistance Coefficient – 100
- Cooling Flow in Use – 5996cfm
- Net Cooling Power – 35.5kW
- Total Cooling Power – 37.7kW

4.5.5 Sensors

These are typically used as measurement devices and can be placed anywhere in the model to gather data about the environment. The data collected are used as inputs to the Controllers (represent the control system that takes inputs from Sensors and produce a control signal that can be used by the CRAC units, Heat Exchangers, Supply Vents etc.). For this study, temperature sensors were used to monitor the inlet temperature at different set-points along the height of the C cabinets for the qualitative comparison of the baseline case and the flat-top snorkels.

4.5.6 Solid Obstructions

Solid obstructions are physical objects that are not necessarily represented by any particular objects but are significant to airflow and heat transfer within the model. They are rectangular brick-shaped cylindrical arbitrary polygon or polyline extruded as plates. They can be used to represent miscellaneous solid objects that present an obstruction to airflow. For this study, solid obstructions were used as blanking panels to obstruct airflow across the central cold aisle through a path without a server cabinet. They were also used to model the snorkel device.

4.5.7 Power Distribution Units (PDUs)

These are included in the model to serve the purpose of providing power to the equipment as well as to represent the heat they produce, the obstruction they create as well as any cooling airflows. Two PDUs were used for the models in this study. Some of the default boundary conditions are listed thus:

- Heat Dissipated – 5625kW
- Temperature Limit – 40°C
- Inertial Resistance Coefficient – 10

Chapter 5

Computational Model

5.1 Test Cases for Computational Study

The method employed for this work was the CFD model of representative data center models with under-floor configuration, using commercially available code [37]. These models were built with the objective to compare the existing traditional airflow isolation techniques (Hot/Cold Aisle Containment) with snorkels as a rack containment strategy. It was then possible to explore the usefulness of snorkels in mitigating data center hotspots while comparing its effectiveness in minimizing cabinet inlet temperatures with the other techniques. Two different snorkel designs, the flat-top snorkel and angle-top snorkel were examined and used for the analyses in this study. Meanwhile, some other dynamics of comparison such as the snorkels (both designs) deployed simultaneously with cold aisle containment was also considered to determine the optimal application of this concept.

5.1.1 Baseline Model

The full symmetry baseline model has a footprint dimension of 1007.8 ft^2 (93.6 m^2) and is 9.3ft (2.8 m) from the raised floor to the ceiling deck. A false ceiling is installed at 0.79ft (0.24 m) from the ceiling deck, making the distance from the raised floor to the false ceiling, 8.5ft (2.6 m). The plenum depth is 2.1ft (0.64 m).

There are 24 cabinets arranged in a hot-aisle cold aisle layout (3 cold aisles and 2 hot aisles) and each cabinet is assumed to be 6.72ft (2.05 m) tall and one tile (1.96ft or 0.60m) wide as shown in figure 9. The number of cabinets and perforated floor tiles (with 50% perforation) are in line with the design and the cabinets in the cold aisles, being supplied with floor grilles are positioned in rows situated front to front and back to back. This concept is used to ensure that a certain level of separation between the cold air supply and hot air return from the hot aisle is achieved [36]. Note that the cabinets and floor tiles are labeled in rows as C, G, J, N and B, H, I, O respectively. For the initial test run, each cabinet is filled to capacity with IT equipment (5 generic servers at 0.8kW of input power i.e. installed cabinet IT load of 4kW/cabinet and critical cabinet IT load of 96kW for all 24 cabinets) and air is assumed to be forced through them with a constant velocity across the front and back by the air moving device (server fans). The minimum amount of airflow through each cabinet is 120cfm/kW. The reader may note that for investigating the impact of increasing rack densities, the baseline and flat-top snorkel cases were considered; the rack densities were increased for only the C-cabinets. The total number of IT equipment installed in the data center model is 120. Four CRAC units with a nominal cooling capacity of 161kW, deliver a total cooling flow of 5996cfm from which an average airflow through each cabinet is 480cfm. The supply temperature of chilled air entering the room from the under-floor plenum was fixed at 22ºC. Two PDUs (Power Distribution Units) are installed on the east end of the data center model to supply power to the IT components and are affixed with cable trays that protect and house the overhead and under-floor cables.

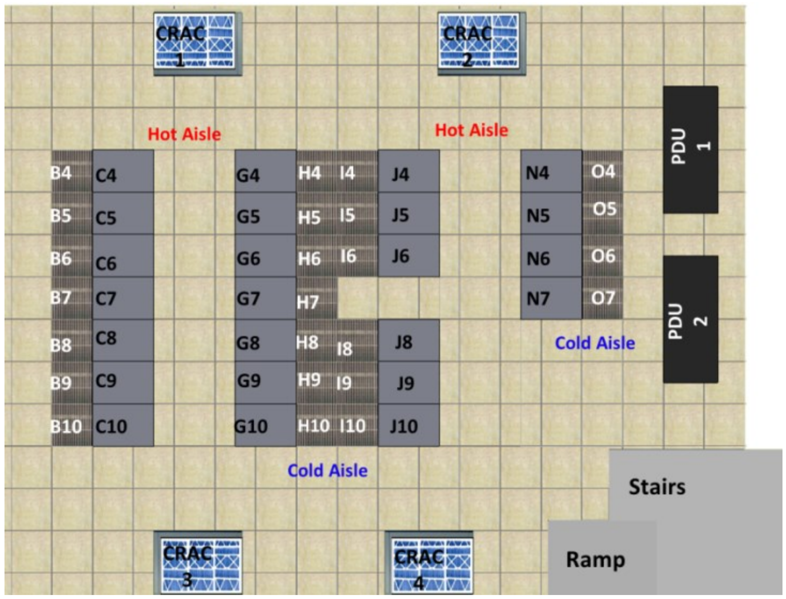

Figure 5-1 Baseline Model: Plan View

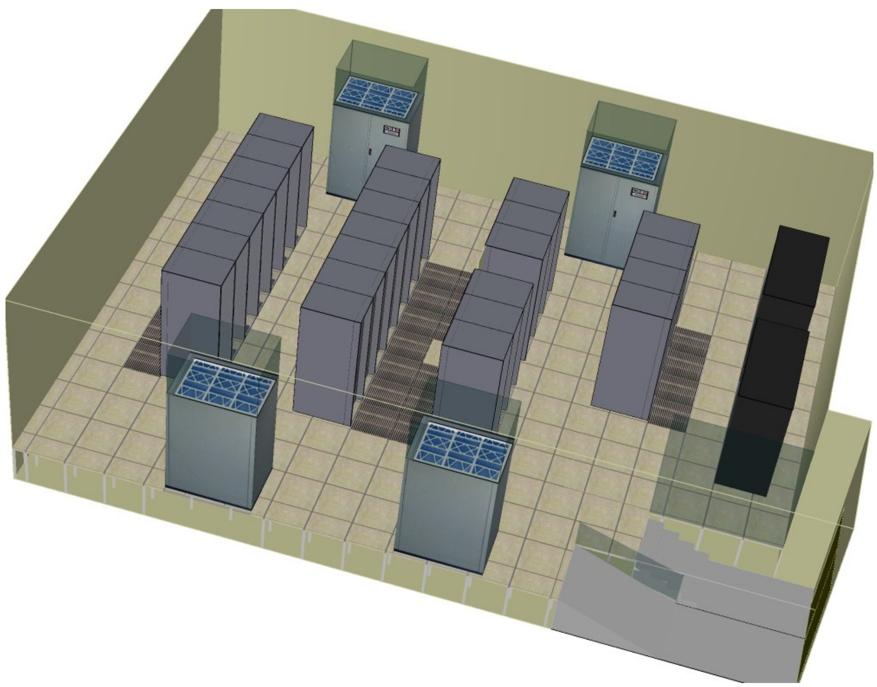

Figure 5-2 Baseline Model: ISO View

5.1.2 Cold Aisle Containment Model

The cold aisle containment model was designed with the same parameters as the baseline model, except that the central cold aisle is contained. The central cold aisle is covered on the top and at the end of the rows in order to achieve a full separation between supply and return air as shown in figure 10 below.

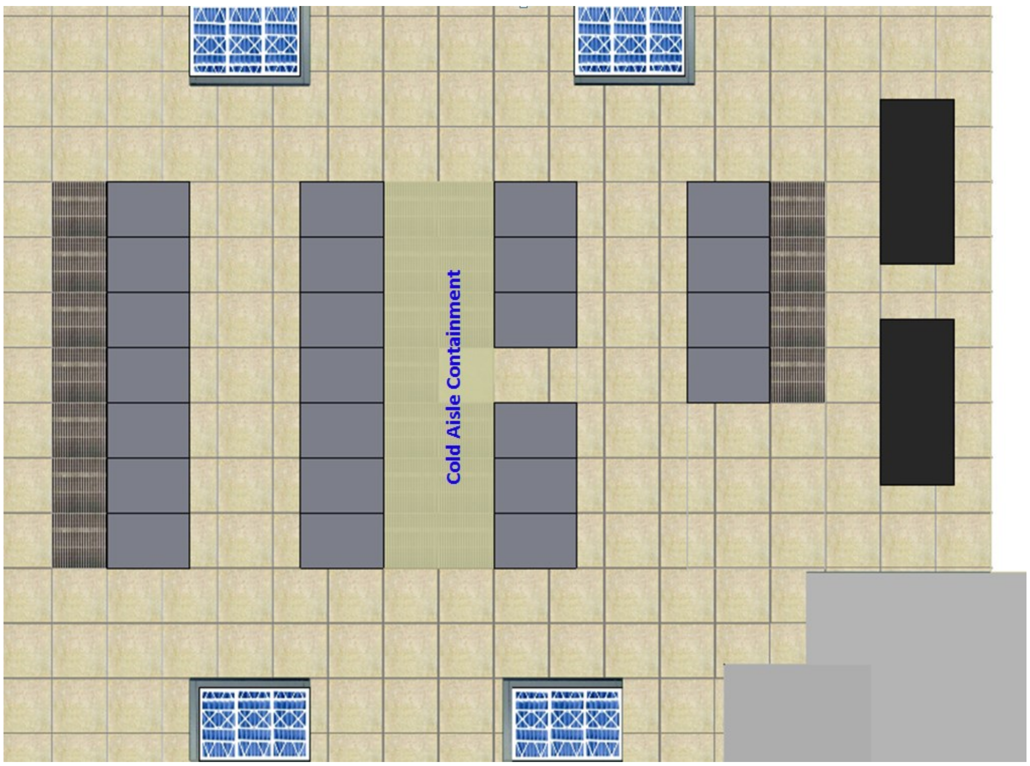

Figure 5-3 Cold Aisle Containment Model: Plan View

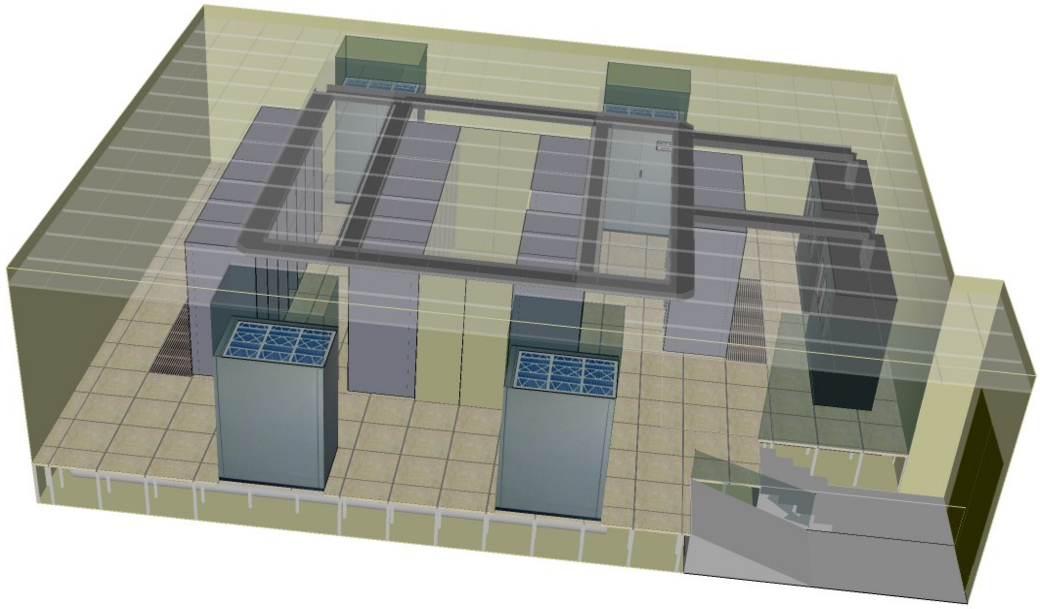

Figure 5-4 CAC Model: ISO View

5.1.3 Hot Aisle Containment Model

The hot aisles were modeled to be in-between the cabinets that are positioned back to back, as shown in figure 11. The design was such that the hot aisles are ducted to the false ceiling so that the exhaust air is directly channeled back to the CRAC units through chimney-like ducts that connect directly from the false ceiling. This way, when cold air from the plenum is supplied to the cabinets, hot exhaust air makes it back to the CRAC unit and a full separation between supply and return air is achieved. This design ensured that the room remained at a low temperature level as shown in figure.

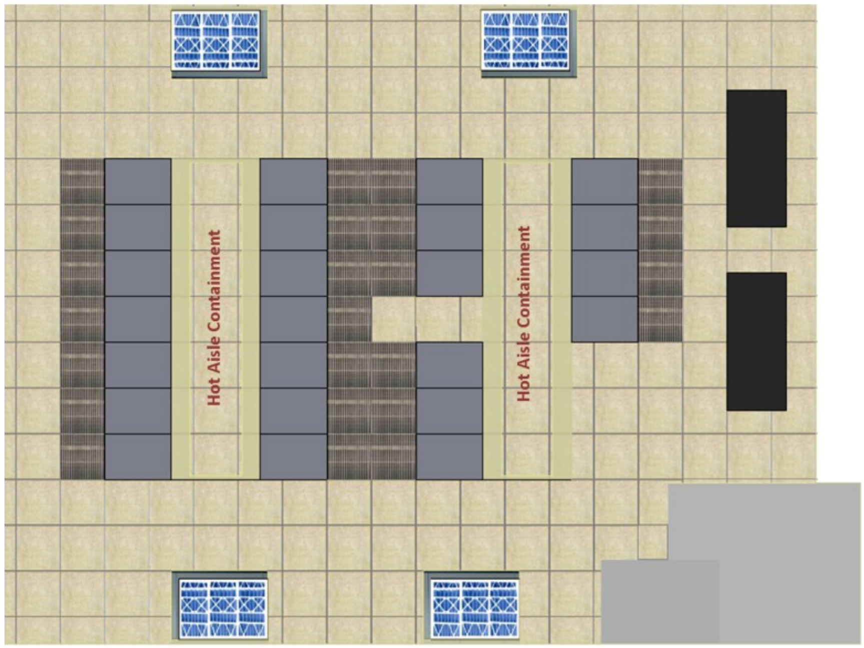

Figure 5-5 Hot Aisle Containment Model: Plan View

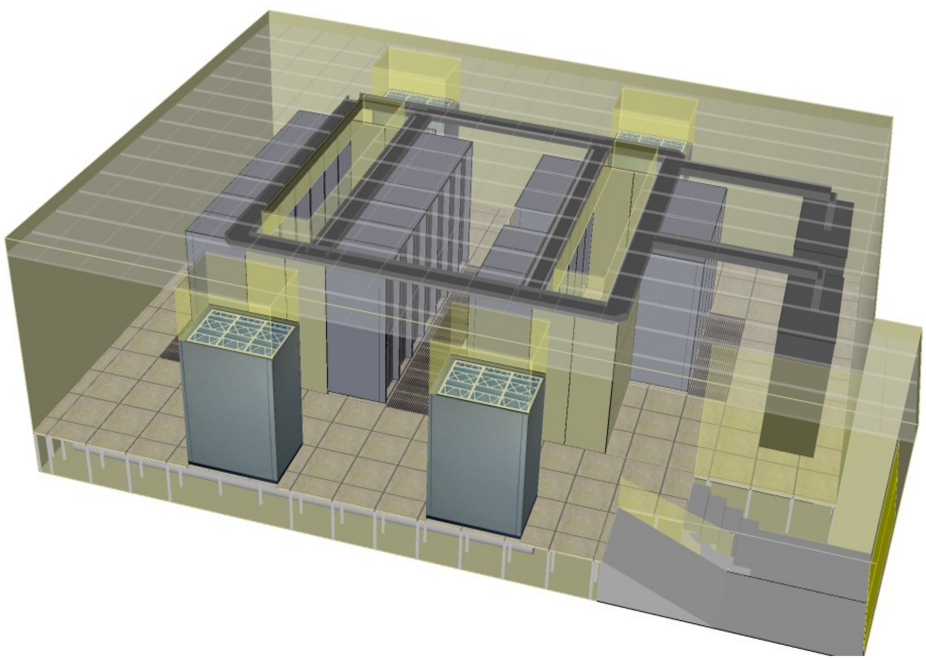

Figure 5-6 Hot Aisle Containment Model: ISO view

5.2 Snorkel Design

Snorkels are a type of rack containment devices, actually Plexiglas casings that can be attached in front of server racks/cabinets. Similar to the objective of containment devices, they are capable of encapsulating the region around the inlet to the cabinets and maintaining the temperature of the cool air from the plenum. The original idea of this concept was to install them on less-densely populated racks to direct and aim cool air from the plenum into the racks and prevent mixing with ambient air. When pressurized supply air from the CRAC unit is introduced through the floor tiles into the cold aisle, snorkels have been shown to be capable of channeling the streamline along the length of the rack, inhibiting mixing with ambient air in the cold aisle or recirculated air from the hot aisle as narrated in section 3.1.4. The focus of this work however, is on the CFD analysis of two different snorkel designs, the flat-top and the angle-top snorkels.

5.2.1 Flat-top Snorkel Design

The flat-top snorkel was modeled as a rectangular cuboid shape with a volume of 24.57ft^3 and a total surface area of 57.3 ft^2 (5.3m^2). It has two open sides, the one side that attaches and perfectly aligns with the open area of the cabinet front door, and the bottom side through which the cold air from the plenum is admitted. This shape acts as an enclosure and effectively channels the cold air stream into each cabinet.

The material used to model this, Plexiglas (actually a trade name for acrylic glass-PMMA or Poly Methyl Methacrylate) is a light weight (with a density of 1.17 to 1.20 g/cm^3), shatter-resistant transparent thermoplastic that is often used as an alternative to glass or polycarbonate when extreme strength is not desired. Its moderate properties, easy handling and processing, as well as its low cost make it preferable for so many applications. For this application however, it not only provides the same transparency required to see through and into the cabinet inlets when they have been enclosed as would glass, but it also has a higher impact strength and is less than 50% as dense[55]. Also of particular importance to this work is its relatively high coefficient of thermal expansion of (5 -10) x 10^{-5} K^{-1} which offers a better environmental stability than other plastics can provide. Predominantly, its low thermal conductivity of (0.17 - 0.20) W m^{-1} K^{-1} [56] is an advantage since the objective is to maximize the low temperature of the cool supply air.

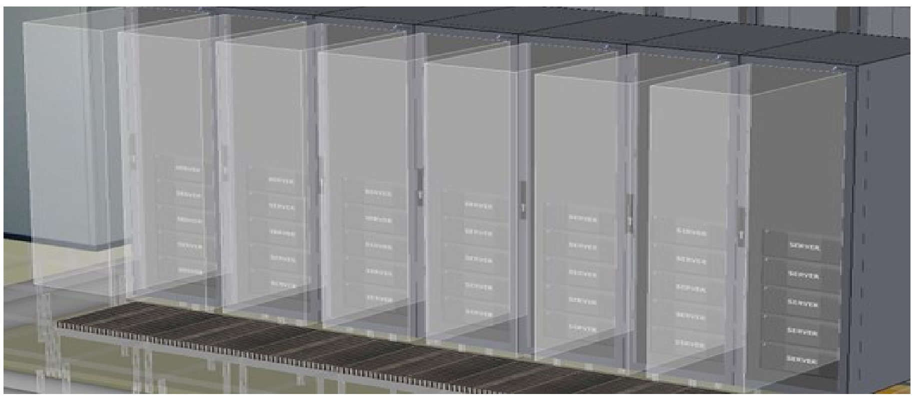

Figure 5-7 Flat-top Snorkels: Close-in View

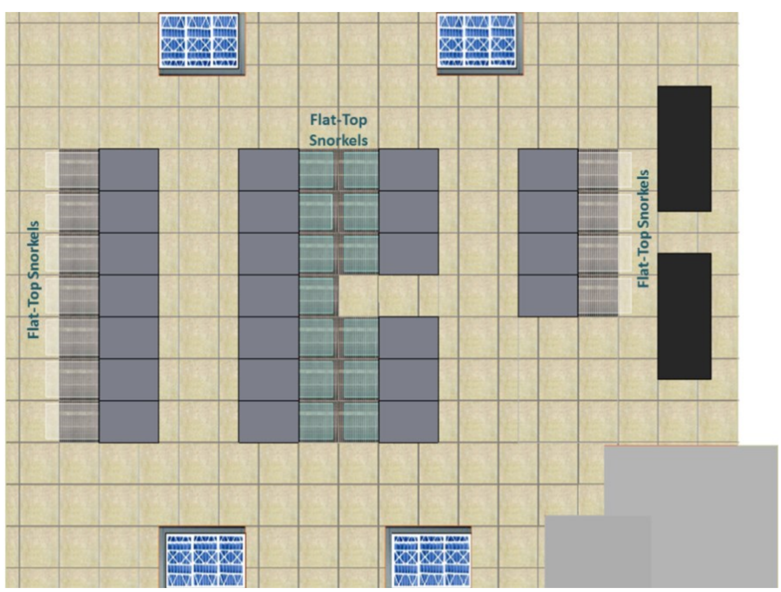

Figure 5-8 Flat-top Snorkels: Plan View

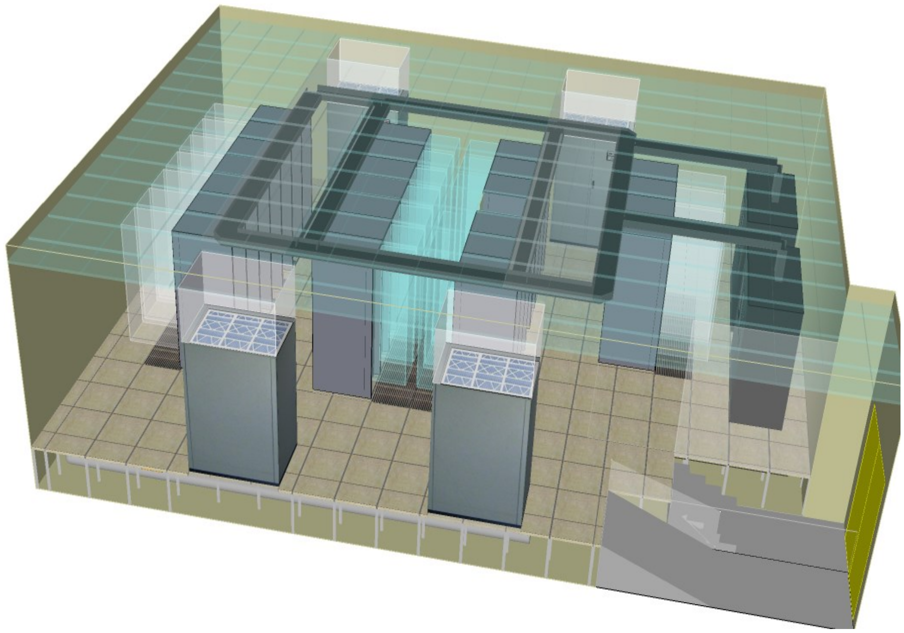

Figure 5-9 Flat-top Snorkels: ISO View

5.2.2 Angle-top Snorkel Design

The angle-top snorkel was modeled as a trapezoidal prism shape with a total volume of 23.59ft^2 (0.67m^2) and a surface area of 61.64 ft^2 (5.73m^2). It is similar to the flat-top snorkel in that it has two open sides, the one side that attaches and perfectly aligns with the open area of the cabinet front door, and the bottom side through which the cold air from the plenum is admitted. As the name implies, it is designed with the top side slanted at 45 degrees.

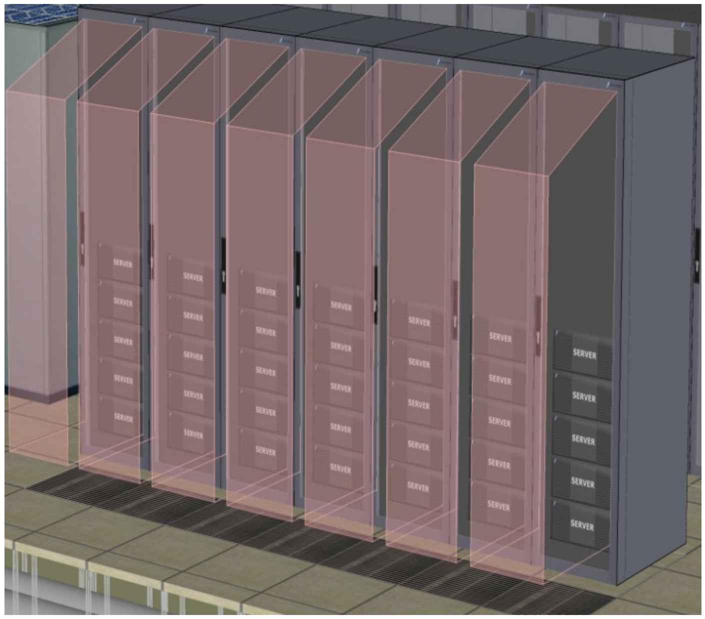

Figure 5-10 Angle-top Snorkels: Close-in View

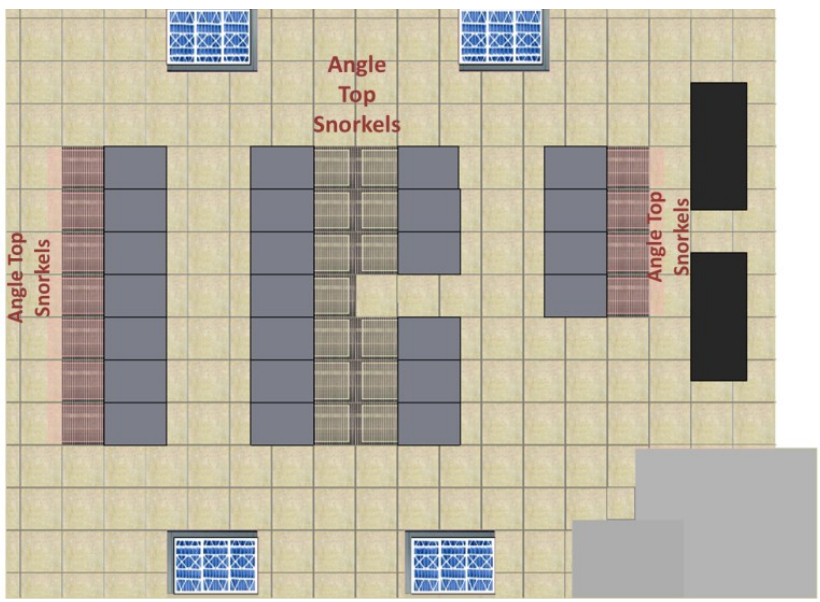

Figure 5-11 Angle-top Snorkels: Plan View

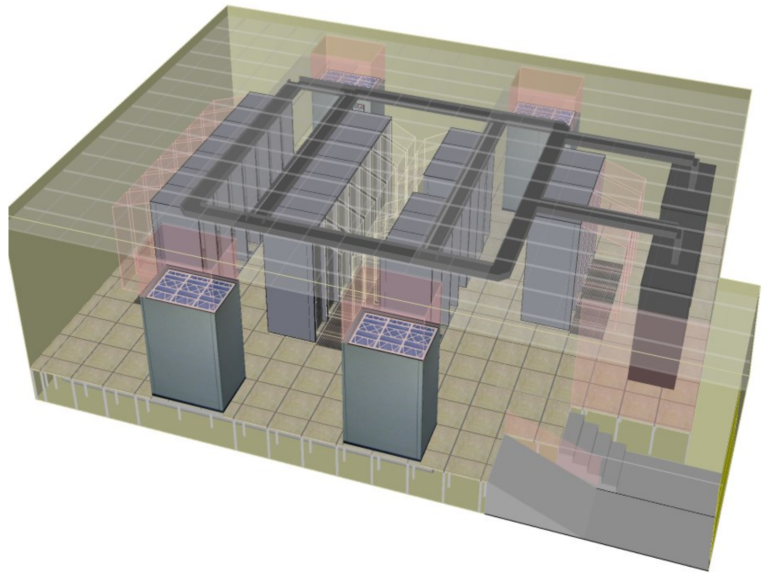

Figure 5-12 Angle-top Snorkels: ISO View

5.2.3 Snorkels with Cold Aisle Containment

As part of the comparative analysis, it was interesting to see the impact of deploying snorkels simultaneously with cold aisle containment. The snorkels were particularly installed on the end rows C and N while the central cold aisle (with rows G and J) was contained. The reason was to observe the impact of snorkels on those cabinets not benefitting from the contained cold aisle and that would invariably be exposed to the effect of large temperature gradients resulting from the containment strategy. This comparison was done as a way to hopefully indicate which of the snorkel designs worked better with the given arrangement. The following figures show the floor layout with this arrangement.

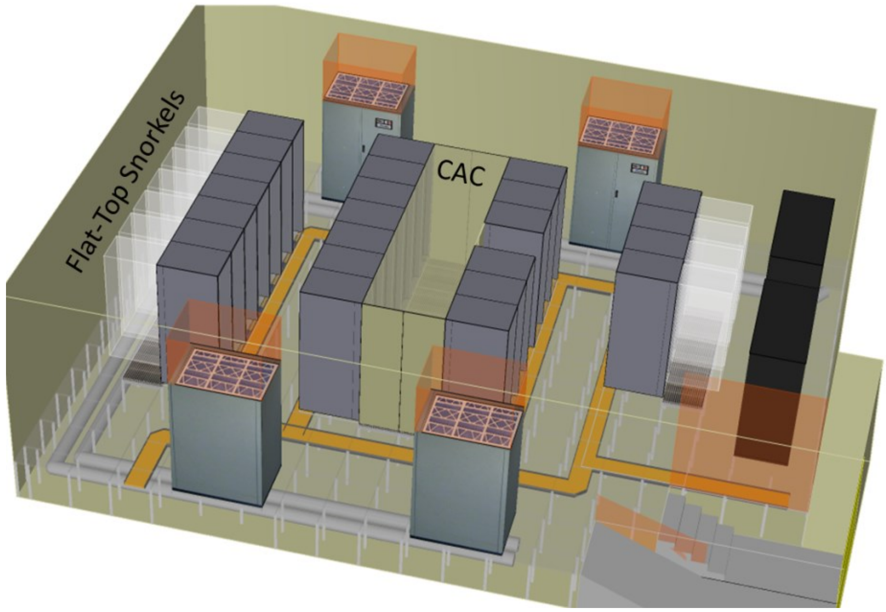

Figure 5-13 Flat-top Snorkels and Cold Aisle Containment

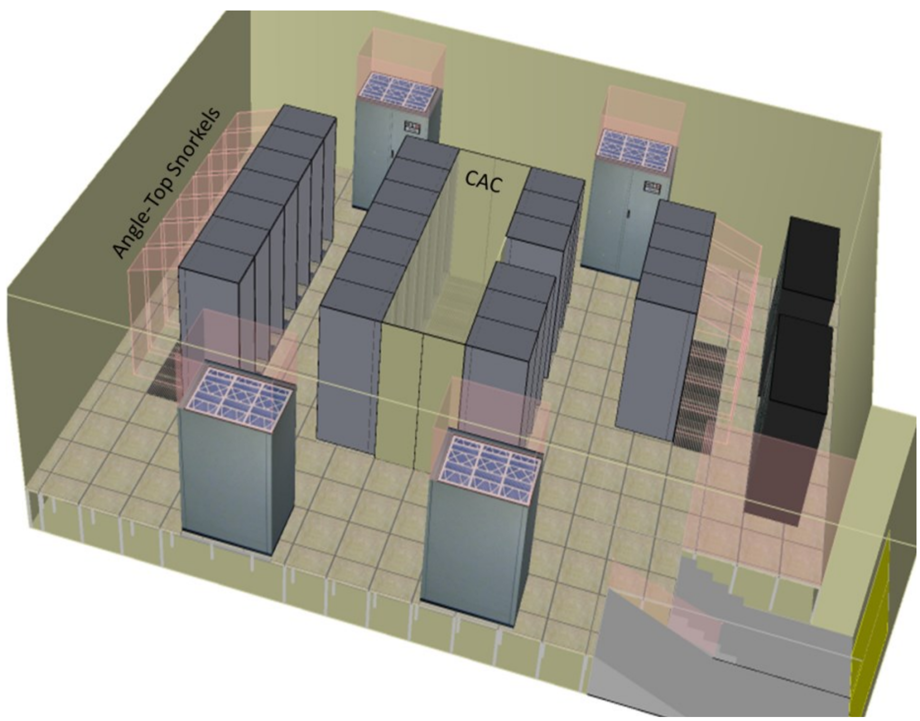

Figure 5-14 Angle-top Snorkels and Cold Aisle Containment

Chapter 6

Results and Discussion

6.1 Mesh Sensitivity Analysis

As mentioned in the previous chapter, the benefits of snorkels have been examined in comparison with other traditional airflow management strategies through CFD simulations. The elements cell count was within 1,000,000 to 10,400,000 (precisely 1.3 million, 2.6 million, 5.4 million and 10.4 million cells) and mesh sensitivity analysis was carried out for each configuration to establish the independence of output variables on the grid size. To determine the appropriate mesh size, output variables were monitored for the different grid sizes. On a PC with Intel ® Core, 3.4 GHz processor with 16.3 GB of RAM, convergence for temperature and continuity was achieved in about 1000 iterations within 1 to 24 hours depending on the cell count. A full simulation of 10.4 million cells took about 24 hours to solve.

6.2 Thermal Profiles

For the purpose of comparison, the temperature plots have been shown to visualize the temperature distribution at 3.3ft (1.0 m) above the raised floor for the various test cases of the model. For the baseline case shown in figure 6-1, the temperature plot represents the thermal profile of the model at that height, when no airflow management solution has been implemented. In the CAC test case, figure 6-2 portrays a significant recirculation of hot air from the hot aisles as a result of containing the cold aisle. In figure 6-3, the HAC test case presents a perfectly uniform temperature distribution due to the containment of the hot aisle. Again, we examine the temperature profiles when the flat-top and angle-top snorkels are deployed on all the cabinets, as seen in figures 6-4 and 6-5 respectively. The snorkels show a relative capacity for hot-spot removal by maintaining fairly low cabinet inlet temperatures, despite the hot air recirculation occurring at the front and around the cabinets. These profiles are a good representation of temperature distribution in the models, for all the cases tested.

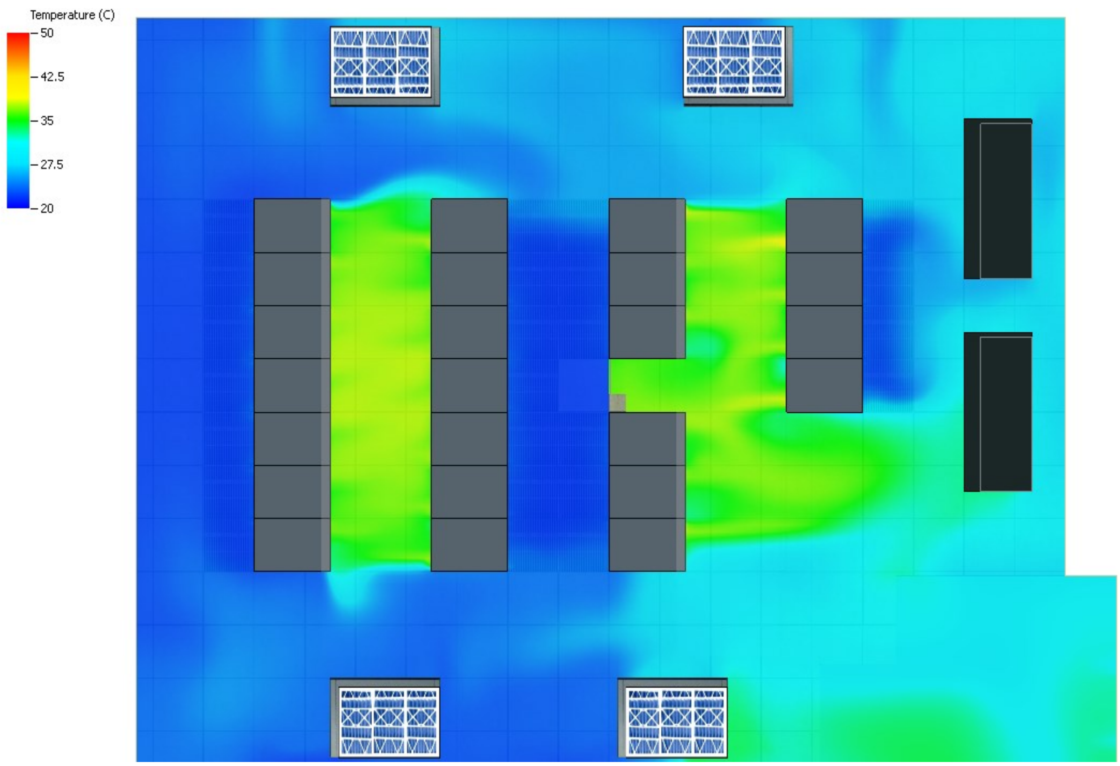

Figure 6-1 Thermal Profile: Baseline Model [Result Plane at 3.3ft (1m)]

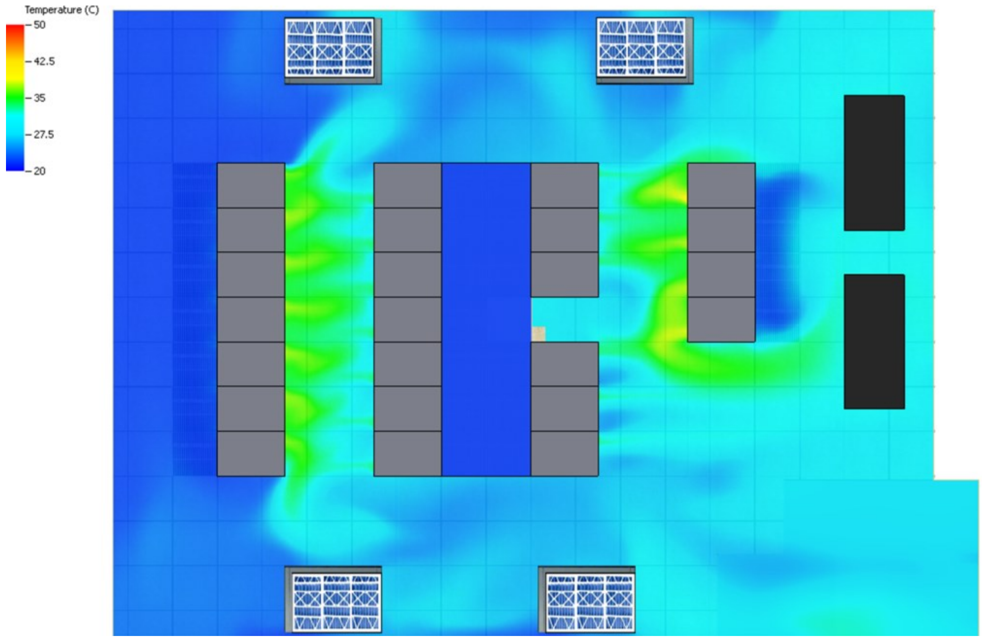

Figure 6-2 Thermal Profile: Cold Aisle Containment Model [Result Plane at 3.3ft (1m)]

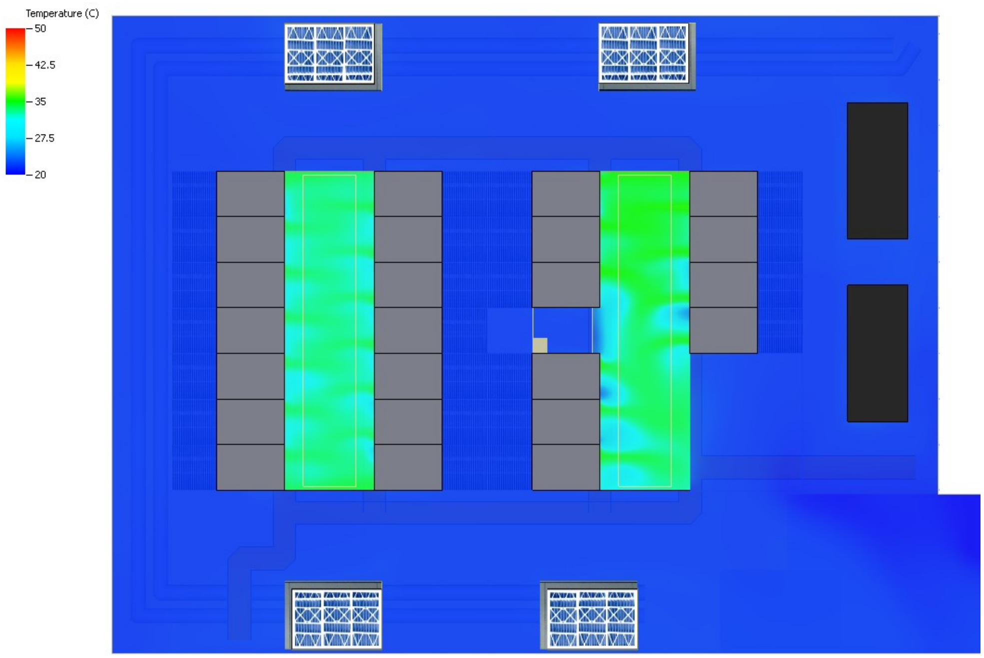

Figure 6-3 Thermal Profile: Hot Aisle Containment Model [Result Plane at 3.3ft (1m)]

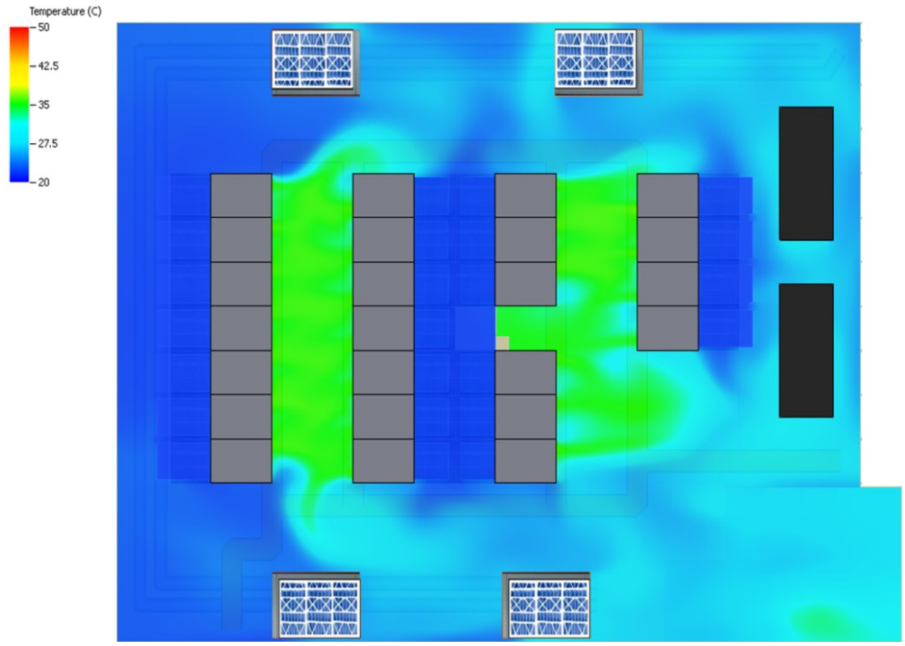

Figure 6-4 Thermal Profile: Flat-top Snorkels Model [Result Plane at 3.3ft (1m)]

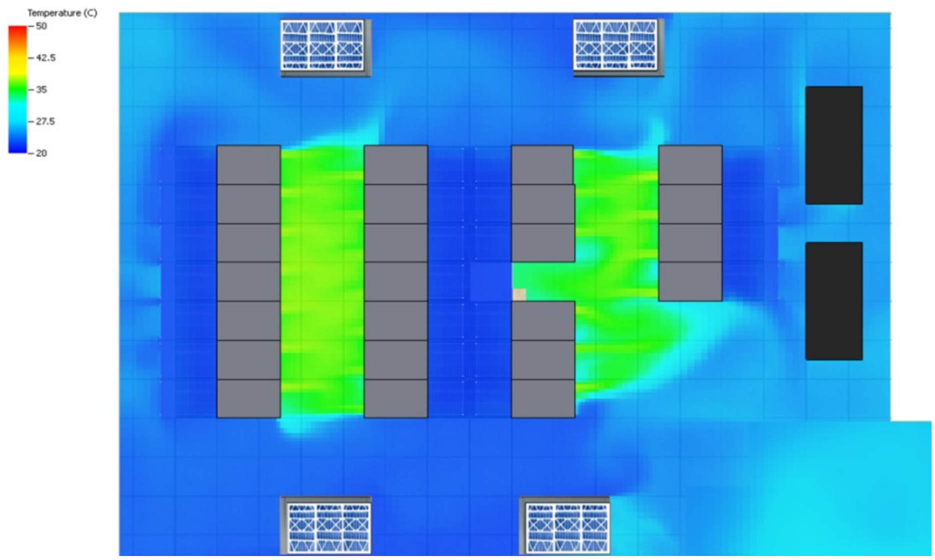

Figure 6-5 Thermal Profile: Angle-top Snorkels Model [Result Plane at 3.3ft (1m)]

6.3 Snorkels on End Rows

This section seeks to examine the performance of snorkels mounted on the exterior cold aisles of the model that cannot be contained with the traditional cold aisle containment technique, (due to the non-symmetric layout) while keeping the central cold aisle (with two cabinet rows facing the other) contained. These cabinets were selected because they were the most-susceptible to ambient temperature gradients – row N for instance, is placed in close proximity to the power distribution units which emitted a considerable amount of heat capable of causing the warmer air to recirculate with the cool air in the cold aisle. Since the configuration only allowed for full containment of the central cold aisle, the snorkels were installed on the end rows. In figures 6-6 and 6-7, the result planes placed at 3.3 feet (1.0 m) from the raised floor show the temperature distribution for the flat-top snorkels and angle-top snorkels used with CAC respectively . For this study, the central cold aisle was contained and snorkels were deployed on the end rows. As can be observed, large temperature gradients exist in front and around the cabinets and the snorkels in row N clearly maintain low inlet temperatures, despite significant recirculation as exhaust hot air is drawn from the hot aisles into the cold aisle. The snorkels in row C, on the other hand, show a slightly distinct temperature pattern in front of the cabinets even though the region is barely affected by recirculation. In both cases, the cabinets on the end rows show reduced mixing of hot and cold air from the top and sides due to the snorkels being in place.

For a closer look at the impact of using snorkels on the end rows, charts in figures 6-8 and 6-9 give a good illustration. The angle-top snorkels in row C, when compared with the rest of the test cases only showed lower temperatures than the baseline and CAC cases for most of the cabinets. They seemed to perform better when used independently than when deployed simultaneously with CAC solutions, as they showed a slightly lower maximum inlet temperature for more than half of the cabinets in that row. Such similar trend is observed in row N.

The flat-head snorkels in row C, whether used independently or simultaneously with CAC, showed relatively low maximum inlet temperatures, next to the HAC case which clearly has the least maximum inlet temperatures. For row N however, the usefulness of the flat-top snorkels becomes peculiar because the maximum inlet temperatures shown for these cases are consistently lower for the snorkel cases than for the other cases, besides the HAC case for the first two cabinets.

Apparently, the flat-top snorkels, unlike the angle-top snorkels performed better when deployed simultaneously with CAC than when used independently, as depicted by the lower inlet temperatures. A useful application of this concept could be in a case where quick, easy and/or even temporary solution needs to be implemented to cater for randomly-fluctuating room temperatures in a data center with CAC solution.

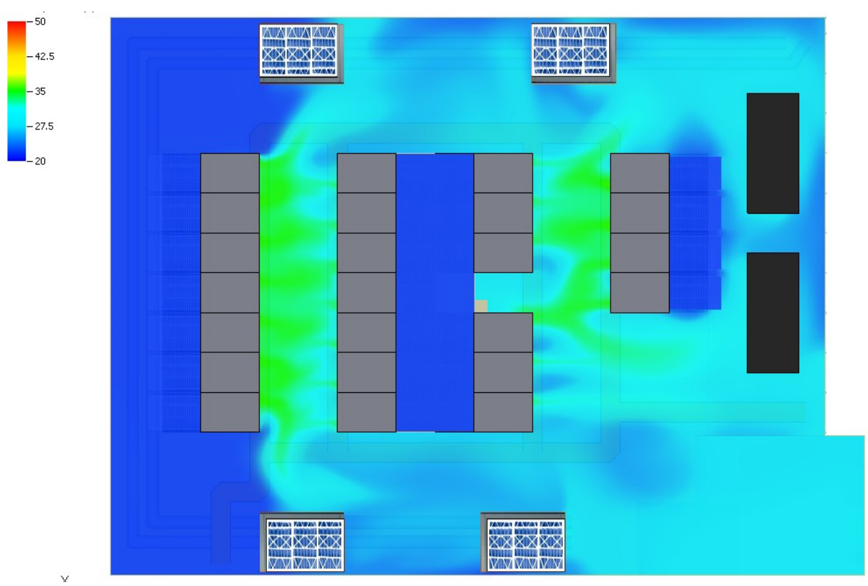

Figure 6-6 Thermal Profile: Flat-top Snorkels (Exterior aisles) and Cold Aisle Containment (Central aisle)

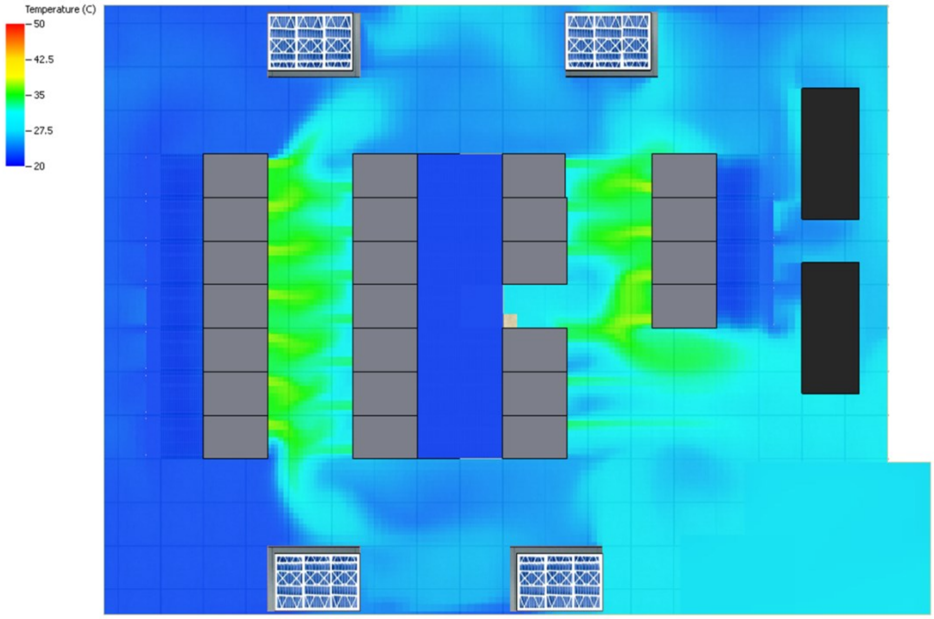

Figure 6-7 Thermal Profile: Angle-top Snorkels (Exterior aisles) and Cold Aisle Containment (Central aisle)

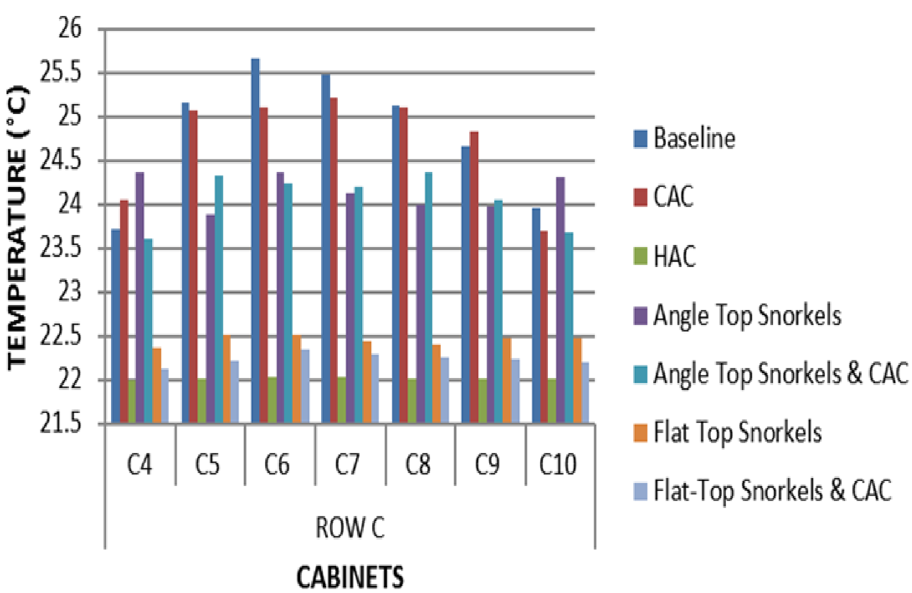

Figure 6-8 Maximum Rack Inlet Temperature Variation on Row C

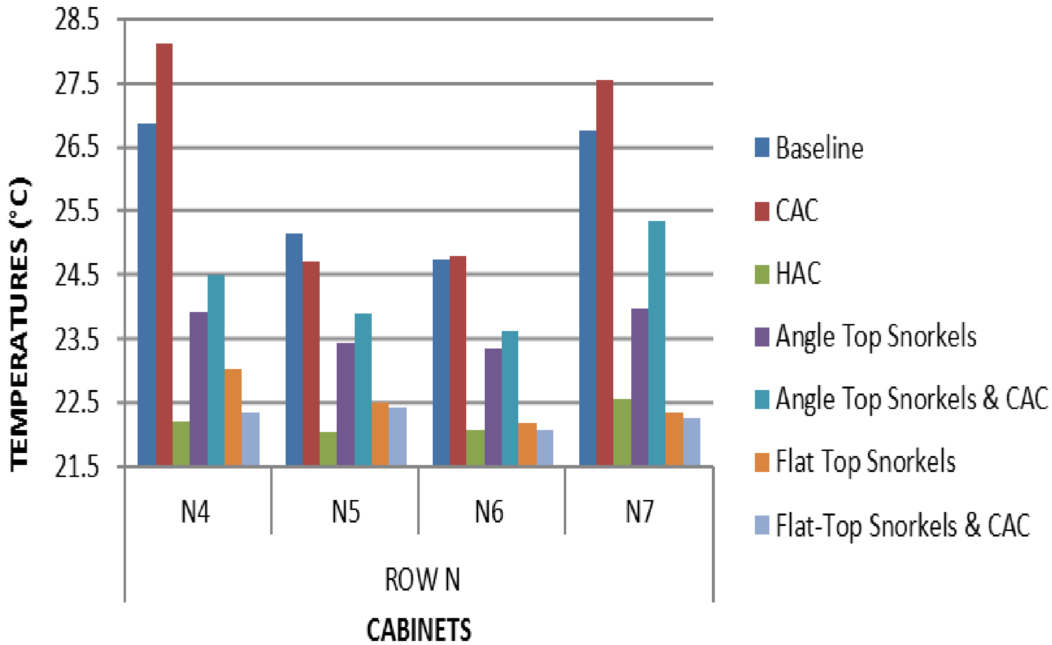

Figure 6-9 Maximum Rack Inlet Temperature Variation on Row N

6.4 Mean and Maximum Cabinet Inlet Temperatures

The charts in figures 6-8 and 6-9 show the mean and max inlet temperatures on the end rows. However, the graphs in figures 6-10 and 6-11 give a good illustration of these temperatures for all the cabinets in all the models.

The non-uniformity of the temperature pattern observed for the baseline case can be attributed by-pass flow and hot air recirculation which obviously created hot-spots at the cabinet inlets. This inconsistent pattern continues for the whole cabinets since there is no control strategy to improve the airflow distribution.

As stated in the previous section, the angle-top snorkels do not perform as well as the flat-top snorkels with CAC, and that case only shows consistently low cabinet inlet temperatures on the central contained cold aisle. The CAC test case is similar to the CAC/angle-top snorkel test case – a look at the cabinets in the central cold aisle G and J show a consistency with low temperatures and uniformity while the cabinets C and G on the end rows show higher temperatures due to some hot air recirculation (see figures 6-10 and 6-11).

In comparison, the HAC case and both cases of the flat-top snorkels (with and without CAC) show an exclusively uniform temperature distribution for all the cabinets, the later with a slight elevation by less than 0.5 ºC for the first cabinets in rows G, J and N. Inlet temperature uniformity is maintained at over 80% with the flat-top snorkels alone and about 96% when deployed simultaneously with CAC.

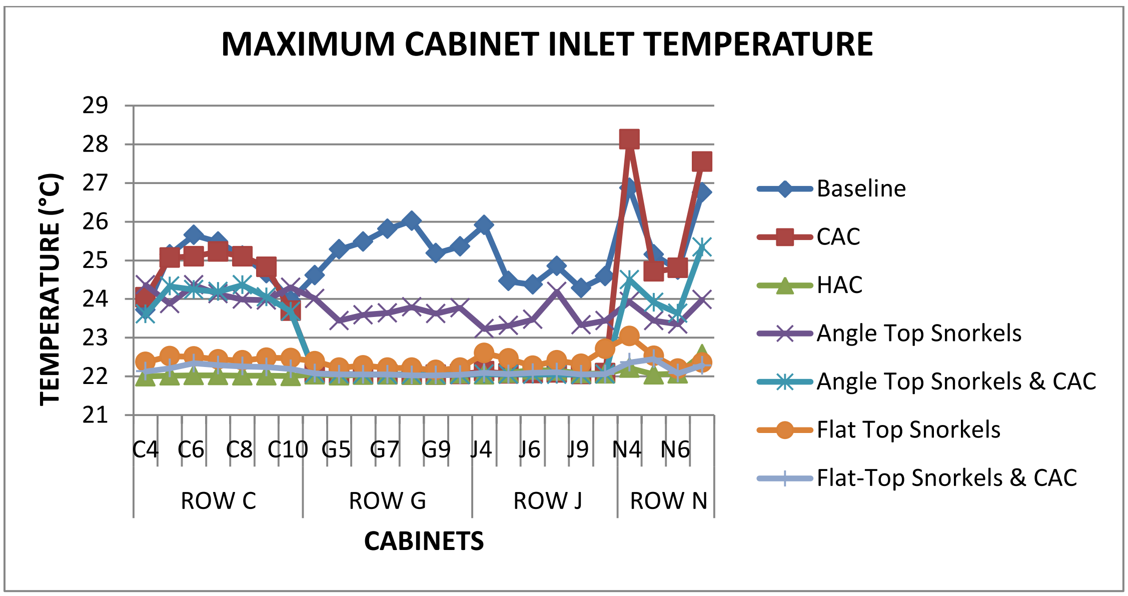

Figure 6-10 Maximum Rack Inlet Temperature Variation: All cabs

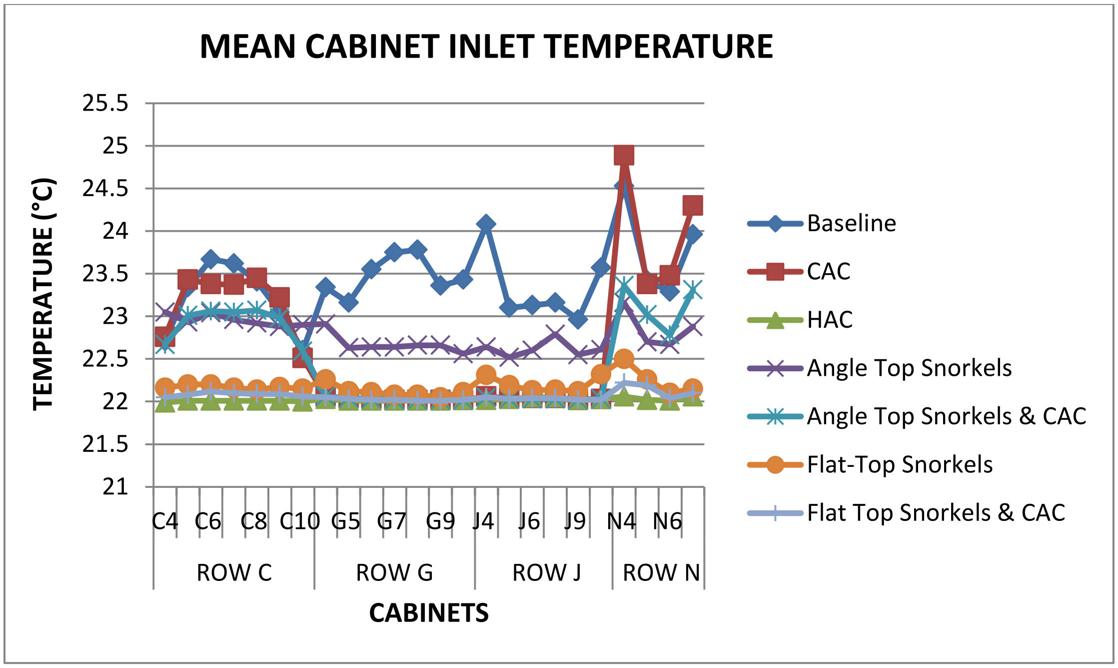

Figure 6-11 Mean Rack Inlet Temperature Variation: All cabs

6.5 Effect of Increasing Rack Density on Inlet Temperatures and Airflow Balancing

Containment is known to make running data centers at high density more affordable by bringing the power consumption to cooling ratio down to a nearly 1 to 1 match in kW consumed [42]. Hence it becomes needful to needful to see the viability of snorkels when IT load is increased. This particular inspection was carried out as a qualitative comparison between both the flat-top snorkels and baseline cases. In row C, rack density was varied from 4kW to 10kW and the rest of the cabinets G, J and N were left at 4kW for all the cases (as shown in figures 6-12 to 6-15). Temperature sensors placed at four set-points of 1ft, 2ft, 5ft and 6ft along the length of the cabinets were used to monitor the data. The Supply Air Temperature (SAT) was kept at 22ºC and the average supply airflow at 480cfm/cabinet for all cases. The flat-top snorkels were used for this analysis and maintain a fairly uniform inlet temperature from 2ft to 6ft as IT load is increased from 4kW to 8kW (Figure 6-12 to 6-14).

A steep temperature gradient however, is seen to occur at 1ft up the length of all cabinets and this is largely because the snorkel was designed to be placed at about 0.85ft (0.26 m) off the raised floor. This leaves the region directly below the first sensor (at 1ft) potentially exposed to ambient hot recirculated air, as can be observed when the data points in the both cases in comparison are matched.

In figure 6-15, the cooling provision of the data center model was overstretched as IT load was increased to 10kW for all the cabinets on row C, and exceeded more than 90% of the total nominal cooling capacity of all 4 CRAC units combined. Lack of sufficient cooling airflow through the floor tiles would limit the available airflow to the cabinets below what is required, thereby setting up an inlet temperature infraction. This results in load piggybacking on the CRAC unit offering the highest cooling provision to the higher load cabinets (in this case, the C-cabinets) by the neighboring CRAC units, further increasing its load. Load swapping also occurs amongst the 4 CRAC units due to this rack density adjustment. With very low rack cooling indices, this would ensure that there was inadequate cooling for the IT equipment and consequently, a sharp hike in the inlet temperatures is observed. For the first 4 cabinets, there is no distinctive impact by the snorkels but the last 3 scenarios for the cabinets C8, C9 and C10 show the snorkels attempt to reduce the inlet temperatures and mitigate the pre-existing hot-spots at such severe temperatures, improving cooling by a little over 13%. Interestingly in varying the IT load in this row, the most cooling improvements by over 90% are seen at the top of the cabinets (6ft).

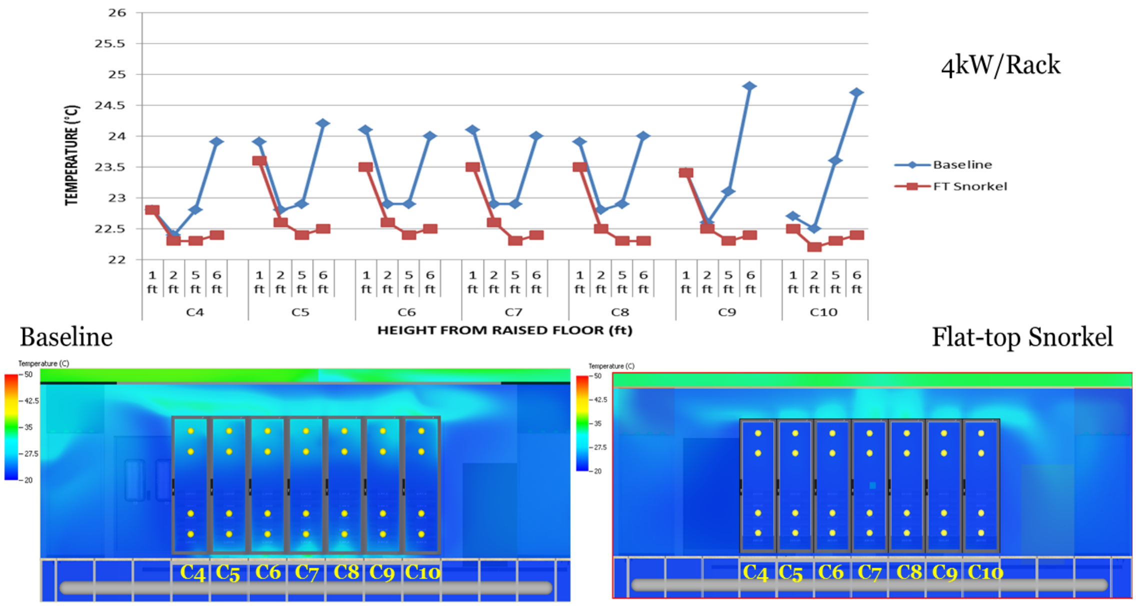

Figure 6-12 Heat Load on C: 4kW

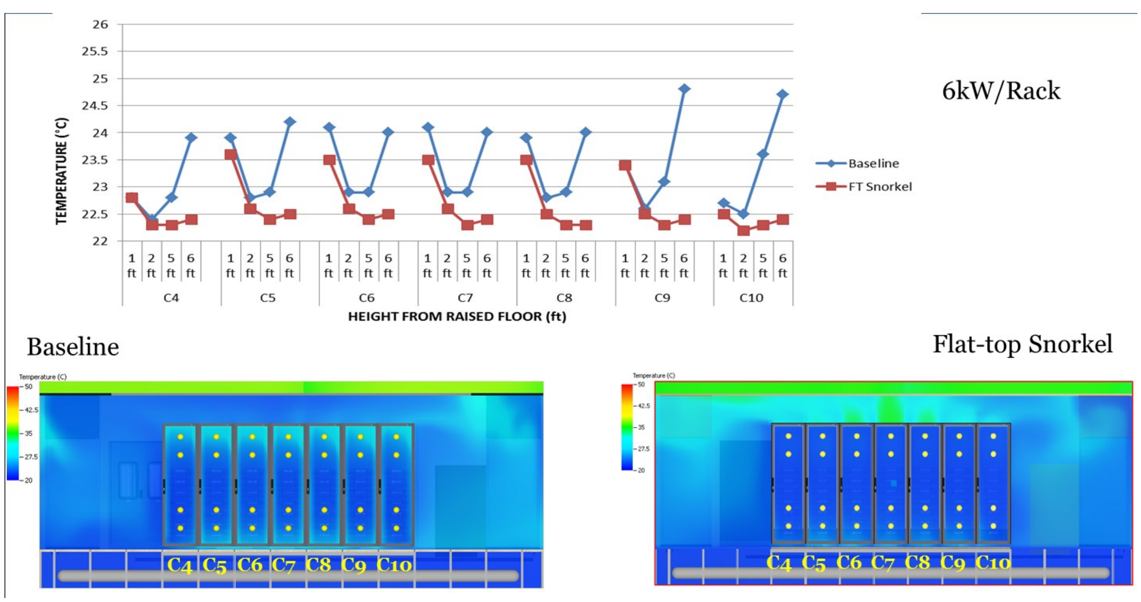

Figure 6-13 Heat Load on C: 6kW

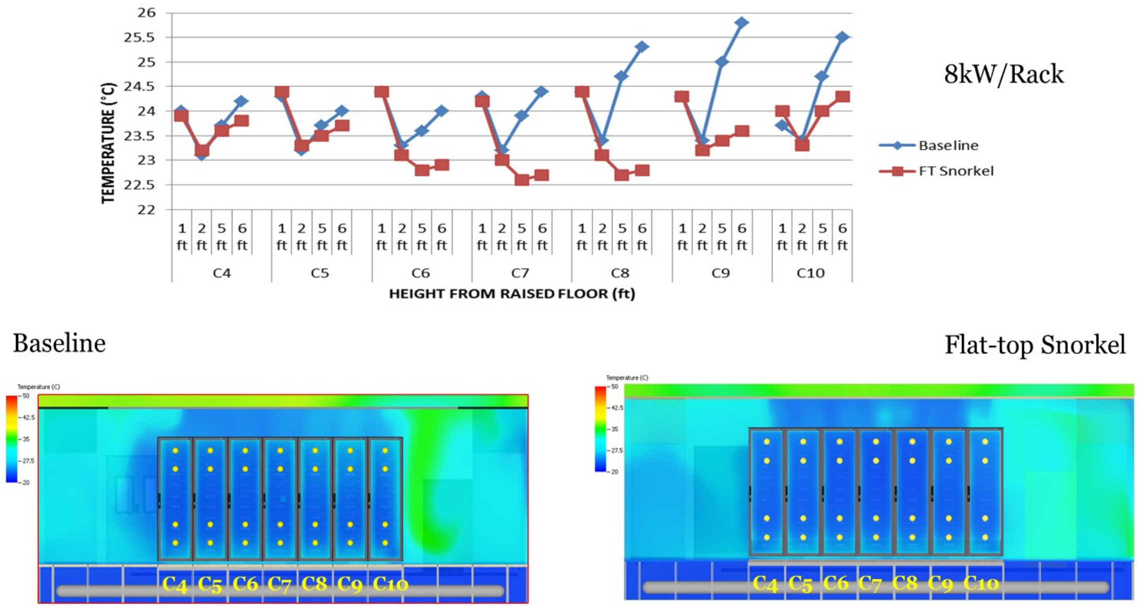

Figure 6-14 Heat Load on C: 8kW

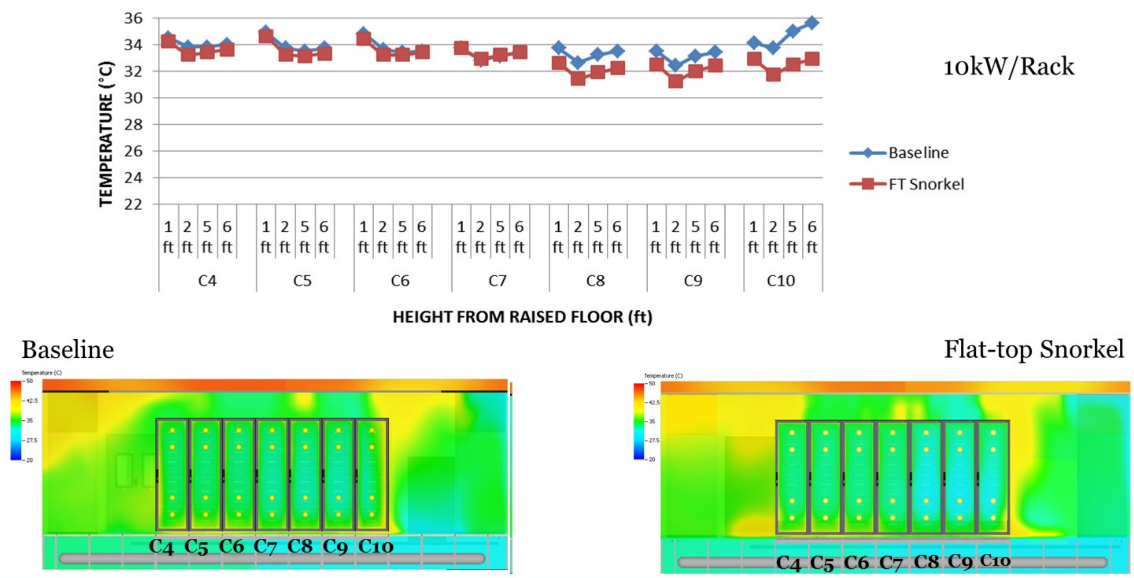

Figure 6-15 Heat Load on C: 10kW

It was also necessary to see the effect of these adjustments on the airflow balancing within the models, reason being that whenever such changes are made to the electronic equipment inventory in the data center, the air distribution system would initiate a lot of changes to prevent the thermal degradation of the equipment environment. Only the extreme cases of 4kW/rack and 10kW/rack were considered for this inspection. Tables 6-1 and 6-2 show the three airflow categories while the graphs in figures 6-16 and 6-17 show the airflow distribution (available airflow) across the C cabinets for the cases considered. (Note: FTS = Flat Top Snorkels)

The airflow categories are defined thus:

- Supplied Airflow: This refers to the amount of airflow supplied through the perforated tiles as a proportion of the total airflow supplied by the CRAC units.
- Required Airflow: This is the amount of airflow that goes into the racks to cool the servers (The minimum airflow required per kW by the racks/cabinets is 120cfm/kW-i.e 4kW/Rack = 480cfm; 6kW/Rack = 720cfm; 8kW/Rack = 960cfm and 10kW/Rack = 1200cfm)
- Available Airflow: This is essentially the difference between the supplied airflow and the required airflow.

For the first case of 4kW/rack, available airflow was more for the flat-top snorkels which is easily attributable to the additional pressure drop it imposes on the system, which in turn forces the CRAC fans to spin faster and produce more airflow. For the second case of 10kW/rack however, because of lack of sufficient supplied airflow, there is seen to be an airflow deficit to all the cabinets but the amount of airflow deficit is less for the flat-top snorkels.

Table 6-1 Airflow Balancing in row C at 4kW/rack

4kW/R	Cabinets	Supplied Airflow (cfm)		Required Airflow (cfm)		Available Airflow (cfm)	
		Baseline	FTS	Baseline	FTS	Baseline	FTS
	C4	663	840	429	488	233	352
	C5	744	900	480	488	264	412
	C6	859	987	480	490	379	497
	C7	954	1037	480	492	474	545
	C8	1062	1015	480	492	581	523
	C9	888	935	480	489	408	445
	C10	741	850	480	362.7	261	487

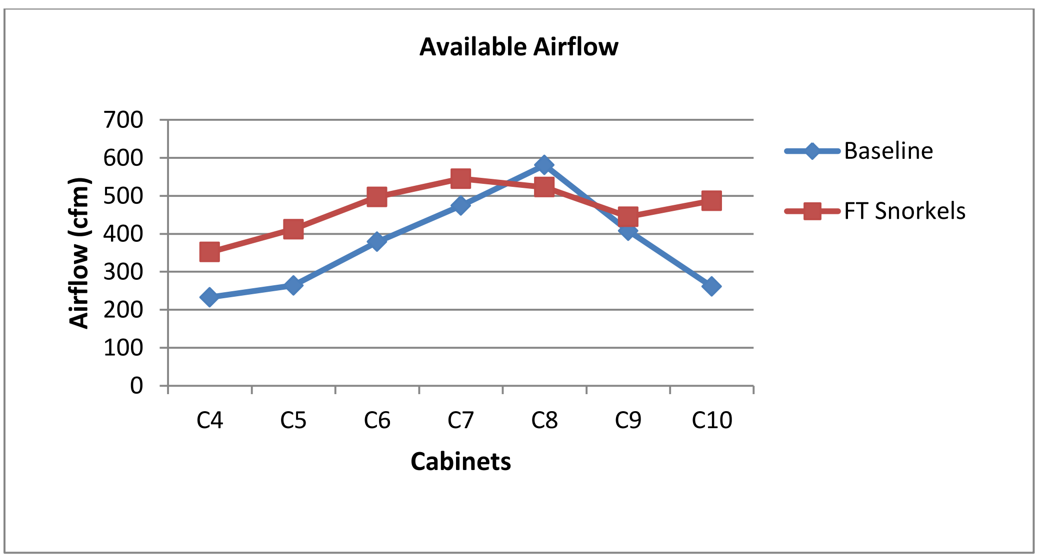

Figure 6-16 Available Airflow in row C at 4kW/rack

Table 6-2 Airflow Balancing in row C at 10kW/rack

10kW/R	Cabinets	Supplied Airflow (cfm)		Required Airflow (cfm)		Available Airflow (cfm)	
		Baseline	FTS	Baseline	FTS	Baseline	FTS
	C4	863	885	1200	1200	-337	-315
	C5	946	952	1200	1200	-254	-248
	C6	1053	1037	1200	1200	-147	-163
	C7	1054	1088	1200	1200	-146	-112
	C8	993	1060	1200	1200	-207	-140
	C9	953	980	1200	1200	-247	-220
	C10	844	889	1200	1200	-356	-311

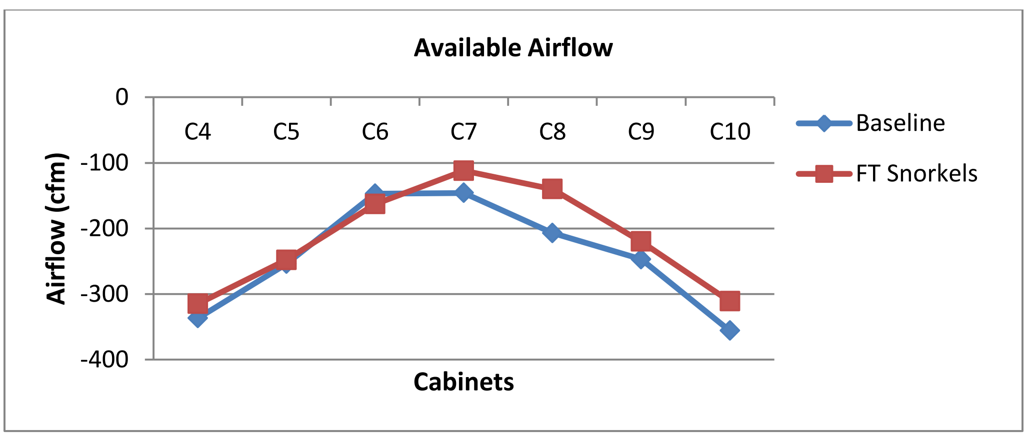

Figure 6-17 Available Airflow in row C at 10kW/rack

6.6 Comparative Metrics:

Some metrics were used to compare the performance of the different test cases with the snorkels in order to sufficiently evaluate the cooling improvements provided to the racks. The performance metrics used were the Rack Cooling Index-RCI (%), the Return Temperature Index- RTI (%) and the Supply Heat Index- SHI (%).

6.6.1 Rack Cooling Index -RCI (%)

The rack cooling index presents a way to measure how effectively the IT equipment racks are cooled and maintained within industrial thermal guidelines, according to Herrlin [39]. This index aids in verifying equipment health at the high and low ends of a temperature envelope as specified by ASHRAE, hence providing a meaningful measure of rack cooling effectiveness.

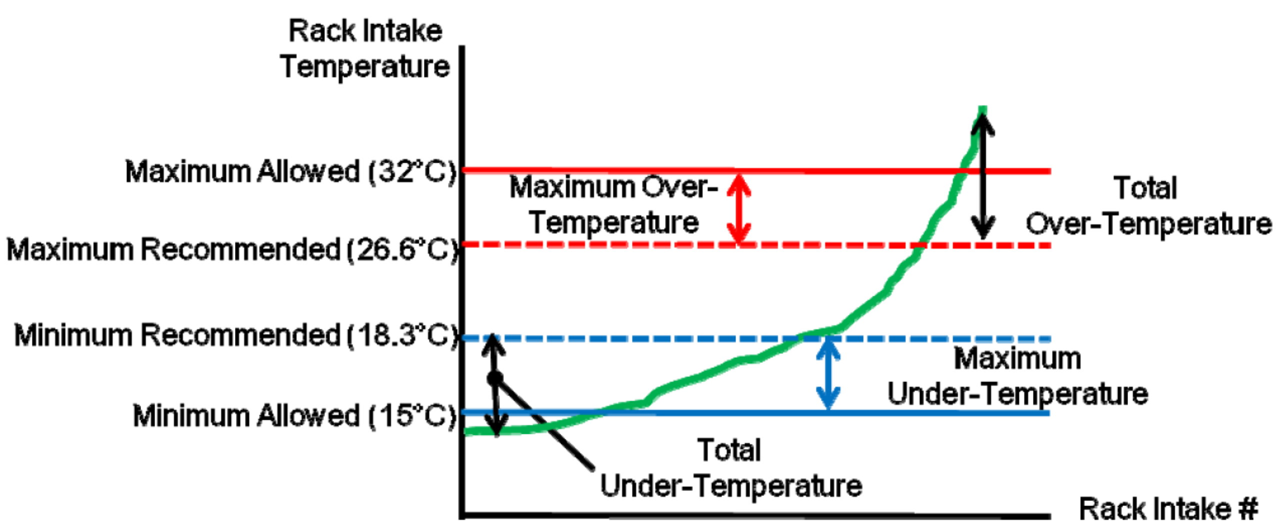

Figure 6-18 Rack Cooling Index (%): ASHRAE-specified Temperature Envelope [39]

Figure 6-18 gives an indication of the ASHRAE recommended rack inlet temperature and allowed temperature ranges. As shown, Maximum Over-Temperature represents the difference between the Maximum Allowed Temperature and the Maximum Recommended Temperature while Maximum Under-Temperature represents the difference between the Minimum Allowed Temperature and the Minimum Recommended Temperature. Again, the Total Under-Temperature represents the difference between the recorded rack inlet temperature and the minimum recommended temperature while the Total Over-Temperature similarly represents the difference between the recorded rack inlet temperature and the maximum recommended temperature, respectively.

Based on the supply air temperature, the rack cooling indices were calculated for all the test cases and a variation is observed as the supply temperature is raised from 22ºC to 26ºC (Table 6-3). The baseline case starts to show a reduction at 24ºC and at 26ºC, it becomes apparent that about 9% of the cabinets in the room went beyond the ASHRAE maximum allowed temperature limit of 32ºC. A near similar trend is observed with the CAC case. With an RCI-High of 100% for all the SATs considered, the HAC and both cases of flat-top snorkels maintained the rack inlet temperatures within the recommended environmental envelope. An RCI-low of 100% was obtained for all the test cases, for the given SAT range, which indicates that there was no over-provisioning since none of the cabinet inlet temperatures went below the minimum allowed temperature of 15 ºC.

Table 6-3 Rack Cooling Index-High (%)

Supply Air Temperature (°C)	Rack Cooling Index- High (%)						
	Baseline	CAC	HAC	Angle-Top Snorkels	Angle-Top Snorkels with CAC	Flat-Top Snorkels	Flat-Top Snorkels with CAC
22	100	100	100	100	100	100	100
23	100	100	100	100	100	100	100
24	99.98	99.96	100	100	100	100	100
25	98.35	98.79	100	100	100	100	100
26	91.01	95.6	100	99.07	98.76	100	100

Table 6-4 Rack Cooling Index Interpretation

Ideal	100%
Good	95% - 100%
Bad	90% - 95%
Poor	<90%

Table 6-5 Rack Cooling Index High (%) (While Increasing Heat Load on the C Cabinets)

Rack Density (C Cabinets)	Rack Cooling Index- High (%)	
	Baseline	Flat-top Snorkels
4kW/Rack	100	100
6kW/Rack	100	100
8kW/Rack	100	100
10kW/Rack	11.3	28.87

For this consideration, RCI values were sought for increasing heat load on C (at constant supply air temperature of 22°C) and even though the snorkels were not perfect at 10kW/rack, they still show a better performance than the baseline case without any solution.

6.6.2 Return Temperature Index - RTI (%)

Return temperature index is a measure of the level of by-pass air or recirculation air in data centers. With an ideal value of 100%, SHI values below that indicate by-pass air and such above that indicate recirculation air. Table 6-6 and 6-7 show these values (as calculated by 6SigmaRoom for both cases when the Supply Air Temperature (SAT) is increased progressively from 22°C to 26°C (for a constant heat load of 4kW/rack in all cabinets, including the C cabinets) and when the heat load is increased from 4kW/rack to 10kW/rack (at a constant SAT of 22°C). All the models indicate evidence of by-pass air for being lower than 100%. The baseline case has the most susceptibility to by-pass airflow while the Flat-top Snorkel/CAC case has the least susceptibility to by-pass air depending on their corresponding values. For the cases where heat load is increased in table 8.0, both models show a reduction in the level of by-pass air as heat load is increased on C4 through C10. Impact is also slightly better for the model with flat-top snorkels than the baseline. It is important however to note that the performance index is not exactly reflective of snorkel performance on the cabinets being examined at higher heat loads, but rather a depiction of how the changing heat loads on those cabinets impact the entire systems.

Table 6-6 Return Temperature Index (%)

Supply Air Temperature (°C)	Return Temperature Index RTI (%)						
	Baseline	CAC	HAC	Angle-Top Snorkels	Angle-Top Snorkels with CAC	Flat-Top Snorkels	Flat-Top Snorkels with CAC
22	52.86	57.90	57.95	53.03	58.26	54.96	59.70
23	53.61	58.91	58.59	53.71	58.63	55.02	59.68
24	53.59	58.90	58.59	53.69	58.52	55	59.62
25	53.57	58.88	58.59	53.67	58.50	54.99	59.61
26	53.55	58.86	58.59	53.67	58.49	54.98	59.59

Table 6-7 Return Temperature Index (%) (While Increasing Heat Load on the C Cabinets)

Rack Density (C4 to C10)	Return Temperature Index- RTI (%)	
	Baseline	Flat-top Snorkels
4kW/Rack	53.21	54.96
6kW/Rack	60.56	61.70
8kW/Rack	67.53	68.63
10kW/Rack	74.54	75.67

6.6.3 Supply Heat Index-SHI

The supply heat index is a dimensionless measure of hot air recirculation into the cold aisles. A tool required to understand the convective heat transfer in the equipment room and improve energy efficiency. It spans from 0 to 1 and has a typical value of 0.4. Fundamentally, the lower the value of SHI, the better the conditions of a data center facility. As in the previous metrics, tables 6-8 and 6-9 show these values (as calculated by 6SigmaRoom for both cases when the Supply Air Temperature (SAT) is increased progressively from 22°C to 26°C (for a constant heat load of 4kW/rack in all cabinets, including the C cabinets) and when the heat load is increased from 4kW/rack to 10kW/rack (at a constant SAT of 22°C).

For all cases except HAC and Angle-top Snorkels, there is lower likelihood of recirculation into the cold aisle as the SAT is increased. The baseline case has the most susceptibility to HA recirculation while the HAC and Flat-top Snorkel/ CAC cases have the least susceptibility to recirculation air. When heat load is increased in the C cabinets as shown in table 10.0, SHI is lower than the typical value of 0.4 in both cases but flat-top snorkels show an improvement of over 10% for every increase in heat load with lower SHI values. There is however, higher possible recirculation with increasing rack density, especially at 10kW/rack but the rate of increase is less for flat-top snorkels.

Table 6-8 Supply Heat Index

Supply Air Temperature (°C)	Supply Heat Index SHI						
	Baseline	CAC	HAC	Angle-Top Snorkels	Angle-Top Snorkels with CAC	Flat-Top Snorkels	Flat-Top Snorkels with CAC
22	0.0875	0.0449	0.0015	0.0497	0.0311	0.012	0.0045
23	0.0856	0.0438	0.0027	0.0498	0.0309	0.017	0.0045
24	0.0857	0.0438	0.0027	0.0497	0.0312	0.017	0.0043
25	0.0856	0.0438	0.0027	0.0497	0.0312	0.017	0.0043
26	0.0856	0.0439	0.0027	0.0496	0.0312	0.017	0.0043

Table 6-9 Supply Heat Index (While Increasing Heat Load on the C Cabinets)

Rack Density (C4 to C10)	Supply Heat Index-SHI	
	Baseline	Flat-top Snorkels
4kW/Rack	0.071	0.012
6kW/Rack	0.101	0.027
8kW/Rack	0.125	0.062
10kW/Rack	0.200	0.156

Chapter 7

Conclusion and Future Work

7.1 Opportunities for Implementation

The results obtained from this work clearly indicate the improved performance that data centers can achieve with the air flow management techniques discussed – with aisle containment, a generally accepted best practice. However, not all data center layouts and structures are suitable for these types of systems. For example, many colocation data center facilities serve many different customers in separate secure cages (figure 7-1). A standard hot/cold aisle strategy may not always be possible due to only a few racks being in each cage or an odd number of rows filling the space. Additionally, many facilities are constantly in flux with changing rack and equipment needs, creating challenges for implementing more permanent aisle containment solutions.

Snorkels or rack-level containment may present an opportunity for better management of cooling resources for individual colocation customers or the data center operator as a whole. With the ability to direct airflow and reduce bypass and recirculation, very huge flexibility and granular control can be achieved in data centers.

Figure 7-1 Example of a Colocation Data Center with a Non-symmetric Layout [54]

7.2 Summary and Recommendation

Several airflow management strategies have been shown to offer significant opportunities for maximizing data center cooling and ensuring cooling energy savings. Containment systems generally provide an isolation of cold air and hot air and can be used to achieve maximum cooling airflow as well as supply and return temperatures. For typical data centers where full aisle containment may not be ideal (ex. colocation data centers), rack containment with snorkels can be deployed permanently or temporarily used to remove hot-spots before a more permanent solution is implemented.

Hence, snorkels may prove to be not only a good alternative to aisle containment but can also be used simultaneously with cold aisle containment (which often results in high ambient room temperatures) to effectively reduce cabinet inlet temperatures and remove existing hot-spots in data centers. This effort is just a preliminary step and is mostly computational, with the objective to corroborate the initial experiment by Rajarshi et al [28].

However, as a future work, it will be interesting to investigate the contribution of snorkels to the system resistance of these models. A proper estimate of the additional pressure drop imposed by this strategy on the data center models, just like by any other containment systems will be necessary. This is so because in reality, with increased pressure drop, CRAC fans will be driven to run at higher speeds, increasing the overall cooling infrastructure power requirement.

Also, even though the snorkels were successfully designed with minimal leakage, the steep temperature gradient observed at the cabinet inlet, between 1ft from the raised floor and 2ft (figures 6-12 to 6-15) may raise questions as to what might be the cause. Well, as already suggested, the snorkels only extend 0.15ft (in other words, the snorkels are 0.85ft from the raised floor) below the 1ft data point where the temperature sensors were installed (figure 7-2).

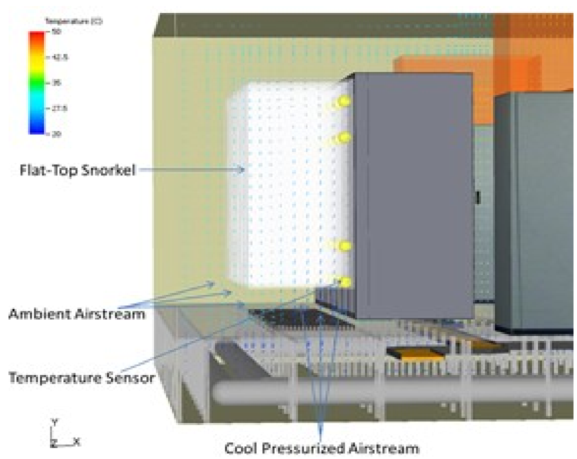

Figure 7-2 Airflow Pattern showing flow path from the plenum upwards

Possible mixing of ambient recirculated air with the cool air proceeding through the perforated tiles is capable of raising the temperature at that point a notch, while the high pressure air stream pushing through ensures that beyond that point, subfloor temperatures are maintained with aid from the insulation provided by snorkels. Hence snorkels can be better designed to extend further down and closer to the perforated tiles in order to prevent such mixing issues.

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Biographical Information

Chris Onyiorah received his Bachelor of Engineering degree in mechanical engineering from Nnamdi Azikiwe University, Nigeria in 2010. After serving for a year as a national youth service corps member with the Nigerian Air Force (NAF), where he was involved in the maintenance of F7 and FT7 fighter jet airframe and power plants, Chris began his graduate studies at The University of Texas at Arlington in August, 2012 and joined the EMNSPC team in December, 2012. From summer 2013 through fall 2013, Chris interned at BTT Technologies where he worked with CNC and manual machines and as a mechanical designer/draftsman on detailed analysis, CAD drafting and designing of machine components and systems to be fabricated by precision machining (mostly of a catcher system for oil horizontal directional drilling). While with the EMNSPC team, he participated in projects on server rack-level fan configuration for efficient rack-dedicated cooling, as well as research on the effectiveness of server rack containment with snorkels for hot-spot mitigation at the data center room level. As part of his future plans, Chris intends to explore opportunities that will foster growth in industry exposure, as well as develop his experience and core interests in areas related to thermal analysis and system design with applications to cooling optimization in data centers, oil, gas and energy industries.