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A Comparative Study of Various High Density Data Center Cooling Technologies

A Thesis Presented

by

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The Graduate School

in Partial Fulfillment of the

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Abstract of the Thesis

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As the power density continues to increase in Data Centers, the need for effective and efficient cooling methods becomes more necessary. Various industry leaders have developed technologies as a solution to the problem of cooling. These proposed solutions aim to improve air-flow management within a data center. By identifying the technologies that allow for better cooling performance, data centers will have an opportunity to reduce cooling costs. This comparative study uses a CFD tool to identify which existing technology provides the best opportunity to reduce the cost of cooling at densities ranging from 2kW per cabinet to 16kW per cabinet (67kW/sq. ft of the data center to 499kW/sq. ft. of the data center). The cooling technologies studied in this work include Hot Aisle / Cold Aisle, Kool-IT, In Row Cooling with Hot Aisle Containment, Cold Aisle Containment, Overhead Cooling, and Cabinets Ducted to Hot Air Plenum. The ASHRAE recommendation (TC9.9) for server inlet temperature is taken into

consideration as a requirement of what is considered adequately cooled equipment. In this study, only data centers are air cooled were considered, while the air is cooled using a heat exchanger that is fed chilled water from a vapor compression refrigeration cycle. Opportunities for cutting cooling costs lies in two key areas: one is to increase the temperature of the chilled water, and the other is to reduce the fan power used to circulate air in the room. It is found that Hot Aisle / Cold Aisle, which has been the industry standard for 15 years, is no longer a viable solution as power densities increase. We found that while many cooling technologies are an improvement over Hot Aisle / Cold Aisle, the Kool-IT technology and Cold Aisle Containment yield the most significant improvements in effectiveness and efficiency.

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List of Symbols

\dot{q} - Rate of heat exchanged

\dot{V} - Volumetric Flow Rate

c_p - Heat Capacity

ρ - Density

ΔT - Change in temperature

COP - Coefficient of Performance

T_H - Temperature of Hot Reservoir

T_L - Temperature of Cold Reservoir

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Chapter 1: Introduction

1.1 Data Center Cooling: Challenges and Motivation

The challenges to providing electrical power have become a prominent issue. Fossil fuel resources have become less available and more costly, distribution systems have been reaching their maximum capability to provide peak loads, and the reduction of the emission greenhouse gases has become a necessity. Meanwhile, the demand for information technology (IT) equipment has continued to rise due to a number of factors. These include healthcare moving to electronic medical records, manufacturing becoming globalized, banking moving away from paper, financial services moving to digital transactions, insurance database growing, retail moving to real-time inventory, and transportation moving toward global positioning system navigation (US EPA 2007).

The Environmental Protection Agency (EPA) forecasts that data center annual electrical use will increase from 61.4 billion kWh / year in 2006, accounting for 1.5 percent of current national electricity use, to 107 billion kWh / year in 2011 at the current efficiency trend. In addition to the need to reduce the amount of power consumed, the need to reduce peak load also alleviates the problems in meeting peak load requirement of power plants and the problems associated with distribution of electrical power in more densely populated areas. In these areas, local utilities have difficulties meeting the peak demand for load during certain hours of day and certain days of the year.

The U.S. data center industry is in the midst of a major growth period driven by several industries having a need for large-scale data processing and storage. The practice of sizing air conditioning systems based on load density is outdated, and the data center

needs to be looked at from the perspective of a thermal environment that needs to be managed at all levels: from the wider scope of cooling a room to the more narrow scope of cooling individual components (Patel 2003).

As stated in the EPA report, as the US economy shifts from paper to digital, data centers, which are primarily used to contain electronic equipment used for data processing, data storage, and communications networks, have become more essential to everyday operations in several industries. Data centers are used in various aspects of the economy including financial services, media, universities, and government institutions. Continued growth is expected as more industries provide electronic services such as online banking, internet communication, electronic records, global commerce, etc.

1.2 Background

As opposed to other types of heating, ventilation, and air conditioning (HVAC) systems, data centers are designed for computers, as opposed to people. The heat that needs to be removed is generated by the continuous operation of IT equipment, which must be removed for proper operation of the data center (EPA 2007).

Hot Aisle / Cold Aisle (HACA) technology for data center cooling was first introduced in 1992 by Robert Sullivan at IBM and had emerged when cabinets supported loads of 250 W/ft². Since then, the power density of data center equipment has increased, and is outpacing the improvements in HVAC technology (Bash 2003). Temperature for server inlets should be an acceptable range for reliable operation of data center equipment (Schmidt 2005).

The advent of new alternative cooling technologies aims to provide enhancements to HACA based data centers. Some of these alternatives include In Row Cooling with Hot Aisle Containment (Rasmussen 2008), Cold Aisle Containment (Emerson Electric Co. 2008), Overhead Cooling (Emerson Electric Co. 2005), and Kool-IT (Fulton 2007). Although there is a need to evaluate the comparative effectiveness of these technologies for use in data center designs with an aim to reduce the cooling cost, a study consisting of a side-by-side comparison of the different data center cooling technologies is not yet available. What makes doing this study difficult is that there is no commonly acceptable standard in comparing different cooling technologies. Furthermore, the different cooling approaches require differing infrastructure requirements and air conditioning units. In addition, the definition of what makes a data center sufficiently cooled varies from server manufacturer specifications to the guidelines recommended by ASHRAE (TC9.9, 2004).

1.3 Problem Description

In this work, a comparison of various data center technologies was conducted. The bases of comparison for these technologies are effectiveness, efficiency, control, and the robustness. These bases are all evaluated at varying power densities. Some of these technologies are Kool-IT from Afco Systems, In Row Cooling with Hot Aisle Containment from APC, Cold Aisle Containment by Knuur, and Overhead Cooling by Liebert.

1.4 Outline

This thesis consists of five chapters. Chapters 1 and 2 describe the need to improve data center cooling, the fundamentals behind data center cooling, and the

emerging technologies that aim to improve cooling performance in data centers. Chapter 3 describes the methodology and tools employed in this study. Chapter 4 reports the results of the study and discusses the results. And finally, Chapter 5 concludes the report.

Chapter 2: General Concepts, Existing Technology, and Emerging Technologies

2.1 Fundamentals

The two main functions of a data center cooling system are to remove heat from the data center and effectively distribute the cool air to data center equipment. Arising from these two functions are two factors that affect the cost of cooling. Factors contributing to the cost of cooling are the cost of heat removal based on the vapor-compression refrigeration cycle (mostly due to compressor power) and the cost of generating air-flow (fan power). Equation 1 describes the relationship of heat exchanged into or out of air passing over a heating or cooling source (computer equipment, chilled water, etc.)

$$\dot{q} = \dot{V} C_p \rho \Delta T \quad (1)$$

The volumetric flow rate, \dot{V} , inside of an air conditioning unit and inside the servers are provided by fans. C_p is the specific heat of air at a constant pressure and ρ , is the density of air, and ΔT is the change in temperature of the air. The heat exchanged, \dot{q} , is the heat removed from the data center equipment by the air at the cabinets. It is also equal to the heat removed from the air by the chilled water at the air conditioning units. In the data centers being modeled in this paper, the heat generated in the data center is equal to the power consumed by the data center equipment (lights, power strips, leaked air, etc. are not considered). Since \dot{q} is determined by the heat generated by the

equipment in the data center and the working fluid in data centers is air, the system that requires less air-flow requires less fan power.

Vapor compression cycle efficiency is the other factor in data center cooling performance. Common practice in data center cooling is to produce chilled water at a location remote from the data center room and deliver the chilled water to heat exchangers in the room. The performance of the refrigeration of the chilled water is dependent on the temperature at which the water is cooled to as well as the ambient environment. Equation (2) predicts the performance of an ideal vapor-compression refrigeration cycle operating between a hot reservoir and a cold reservoir (Cengel and Boles 1998):

$$COP = \frac{1}{\frac{T_H}{T_L} - 1} \quad (2)$$

T_H is considered the temperature of the heat reservoir the water dumps heat to (ambient environment) and T_L is considered the temperature of the chilled water. It can be seen that in an ideal vapor-compression refrigeration cycle, by raising the temperature of the chilled water by 5°F from 50°F to 55°F, the COP of a vapor-compression refrigeration cycle is increased by 30 percent (Note that this equation uses temperatures on an absolute temperature scale, Rankines or Kelvin.), assuming room temperature of 70°F. This is important in that it shows that the absolute ideal efficiency is dependent on the operating temperatures. In a study done by Lawrence Berkeley Labs (Data Center Knowledge 2007), it was determined that raising the chilled water temperature from 42°F to 55°F in a real data center, improves the COP of chilled water production by 15 to 25 percent.

The definition of a sufficiently cooled data center in this study is based on ASHRAE's Thermal Guideline for Data Center Environments (TC9.9). ASHRAE guidelines recommend that server inlet temperatures be between 68°F to 77°F. For the purposes of this study, equipment that surpasses the upper bound of 77°F is considered to be overheated. A sufficiently cooled data center is one in which no cabinet contains any servers that are overheated. In addition, servers which are below the lower bound of 68°F are considered to be overcooled, however, that is typically not the concern of data center equipment.

2.2 Existing Technology

There are two types of air conditioning systems deployed in a data center. One of the ways is to install Computer Room Air Conditioners (CRACs), which are based on a self-contained vapor-compression refrigeration cycle and remove heat from the room and direct it away from the data center. The other system is combining Computer Room Air Handling Units (CRAHs) and a chiller. The chiller uses a vapor-compression refrigeration cycle to chill water, which is sent to the CRAHs to exchange heat with air from the data center. In either case, the cooling devices are used to cool the air in the data center, rather than directly cool the IT equipment (APC Fundamentals of Cooling 2). For this reason, there are various technologies which aim to connect the cooling units to the IT equipment.

2.3 Hot Aisle / Cold Aisle

Like commonplace office computers, data center equipment (servers, storage, etc) have an air inlet and an air outlet. Like computers found in offices and homes, the

equipment is oriented such that the front serves as an inlet, where cool or ambient room air enters, and the back serves as the outlet, where air heated by the equipment is expelled.

HACA was developed as a means of more effective delivery of cold air to IT equipment inlets and a more effective delivery of hot air back to the air conditioning units. In the HACA approach, equipment is loaded into data center cabinets such that all the air intakes, or inlets, face the same way (the front of the cabinet), and the air exhausts, or outlets, consequently, are facing the back of the cabinet. Furthermore, the cabinets are oriented in rows such that the fronts of the cabinets are in line with each other, and the back (or the outlets) are in line with each other. Additional rows are added such that the backs of cabinets in adjacent rows face each other, creating a Hot Aisle, and the front of the cabinets in adjacent rows face each other. Cold air is forced into the aisles in which the cabinet fronts face each other, creating a cold aisle.

This cold air is delivered through perforated tiles that allow air to percolate from a raised floor cold air plenum into the cold aisle. A raised floor is used to allow for a reservoir of cold air that can be drawn from anywhere in the room. Computer room air handlers (CRAHs) are located at the end of the aisles. These units intake air from the room through the top, cool the air by exchanging heat with chilled water, and force cold air into the raised floor.

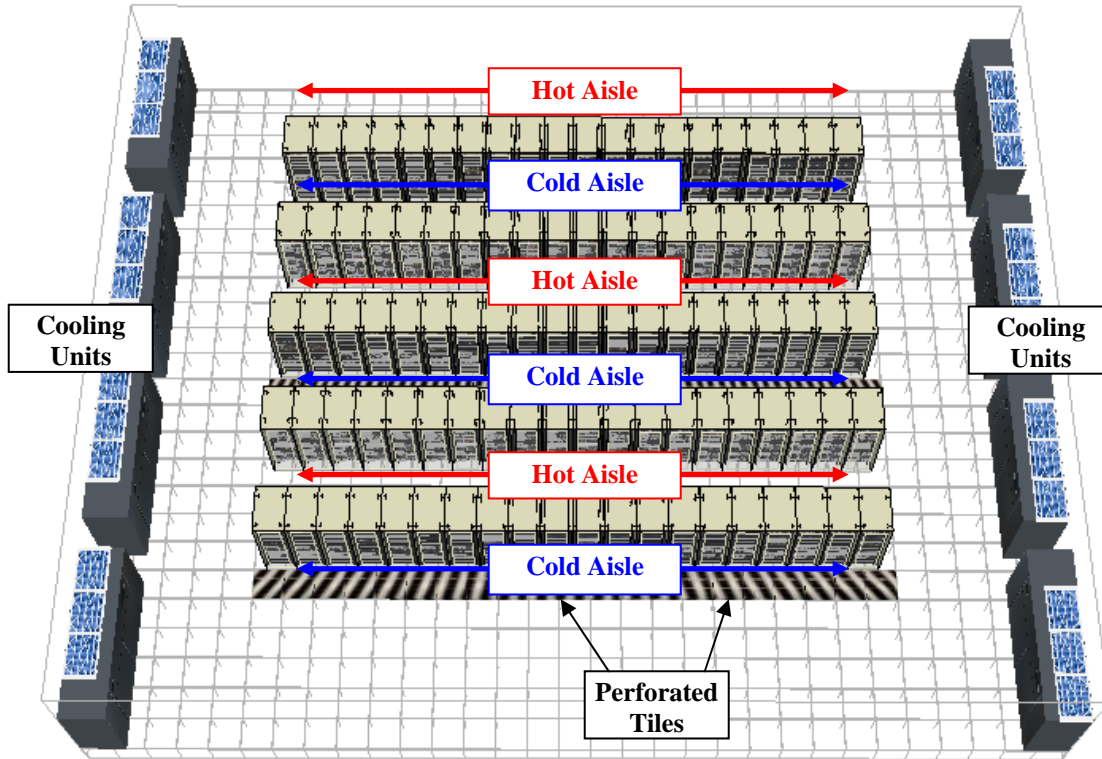


Figure 1: Typical HACA Configuration

2.3 Emerging Data Center Cooling Technologies

A number of technologies have arisen as a means to provide adequate air-flow management within a data center. Each technology is a modification or an enhancement to HACA. These technologies aim to provide better ways to distribute air to IT loads. The EPA has identified several strategies in reducing the electrical cost of heat removal, the most important being improvement of airflow management.

2.3.1 Kool-IT from Afco Systems

Kool-IT technology aims to connect the air conditioning units to the IT equipment and manages the air within the data center more effectively. One of the problems in HACA is the underutilization of air percolating from the raised floor (Fulton

2007). Kool-IT technology makes use of air that is not utilized by the server inlets by mixing the unused cold air with air existing the servers, and allows that air to be recirculated to the data center at a cool temperature. The perforated tiles are eliminated in Kool-IT, and instead, the air is delivered directly into the cabinets from the raised floor through baffles on the bottoms of the cabinets. The top of the cabinets contain fans that provide two functions. They force the cold air that is not utilized to be mixed with room air which is recirculated to the room making it available to the servers. The fans also force hot air away from the cabinets and into the hot aisle, preventing unwanted recirculation. The fans at the top of the cabinets are also of variable speed and controlled by the exhaust air temperature. The analysis performed in this study, however, does not incorporate this feature because the software does not yet have this capability. A ceiling plenum is used in conjunction with Kool-IT when power densities are 12kW per cabinet and above. The ceiling plenum is used as a hot air plenum to collect hot air to aid in the removal of heat.

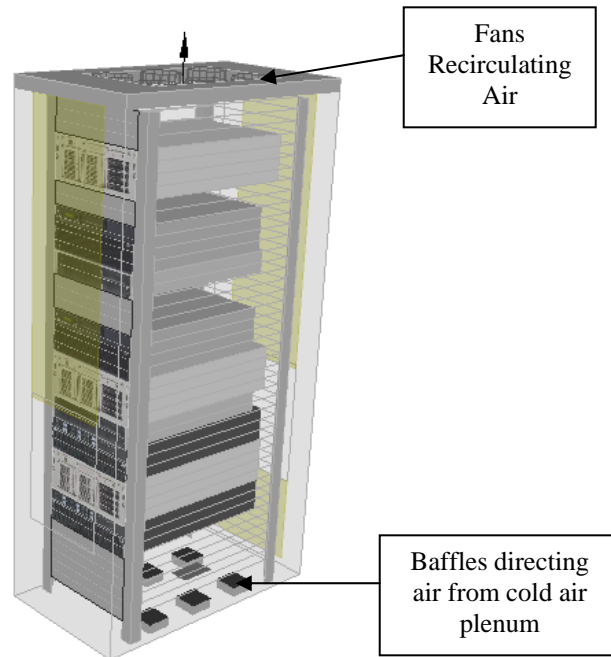


Figure 2: Kool-IT Cabinet (Side Panels and Doors shown Transparent)

2.3.2 In Row Cooling with Hot Aisle Containment from APC

In Row Cooling technology is based on deploying cooling units along side the servers, directly putting cold air into the cold aisle, bypassing the need for a raised floor. This arrangement requires chilled water to be delivered to the rows. The return side of the cooling units face the hot aisle, and the supply side face the cold aisle. The goal is to shift the cooling from a room based approach to a row based approach (Dunlap and Rasmussen 2006). Chilled water is delivered to the cooling units in the rows to remove heat. Note that the cooling units are directed toward each other, Figure 3, such that they build up static pressure in the cold aisle. This is accomplished by having two cooling units direct air towards each other.

Hot aisle containment is used to prevent hot air from the hot aisle from escaping and recirculating to the server outlets. This is accomplished by adding solid obstructions to close off the hot aisle.

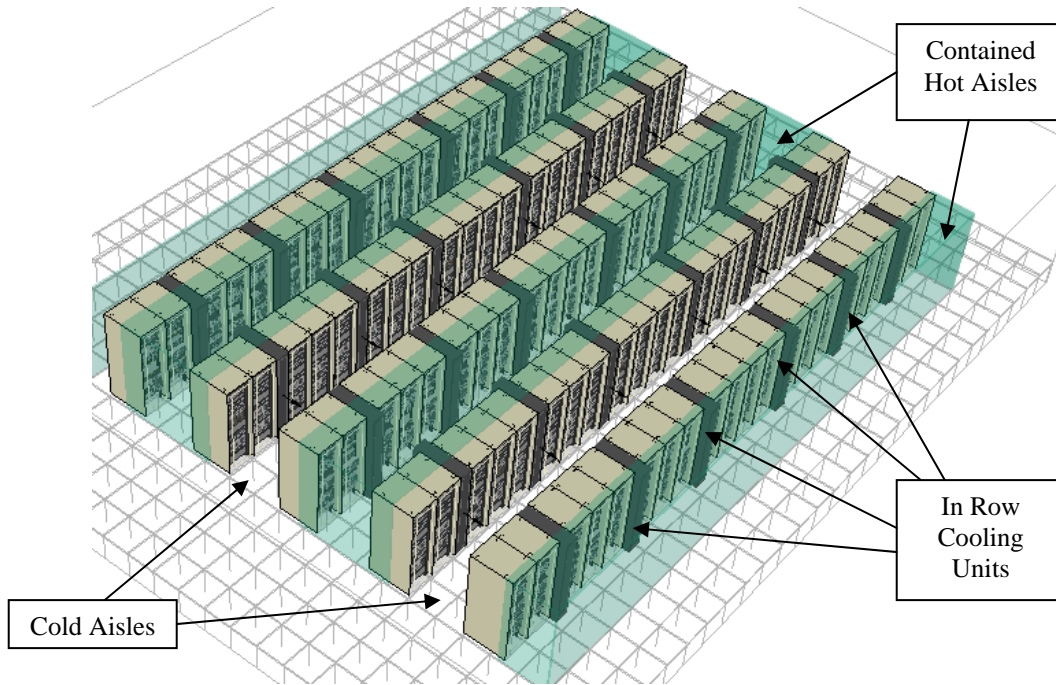


Figure 3: In Row Cooling with Hot Aisle Configuration

2.3.3 Cold Aisle Containment from Knuur

Cold aisle containment (CAC) is identical to HACA with the exception that the cold aisles are closed off and contained with the use of solid obstructions. The goal of this is to prevent the air rising from the raised floor from mixing with air in the room, providing air to the server inlets that is close in temperature to that supplied by the air conditioning unit. The goal of the confinement is to maximize the utilization of the cold air percolating from the raised floor (Emerson Electric Co. 2008).

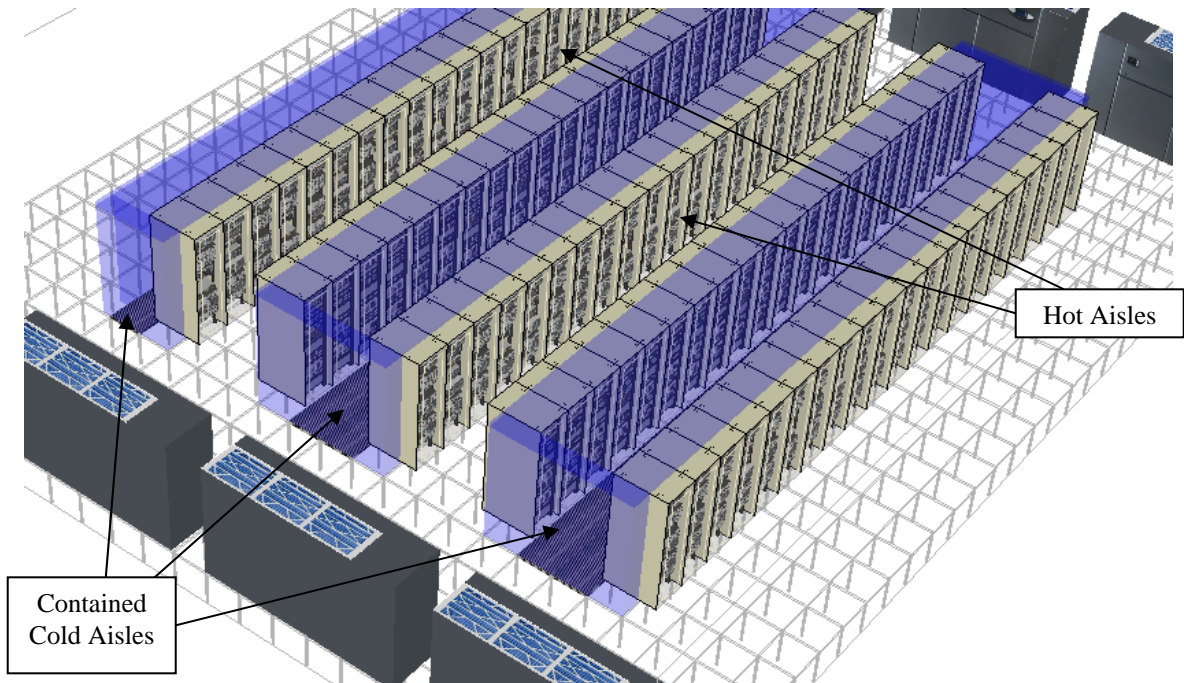


Figure 4: Cold Aisle Containment Configuration

2.3.4 Overhead Cooling from Liebert

For densities over 100kW per square feet, Overhead Cooling is deployed to supplement the standard cooling arrangement in HACA. Cooling units mounted above the cabinets deliver cold air directly to server inlets while taking in hot air from the hot aisle. Like In Row Cooling, the cooling units require chilled water to be delivered to the air conditioning units in the rows. In addition to putting the air conditioning units closer to the cabinets, Overhead Cooling units add more cooling without taking up more floor space by virtue of it taking advantage of vertical space. Note that Overhead Cooling units are auxiliary to the cooling system in the room. Some amounts of standard cooling units are required for humidity control and filtration.

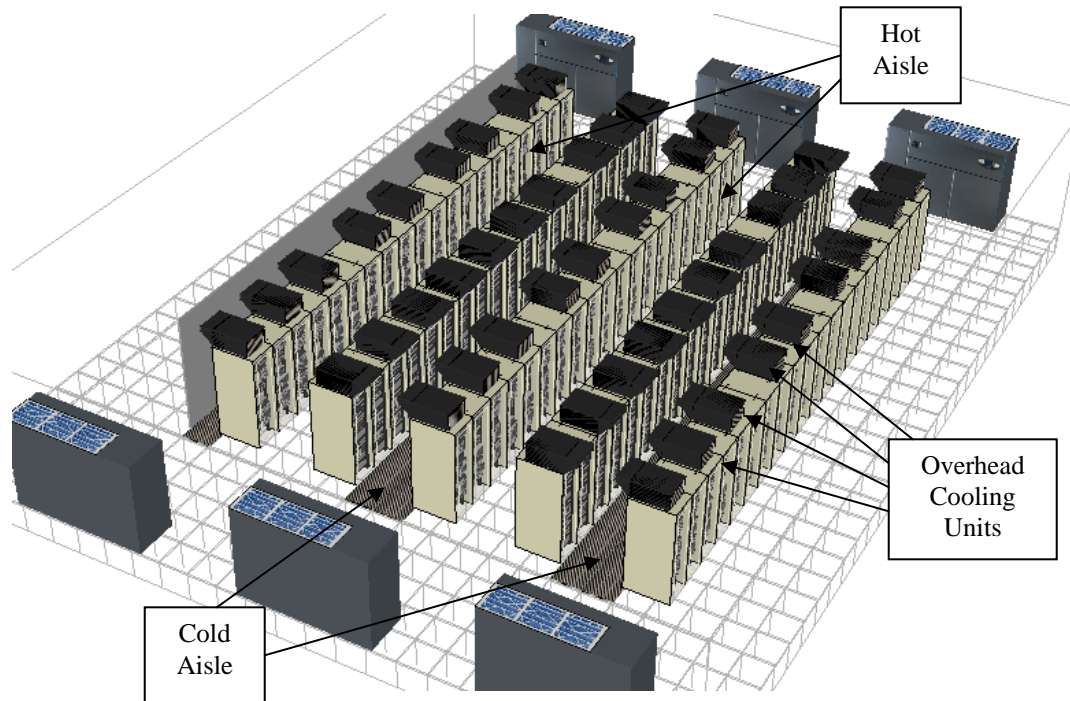


Figure 5: Overhead Cooling Configuration

2.3.5 Cabinets Ducted to Hot Air Plenum

In certain data centers, rooms are built with a dropped ceiling, similar to standard office HVAC setups, to provide a plenum to dump hot air. The cabinets are ducted to these ceilings such that the air from the server outlets is sent directly to the hot air plenum. The return side of the CRAHs are also ducted to intake air directly from the hot air plenum.

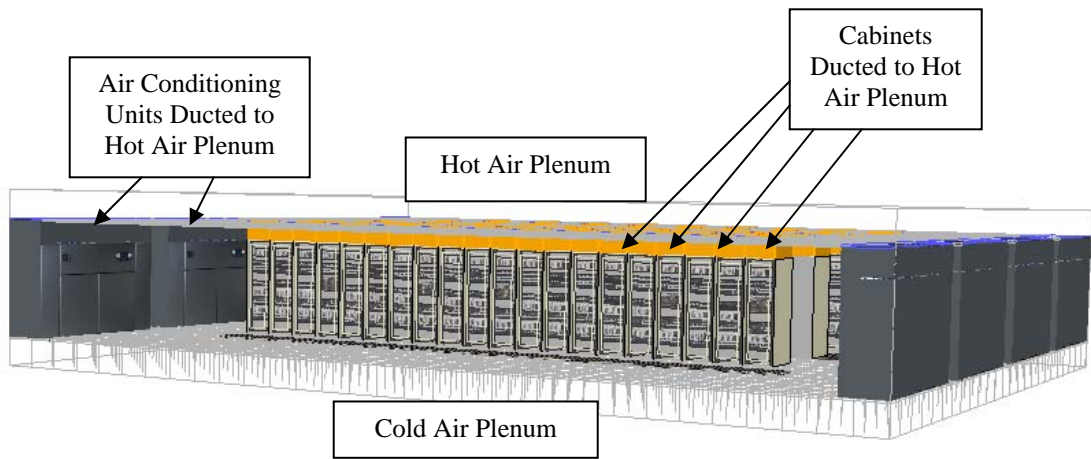


Figure 6: Cabinets Ducted to Hot Air Plenum Configuration

Chapter 3: Study Methodology and CFD Models

3.1 Study Methodology

In this study, the data center is defined with the following constraints:

- 100 Cabinets
- 45% open area perforated tiles
- 64% open area perforated front and rear cabinet doors
- 62ft x 52ft floor space
- 12ft ceiling from bottom of the raised floor plenum (10ft from raised floor)
- 2ft Raised Floor
- Front blanking plates in vacated cabinet spaces

This study focuses on trends as power density increases, starting from 2kW average per cabinet to 16kW average per cabinet. The flow rate of air through each piece of IT equipment is based on 120-160 cfm per kW of heat load consumed by the IT equipment. Within any specified average heat density per cabinet, half the cabinets are loaded at the specified heat density, a quarter of the cabinets are loaded at .75 of the average heat density, and a quarter of the cabinets are loaded at 1.25 of the average heat density. These cabinets are distributed randomly within the room in an HACA configuration.

The amount of maximum cooling provided is 125% of the total power consumption of the IT equipment. For example, a room loaded with 400kW has 500kW of maximum cooling capacity provided to it. The amount of cooling flow is determined

by calculating the air-flow required to have the air conditioning units operate at a temperature difference of 20°F from the return to the supply. In this study, air conditioning units are controlled by supply temperature at a set-point of 54°F, consistent with manufacturers' specifications for data center cooling equipment (APC 2006). Consequently, the return temperature is 74°F

The study focuses on fairly comparing the effectiveness of each technology. The key elements in what is deemed more effective than another are as follows:

1) Overheated Servers – This value is the number of cabinets that have servers with inlet temperatures over 77°F with the air conditioning units at a set-point of 54°F. It is important to see how many servers overheat with each technology given a common set of parameters. This gives an idea of which technology provides a more reliable operating environment. Other important factors are the locations of the cabinets that overheat in relation to where is it in the row and the proximity of the overheated units to the air conditioning units.

2) Maximum Server Inlet Temperature – This is value of the inlet temperature of the server being delivered the hottest air. This value shows the degree in which a technology causes a non-preferable operating environment for the worst case server inlet in the room. This value provides a prediction of which technology allows for operating conditions that best improve vapor-compression refrigeration cycle performance. By raising the supply temperature by the difference the maximum server inlet temperature has against the ASHRAE guideline, improvements in efficiency can be made. It should

be noted that the maximum server inlet temperature reported in this study is the maximum of any point in front of the server inlet, and not the average of that area.

3) Robustness – The sensitivity of a system to the application of blanking plates is also studied. In data centers, rows in the cabinets not occupied by equipment have blanking plates installed to prevent the flow of air from the hot (exhaust) side of the cabinet to the cool (inlet) side of the cabinet. A study is done at the 12kW power density to determine the sensitivity of each technology to the availability of blanking plates.

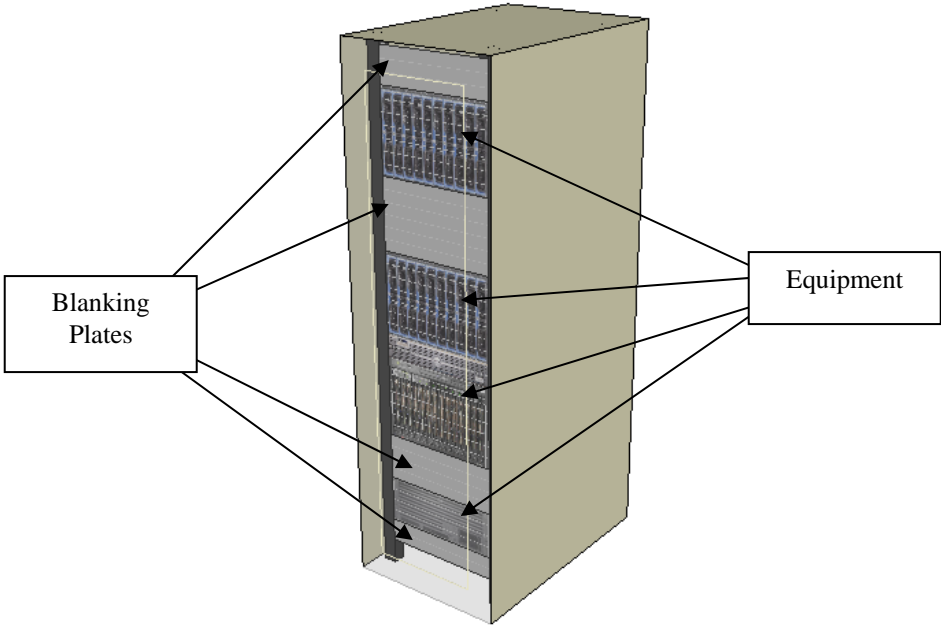


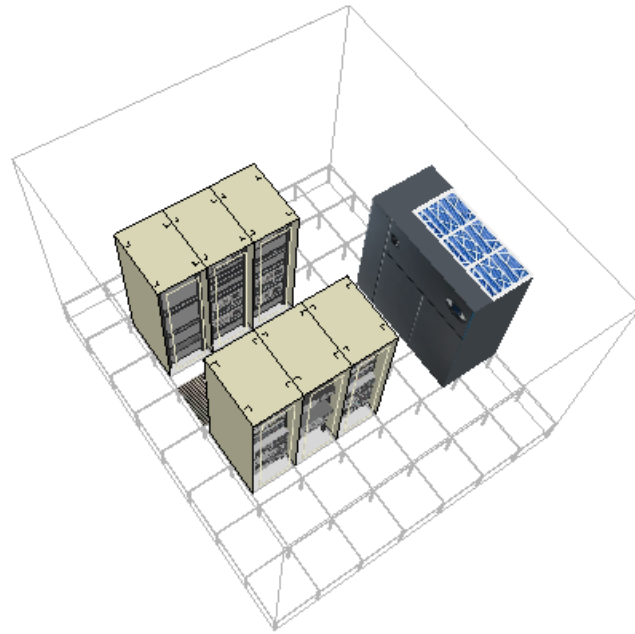
Figure 7: Typical Cabinet with IT Equipment and Blanking Plates Installed (Front Cabinet Door Transparent)

3.2 Future Facilities – 6Sigma Room

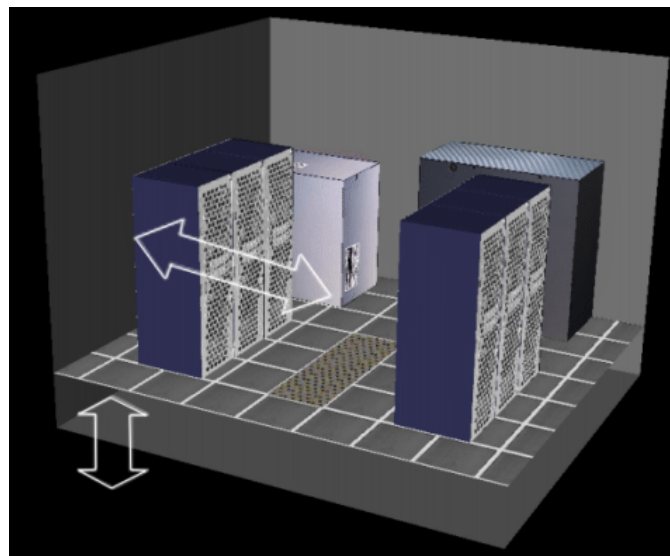
In this study, we have used 6Sigma Room from Future Facilities for creating CFD models. This software provides an easy to use graphical user interface that allows users to create and change architectural geometry, cooling / ventilation, and power and IT configurations in a three dimensional environment. It provides a library of IT equipment, cabinets, and cooling units. The software is capable of predicting the thermal and flow environment of an entire data center, accounting for the full architectural geometry and obstructions. Creation of a 6Sigma room model provides a three dimensional virtual facility to understand the geometric placement of equipment and subsequent thermal environment created by the equipment. (Future Facilities 2007)

3.3 Validation of CFD Software

Validation of this software is done by comparing with a model done in 6SigmaRoom with a model done using a software package made by Flomerics called Flovent (Manning 2007). The room in this example is a hot aisle / cold aisle room using one cold aisle and one air conditioning unit. The simulation is emulated based on the pictorial descriptions of the room as published by Flomerics (Manning 2007). Both 6Sigma and Flovent showed a similar temperature range and gradient. Figures 8 and 9 depict the set up of the room in both Future Facilities (7a) and Flomerics (7b) respectively, and the temperature distributions predicted by Future 6Sigma (8a) and Flomerics (8b) respectively.

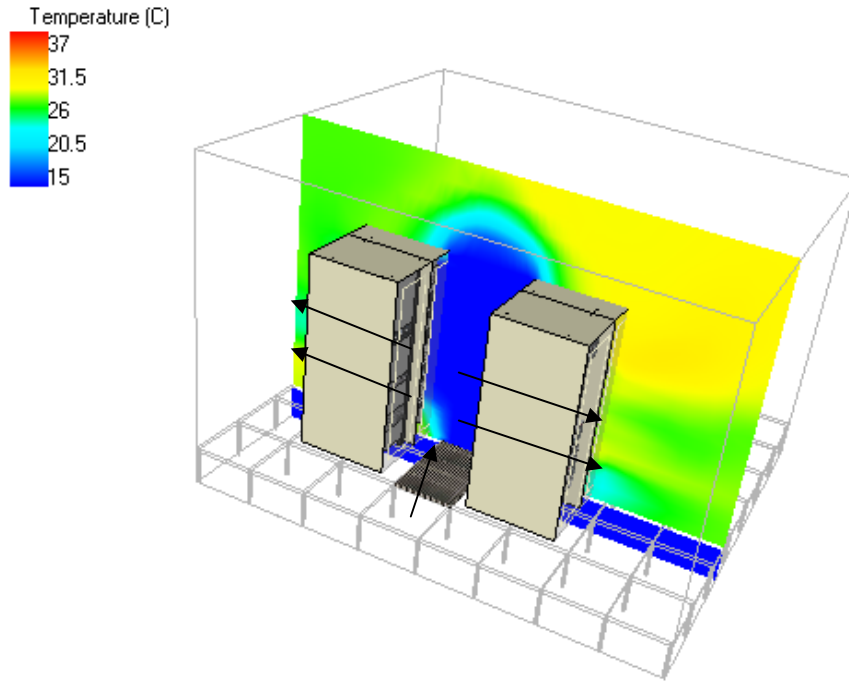


(a)

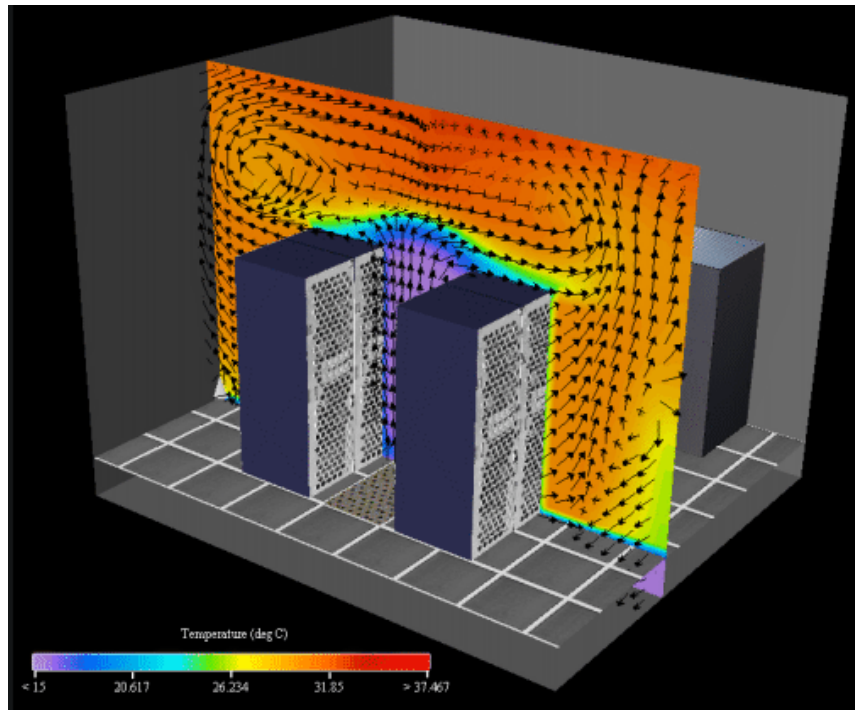


(b)

Figure 8: Test Room for Validation Study - (a) Future Facilities (b) Flomerics (Manning 2007)



(a)



(b)

Figure 9: Validation Study Results – (a) Future Facilities (b) Flomerics (Manning 2007)

The Flomerics study is verified by comparing study results with data center intuition. Part of the study involves varying the equipment height in relation to the cabinet to determine the best height for the equipment within the cabinet.

Chapter 4: Results and Discussions on CFD Simulations

4.1 Hot Aisle / Cold Aisle Results

The streamlines in the HACA approach shows the flow of air percolating from the perforated tiles into to the cold aisle, where the cold air is forced into the server inlets and exhausted out of the back of the servers into the hot aisle. The hot air is then moved to the sides of the room where it is forced into the CRAH's. Figures 11 to 16 show the overheat plots for HACA at the various power densities. From here, it can be seen that HACA arrangement alone is insufficient at keeping all servers under the ASHRAE mandated server inlet temperature of 77°F at all power densities.

As the power density increases, the effectiveness of HACA technology is reduced. At every load density, there are overheated servers. It can be seen from Figures 11 to 16 that the amount of overheated servers increases as power density increases. There is no apparent pattern as to where the cabinets with overheated servers appear. The legend that appears in the following overheat plots show 3 ranges, the green color represents cabinets in which the maximum server inlet temperature is below 68°F, the orange color represents cabinets in which the maximum server inlet temperature is between 68°F and 77°F, and the red color represents cabinets in which the maximum server inlet temperature is above 77°F.

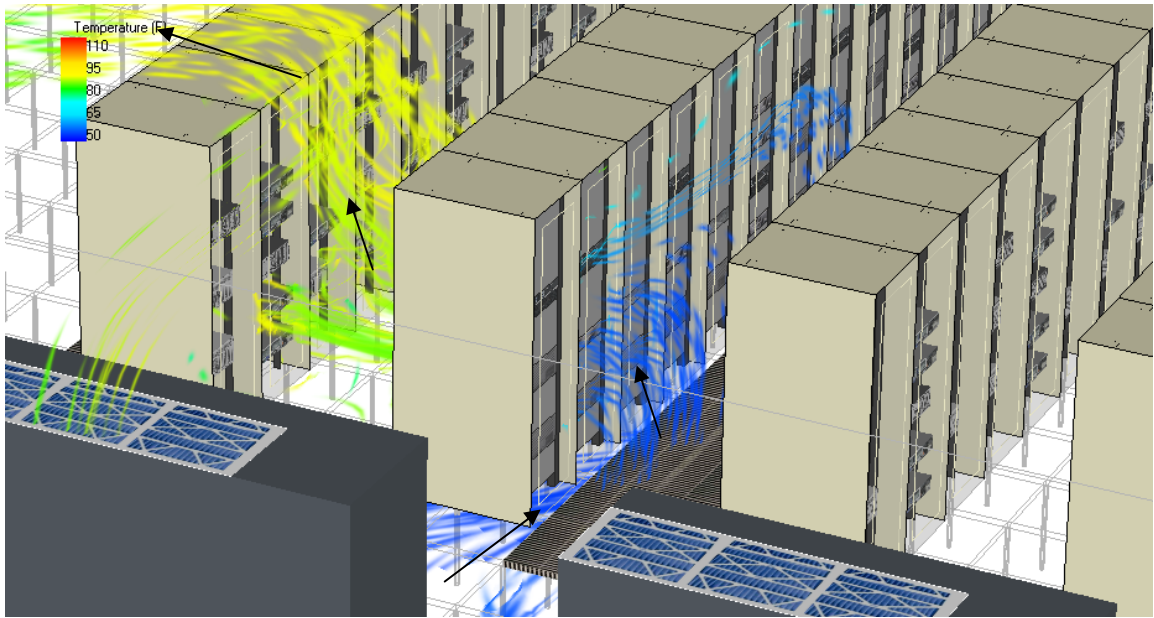


Figure 10: HACA Streamline Plot

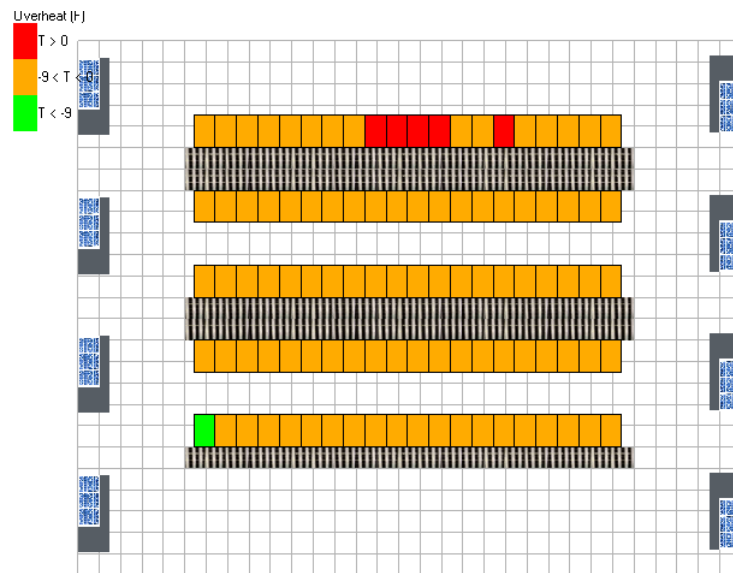


Figure 11: HACA Overheat Plot at 2kW

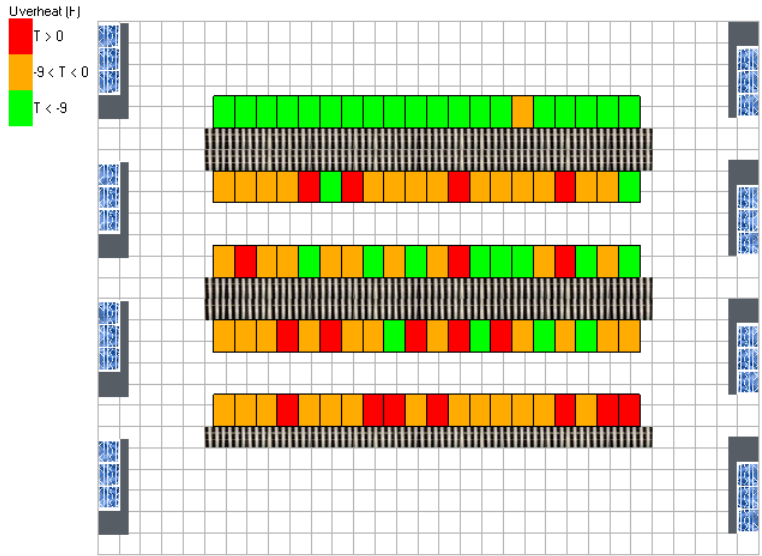


Figure 12: HACA Overheat Plot at 4kW

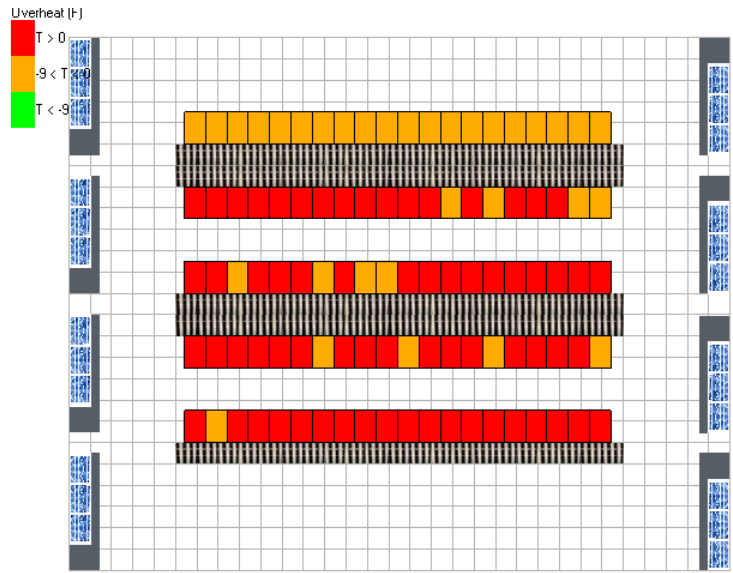


Figure 13: HACA Overheat Plot at 6kW

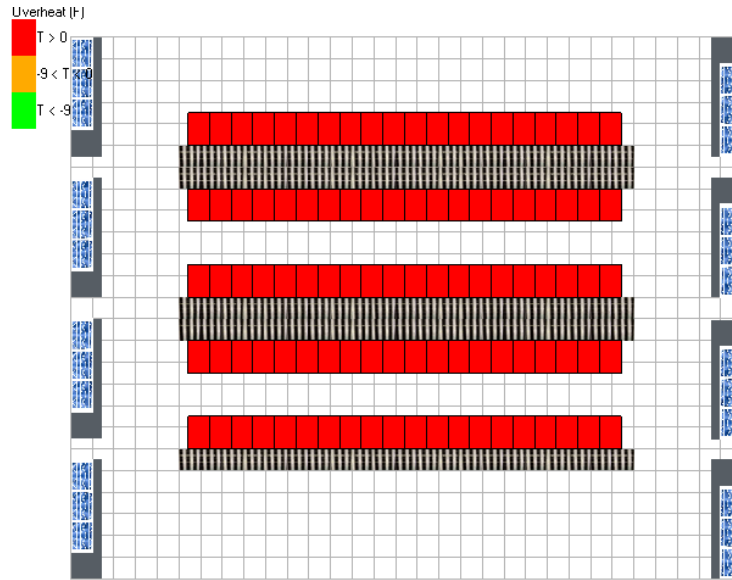


Figure 14: HACA Overheat Plot at 8kW

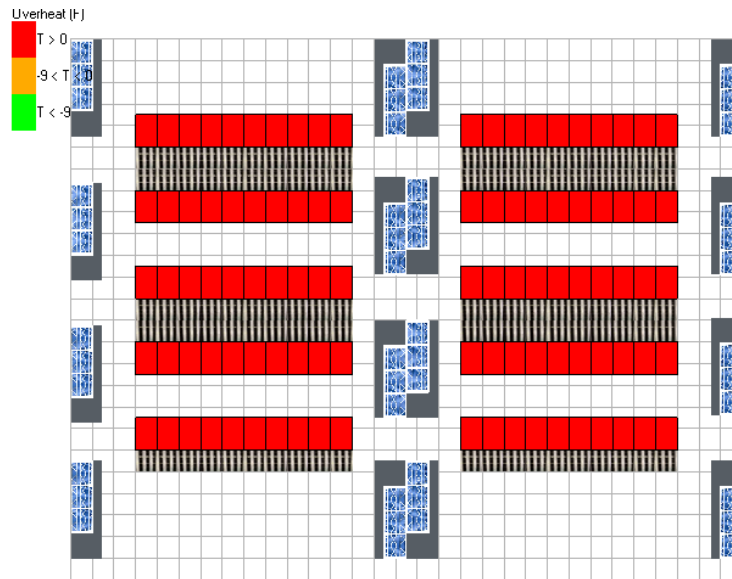


Figure 15: HACA Overheat Plot at 12kW

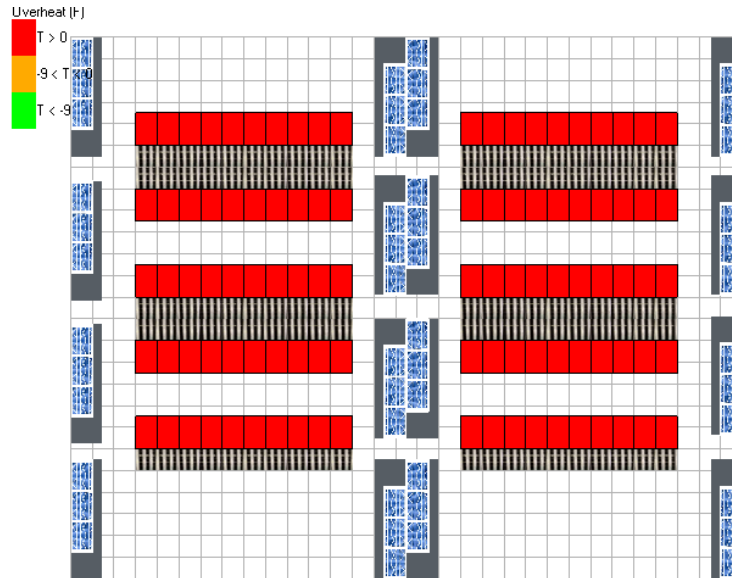


Figure 16: HACA Overheat Plot at 16kW

Figure 17 is a close-up of the streamlines at the inlet side of the server at 12kW per cabinet. It can be seen that there are areas in which there is flow recirculating from the exhaust side of the cabinet. This recirculated air is the cause of the increased server inlet temperatures. The HACA approach creates areas in which the server inlet is receiving air that is a result of a mixture of room air and air exiting from server outlets, rather than from the perforated tiles in the raised floor.

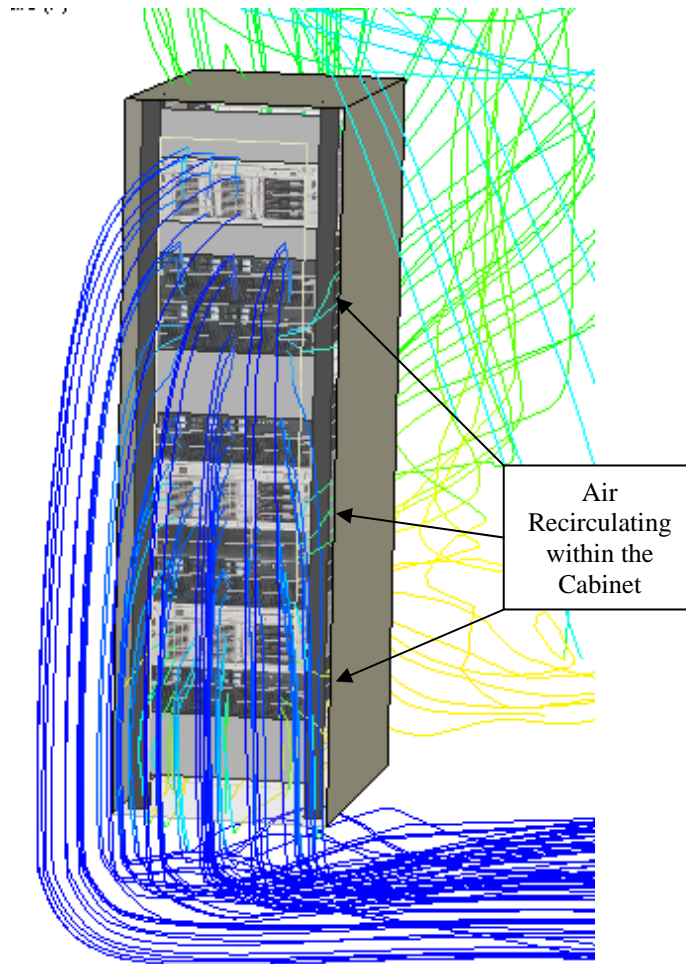


Figure 17: HACA Recirculation

4.2 Kool-IT Results

Figure 18 depicts the streamline plot of a Kool-IT unit at 8kW per cabinet. It can be seen that air not used directly by the servers is forced out of the top by fans and mixed with room air, and made available to the server inlets. This causes a recirculation of air at approximately 73°F to the cold aisle, causing more air to be available to the servers at all densities. In addition, Kool-IT addresses the problem of the bottom servers not getting enough air by baffling the air directly into the enclosure. This increase of air available to the servers eliminates the problem of air leaking from the back of servers to the front due

to the lack of available static pressure in the front of the cabinets. This deliberate amount of mixing and recirculation is effective at both high and low densities. At all power densities, no cabinet contained an overheated server. The Kool-IT approach is effective in reducing the overall room temperature.

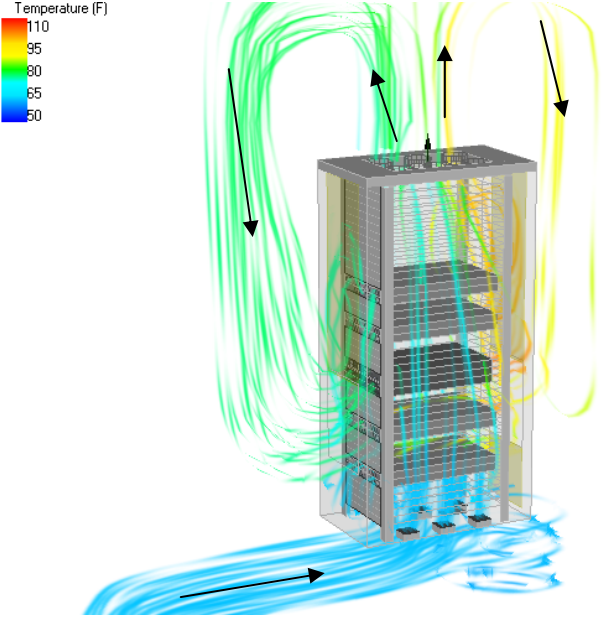


Figure 18: Kool-IT Streamline Plot at 8kW

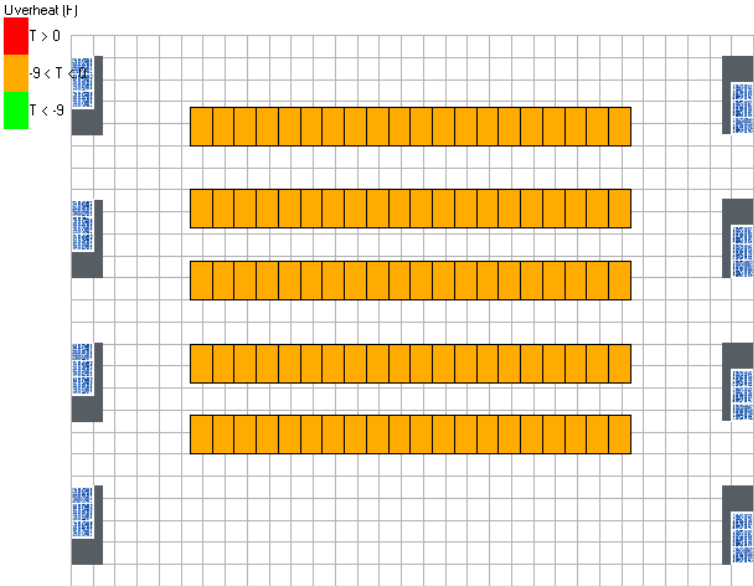


Figure 19: Kool-IT Overheat Plot at 2kW

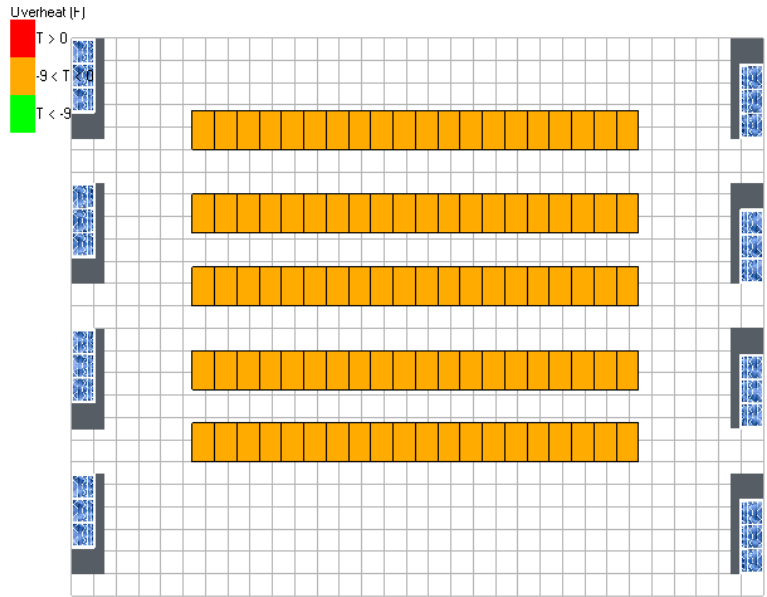


Figure 20: Kool-IT Overheat Plot at 4kW

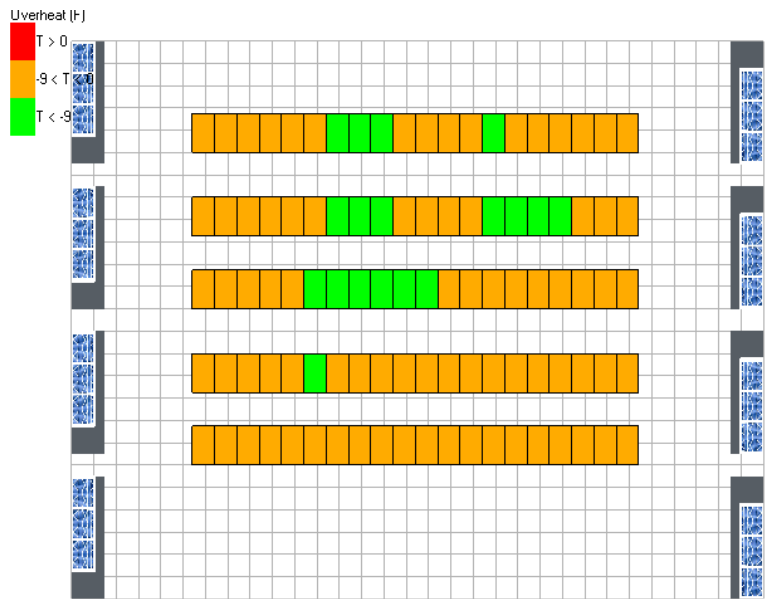


Figure 21: Kool-IT Overheat Plot at 6kW

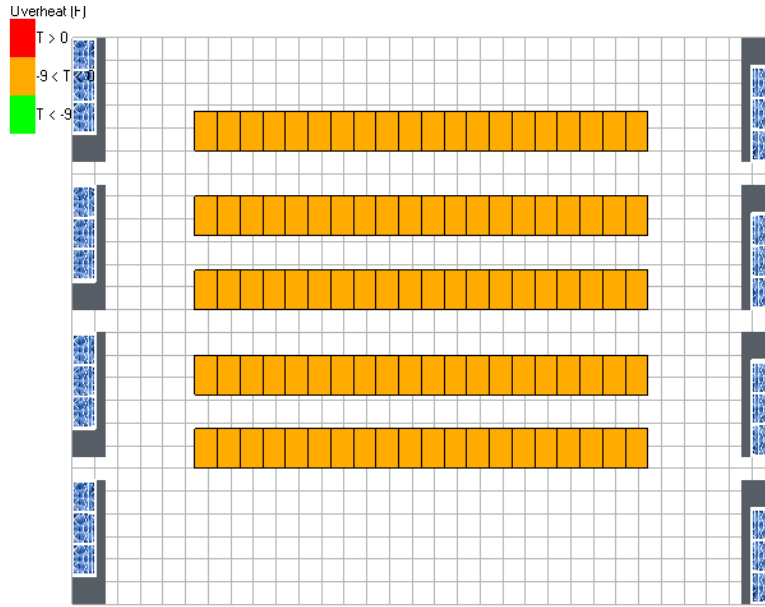


Figure 22: Kool-IT Overheat Plot at 8kW



Figure 23: Kool-IT Overheat Plot at 12kW

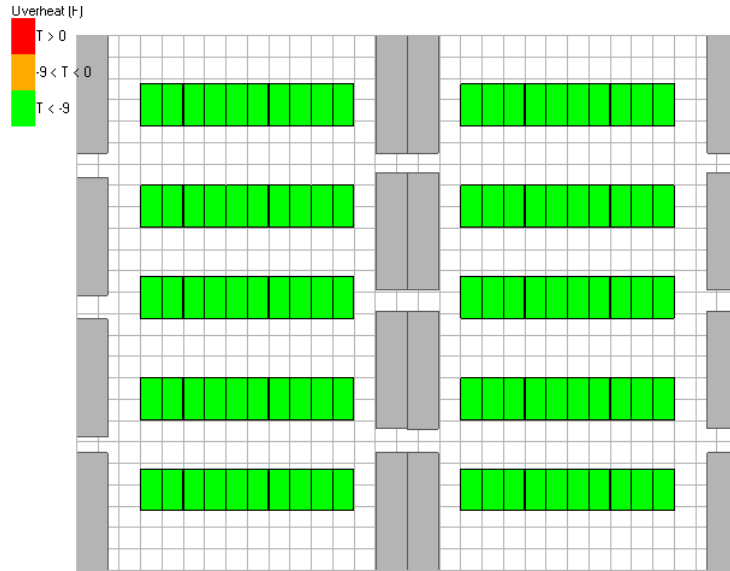


Figure 24: Kool-IT Overheat Plot at 16kW

4.3 In Row Cooling with Hot Aisle Containment Results

Figure 25 shows the streamline plot of In Row Cooling units in a room with contained hot aisles. It can be seen that the containment causes an effective thermal and mass boundary between the hot aisle and cold aisle. Because In Row Cooling units are distributed along the aisles, as opposed to at the end of the aisles in HACA, they are more effective in providing a better distribution of cold air and static pressures to the cold aisle than HACA.

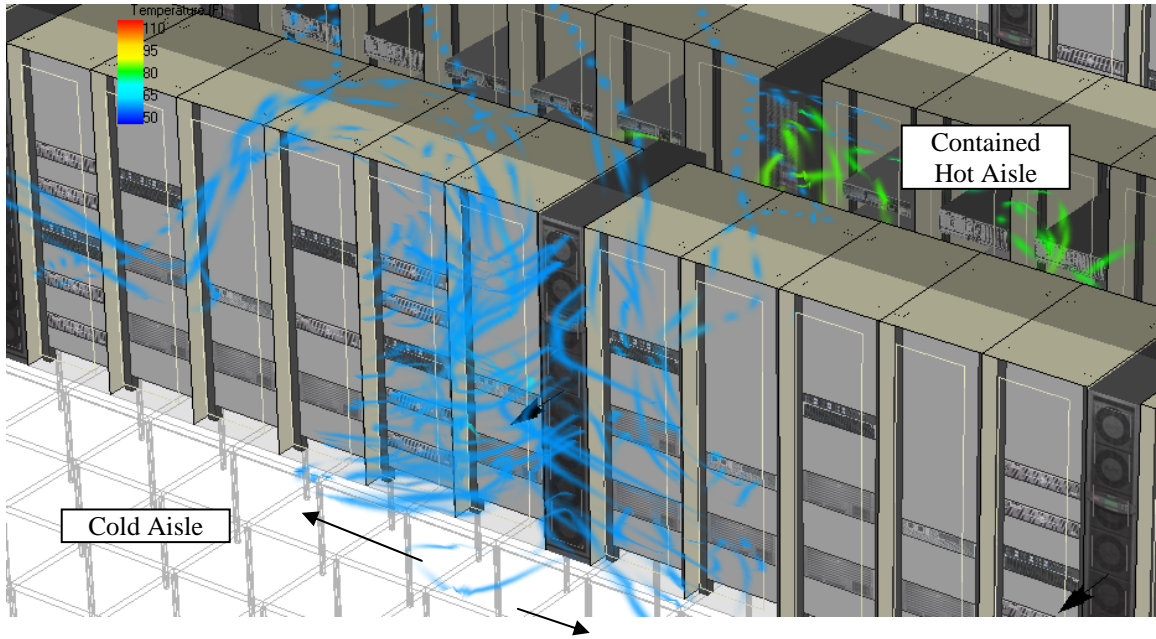


Figure 25: In Row Cooling with Hot Aisle Containment Streamline Plot

As shown in Figures 26 to 31, cabinets adjacent to the cooling units, where the velocity is high and the static pressure is low, have a higher occurrence of cabinets containing overheated servers, with overheating occurring in the 6kW case. The lack of static pressure causes a forced leakage from the hot aisle to meet the demand for air.

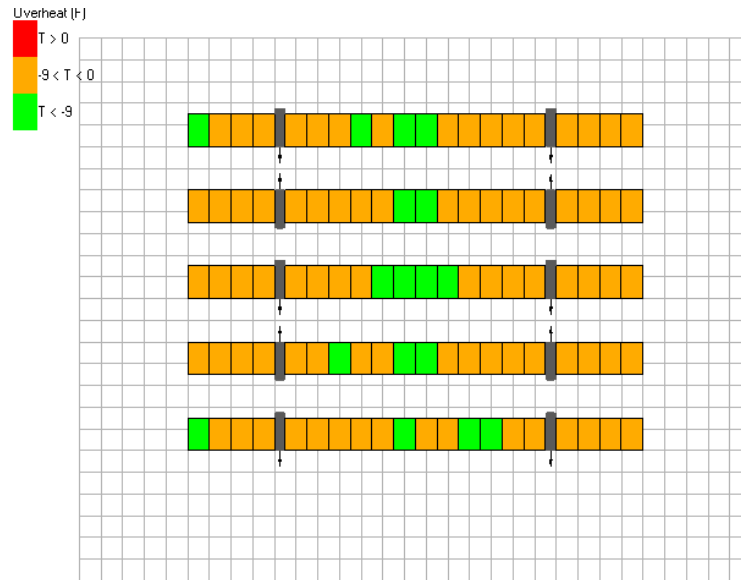


Figure 26: In Row Cooling with Hot Aisle Containment Overheat Plot at 2kW

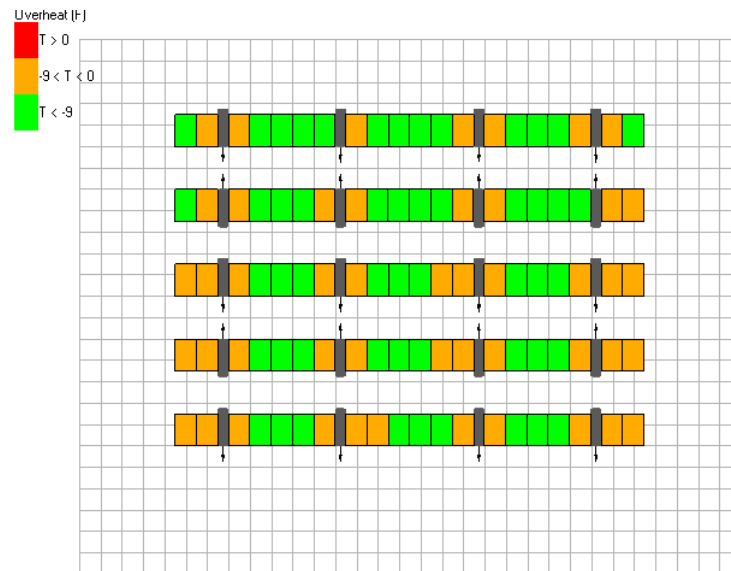


Figure 27: In Row Cooling with Hot Aisle Containment Overheat Plot at 4kW

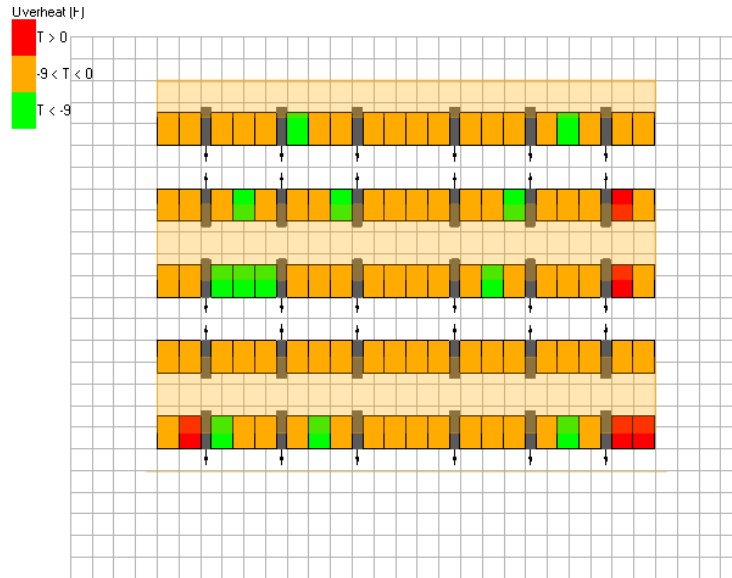


Figure 28: In Row Cooling with Hot Aisle Containment Overheat Plot at 6kW

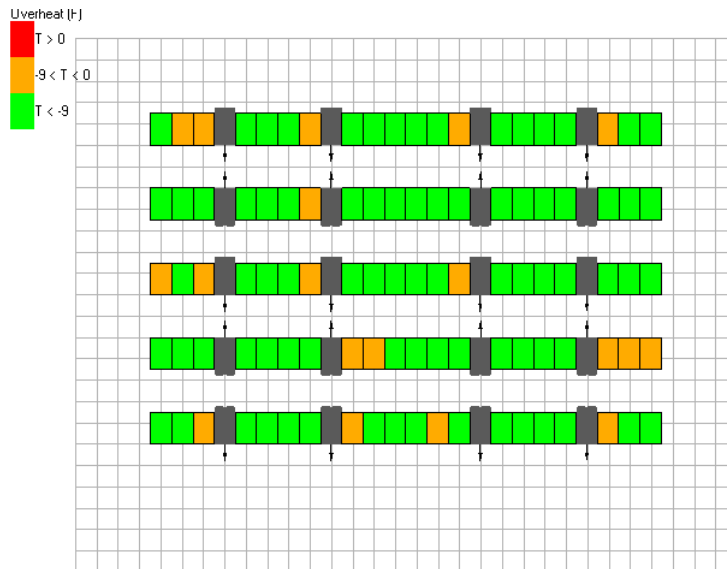


Figure 29: In Row Cooling with Hot Aisle Containment Overheat Plot at 8kW

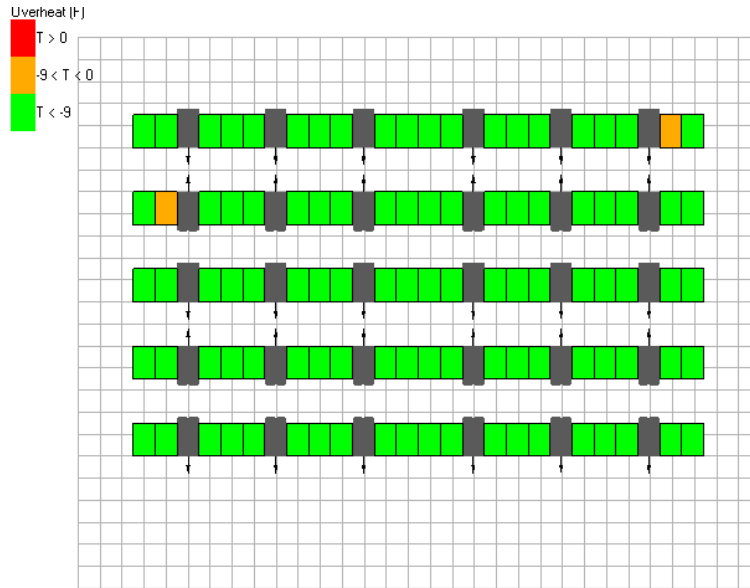


Figure 30: In Row Cooling with Hot Aisle Containment Overheat Plot at 12kW

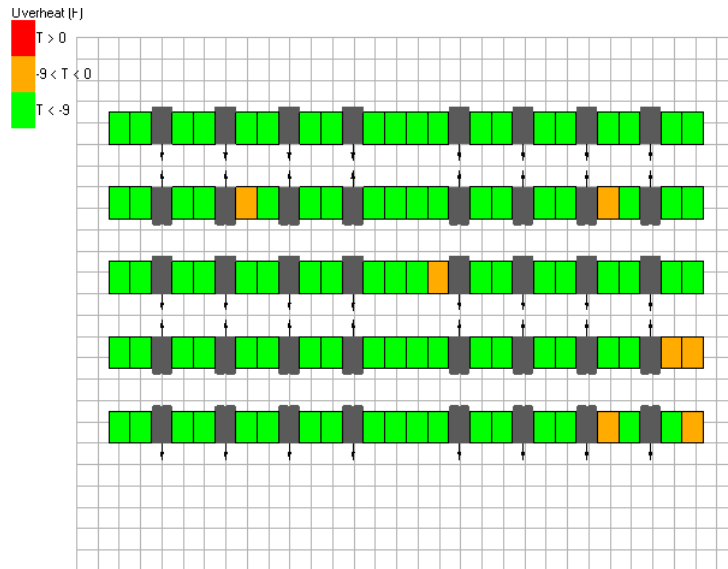


Figure 31: In Row Cooling with Hot Aisle Containment Overheat Plot at 16kW

As the power density increases to 8kW per cabinet and above, In Row Cooling technology has less of a problem providing adequate static pressure to the servers adjacent to the air conditioning units than at the lower power densities. As the power density increases, the air conditioning units are scaled accordingly to provide more flow

to meet the cooling needs. Although this increase in cooling flow is common to all the setups, it is particularly more effective in the In Row Cooling arrangement than in the arrangements that use CRAHs along the side of the rows. Table 1 tabulates the static pressure 18 inches in front of front door of the cabinets in the third row from the top of the room at the studied power densities. The change in performance occurs because the distance between the cooling units remains the same, but the amount of cool air forced into that area increases, which allows the air conditioning units to build up an adequate amount of static pressure. Consequently, there are fewer overheated servers and the maximum server inlet temperature is lower as densities increase.

Table 1: Static Pressure at a Plane Parallel to Aisles

Power Density (kW)	Maximum Static Pressure 18 inches in front of Inlet side of Cabinet (psi)
2	0.0007994
4	0.0009400
6	0.0008892
8	0.0010400
12	0.0010400
16	0.0011420

4.4 Cold Aisle Containment Results

Cold Aisle Containment effectively creates a thermal and mass flow boundary between the cold aisle and hot aisle, Figure 21. The contained cold aisle also creates an enclosure for mass to be trapped, which creates a high static pressure region.

The air received by the servers is nearly the same temperature as the air at the supply of the CRAHs. However, the air in front of the servers at the bottom of the cabinets is moving at a high velocity, causing a low static pressure. This causes the

servers to pull air from the hot aisle, causing high server inlet temperatures. Cabinets with overheated servers are only observed in the 4kW and 6kW cases, Figure 34 and 35.

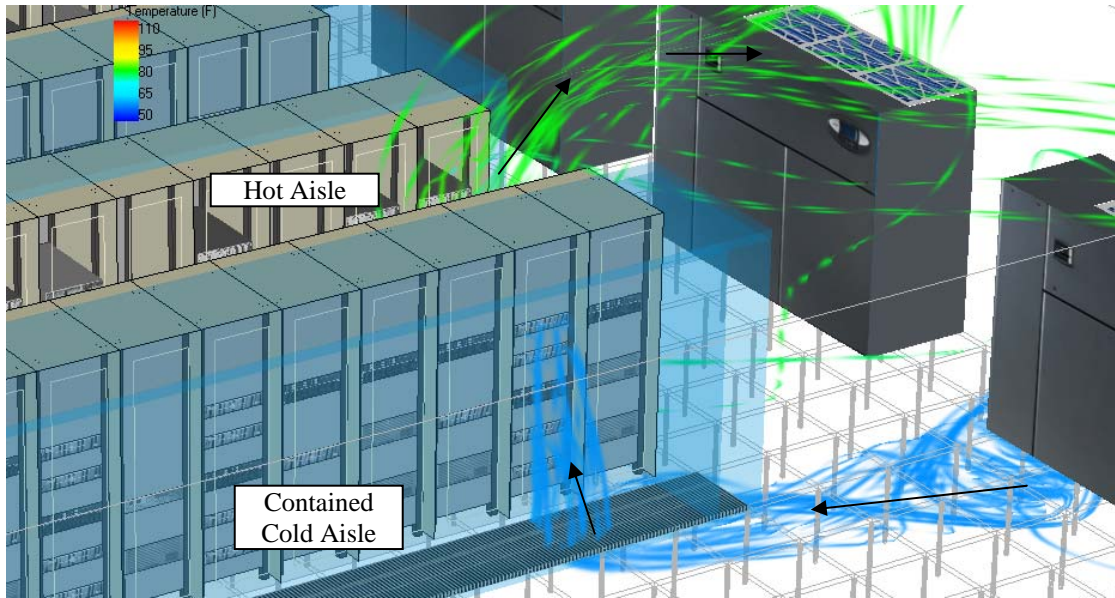


Figure 32: Cold Aisle Containment Streamline Plot

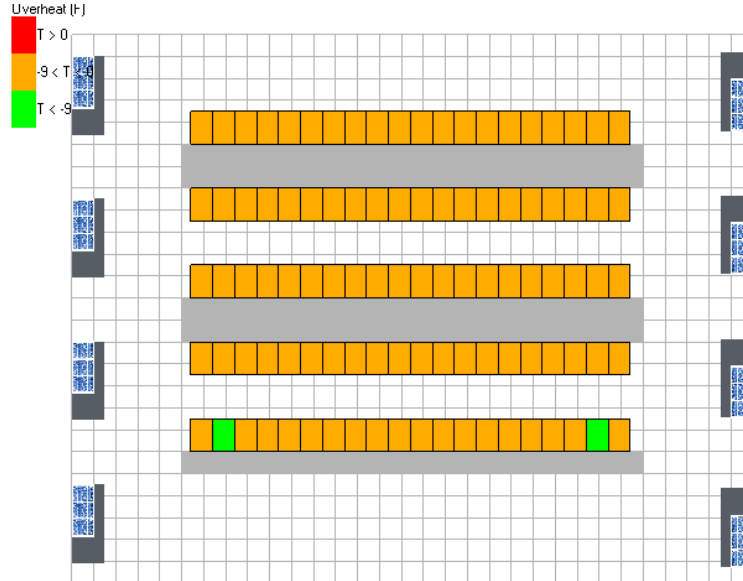


Figure 33: Cold Aisle Containment Overheat Plot at 2kW

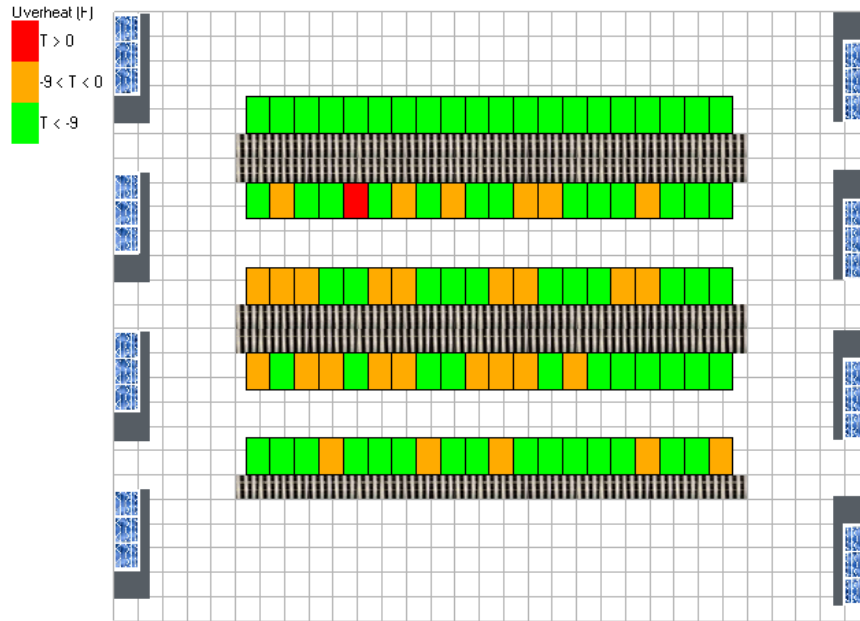


Figure 34: Cold Aisle Containment Overheat Plot at 4kW

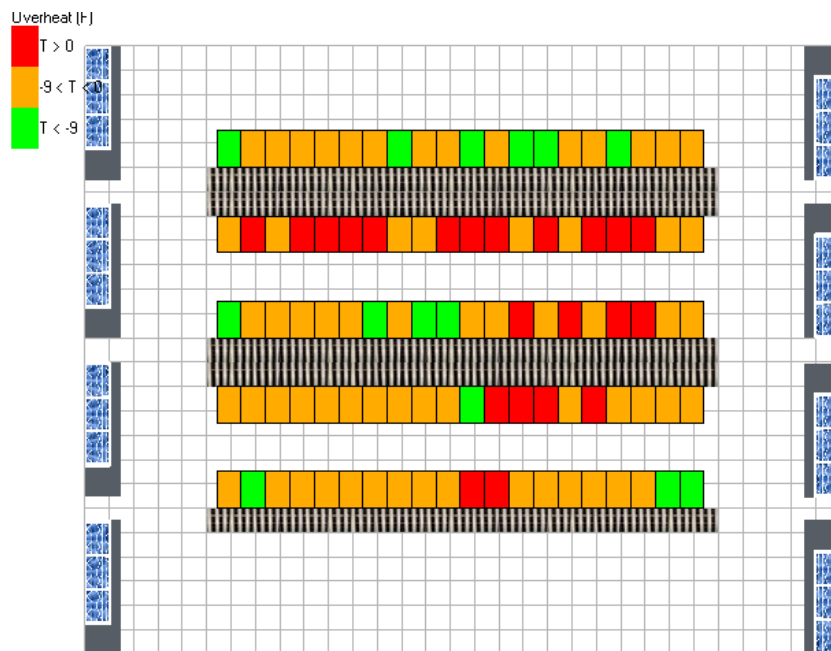


Figure 35: Cold Aisle Containment Overheat Plot at 6kW

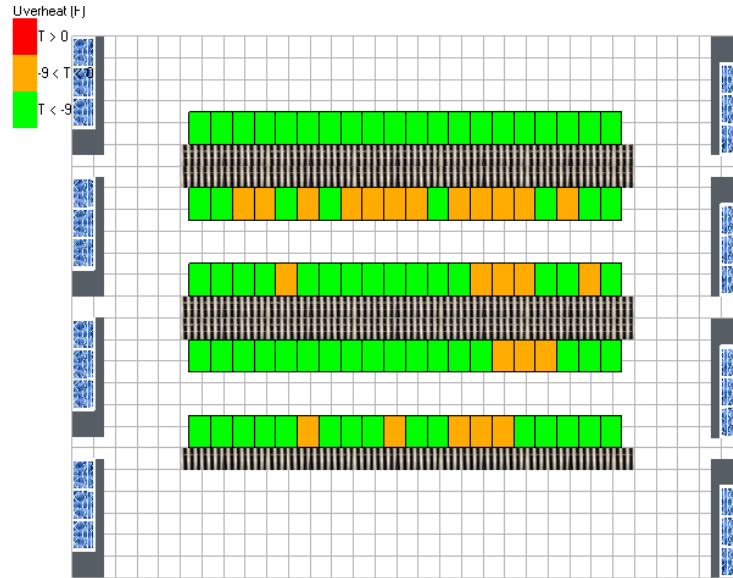


Figure 36: Cold Aisle Containment Overheat Plot at 8kW

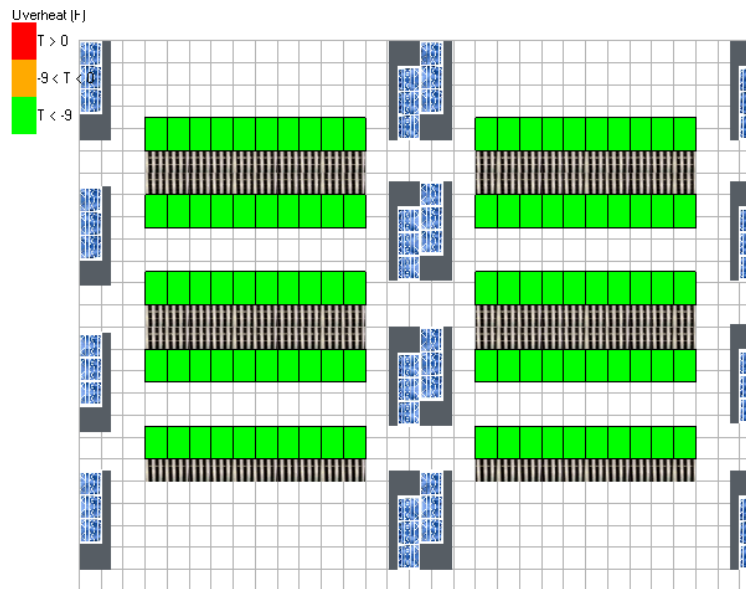


Figure 37: Cold Aisle Containment Overheat Plot at 12kW

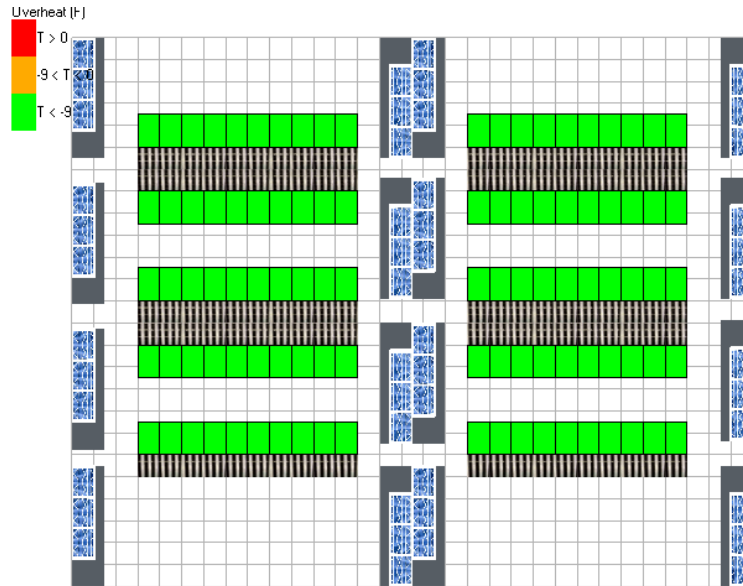


Figure 38: Cold Aisle Containment Overheat Plot at 16kW

Since the cooling flow is scaled with power density, increased power density yields increased airflow to the cold aisle. Because the cold air enters an enclosed cavity (the cold aisle containment structures), there is an increase of static pressure of cold air as the cooling flow increases. Undesired flow leaking from the hot aisle to the cold aisle is less common. The difference in static pressure between different loading scenarios is shown in Table 2 at 4 inches above the perforated tiles, parallel to the raised floor, in the cold aisle. Similar to In Row Cooling, the increased volume of cooling flow causes Cold Aisle Containment to become more effective as power density increases.

Lower power density cases show that the low static pressure, due to lesser amount of air-flow from the CRAHs causing inadequate buildup of static pressure near the floor of the Cold Aisle Containment, does cause higher server inlet temperatures at the servers located close to the floor. This behavior does decrease as the total flow of cold air in the

room increases. The servers located higher in the cabinets are subjected to a higher static pressure of cold air due to the enclosure trapping air.

Table 2: Static Pressure at a Plane Parallel to Raised Floor

Power Density (kW)	Maximum Static Pressure in Cold Aisle One Inch Above Raised Floor (psi)
2	0.0000756
4	0.0001460
6	0.0003382
8	0.0008646
12	0.0018850
16	0.0036330

4.5 Overhead Cooling Results

Figure 39 shows the streamline plots typical of Overhead Cooling. It can be seen that the cold air is delivered directly to the inlet side of the cabinets. Adding Overhead Cooling units is advantageous when space is limited because it makes use of the space above the cabinets rather than floor space. The Overhead Cooling units prevent recirculation at the top of the cabinets by providing a shorter path to an air conditioning unit than in cases where the CRAHs are located exclusively at the sides of the room. The server inlets that face the Overhead Cooling unit outlets receive an adequate amount of cold air. The server inlets directly under the Overhead Cooling units, especially those near the top of the cabinet, however, are under a condition in which the air velocity in front of the server inlets are high, and not building enough static pressure. Overhead Cooling units, similar to In Row Cooling units, distributes cold air better than standard HACA.

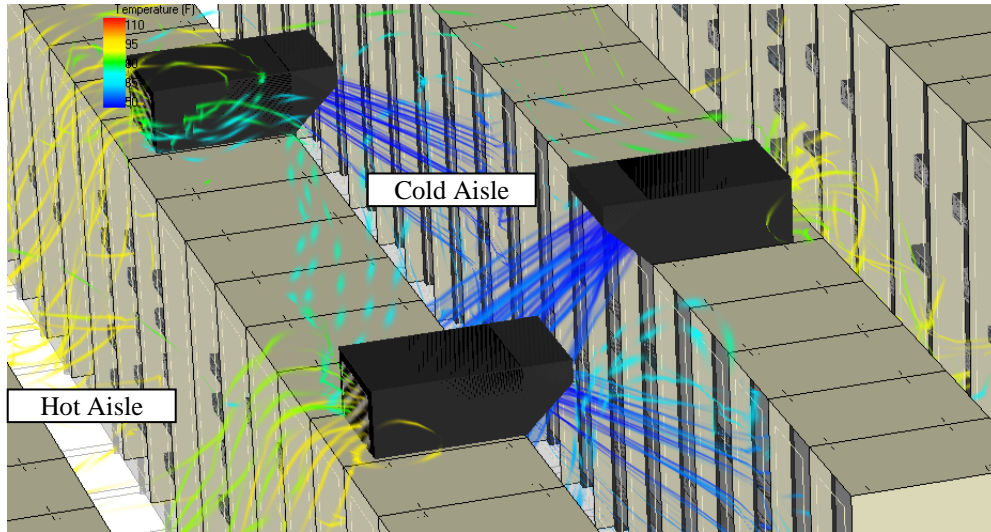


Figure 39: Overhead Cooling Streamline Plot

Unlike HACA, Overhead Cooling maintains its cooling performance as power densities increase. Similar to In Row Cooling, Overhead Cooling units have some trouble building up enough static pressure at low power densities. As can be seen in Figures 40 to 42 that the servers at the ends of the aisles, where it is more difficult to build static pressure due to aisle ends being open, servers are at risk of overheating. Cabinets with overheated servers are only observed in the 4kW, 6kW and 8kW case.

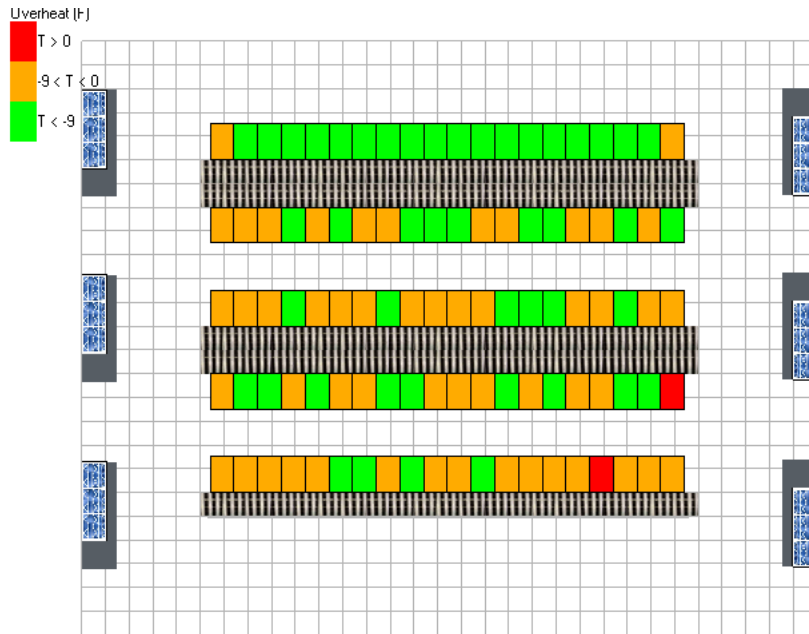


Figure 40: Overhead Cooling Overheat Plot at 4kW

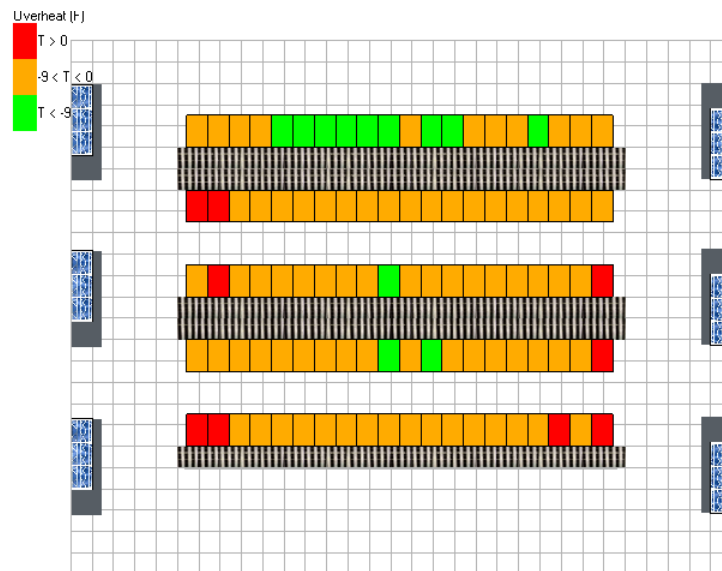


Figure 41: Overhead Cooling Overheat Plot at 6kW

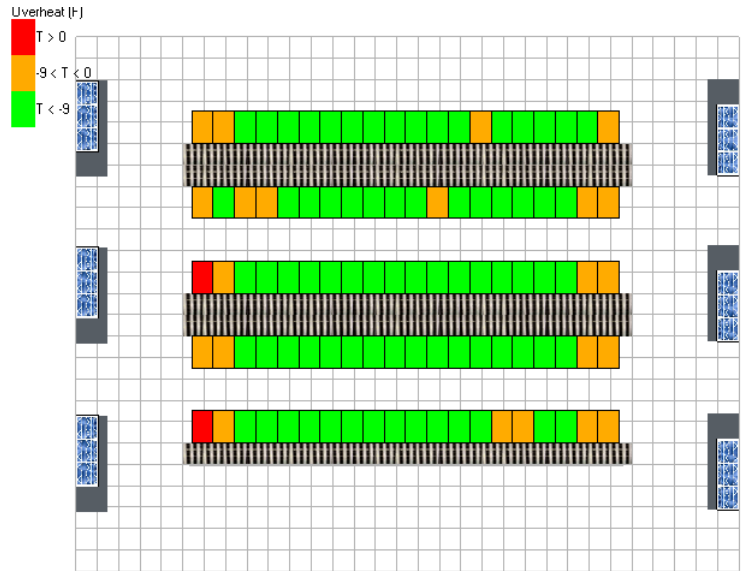


Figure 42: Overhead Cooling Overheat Plot at 8kW

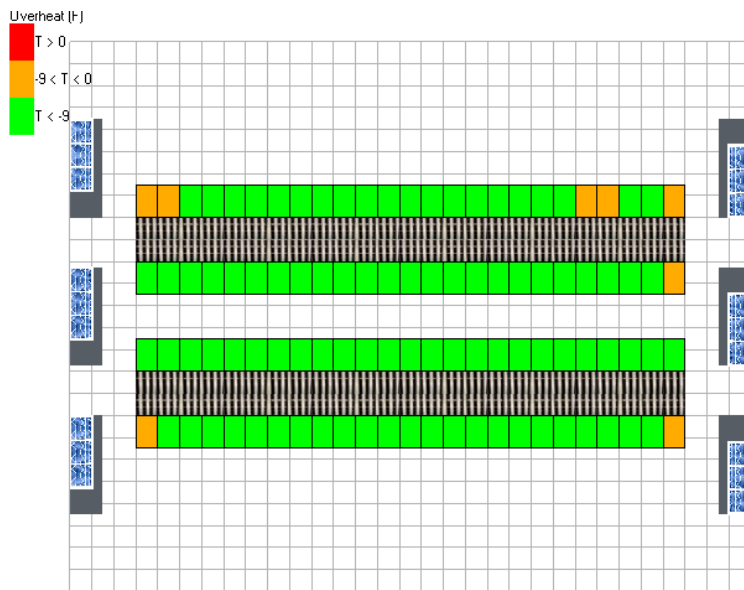


Figure 43: Overhead Cooling Overheat Plot at 12kW

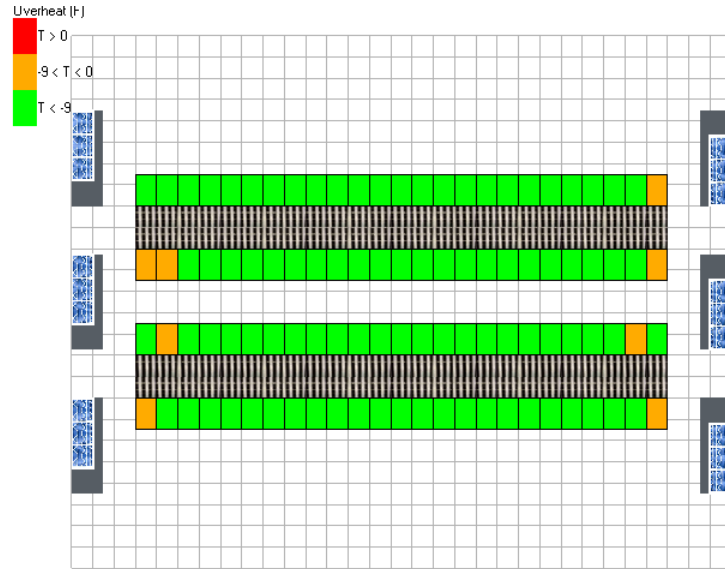


Figure 44: Overhead Cooling Overheat Plot at 16kW

4.6 Cabinets Ducted to Hot Air Plenum Results

The configuration of ducting cabinets to hot air plenums creates a direct path for server outlet air to get to the air conditioning units, Figure 45. This creates a thermal and mass boundary between the hot aisle and the cold aisle and connects the air conditioning units to the cabinets.

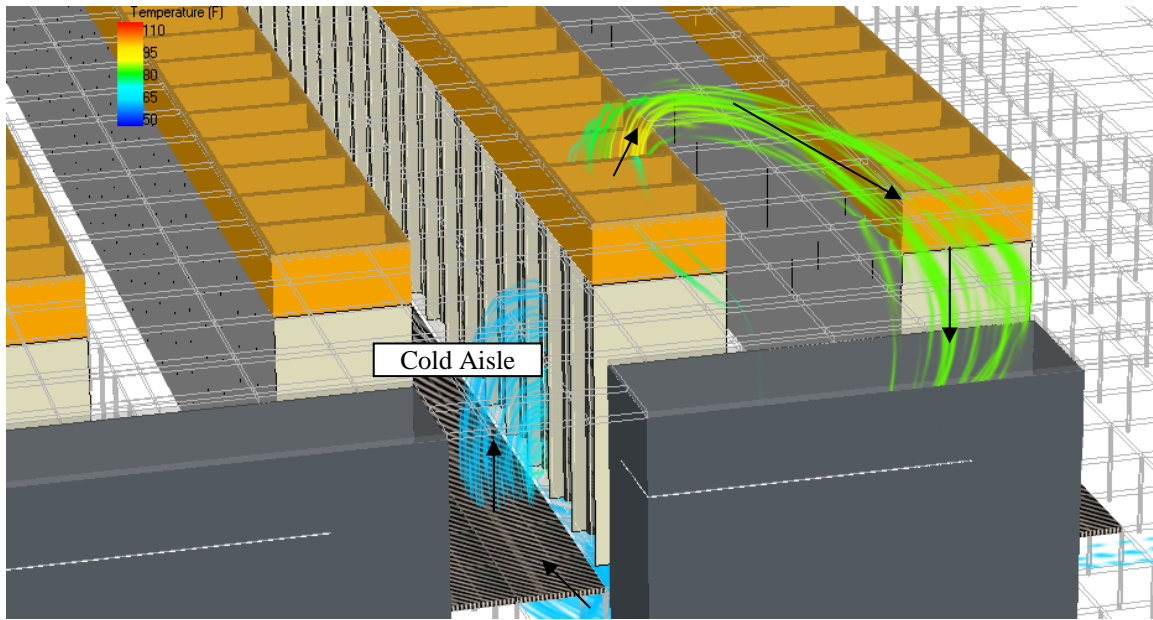


Figure 45: Cabinets Ducted to Hot Air Plenum Streamline Plot (Hot Air Plenum Shown Transparent)

The ducted path created by the blocked off back door and the duct to the hot air plenum creates high static pressures of hot air right outside the server outlets. This buildup of static pressure causes the server inlets to draw air from the backs of the cabinets, causing many servers to overheat, Figures 46 to 51. This solution does not address the problem of providing an even distribution of cold air to the cold aisle, and it does not address the problem of building up adequate static pressure in front of the server inlets. As the power density increases, the effectiveness of the ducted approach does not improve.

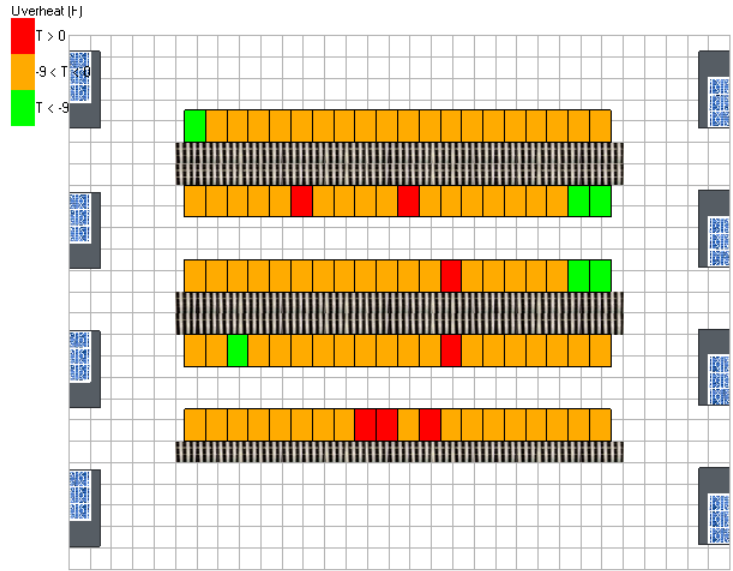


Figure 46: Cabinets Ducted to Hot Air Plenum Overheat Plot at 2kW

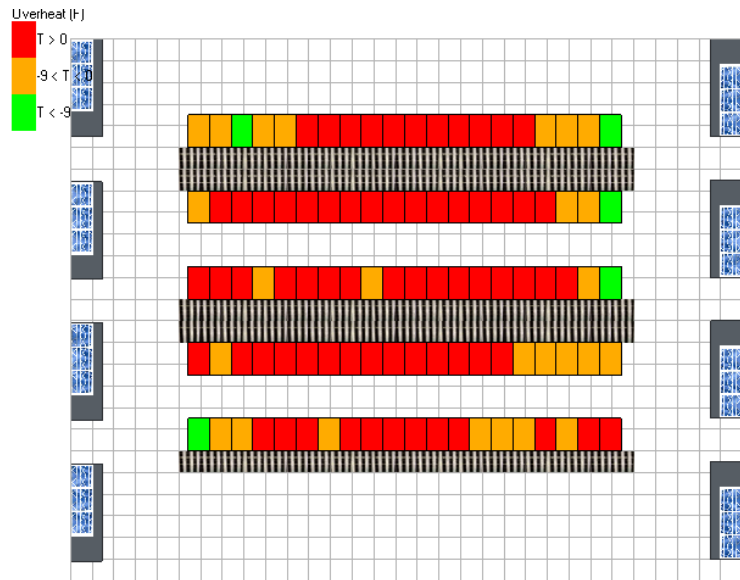


Figure 47: Cabinets Ducted to Hot Air Plenum Overheat Plot at 4kW

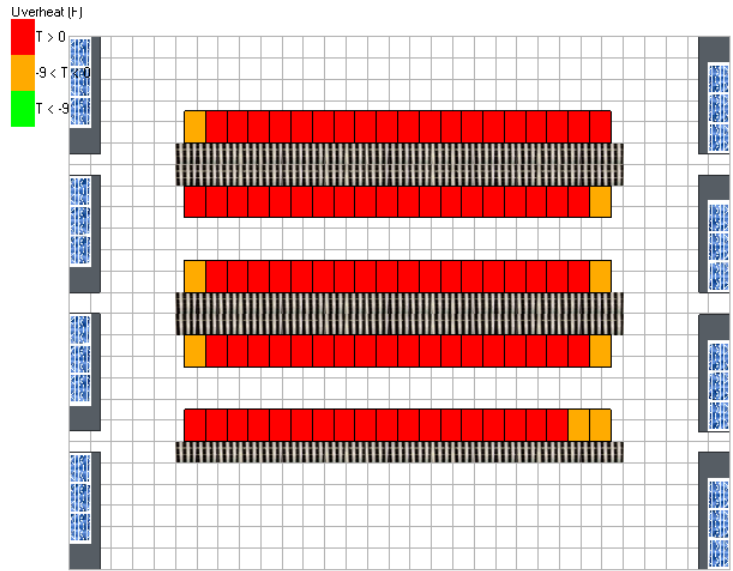


Figure 48: Cabinets Ducted to Hot Air Plenum Overheat Plot at 6kW

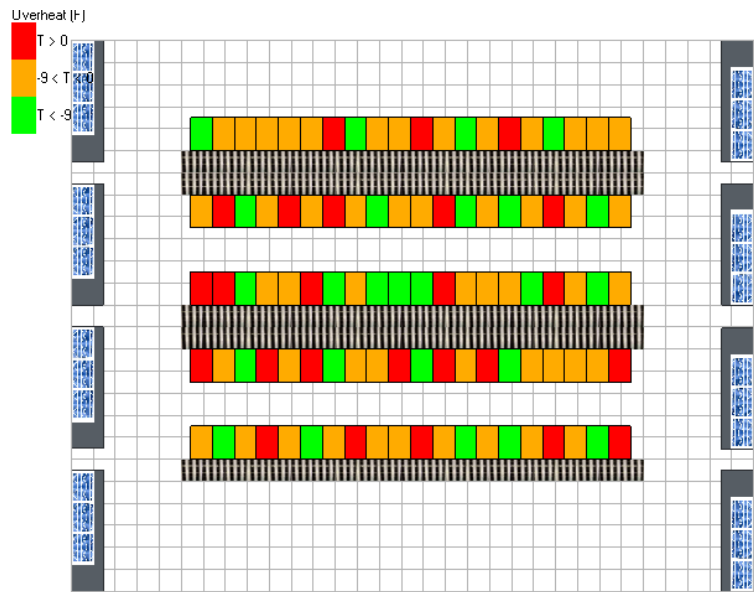


Figure 49: Cabinets Ducted to Hot Air Plenum Overheat Plot at 8kW

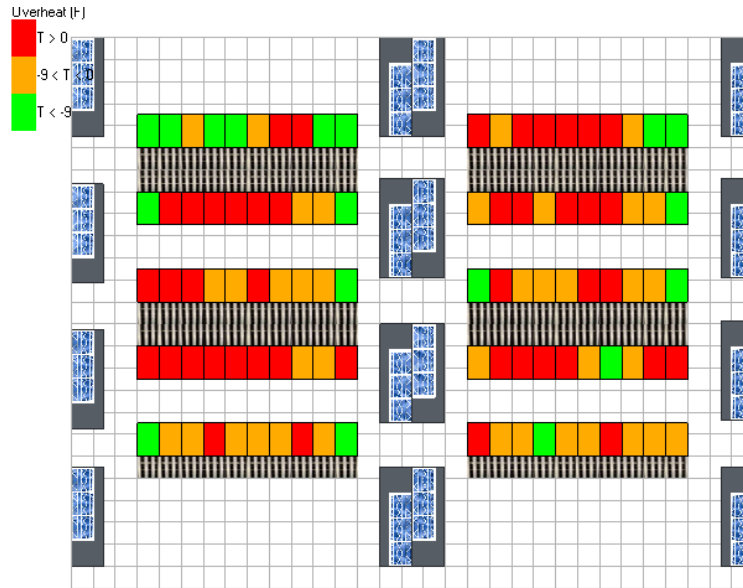


Figure 50: Cabinets Ducted to Hot Air Plenum Overheat Plot at 12kW

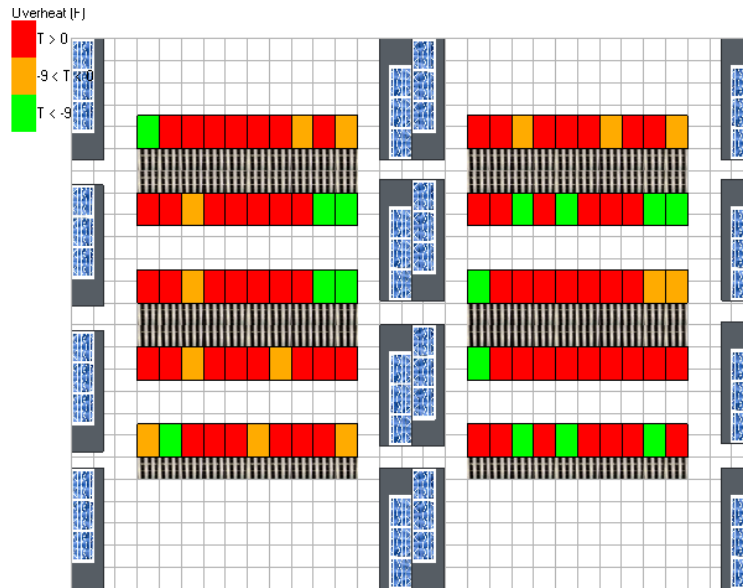


Figure 51: Cabinets Ducted to Hot Air Plenum Overheat Plot at 16kW

Chapter 5: Evaluations

5.1 Trends as Power Density Increases

It is important to find a solution that can address data center cooling at all power densities. Tables 3, 4, and 5 summarize the maximum inlet temperatures of the study at 4kW, 8kW, and 16kW, respectively.

Table 3: Summary of Performance at 4kW

Technology	Overheated Servers	Max Inlet Temperature (°F)
HACA	19	81.35
Kool-IT	0	71.16
In Row Cooling	0	76.69
CAC	1	77.64
Overhead Cooling	2	77.52
Ducted	69	85.2

Table 4: Summary of Performance at 8kW

Technology	Overheated Servers	Max Inlet Temperature (°F)
HACA	97	94.58
Kool-IT	0	74.46
In Row Cooling	0	75.04
CAC	2	78.8
Overhead Cooling	2	83
Ducted	25	90.56

Table 5: Summary of Performance at 16kW

Technology	Overheated Servers	Max Inlet Temperature (°F)
HACA	100	109.3
Kool-IT	0	62.86
In Row Cooling	0	72.3
CAC	0	65.09
Overhead Cooling	0	74.04
Ducted	71	103.3

It can be seen from this summary that for both low and high densities, Kool-It and In Row Cooling with Hot Aisle Containment technology are effective in preventing servers from overheating. Kool-IT also provides a lower maximum server inlet temperature at all power densities.

5.2 Effectiveness

The effectiveness of a technology is determined by its ability to keep data center equipment from overheating regardless of the power density of the room. As stated earlier, a server is considered overheated if the inlet temperature exceeds 77°F. Figure 52 shows the number of overheated cabinets containing overheated servers as average power density increases.

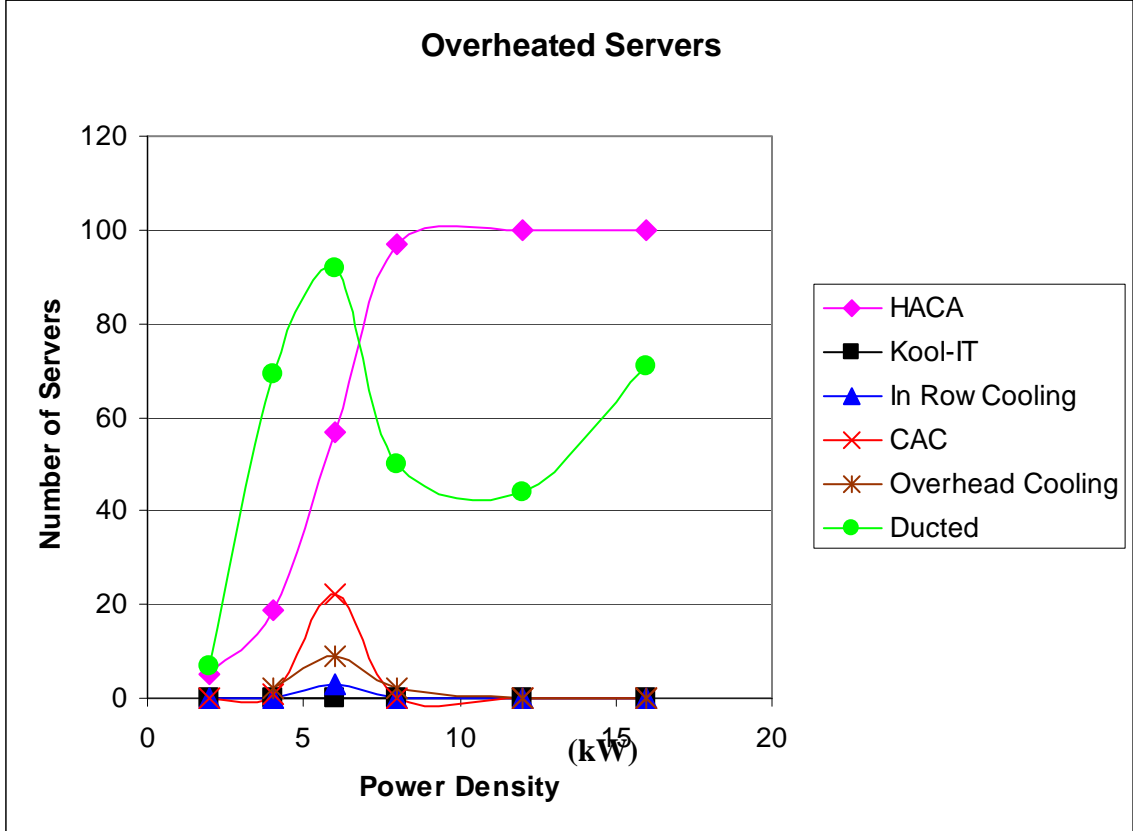


Figure 52: Number of Cabinets with Overheated Servers as Power Density Increases

It can be seen that Kool-IT, In Row Cooling, Cold Aisle Containment, and Overhead Cooling all have an advantage over HACA. As power densities increase, Kool-IT, In Row Cooling, Cold Aisle Containment, and Overhead Cooling continues to perform. Furthermore, Kool-IT does not overheat servers at any power density from 2kW to 16kW.

5.3 Performance

Figure 53 shows the maximum inlet temperature average power density increases. As can be seen, Kool-IT provides the lowest server inlet temperatures at most power densities, including all power densities below 8kW per cabinet.

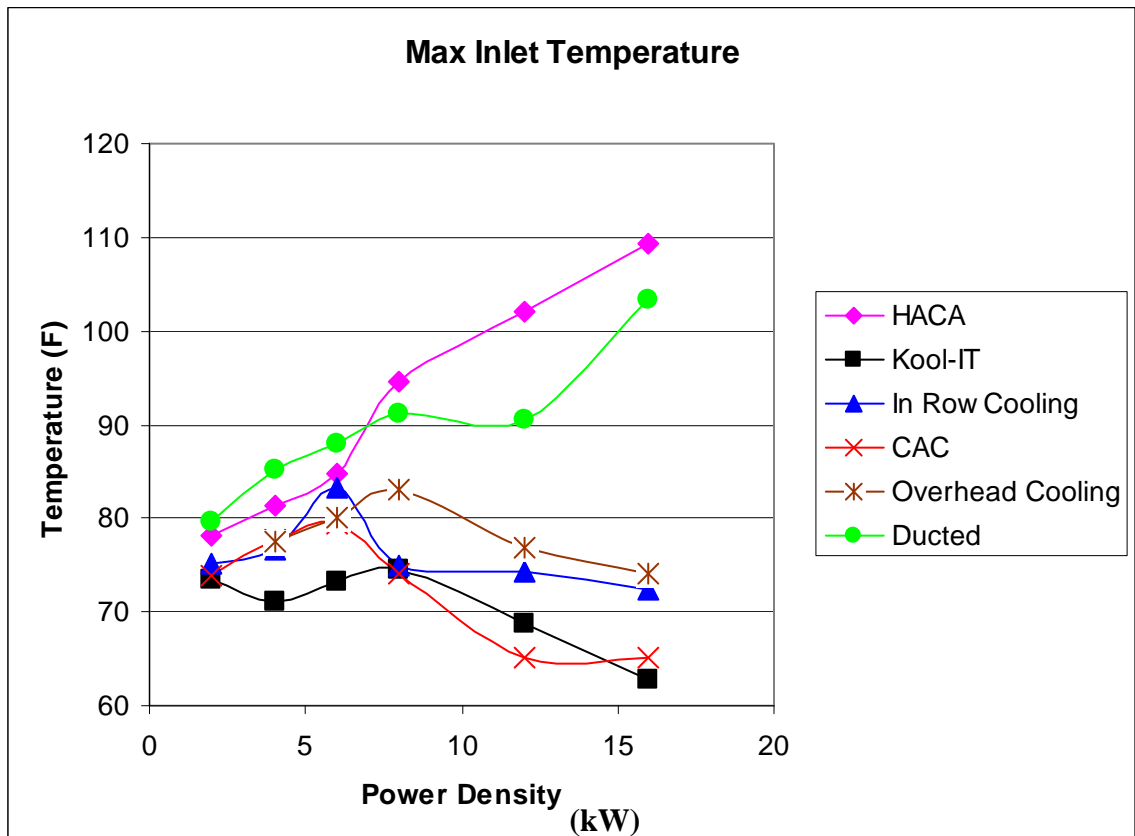


Figure 53: Maximum Server Inlet Temperature as Power Density Increases

As can be seen, Kool-IT provides the lowest server inlet temperatures for power densities below 8kW per cabinet. As noted earlier, a raise in the chilled water temperature yields an increase in vapor-compression refrigeration cycle efficiency. Technologies that provide an opportunity to raise room temperature are ones that has an opportunity for increased cooling performance. Kool-IT and Cold Aisle Containment both provide an opportunity at high power densities for server inlets to increase in

temperature while still meeting the ASHRAE guidelines. This increase in inlet temperature can be adjusted at the air conditioning unit level. An air conditioning unit that can output warmer air can use chilled water of a higher temperature, thus reducing the operational cost of cooling a data center.

5.4 Air-Flow Management

From the perspective of air-flow management, the technology which yields a more narrow distribution of server inlet temperatures is considered to be better at delivering cold air to where it is needed. This can be studied based on temperature distribution of the server inlet temperatures. Represented in Figure 54, Figure 55, and Figure 56 are histograms highlighting the distribution of server inlet temperatures for each technology at 4kW per cabinet, 8kW per cabinet, and 16kW per cabinet, respectively.

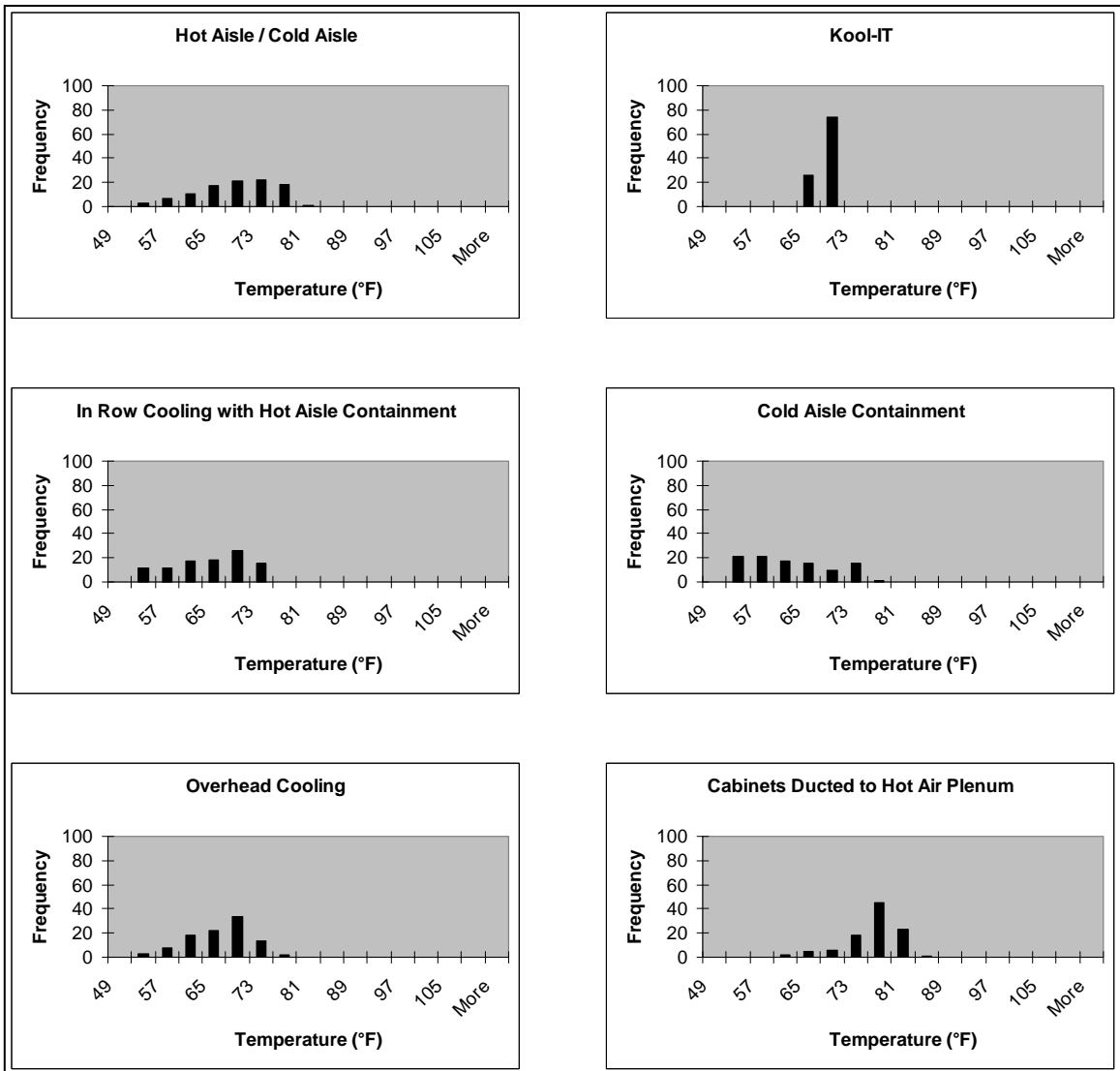


Figure 54: Histograms of Server Inlet Temperatures at 4kW per Cabinet

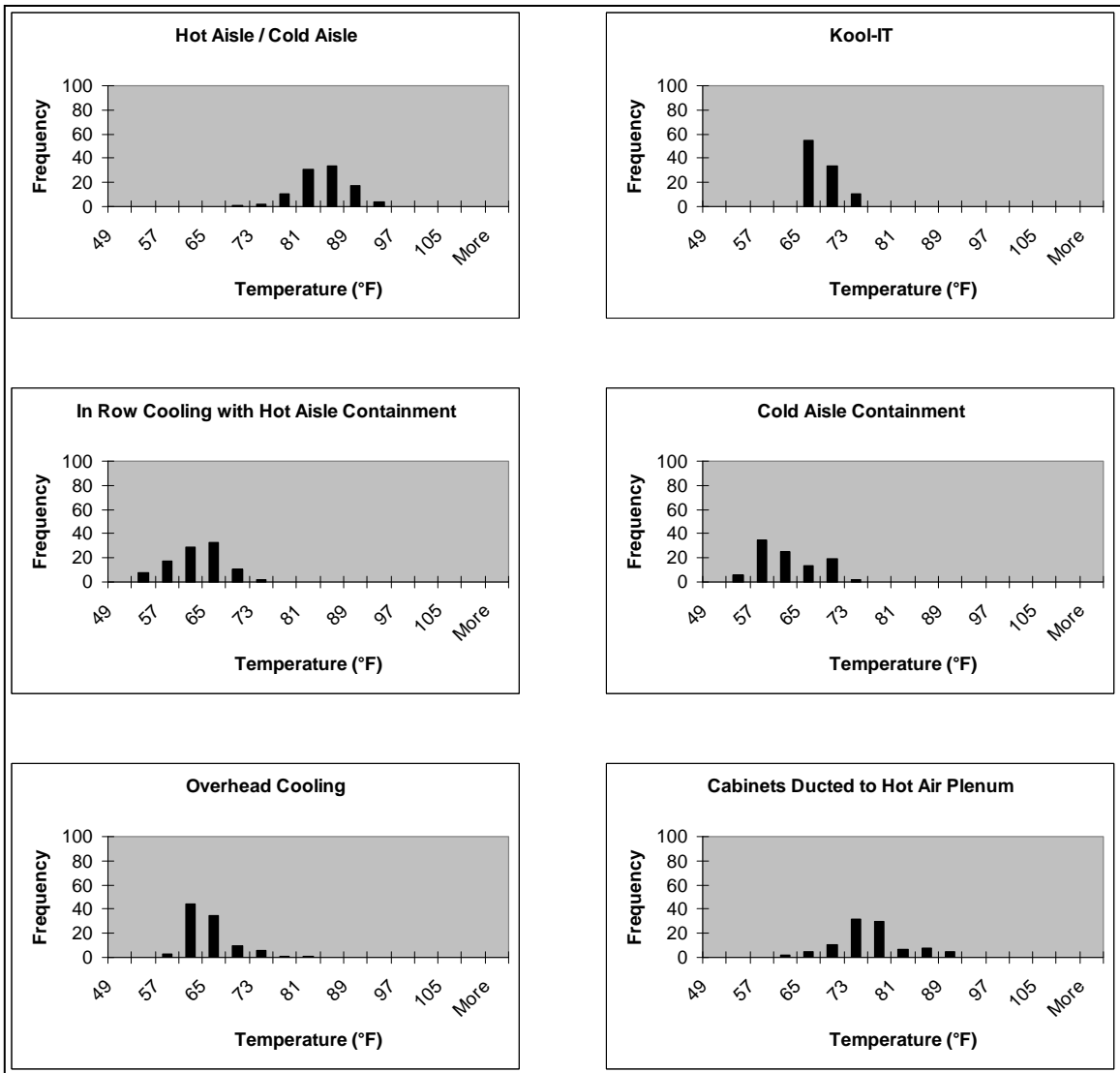


Figure 55: Histograms of Server Inlet Temperatures at 8kW per Cabinet

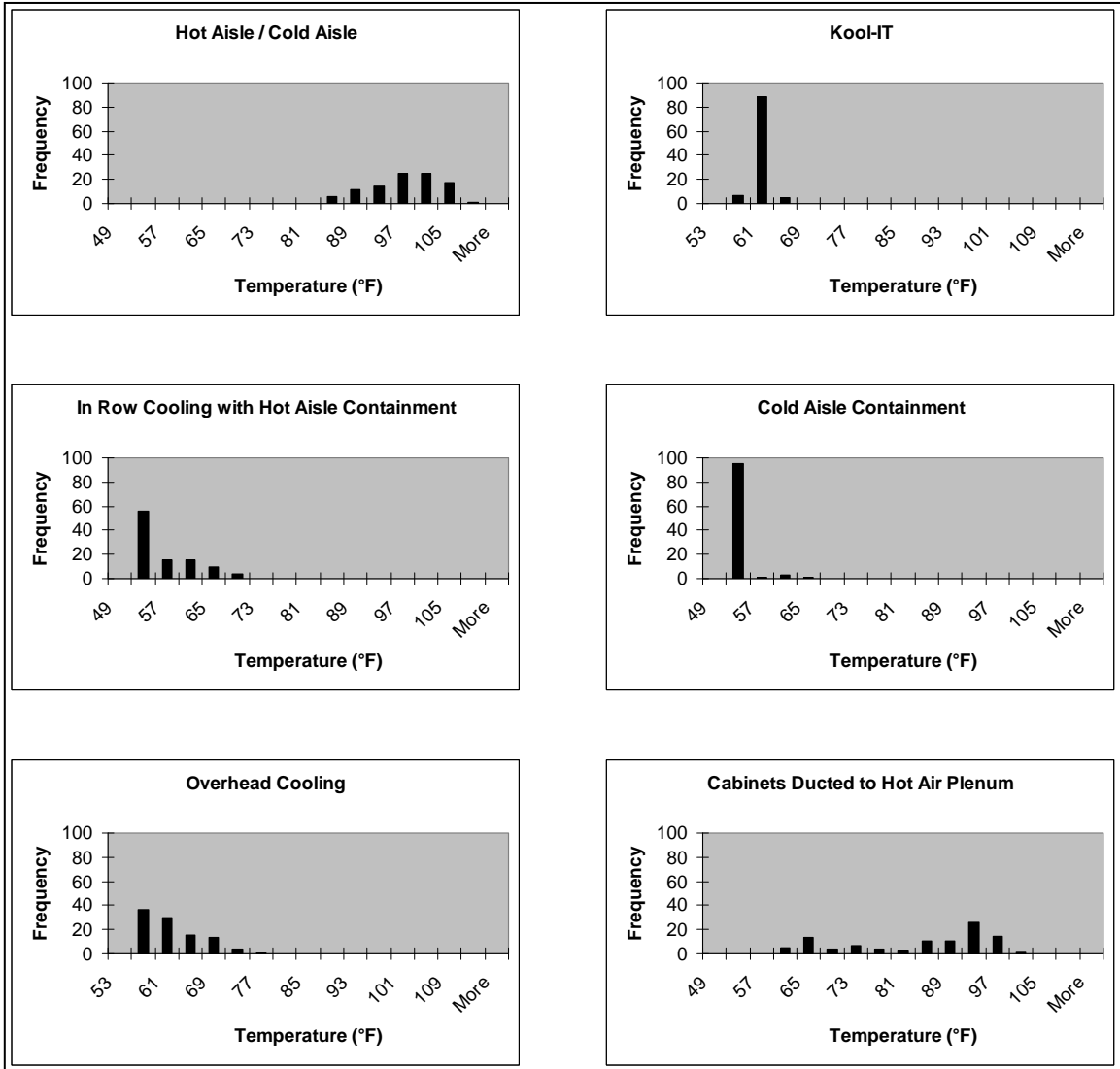


Figure 56: Histograms of Server Inlet Temperatures at 16kW per Cabinet

The technology that provides the narrowest band is considered one that best distributes cold air, giving more control to the temperature of the server inlet air. The technology that provides the coolest air is considered the one that utilizes the greatest amount of cold air from the air conditioning units, as opposed to undesirably utilizing air directly exited from the server outlets or room air that is hotter than desired. It can be seen that Kool-IT has a narrow distribution, suggesting a high level of control.

Histograms that show a wide distribution suggests that it will be difficult to keep all the cabinets within a narrow band. Because it is difficult to simulate exactly a real world data center, it is desirable to have a high level of control. It can be seen that Kool-IT, In Row Cooling, Cold Aisle Containment, and Overhead Cooling maintain a good level of both control and temperature as power density increases. Tables 6 and 7 show the averages and the standard deviations resulting from the studies done of the different technologies.

Table 6: Average Maximum Server Inlet Temperature of All the Cabinets in the Room at Various Loading Densities

	4kW	8kW	16kW
Hot Aisle / Cold Aisle	70.45	85.60	99.22
Kool-IT	69.50	69.52	58.26
In Row Cooling with Hot Aisle Containment	66.27	64.28	58.33
Cold Aisle Containment	63.89	63.41	54.65
Overhead Cooling	68.01	66.16	59.88
Cabinets Ducted to Hot Air Plenum	77.87	77.28	85.72

Table 7: Standard Deviation of Server Inlet Temperature of All the Cabinets in the Room at Various Loading Densities

	4kW	8kW	16kW
Hot Aisle / Cold Aisle	6.35	4.37	5.93
Kool-IT	0.66	2.04	1.21
In Row Cooling with Hot Aisle Containment	6.39	4.49	5.05
Cold Aisle Containment	7.01	4.93	1.83
Overhead Cooling	5.13	4.17	4.71
Cabinets Ducted to Hot Air Plenum	4.60	5.81	11.91

The standard deviation, Table 7, provides a measure of control in a given data center. A smaller standard deviation indicated that the maximum inlet temperatures of all the cabinets in the room to fall within a small predictable range, which means there is more control. It can be seen in Table 7 that the standard deviation of Kool-IT is the lowest at 4kW, 8kW and 16kW, suggesting that it has the highest level of control.

5.5 Robustness

A concern in data centers is the ability of a system to perform without being set up in an ideal fashion. It is possible for data centers to be maintained in a poor fashion. One of the ways this has been done is the disregard of ensuring each cabinet has a full set of blanking plates. Blanking plates block the flow of air inside a cabinet in spaces that are empty. Generally, a vacant area for IT equipment is filled with blanking plates.

A study was done at 12kW using cabinets in which 30% of the blanking plates have been removed. Table reports the maximum inlet temperatures.

Table 8: Maximum Inlet Temperature with Full Blanking Plates and with 30% Blanking Plates Removed

	Full Blanking Plates	30% of Blanking Plates Removed
HACA	102°F	105.8°F
Kool-IT	68.66°F	69.44°F
In Row	74.36°F	71.52°F
CAC	65.06°F	68.83°F
Overhead	76.79°F	89.47°F
Ducted	90.43°F	95.11°F

As can be seen in Table 8, Kool-IT is the least sensitive to the removal of blanking plates, having less than a degree of change. It should also be noted that In Row Containment with Hot Aisle Containment had lower maximum inlet temperatures with the removal of blanking plates. This is because equipment is distributed randomly in the room, and in some cases, allowing some leakage balances the distribution of cooling such that there are lower peaks. In data centers where there is little control over how strict maintenance is controlled and with the constant change of data center equipment, it is easy to have variations from the ideal set up in a data center (i.e. removal of blanking

plates during maintenance without replacement). Kool-IT is the most resistant to deviations in performance due to the lack of blanking plates.

Chapter 6: Conclusions

A comparison of the various studies shows that for the most part, HACA is indeed not ideal for advanced data centers. The need to provide cool air depends on having cool air available to the server inlets at an adequate static pressure. When this condition is not met, air is recirculated in an undesirable fashion, either directly from the back of the servers to the front or from the ambient room air, which may exceed the ASHRAE guideline for maximum server inlet temperature (TC9.9). The air needs to be managed better in the area near the server inlets and the server exhausts. Approaches to these include those that bring the air conditioning units closer to the servers, containing the pathways for the air, and managing the thermal environment in the room.

Two of the approaches discussed here, In Row Cooling and Cold Aisle Containment, while effective as power density increases, depends on the geometry of the aisle and the amount of air being forced into the cold aisle to build up an adequate amount of static pressure. The Kool-IT approach is effective at all power densities. Unlike the other technologies, Kool-IT is independent of the layout of the room (cabinet location relative to air conditioning units, width of cold aisle). Kool-IT technology also gives a narrow band of predicted maximum server inlet temperatures in each cabinet at all power densities, which is desirable for predictable operation of a real life data center. Kool-IT shows good resistance to performance reduction in the study where the blanking plates are removed.

References

- [1] APC, 2003, "Essential Cooling System Requirements for Next Generation Datacenters," APC White Paper #5.
- [2] ASHRAE Technical Committee 9.9, 2004, "Thermal Guidelines for Data Processing Environments", ASHRAE
- [3] Bash, C. E., Patel, C. D., Sharma, R., 2003, "Efficient Thermal Management of Data Centers - Immediate and Long-Term Research Needs", HVAC and R Research, Vol. 9, Issue 2.
- [4] Beaty, D., Davidson, T., 2003, "New Guideline for Data Center Cooling", ASHRAE Journal, Vol. 45, No. 12.
- [5] Beitelmal, A., Patel, C. D., 2007, "Thermo-Fluids Provisioning of a High Performance High Density Data Center", Distributed and Parallel Databases; An International Journal, Vol. 21, Issue 2-3.
- [6] Boucher, T., Auslander, D., Bash, C. E., Federspiel, C. C., Patel, C. D., 2006, "Viability of Dynamic Cooling Control in a Data Center Environment", Journal of Electronic Packaging, Vol. 128, Issue 2.
- [7] Cengel, Y., Boles., M., 1998, "Thermodynamics: An Engineering Approach", McGraw Hill
- [8] Chatsworth Products, Inc., 2006 "Ducted Exhaust Cabinet - Managing Exhaust Airflow Beyond Hot Aisle/Cold Aisle"
- [9] Chen, K., Auslander, D., Bash, C., Patel, C., 2007, "Local Temperature Control in Datacenter Cooling: Part I, Correlation Matrix," HP Technical Report, HPL-2006-42.
- [10] Data Center Knowledge, "Data Center Cooling Setpoints Debated", www.datacenterknowledge.com
- [11] Doty, S., 2006, "Energy Efficiency in Computing Data Centers", Energy Engineering, Vol. 103, No. 5.
- [12] Dunlap, K., Rasmussen N., 2006, "The Advantages of Row and Rack Oriented Cooling Architectures for Data Centers" APC White Paper #130.
- [13] Evans, T., 2007, "Fundamental Principles of Air Conditioning for Information Technology" APC White Paper #57.
- [14] Emerson Electric Co., 2005, "Liebert XD, Cooling Solutions for High Heat Density Applications" Liebert Technical Document.
- [15] Emerson Electric Co., 2008, "Knurr Coolflex", Knurr Technical Document.
- [16] Fulton, J., 2007, "A Strategic Approach to Datacenter Cooling" Afco Systems White Paper.

- [17] Future Facilities, "6Sigma Room",
<http://www.futurefacilities.com/software/6SigmaRoom.htm>
- [18] Garday, D., Costello, D., 2006, "Air-Cooled High-Performance Datacenters: Case Studies and Best Methods," Intel Corporation, White Paper, November.
- [19] Greenemeier, L., Zaino, J., 2003, "Concerns Heat Up Over Keeping Blades Cool," Information Week, March 10.
- [20] Hayama, H., Enai, M., Mori, T., Kishita, M., 2004, "Planning of Air-Conditioning and Circulation Systems for Data Centers", IEICE Transactions on Communications, Volume E87B, Issue 12.
- [21] HP web site, http://www.hpl.hp.com/research/dca/smart_cooling/
- [22] Juran, 1951, "Quality Control Handbook".
- [23] Kang, S., Schmidt, R. R., Kelkar, K., Radmehr, A., Patankar, S., 2001, "A Methodology for the Design of Perforated Tiles in Raised Floor Data Centers Using Computational Flow Analysis", IEEE Transactions on Components and Packaging Technologies, Vol. 24, No. 2.
- [24] Karki, K., Patankar, S., 2005, "Airflow Distribution through Perforated Tiles in Raised-Floor Data Centers", Building and Environment, Vol. 41.
- [25] Karlsson, J. F., Moshfegh, B., 2004, "Investigation of Indoor Climate and Power Usage in a Data Center", Energy and Buildings, Vol. 37.
- [26] Koplín, E., 2003 "Data Center Cooling" ASHRAE Journal, Vol. 45, No. 3.
- [27] McFarlane, Robert, 2005, "Cabinets, bloody cabinets!!",
<http://expertanswercenter.techtarget.com>
- [28] Pacific Gas and Electric Company, 2006 "High Performance Data Centers".
- [29] Pan, Y., Rongxin Y., Huang, Z., 2007, "Energy Modeling of Two Office Buildings with Data Center for Green Building Design" Energy and Buildings, j.enbuild.2007.10.008.
- [30] Patel, C. D., 2003, "A Vision of Energy Aware Computing from Chips to Data Centers", The International Symposium on Micro-Mechanical Engineering, ISMME2003-K15.
- [31] Patel, C. D., Sharma, R. K., Bash, C. E., Beitelmal, M., 2006, "Energy Flow in the Information Technology Stack: Introducing the Coefficient of Performance of the Ensemble", 2006 ASME International Mechanical Engineering Congress and Exposition, IMECE 2006-14830.
- [32] Rasmussen, N., 2008, "An Improved Architecture for High-Density Data Centers", APC White Paper 126.
- [33] Schmidt, R. R., Cruz, E. E., Iyengar, M. K., 2005, "Challenges of Data Center Thermal Management" POWER5 and Packaging, Volume 49, Number 4/5.

[34] Server Technology, Inc.

[35] Sharma, R., Bash, C., Patel, C. D., 2003, "Balance of Power: Dynamic Thermal Management for Internet Data Centers" HP Technical Report, HPL-2003-5.

[36] Shrivastava, S., VanGilder, J. W., Sammakia, B. G., 2007, "Prediction of Cold Aisle End Airflow Boundary Conditions Using Regression Modeling", IEEE Transactions on Components and Packaging Technologies, Vol. 30, No. 4.

[37] US Environmental Protection Agency, 2007, "Report to Congress on Server and Data Center Energy Efficiency"