CFD ANALYSIS OF DIRECT EVAPORATIVE COOLING ZONE OF AIR-SIDE ECONOMIZER FOR CONTAINERIZED DATA CENTER

By

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ABSTRACT

CFD ANALYSIS OF DIRECT EVAPORATIVE COOLING ZONE OF AIR-SIDE ECONOMIZER FOR CONTAINERIZED DATA CENTER

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Conventional data centers are extremely large buildings that have complex power distribution and cooling systems. These traditional brick and mortar data centers employ relatively expensive cooling systems and are inefficient. It has in turn led to an increase in construction and operational costs. Jonathan Koomey, Ph.D. of Lawrence Berkeley National Laboratory estimated that worldwide data center power consumption was 152.5 Billion kWh in 2005. In 2007, the US EPA estimated that servers and data centers, “consumed about 61 billion kilowatt-hours (kWh) in 2006 (1.5 percent of total U.S. electricity consumption) for a total electricity cost of about $4.5 billion.

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

The first part of the thesis will discuss various cooling techniques available for air-side economizer. The effect of various ambient environment conditions corresponding to different controls and/or environmental conditioning are required to optimize energy efficiency is studied. ASHRAE recommended Psychrometric chart for the operating environment is used to determine the water requirements for direct evaporative zone. In the second phase, computational fluid dynamics (CFD) analysis is performed using commercially available CFD tool, Fluent, to determine the performance of direct evaporative cooling in an air-side economizer. Various factors that affect performance of evaporative cooling, such as particle sizes of atomized water, ambient air temperature and humidity, water temperature are invested in this study.

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NOMENCLATURE

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

C_s	Concentration of the Vapor at the Droplet Surface
C_∞	Vapor Concentration of the Bulk Flow
Sh	Sherwood Number
Sc	Schmidt Number
F_d	Drag Force
F_g	Gravity Force
F_o	Other Force
v_p	Droplet Velocity
h_{fg}	Latent Heat
G_k	Generation of Turbulence Kinetic Energy
τ_{ij}	Symmetric Stress Tensor
$\mu\Phi$	Heat of Dissipation
Nu_d	Nusselt Number of droplet
RH	Relative Humidity
%	Percentage

CHAPTER 1

INTRODUCTION TO MODULAR DATA CENTERS AND LITERATURE REVIEW

1.1 Introduction to Modular/Containerized Data Centers

1.1.1 Modular Data Centers: An Introduction

Data center is a facility that contains concentrated equipment to perform one or more of the following functions: Store, Process, manage and exchange digital data and information. The compute servers that process the data and, storage servers that store data and network equipment, which is used for communications, are collectively called as “IT Equipment”. In addition to this IT Equipment, data center also houses power conversion equipment and environmental control equipment to maintain operating conditions [1].

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

Modular data center, also termed as containerized data center or data center in a box refers to a portable self-contained environment designed for rapid deployment, energy efficiency and computing density. They are portable and can be deployed much faster than a traditional data center. They are macro modules consisting of thousands or more systems. Instead of building and shipping single systems or racks of systems, the modules are built within shipping containers with all the necessary equipment, configured and shipped as a fully operational unit ready to be powered up. All that is required upon delivery is provision of power, internet connectivity and chilled water supply. Therefore, modular data centers can be deployed anywhere around the world [2].

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

Figure 1.1: Sun Microsystems Modular Datacenter: Project Black box [3]

1.1.2 Importance of Modular Data Centers and Need for Cooling

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

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

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

1.2 Modular Data Centers Description

1.2.1 Why Modular Solutions Should Be Considered

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

1.2.2 First Generation Modular Data Centers

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

1.2.3 Second Generation Modular Data Centers

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

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

Figure 1.2: SCI ICE Cube Air [4]

1.2.4 Comparison between Traditional and Modular Data Center Configurations

Table 1.1: Comparison of Primary Attributes [5]

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

1.3 Modular Data Center Considerations

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

1.3.1 Selection of Cooling Technology

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

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

1.3.2 Additional Requirements and Considerations

Deployment of modular data centers depends on several additional requirements such as availability of maintenance and service in the instance of failure of cooling system components such as fans, filters and control systems. Cooling units using refrigerants require more maintenance to those of which use water. Control systems which are used for monitoring the devices should be compatible with existing building management, power management and energy management systems. Failure of even one such management system can lead to loss of considerable amount of data. These modular data centers must be in close proximity to existing power and chilled water distribution systems. Fire suppression systems and smoke detection systems should be installed and periodically monitored to avoid hazardous situations [5].

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

Where modular units with air side economizers are used, module orientation with respect to wind direction will improve free cooling and energy efficiency [5].

1.3.3 Attributes of Modular Data Centers

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

Advantages of energy efficient modular data centers are [5]:

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

1.3.4 Power Usage Effectiveness: Metric for Energy Efficiency

Power usage effectiveness (PUE) is a standard/metric developed by The Green Grid consortium in order to determine energy efficiency within a data center [6]. Since power and cooling are two of the biggest challenges in data centers, companies require different solutions to reduce costs and maximize energy efficiency. By doing so, companies can increase computing; achieve lower energy costs and reduce the total cost of ownership (TCO) [7].

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

PUE = Total Facility Power/IT Equipment Power

Total facility power includes all the components which support the IT equipment load such as power systems like generators, UPS systems and batteries and power distribution units, cooling systems such as chillers, cooling towers, computer room air handling units (CRAHs), mechanical components such as compressors and condensers, pumps and direct expansion systems [8].

The IT equipment power includes the IT equipment load such as computing and storage devices (servers), network equipment and other additional devices such as computers, workstations and laptops and KVM switches which are used for monitoring and controlling the data center [8].

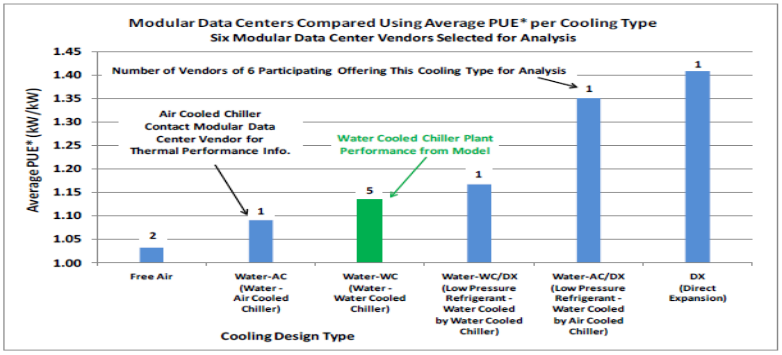

Figure 1.3: Example of PUE Comparison for Different Cooling Designs [5]

1.4 Literature Review

1.4.1 Modular Data Center Technologies

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

Schmitt et al. [9] patented an enclosure comprising of a processing subsystem and infrastructure subsystem in separate shipping containers which cooperate to process information between each other. The processing subsystem houses the information handling systems in one shipping container and the infrastructure equipment is housed in the second shipping container. These shipping containers are arranged in a stacked configuration as a result of which the cooled air and exhausted air are exchanged through vents located in the ceiling and floor of the stacked shipping containers. The intake and exhaust vents of the processing subsystem are located in a floor and the processing subsystem container rests on top of the infrastructure subsystem shipping containers. Chilled water is provided from an external source to the infrastructure subsystem shipping container through coil assemblies.

Jimmy Clidaras et al. [10] developed a solution for modular data centers which includes a connecting hub and a plurality of containers. The connecting hub in turn may have a plurality of docking stations to which the containers are connected and powered up. The connectivity hub is configured with each of these docking stations in order to supply electrical power, network connectivity, cooling fluid supply and cooling fluid return. The docking station of each container is attached to a central power spine. Each shipping container would include a number of processing units or servers. The cooling technology adopted includes a first heat exchange circuit where heat is transferred from the servers to a heat exchanger and a second heat exchange circuit comprising of the heat exchanger, cooling fluid supply and cooling fluid return so that heat is transferred from the heat exchanger inside the container to an external system using cooling fluid through the cooling fluid supply and cooling fluid return. The docking stations which connect to the spine would receive the cooling fluid from the cooling fluid supply, and discharge return cooling fluid to the cooling fluid return.

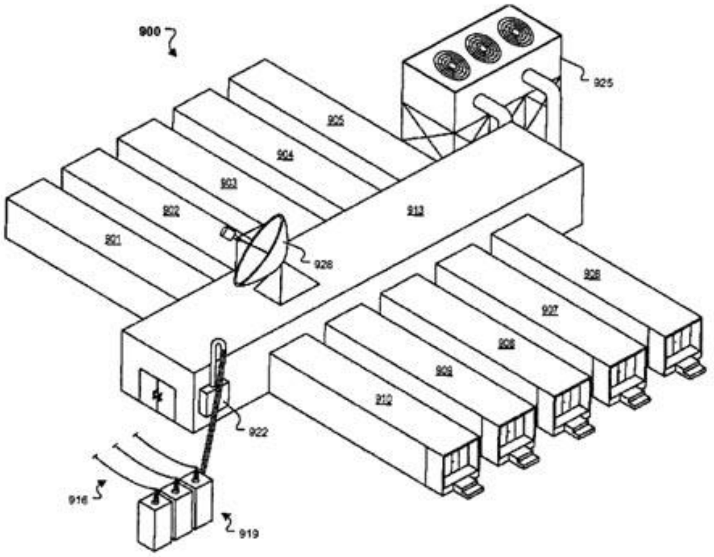

Figure 1.4: Containerized Data Centers with a Connecting Hub by Google [10]

Jimmy Clidaras et al. [10] also indicated that another solution for modular data centers would include stacking shipping containers one above the other which would also include a facility level cooling system.

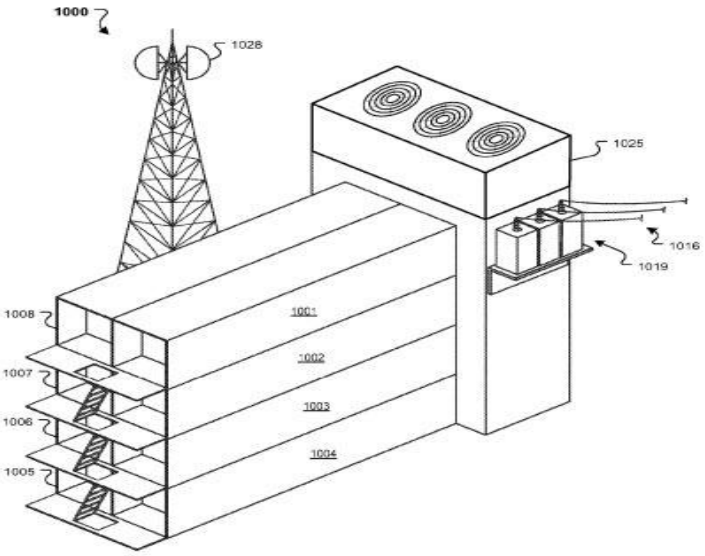

Figure 1.5: Stacked Data Center Containers by Google [10]

Hewlett Packard's Performance Optimized Data Center [11] also known as the EcoPOD features two 40-foot containers joined together in order to increase expansion capacity. This modular design uses outside air as the cooling mechanism. The EcoPOD can house 44 racks of IT equipment and includes two cold aisles and an 8-foot hot aisle due to the wider design. Apart from the use of outside air, the cooling module also features a direct expansion cooling system and depending on environmental conditions and heat load, the cooling module can automatically adjust to use ambient air and switch to direct expansion cooling during a warmer climate. The EcoPOD modular design has an expected Power Usage Effectiveness rating of 1.05 to 1.30.

Figure 1.6: Hewlett Packard Performance Optimized Data Center [12]

Figure 1.7: Cisco Containerized Data Center [13]

Cisco's Containerized Data Center [13] is a 40-foot container which uses chilled water cooling technology. The containerized data center can house 16 racks, each with 44 rack units and is capable of supporting up to 25 kilo watts. Each rack in the container has a sensor that controls and monitors rack inlet and exhaust temperatures, humidity, coolant leaks, rack cooling fans and rack coolant flow rates. [14]

Brewster Kahle, founder of the Internet archive, studied and applied the containerized transport and delivery approach to data storage. Kahle proposed and built the Petabox [15] which is a storage subsystem supporting a petabyte of storage in a standard shipping container that could be efficiently deployed and transported anywhere in the world. Rackable systems [15] focus primarily on power and cooling of standard 40 foot shipping containers in order to achieve power densities as high as 750 watts/sq ft and achieve cooling savings approaching 30%. The Rackable systems containerized data center design houses 1,152 systems.

The Sun Microsystems modular data center [16] is designed to cool up to 200 KW of load with 22 KW reserved for its own infrastructure and external solar loading in high temperature conditions. Hence, it is capable of supporting up to 178 KW of equipment load. The Sun modular data center has eight 19 X 32 inch standard racks with 40 rack units per rack. The outer surface of the modular data center is designed to operate in environmental conditions where in the temperature ranges from -20°F to as high as 130°F with a relative humidity of 100 percent. The container is designed to withstand inside operating temperatures ranging from 50°F to 95°F with a relative humidity between 20 to 80 percent. The Sun modular data center uses chilled water for cooling with two redundant chilled water attachments. Heat exchangers are used for distribution of cooling between equipment racks. A heat exchanger is placed between each pair of racks and contains cooling coils and ten variable speed fans. Each of the fans has a maximum operating capacity of 1100 CFM. Filter banks provided at one end restrict the entry of particulate matter. The heat exchanger fans run at only 20 percent in order to maintain cooling resulting in major energy savings.

CHAPTER 2

FREE AIR COOLING FOR AIR SIDE ECONOMIZER

2.1 Introduction to Free Cooling

2.1.1 Introduction

Servers have become an integral part of today's computational world. They are the source for data storage and enormous computational power. Data centers have become the source for housing and powering large volume of servers. Until recently, the performance of processors and servers in terms of energy and power utilization has been of less concern compared to their computational performance. Although the initial capital for these powerful servers has become comparatively cheaper due to Moore's law and lower manufacturing prices [17], operating these devices for longer and continuous durations require significant amount of energy. Consumers are demanding higher server performance due to increased computing power at the chip level. Although these devices have become extremely efficient in terms of computational output per watt, however due to high performance, it has led to an increase in power density. Continuous operation of these devices leads to the generation of a large amount of heat. One of the major goals is to reduce the power usage effectiveness in order to improve efficiency of data centers. The average power usage effectiveness value ranges between 2 and 2.5. Cooling systems play a very important role in removing heat from server racks, but require significant amount of power. This has caused an increase in electricity and as a large amount of energy is required for cooling systems.

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

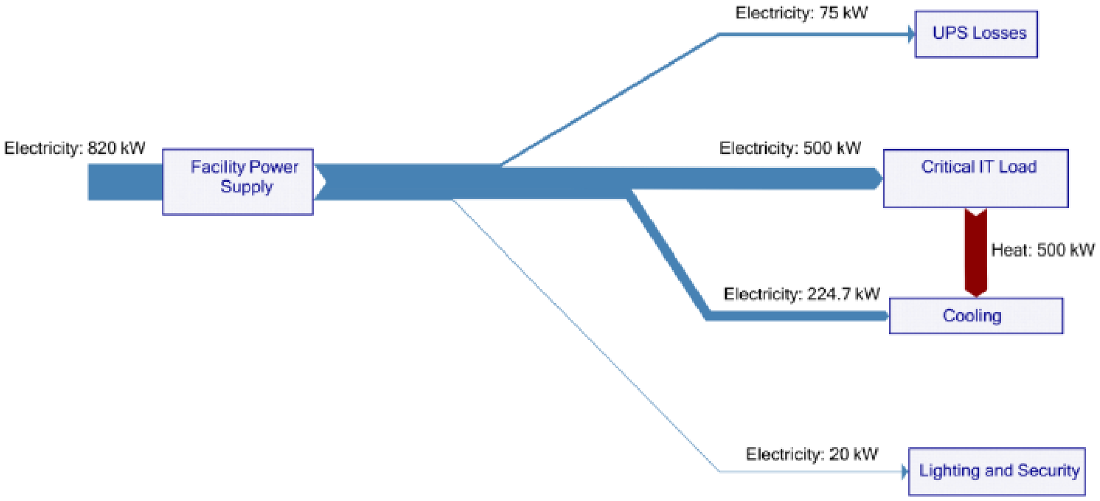

Figure 2.1: Data Center Energy Flow Diagram [18]

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

2.1.2 Free Cooling Definition

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

2.1.3 Types of Free Cooling Systems

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

2.1.3.1 Air Side Cooling

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

2.1.3.1.1 Air Side Economizers

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

A study by Shehabi et al. [19] compares the energy implications of conventional data centers with newer technologies employing waterside and air side economizers in five different climate zones in the state of California. They report that airside economizer performs consistently better in all climate zones. In fact according to another study by Syska Hennessy Group [20], outside air can be used for almost entire year in San Francisco.

Intel's proof of concept test [21] has provided good insight on air side economizers. Intel IT used 900 production servers which ran at very high rate of utilization. This high density datacenter used 100 percent air exchange at 90°F and without any humidity restrictions. The filtration was kept at minimal level. It was estimated that with the economizer in use 91 percent of the time, nearly 67 percent of energy can be saved. The proof of concept test also illustrated that no significant rise in failure rates were observed when air side economizer is used.

Intel has also conducted experiments on the implementation of air side economizers in New Mexico. The test setup consisted of many servers more than two years old which were housed in two experimental data centers. Each of them comprised of 8 racks with 4 blade chassis. The server inlet temperature was closely controlled at 20°C and with good filtration. The economizer was controlled to bring in outdoor air at 18°C and maintain the server inlet temperature by recirculating the hot exhaust air with the cold incoming air. DX cooling units were also used in case environmental conditions reached higher temperatures. It was estimated that an air side economizer would require only 26.9 percent of the energy removal as a fully closed system which would result in significant energy savings. The testing revealed that using the new ASHRAE recommended temperature and humidity ranges coupled with air side economizers and DX cooling systems would yield significant operational savings. Also, the use of ASHRAE standard 52.1-92 rated filters at 85 or 95 percent would ensure efficient filtration using air side economizers. [22]

A few suggestions made by Ron Spangler of Emerson Network Power are that air side economizers can save about 50 to 60 % of total power savings considering the CRAC units with the system as a whole. These savings would vary depending on the city and environmental conditions. Air side economizers provide about 60 % savings in moist coastal climates such as Portland Oregon. [23]

Saket et al. [24] studied the effect of air side economizers for various cases. Numerical models were designed and analyzed to determine their performance at various operating conditions. Four different scenarios were analyzed where the first configuration included a conventional data center with CRAC units and an under floor plenum supply. The remaining three configurations comprised of air side economizers for bringing in outside air into the data center. For all four scenarios, the system dimensions were the same and the parameters such as heat load, flow rate, rack layout and percentage open area ratio for the tiles remained the same. The results indicated that substantial energy savings can be made using air side economizers. The three scenarios where air side economizers were used yielded better results as compared to the model with the CRAC unit.

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

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

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

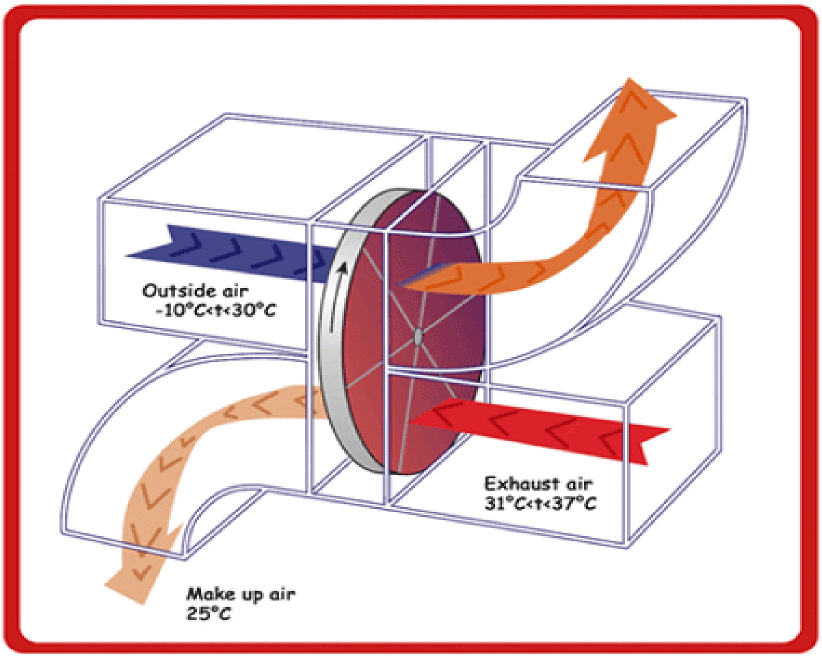

Figure 2.2: Diagram of Thermal Wheel or Rotary Heat Exchanger [25]

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

2.1.3.2 Water Side Cooling

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

2.1.3.2.1 Direct Water Side Systems

Water side economizers are an example of direct water side systems. These systems eliminate need for cooling via compressors and condensers by physically interconnecting the chilled water and condenser circuits. During favorable environmental conditions (free cooling operation), the heated water or warm return water is redirected to the economizer where the heat is rejected outside by a cooling tower or dry cooler. The return water is filtered, treated and cooled back to the desired temperature and returned to the chilled water supply. The advantage of direct water side systems is that they can significantly reduce energy usage. Direct water side systems require high maintenance in order to prevent dirty return water circulating back to the chilled water interconnects which could cause fouling of chilled water circuits leading to corrosion and blockage [26].

2.1.3.2.2 Indirect Water Side Systems

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

2.1.4 Miscellaneous Free Cooling Systems

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

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

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

Google Inc. has come up with an innovative approach to use sea water cooling for its Hamina data center in Finland where raw sea water is pumped into a sea water tunnel built for an existing paper mill. The sea water is cleaned and filtered through a sequence of operations and sent to a water to water heat exchanger where it cools a separate water loop in order to cool the data center. The warmer sea water is sent back to a tempering building where it is mixed with fresh incoming sea water so that when it is returned back to the gulf, the temperature is approximately similar to that of the inlet temperature. In doing so, Google aims to minimize any environmental impact [27].

2.1.5 Conclusion

Each of the above mentioned free cooling techniques require certain environmental/ambient conditions to operate in except evaporative cooling. If such conditions are available for each of these free cooling technologies to operate, then they can reduce energy consumption taken up by mechanical systems such as compressors. That is why for this study, evaporative cooling techniques is being investigated.

2.2 Evaporative Cooling

Conventional cooling systems operate on a refrigeration cycle, and they can be used in any part of the world. But they have a high initial and operating cost. In desert (hot and dry) climates, we can avoid the high cost of cooling by using evaporative technique, also known as mist cooling, spray cooling or evaporative cooling. Evaporation is a type of vaporization of a liquid that occurs only on the surface of a liquid. The other type of vaporization is boiling, which, instead, occurs on the entire mass of the liquid [28].

2.2.1 Evaporation Principle

Evaporative cooling differs from typical air conditioning systems which use vapor-compression or absorption refrigeration cycles. For molecules of a liquid to evaporate, they must be located near the surface, be moving in the proper direction, and have sufficient kinetic energy to overcome liquid-phase intermolecular forces. Only a small proportion of the molecules meet these criteria, so the rate of evaporation is limited. Since the kinetic energy of a molecule is proportional to its temperature, evaporation proceeds more quickly at higher temperatures. As the faster-moving molecules escape, the remaining molecules have lower average kinetic energy, and the temperature of the liquid, thus, decreases. This phenomenon is also called evaporative cooling [29].

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

Evaporative cooling is a common form of cooling buildings for thermal comfort since it is relatively cheap and requires less energy than other forms of cooling. Evaporative cooling is a reliable and energy efficient system than refrigeration system. Here are some pros and cons of evaporative cooling system [28].

Evaporative Cooling Pros:

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

Evaporative Cooling Cons:

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

2.2.2 Types of Evaporative Cooling Techniques

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

2.2.2.1 Direct Evaporative Cooling

- Traditional Evaporative Cooing

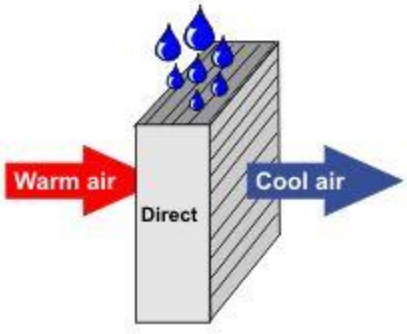

Figure 2.3: Diagram of Direct Evaporative Cooling [28]

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

As shown in figure 2.4, U.S map showing climate zones suitable for direct evaporative cooling. Map is based upon wet bulb temperatures at 1% design conditions. Evaporative coolers would work best in the dry climates (areas marked A), may work somewhat in the areas marked B. However, in the eastern parts of the country, other types of air conditioners should be used.

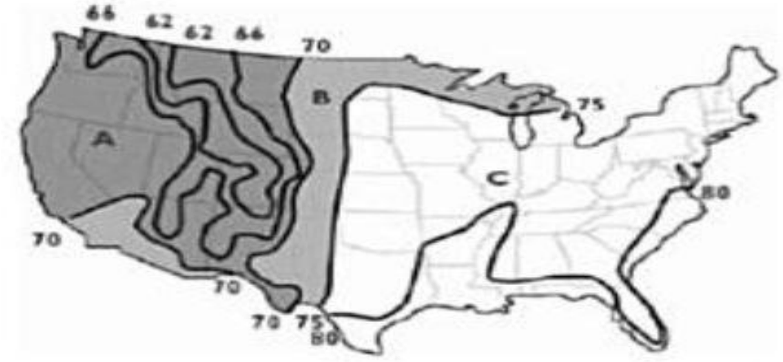

Figure 2.4: U.S Geological Survey Map [29]

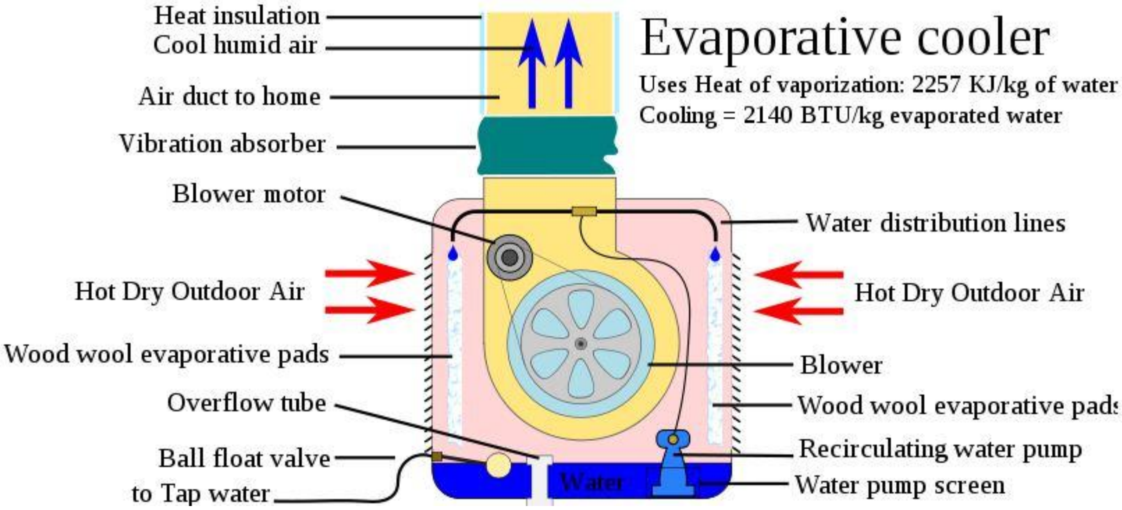

Figure 2.5: Diagram of Typical Direct Evaporative Cooler [30]

The presence of a media type evaporative cooler inherently creates a pressure drop and this will create a drop in blower output. Increases in inlet duct differential pressure will cause a reduction of blower mass flow and also operating pressure. This factor is important when considering the application of any inlet technology such as evaporative cooling system, refrigeration etc [31].

- Direct inlet Fogging

Figure 2.6: Diagram of Inlet Fogging Cooler [30]

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

A comparison between traditional and direct evaporative cooling is shown in Table 2.1.

Table 2.1: Qualitative Comparison Between Traditional Evaporative Cooling and Inlet Fogging

	Traditional Evaporative Cooling	Direct Inlet Fogging
Need for high quality water	Not required particular kind of water	Demineralized water is a must
Incremental inlet Delta P	Higher	Low – practically nil

Table 2.1 – Continued

Size foot print	Large	Small
Effectiveness	0.85 to 0.9	0.97 to 1.0
Maintenance	Higher	Comparatively lower
Aux power consumption	Requires pump	High pressure pumps needed
Sensitivity to relative humidity	High	Lower
Installation down time	Extended outage	Can be done in 2-3 days

2.2.2.2 Indirect Evaporative Cooling

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

Here is sequential explanation of indirect evaporative cooling system.

1. Hot outside air is blown through a heat exchanger that is supplied with water. One design for this type of heat exchanger features a series of metal tubes that are kept wet on their outside surfaces. As hot air passes over these tubes, the water evaporates and the tubes are cooled. After passing over the tubes, the cool, moist air is exhausted to the outside.
2. As cooling happens on the heat exchanger’s exterior surfaces, hot exterior air is drawn through the tube interiors. This air is cooled, but without gaining any extra humidity, before it is blown through ductwork to the building interior.

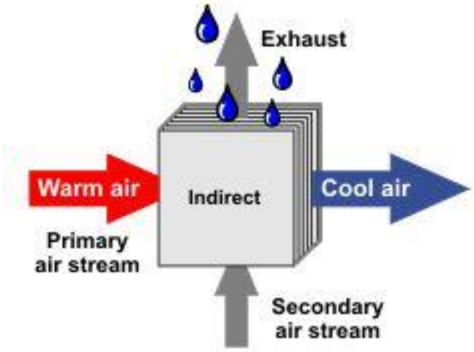

Figure 2.7: Diagram of Indirect Evaporative Cooling [28]

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

CHAPTER 3

CONTAINERIZED DATA CENTER WITH EVAPORATIVE COOLING

3.1 Introduction to Containerized Data Center

3.1.1 Introduction

Data centers are becoming one of the single largest industrial energy users consuming 61 billion KW of power in the US alone which is almost 1.5 percent of all electricity consumption. Nearly about 30 percent of this energy is being utilized by cooling system and approximately 40 percent is being utilized by IT servers is shown in figure 3.1 [31]. Thus, the energy consumption of cooling system and servers is depending on several parameters, including ambient conditions and system economizer configuration.

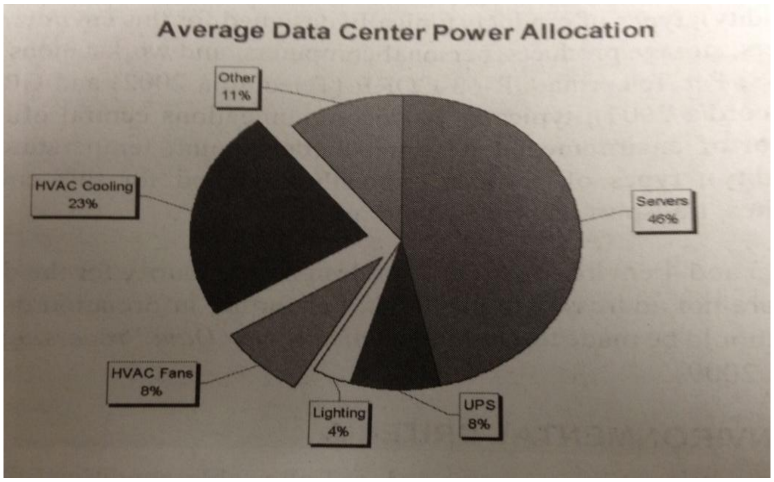

Figure 3.1: Energy Consumption Distribution of Data Center [31]

Cooling is one of the key issues which are being addressed globally for data center cabinets. Cabinets are an important part of the data centers air flow management design and they have a major impact on the thermal performance. Air and liquid cooling are some of the common methods which have been incorporated for data center cooling. Liquid cooling is very efficient, however, requires an enormous volume of water to cool high density servers. According to a US geological survey, 39 percent of the water is consumed for power production alone in the United States. Also, liquid cooling is relatively expensive and less energy efficient compared to free cooling. With growing demands of power in the IT industry, several efforts is being made to improve the “Power Usage Effectiveness” (PUE) through use of the air-side economization, also known as “free cooling”. Air-side economizers bring in large amounts of ambient air to cool the internal heat loads when weather conditions are favorable and result in substantial monitoring savings that drives the cooling resources. However, if ambient air properties are not suitable to cool the information technology (IT) equipment directly, ambient air needs to be conditioned before entering the IT equipment. One method of conditioning outside air is to use direct evaporative cooling (direct inlet fogging) which sprays atomized water as air passes through an evaporative cooling zone.

3.2 System Configuration of Containerized Data Center

In this study, design specification for containerized data center is provided by CommScope Inc. is illustrated in figure 2.8. The size of the container is 50ft (L) x 40ft (W) x 10ft (H) and divided mainly in four parts. Front part is allocated for power cooling module, other two parts are for IT servers and last part reserved for cold air plenum. This container provides cooling solution for IT servers through free cooling, when ambient condition is favorable, as well as through direct evaporative cooling or adiabatic cooling, when ambient conditions are harsh ($T_{ambient} > 27^{o}C$). There is also provision for mixing of cold air and exhaust hot air when ambient air is colder than the ASHRAE recommended range ($T_{ambient} < 17^{o}C$). The estimated PUE with the free and adiabatic hybrid cooling system is 1.10 or less.

3.2.1 Power Cooling Module

The purpose of this study is to investigate the CFD analysis of direct evaporative cooling zone that is why power cooling module is our area of interest. Figure 2.9 shows the photograph of power cooling module which has dimension of 40ft (L) x 12ft (W) x 10ft (H). As you can see in the figure, the opening for the air intake is 12ft (W) x 10ft (H). Power cooling module contains series of MERV11 or MERV14 filters, matrix of nozzle for adiabatic cooling, spray mist eliminator media for capturing the water droplets , bank of variable speed fans, water tanks and pumping system for adiabatic cooling, and three flywheel UPS for power backup.

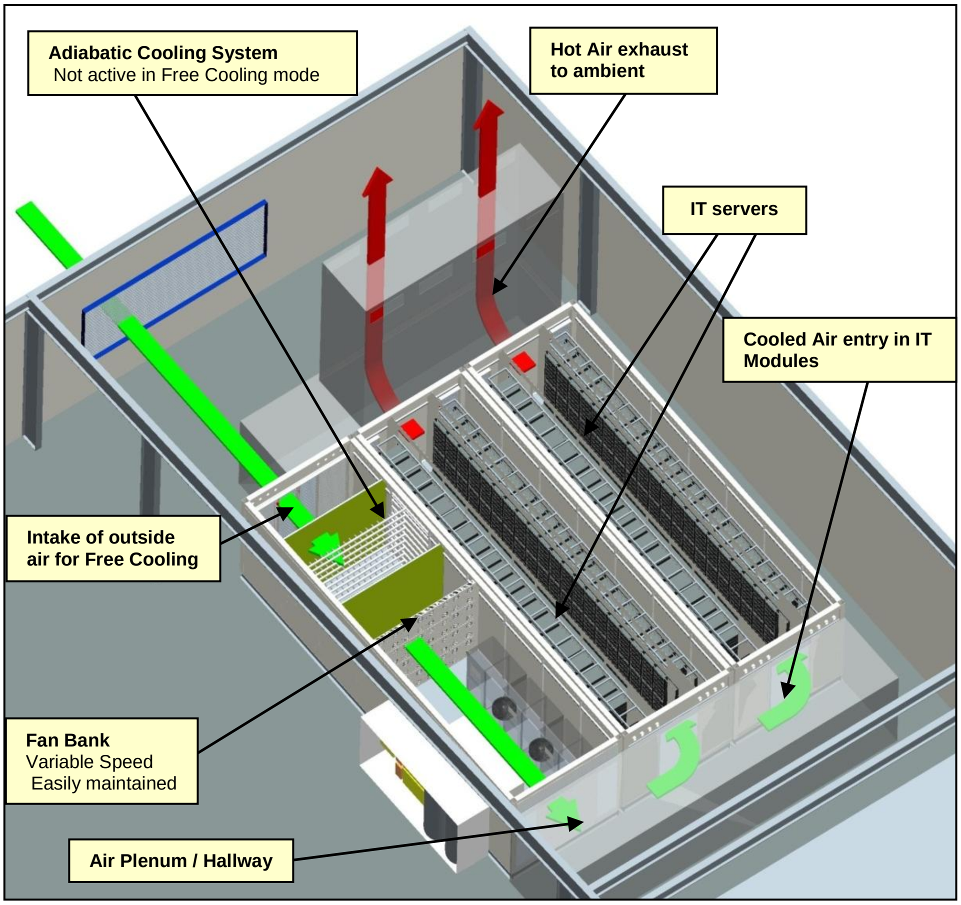

Figure 3.2: System Description of Containerized Data Center

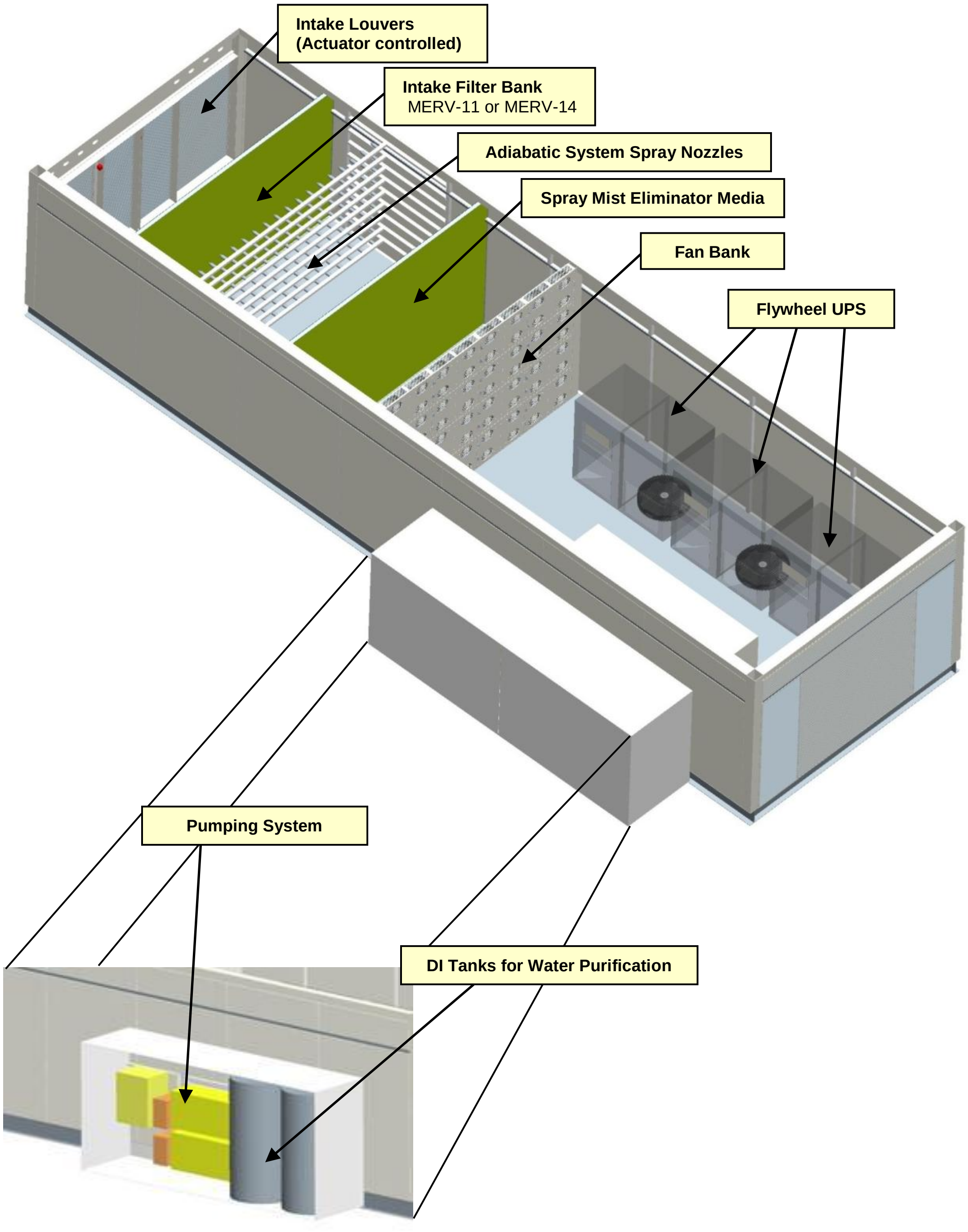

Figure 3.3: System Description of Power Cooling Module

3.2.2 Airflow Overview

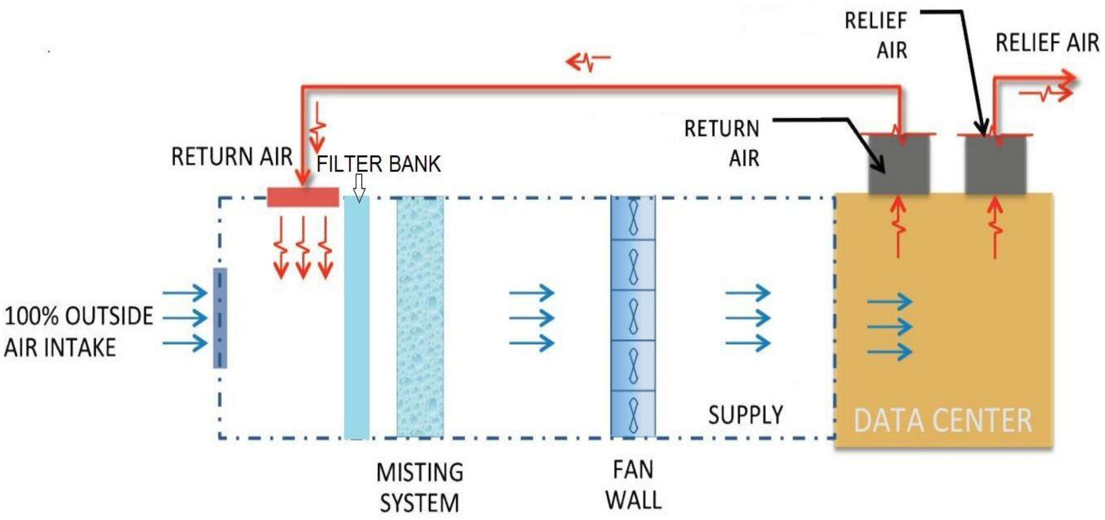

Figure 3.4: Diagram of Airflow Pattern In Power Cooling Module [32]

1. Outside air enters through vertical drainable louvers in the container.
2. The outside air may mix with data center return air (when outside air is too cold) and passes through the filter bank.
3. Air enters the evaporative cooling zone and may get sprayed by the misting system.
4. Then air passes through mist eliminators to prevent water carryover.
5. Now, cold and humidify air enters the supply fan area, and gets pushed down the supply air openings to the container cold aisle.
6. The air enters the front of the server cabinets, passes to the contained hot aisles, which then enters the return air plenum. The air then is returned back to the filter room or exhausted out of the building by natural pressure and/or relief fans.

3.3 Power Cooling Module Functions and Features

The power cooling module is designed to provide the following functions and features.

3.3.1 Filters

MERV11 (ASHRAE 80%) cartridge filters with low initial pressure drop and high dust loading capability will be provided. The size of the filter is 2ft (W) x 2ft (H) and thickness of the filter is 4inch. The filter can be upgraded to MERV14 (95% ASHRAE) if outside environment is polluted. However, the pressure drop increases from 0.23 inch H_2O at 500 FPM to 0.43 inch H_2O.

Figure 3.5: Diagram of MERV11 Filter [33]

3.3.2 Spray Nozzles

The nozzles are key component for inlet fogging cooling (evaporative cooling system) because generation of fog is depend on the type of nozzle will be used. For this study, MeeFog IP-16 impaction pin nozzles are used, have an output of 16 pounds per hour (lb/hr) or 0.032 gpm and at an operating pressure of 1000 psi as shown in figure 3.6. Diameter of the nozzle opening is 0.006 inch which produces billions of ultra-fine droplets per second. At an operating pressure of 1000 psi, the resulting average droplet size is far below 25 microns in diameter, about one-fourth the size of a single strand of hair. DV90 diameter is less than 25 microns; meaning 90% of the water mass flow is in droplets that are 20 microns or smaller. The average droplet size is 5 microns.

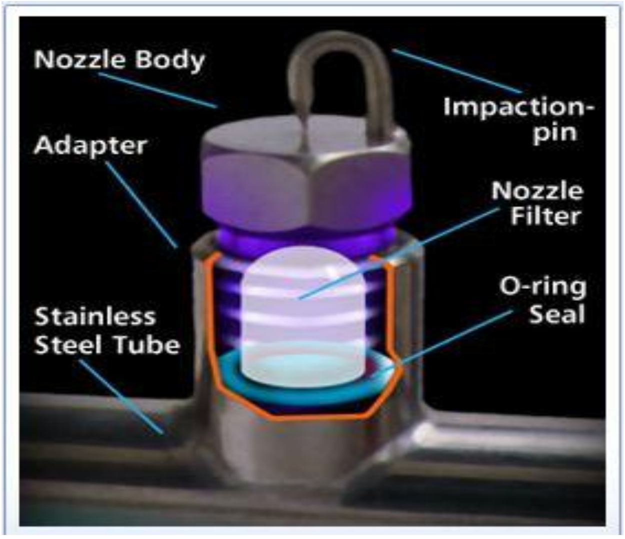

Figure 3.6: Impaction Pin Nozzle [34]

3.3.3 Droplet Size

Droplet size itself is a critical factor for the direct evaporative cooling because evaporation rate is a strong function of the exposed surface area, thus evaporation occurs only at the water/air interface. For instance, a 10-micron droplet has only about 13 percent the mass of a 20-micron droplet and a given mass of water divided into 10-micron droplets results in four times more surface area than the same mass of water divided into 20-micron droplets. Therefore small droplets evaporate much faster and also more likely to follow the airflow stream and less fall out. Wherein large droplets have may potential drawbacks such as,

- Less evaporation efficiency
- More likely to be removed from the air stream by gravity
- More fallout can lead to excessive pooling of water on the floor

Droplet size distribution is also depend on other several factors such as type of nozzle, operating pressure, nozzle capacity and nozzle flow rate etc.

3.3.4 Nozzle Placement

Following care has to be taken while arranging the nozzles.

- The nozzles can be directed into the incoming air stream so the moisture has the greatest mixing opportunity with the air as it turns around and flows towards the discharge.
- With this arrangement, the nozzle headers will need to be mounted far enough from the front of the section to prevent water from impinging on filters.
- This orientation results in a little more dripping since the moisture hits the nozzle headers as it is carried towards the back of the section. To reduce dripping on shut off, the nozzles can be fitted with anti-drip check valves that will close when the nozzle header is off. Another arrangement is to point the nozzles at an angle either with the air stream or against it.
- First and last nozzle on each header should be approximately 8-12 inch from the sides of the wall. The top and bottom header should be approximately 8-12 inch from the top and bottom of the wall. Therefore, 99 ((12-1) x (10-1)) places available for nozzles in 12 ft x 10 ft container. This is one limitation.
- The spacing between adjacent nozzles and adjacent headers should be a minimum of 8 inch, and should be evenly spaced vertically and horizontally so the moisture will be dispersed across the section.
- The nozzle headers should be located so any dripping from the headers will fall into the drain pan.
- The humidifier section should be constructed so there are no obstructions in the path of the moisture to cause dripping or condensation.

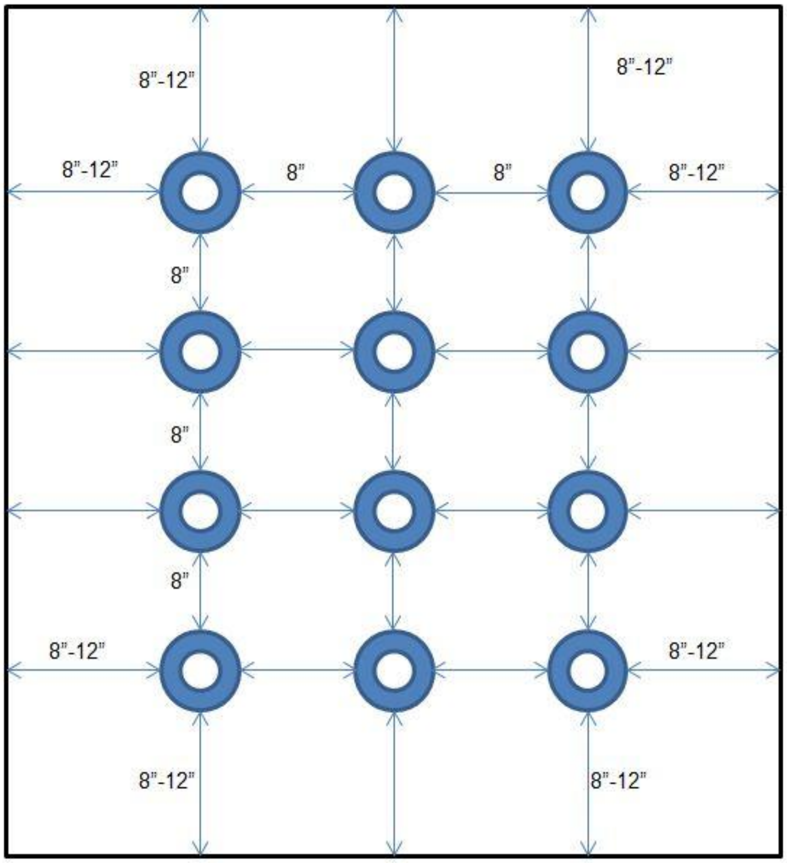

Figure 3.7: Nozzle Header Arrangement [34]

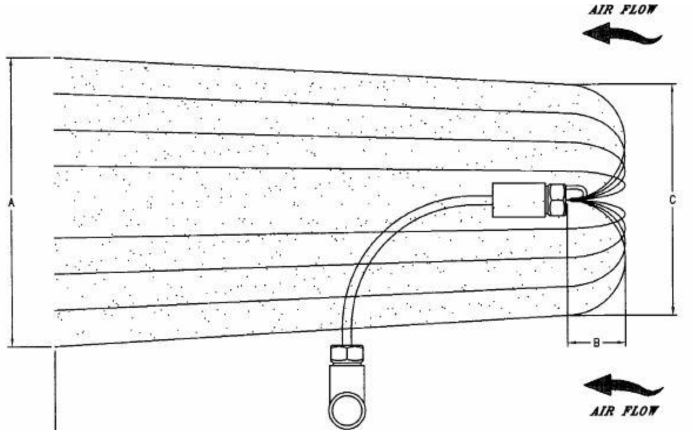

Figure 3.8: Nozzle Pointed Directly into Air Stream [34]

3.3.5 Droplet Filter

Droplet filters are generally made of a special synthetic fiber that is impregnated with an antimicrobial substance to inhibit the growth of mold or bacteria. The droplet filters can be used at air velocities up to 650 ft/min. At higher air velocities large droplets may be stripped off the back of the filter and can re-enter the air stream, where at very low air velocities, some droplets may migrate through the filter. The distance from the nozzle to the droplet filter is called the spray distance, is a key parameter for the evaporation. Longer spray distance are desirable because more of the fog will evaporate before reaching the droplet filter. It is important to supply clean, well-filtered air to the humidification section. If dust and dirt accumulates on the droplet filters it can inhibit the anti-microbial action of the impregnated fibers. Normally, droplet filter media can be cleaned with soap and water.

Figure 3.9: Droplet Filter [34]

3.3.6 Water Requirement

The high pressure pump must be supplied with filtered and softened water or RO water. The treated water should only be carried in PVC or stainless steel piping. If inlet water is D.I. water then piping material should be Grade 316 stainless steel because D.I water creates static charges on the nozzle tips and inside the pipe. The use of water filtered through a Reverse Osmosis system is recommend for all direct inlet fogging systems. The removal of minerals and dissolved solids from the supply water will reduce routine maintenance and extend the time between filter changes. A typical RO system will comprise carbon pre-filters, water softener, RO unit, repressurization pump and UV light to kill bacteria. According to the Mee Fog Inc. supply water temperature should be within 40^oF- 100^oF [35]. As per American weather survey, the temperature of the ground water in all over the United States is between the 40^oF to 100^oF that saves a lot of energy for either cooling or heating a ground water [35]. Chapter 5 tells more detailed analysis about the effect of the water temperature on evaporation.

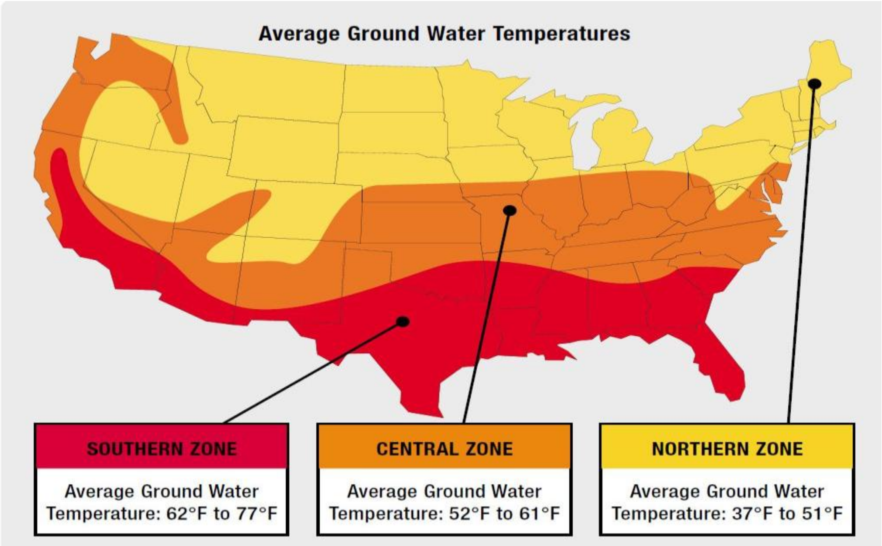

Figure 3.10: Average Ground Water Temperatures in USA [35]

3.3.7 Pumping System

High pressure pumping systems consist of a water inlet panel, pump control panel and high pressure pump unit or some combination of panels. The water inlet panel filters the water through high efficiency cartridge filters down to 0.35 microns absolute. The pump is controlled from the pump control panel.

3.3.8 Piping Requirements

The low pressure inlet water piping should be of a material compatible with the quality of water being supplied to the system.

- Filtered tap water - 80 PVC or copper piping
- RO system – PVC or 304/316 Grade stainless steel
- RO/DI – Grade 316 stainless steel or schedule 80 PVC

CHAPTER 4

ENVIRONMENTAL CRITERIA AND PSYCHROMETRIC CHART

4.1 Environmental Criteria

4.1.1 Introduction

The choice between the alternative cooling technologies is strongly depend on the environmental condition. For example, if ambient air temperature is in between $18^{o}C$ to $27^{o}C$, then there is no need of any refrigeration unit or any evaporative cooling system. While at the other side air-side economizer alone is not a good option when ambient air temperature is greater than $27^{o}C$. Therefore, it is advisable that the site's temperature profile for full year of hourly data with the 30 year average wet and dry bulb temperature will be analyzed while selecting the cooling technology.

The flow this chapter will be to introduce the generally accepted environmental classes for datacom facilities according to ASHRAE Datacom Series 6 [31]. A discussion of the impact of the environmental conditions corresponding to these classes on datacom energy use follows.

4.2 Environmental Classes

Typically, telecommunication environments are classified in three categories. Class 1, Class 2, and NEBS [31].

- Class 1: A datacom facility with tightly controlled environmental parameters and mission critical operations; types of products typically designed for these environments are enterprise servers and storage products.
- Class 2: A datacom space or office or lab environment with some control of environmental parameters; types of products typically designed for these environments are small servers, storage products, personal computers and workstations.

- NEBS: Per Telcordia GR-63-CORE and GR-3028-CORE, typically a telecommunications central office with some control of environmental parameters; types of products typically designed for this environment are switches, transport equipment and routers.

Table 4.1: Class 1, and Class 2 Design Conditions [31]

Condition	Class 1/ Class 2	
	Allowable Level	Recommended Level
Temperature Control Range	$59^oF – 90^oF$(Class 1) $50^oF – 95^oF$ (Class 2)	$64.4^oF – 80.6^oF$
RH Control Range	20% - 80% 63^oF. Max dew point(Class 1) 70^oF. Max dew point (Class 2)	41.9^oF dew point – 60% RH and 59^oF dew point
Filtration Quality	65 %, min 30% (MERV 11, min MERV8)	

Most of the network devices required for containerized data center is classified in Class 1 and Class 2. And this is why NEBS class is omitted in this study. Figure 4.1 shows recommended temperature and humidity condition for Class 1 and Class 2 [31]. Table 4.1 shows allowable temperature and humidity conditions for the same classes. It should be noted that the dew-point temperature is also specified, as well as the relative humidity. The stated conditions correspond to conditions at the inlet to the datacom equipment, not to “space conditions” or to conditions at the return to the air-conditioning equipment. Temperature in other parts of the datacom spaces, such as hot aisles, can exceed the recommended conditions. Environmental conditions for ancillary spaces (e.g., battery storage and switchgear rooms) do not necessarily require the stringent environmental conditions of Class 1 and Class 2.

ASHRAE has also published recommended operating conditions for the direct evaporative cooling as shown in figure 4.2 [36]. Region 1 in figure 4.2 encompasses the ambient temperature below 64.4^{o}F dry bulb when both cooling and humidification is required. Both may be achieved without energy expenditure for either refrigeration or humidification one way to achieve this is mixing of ambient air with the exhaust hot air. Region 2 represents outdoor conditions where cooling without refrigeration is possible. This zone requires only mechanical cooling and humidification. Region 3 shows ambient conditions above 58^{o}F WB and less than 64^{o}F WB where the direct evaporative cooling device will help minimize mechanical cooling

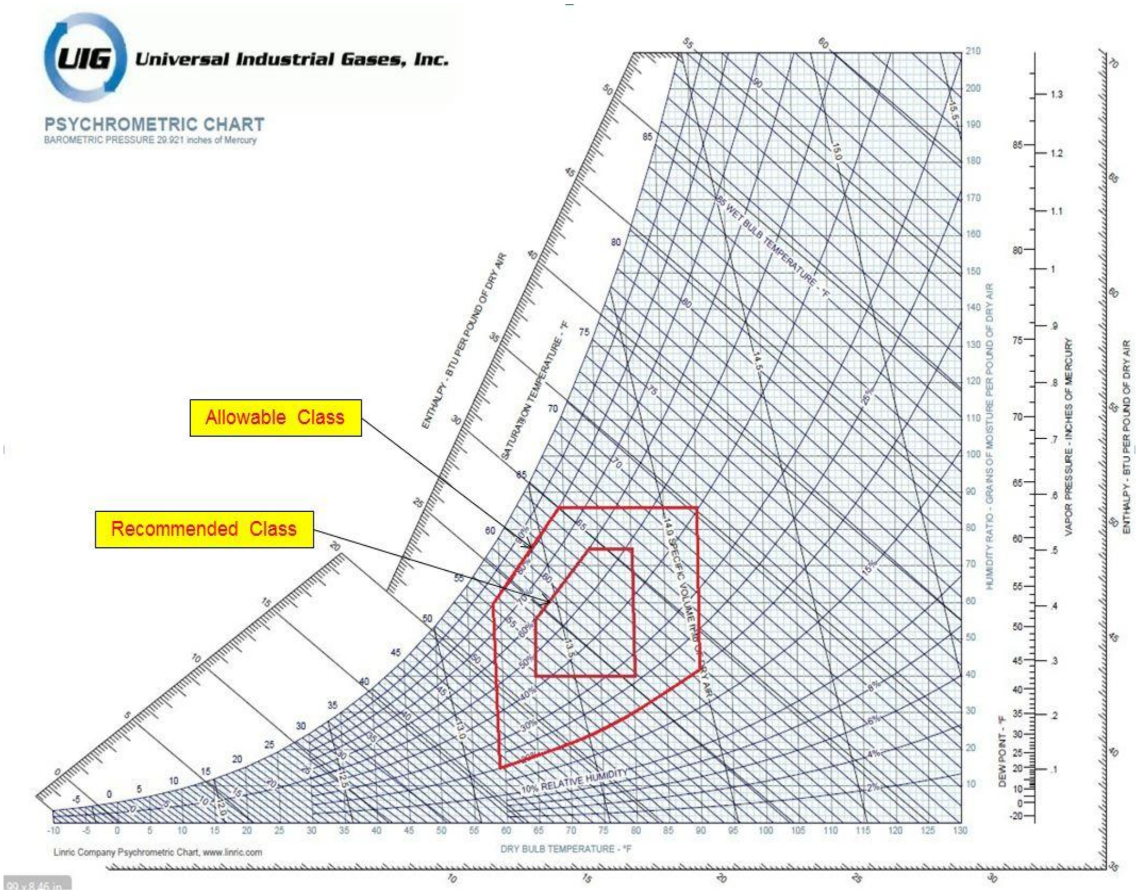

Figure 4.1: Recommended Data Center Class 1 and Class 2 Operating Conditions According to ASHRAE [36]

requirements. Region 3A requires dehumidification system that can achieve by desiccant. Region 4 needs refrigeration system with the humidity control.

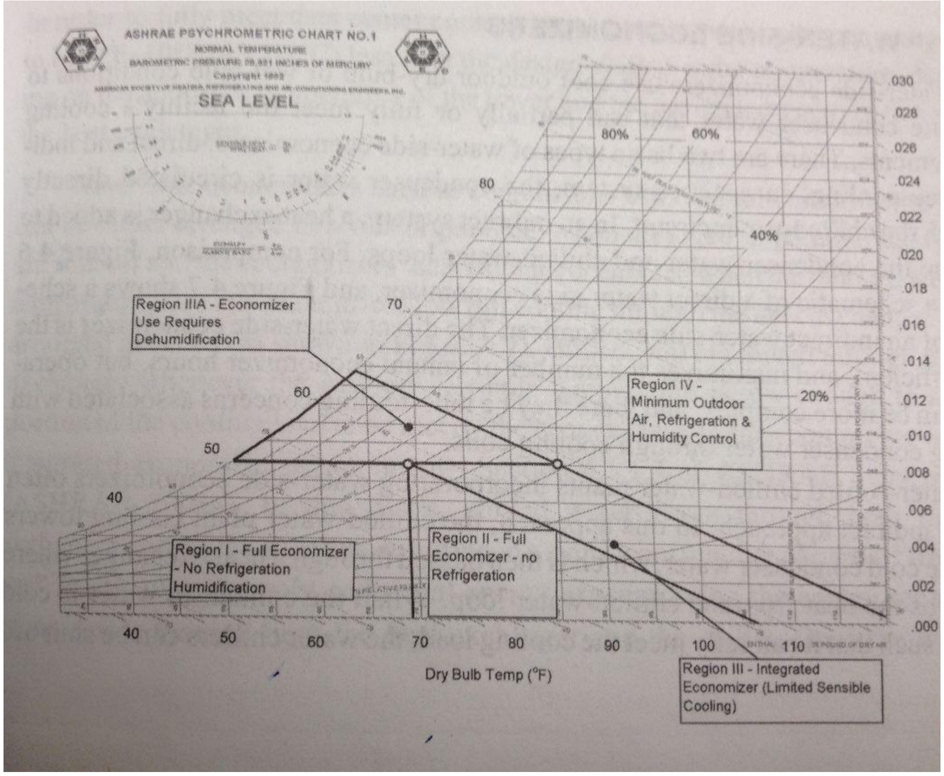

Figure 4.2: Recommended Operating Conditions for Direct Evaporative Cooling for Air-Side Economizer [37]

Based on the above two Psychrometric chart, operating conditions for the inlet fogging system with air-side economizer for containerized data center are shown below in figure 4.3. Zone 1 is recommended envelope for inlet operating conditions for air-side economizer for containerized data center. Zone 2 shows ambient conditions above 50°F WB and less than 66°F WB where direct evaporative cooling can be operated and can achieve ASHRAE recommended operating conditions without use of any refrigeration systems.

4.3 Psychrometric Chart

Psychrometric chart is a graphical representation of all the air properties such as dry bulb temperature, wet bulb temperature, relative humidity, specific humidity, dew point temperature, enthalpy etc. These all properties are calculated at standard atmospheric pressure. Psychrometric Chart is one of the very important tools for data centers to carry out

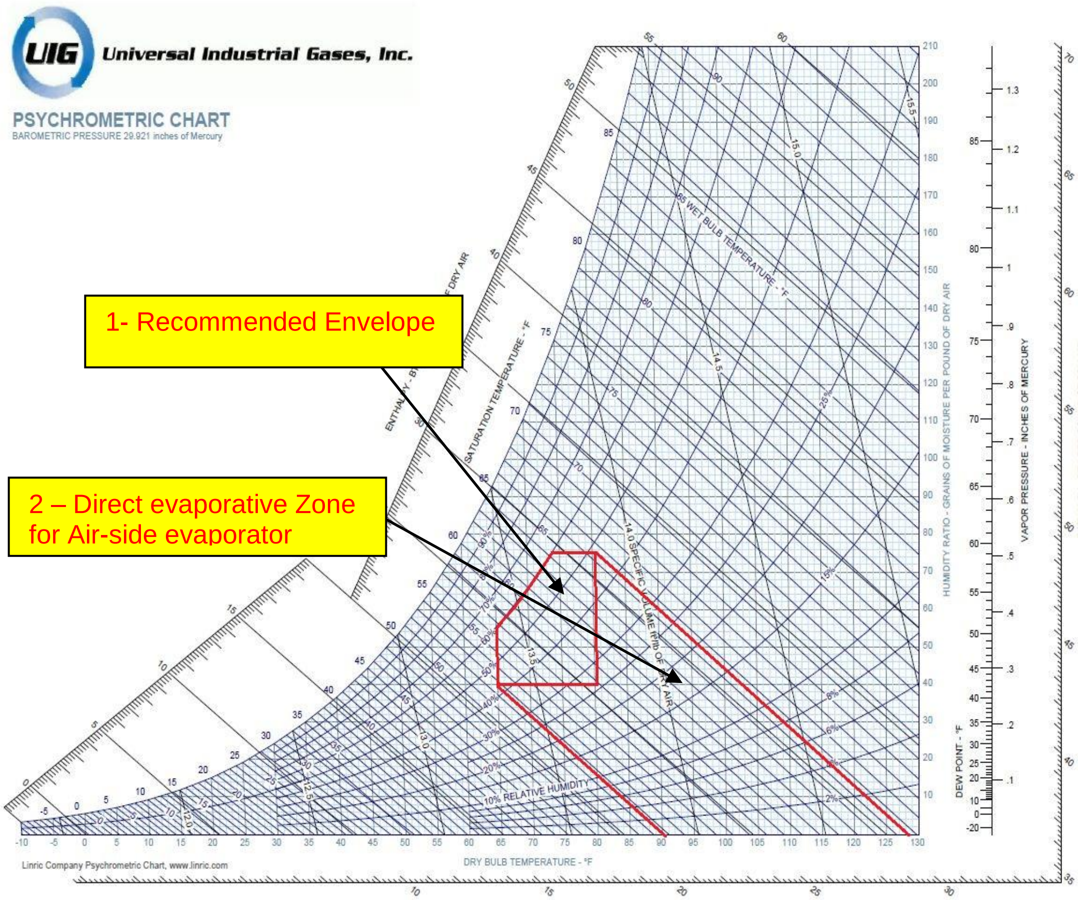

Figure 4.3: Operating Conditions for Direct Evaporative Cooling for Containerized Data Center

heat load and cooling load calculations and find solutions to various air conditioning related problems. For examples, a Psychrometric chart can calculate how much water is needed for inlet fogging system. A following condition is assumed for the ambient Conditions: Dallas, TX [37]

- Ambient Air Temperature: 100^{o}F with 15% RH
- Target Air Temperature : 80^{0}F with 49% RH
- Flow rate of the Air : 9500 CFM (4.48 m^{3}/sec)

STEP 1: Find the ambient condition on the chart (start point).

Moisture content at this condition: 43 grains (H20)/lb (dry air)

STEP 2: Follow the constant wet bulb temperature and find the targeted point.

Moisture content at this condition: 75 grains (H20)/lb (dry air)

STEP 3: Calculate how much moisture has to added to the air stream to reach the wet bulb temperature: [75 - 43] = 32 grains/lb

STEP 4: Compute the required water for data center air-mass flow rate of 9500 CFM

The water required would be: 9500 CFM x 32 grains/lb : 0.0512 lb/sec

So, the required water to cool 9500CFM air is 0.0512 lb/sec

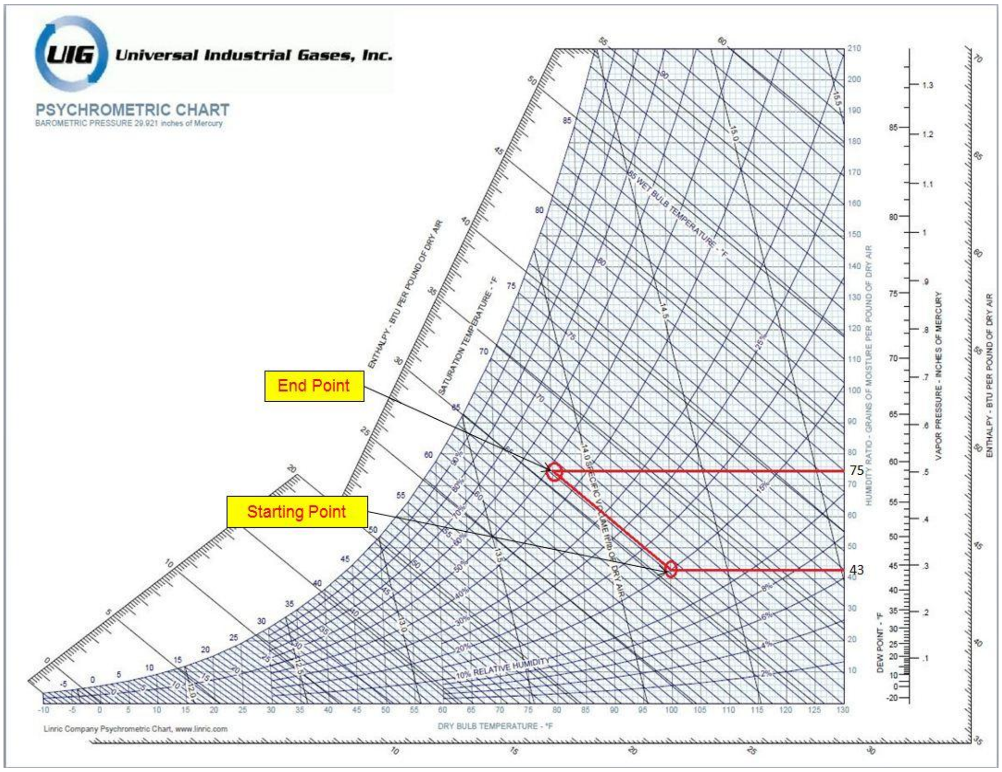

Figure 4.4: Psychrometric Chart Showing Initial Condition and Final Condition for Evaporative Cooling

Also, number of nozzles can be calculated by using Psychrometric chart, if the flow rate of the nozzle is known.

CHAPTER 5

CFD (COMPUTATIONAL FLUID DYNAMICS) ANALYSIS

5.1 Introduction to CFD Analysis

CFD (Computational fluid dynamics) is the branch which deals with the numerical simulation and analysis of fluid flow, heat transfer characteristics and pressure characteristics. Computational fluid dynamics is applied in order to simulate and analyze the effect of fluids in various systems using numerical methods. The advantage of using these numerical methods is that the problem can be discretized based on a set of numerical parameters and solved. The simulation tools offer a repository of features that can be used such as grid generation, mesh sensitivity analysis and several other features. A numerical prediction is used for the generation of a mathematical model which represents the physical domain of interest to be solved and analyzed. The effects of droplet size, droplet distribution, humidity on the cooled air temperature distribution are examined. Also, the effect of water temperature on the incoming air is investigated in this study. Fluent, a commercially available, is selected as a CFD tool.

5.2 Numerical Model

In a real application, the air/fog mixture can travel through a big rectangular container or channel. To study the adiabatic cooling behavior, 20ft (L) x 12ft (W) x 10ft (H) size container is selected as a physical domain. Although the computational domain can be quarter of the physical geometry due to symmetry, half symmetry model is used in computation because it is convenient to examine the trajectory of droplets, which subject to the influence of random turbulence influence, could cross the physical symmetric planes.

The commercial software package Fluent from Fluent, Inc. is used in this study. The simulation uses the segregated solver, which employs an implicit pressure-correction scheme. The COUPLED algorithm is used to couple the pressure and velocity. First order upwind scheme is used to spatial discretization of the convective terms and seconder order accuracy for the diffusion term. The Lagrangian trajectory calculations were employed to model the dispersed phase of droplets including coupling with the continuous phase. The impact of the droplets on the continuous phase is considered as source terms to the governing equations. After obtaining an approximate flow field of the continuous phase, Fluent traces the droplet trajectories and computes heat and mass transfer to/from them. Detailed numerical models are given next.

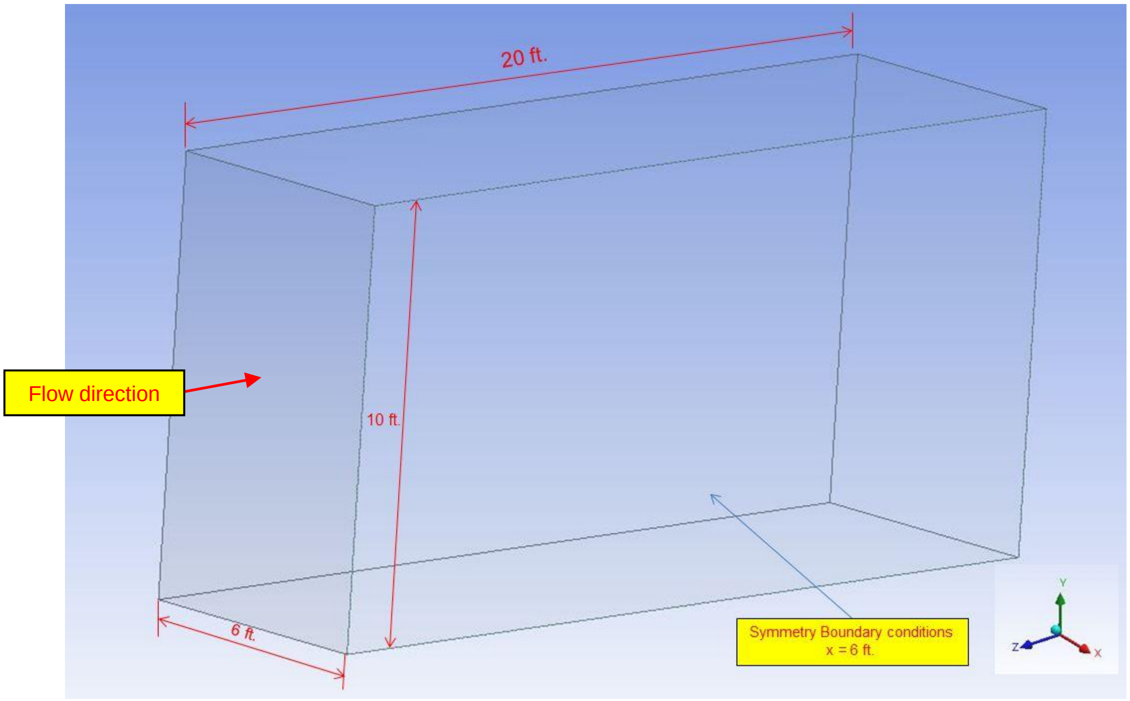

Figure 5.1: Computational Geometry

5.2.1 Continuous Phase (Air)

5.2.1.1 Governing Equation

Considering a steady-state flow, the equations for conservation of mass, momentum and energy can be given as:

Conservation of mass

$$\frac{\partial}{\partial x_i}(\rho u_i) = S_m$$

Conservation of momentum

$$\frac{\partial}{\partial x_i}(\rho u_i u_j) = \rho g_j - \frac{\partial P}{\partial x_j} + \frac{\partial \tau_{ij}}{\partial x_i} + F_j$$

Conservation of energy

$$\frac{\partial}{\partial x_i}\left(\rho C_p u_i T\right) = \frac{\partial}{\partial x_i}\left[\lambda_{eff}\frac{\partial T}{\partial x_i}\right] + \mu\Phi + S_h$$

Where the source terms (S_m, F_j and S_h) are used to include the contributions from the dispersed phase. τ_{ij} is the symmetric stress tensor, which can be expressed as

$$\tau_{ij} = \mu\left[\frac{\partial u_j}{\partial x_i} + \frac{\partial u_i}{\partial x_j} - \frac{2}{3}\delta_{ij}\frac{\partial u_k}{\partial x_k}\right]$$

$\mu\Phi$ is the heat of dissipation and λ_{eff} is the effective heat conductivity. When the turbulence effect is considered, both τ_{ij} and λ_{eff} need to be modeled [37].

5.2.1.2 Turbulence Modeling

The standard k-ε model is selected because the flow in this study does not involve any strong streamline curvature, vortices or rotation. The standard k-ε model is the simplest two-equation model and it is proven to be robust, economic for computation, and reasonably accurate for a wide range of turbulent flow. The equation for the turbulent kinetic energy (k) and its dissipation rate (ε) are:

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

$$\frac{\partial}{\partial x_i}(\rho u_i \varepsilon) = \frac{\partial}{\partial x_i}\left(\left(\mu + \frac{\mu_t}{\sigma_\varepsilon}\right)\frac{\partial \varepsilon}{\partial x_i}\right) + C_{1\varepsilon}G_k\frac{\varepsilon}{k} - C_{2\varepsilon}\rho\frac{\varepsilon^2}{k}$$

The term G_k is the generation of turbulence kinetic energy due to the mean velocity gradients. The turbulent viscosity, μ_t, is calculated from the equation

$$\mu_t = \rho C_\mu \frac{k^2}{\varepsilon}$$

And the effective heat conductivity (λ_{eff}) is calculated by

$$\lambda_{eff} = \lambda + \frac{C_p \mu_t}{Pr_t}$$

The constants $C_{1\varepsilon}$, $C_{2\varepsilon}$, C_μ, and σ_ε used are: $C_{1\varepsilon}$ = 1.44, $C_{2\varepsilon}$ = 1.92, C_μ=0.09, σ_k= 1.0, σ_ε = 1.3 [37].The constant Pr_t is set to 0.85. The equation may include more other source terms, for example, turbulence kinetic energy due to buoyancy and the contribution of fluctuating dilatation in compressible turbulence. In general, the standard k-ε model should be used together with near-wall treatment due to the wall effect on the turbulence. In this study the standard wall functions are selected. More details can be found from Fluent Theory Guide [38].

5.2.2 Discrete Phase (Water Droplets)

Droplet Flow and Heat Transfer – Basically, the droplets in the airflow can encounter inertia and hydrodynamic drags. They can also get heating or cooling from the continuous phase. After the droplet is evaporated due to either high temperature or low moisture partial pressure, the vapor diffuses into the main flow and is transported away. The rate of vaporization is governed by gradient diffusion and corresponding mass change rate of the droplet can be given by,

$$\frac{dm_p}{dt} = \pi d^2 k_c (C_s - C_\infty)$$

Where K_c is the mass transfer coefficient and C_s is the concentration of the vapor at the droplet surface, which is evaluated by assuming that the flow over the surface is saturated. C_∞ is the vapor concentration of the bulk flow, obtained by solving the transport equations. The value of k_c can be calculated from an empirical correlation for droplet evaporation [38].

$$Sh_d = \frac{k_c d}{D} = 2.0 + 0.6 Sc^{0.33} Re_d^{0.5}$$

Where Sh is the Sherwood number, Sc is the Schmidt number (defined as V/D), and D is diffusion coefficient of vapor in the bulk flow. Because of the forces encountered by a droplet in a flow field, the droplet can be either accelerated or decelerated. The velocity change can be formulated by

$$\frac{dv_p}{dt} = F_d + F_g + F_o$$

Where F_d is the drag of the fluid on the droplet and F_g is the gravity. F_o represents the other forces, and V_p is the droplet velocity. Among the forces represented by F_o typically they can include the “virtual mass” force, thermophoretic force, Brownian force, Saffman’s lift force, etc. The heat transfer between droplets and the continuous phase can cause the droplet temperature change. Without considering radiation heat transfer, its sensible heat depends on the convective and latent heat transfer, as shown in the following equation.

$$m_p C_p \frac{dT}{dt} = \pi d^2 h (T_\infty - T) + \frac{dm_p}{dt} h_{fg}$$

Where h_{fg} is the latent heat and h is the convective heat transfer coefficient, which is calculated by the equation of heat/mass analogy.

$$Nu_d = \frac{hd}{\lambda} = 2.0 + 0.6\, Re_d^{0.5} Pr^{0.33}$$

Where Pr is the Prandtl number and λ the heat conductivity of the bulk flow. The effect of turbulence on the dispersion of particles can be considered by using Stochastic particle tracking. Basically, the droplet trajectories are calculated by using the instantaneous flow velocity rather than the average velocity and time scale defined by either of the following equations. Where r is normally distributed random number ranging from 0 to 1.

$$t_e = \frac{0.3k}{\varepsilon}$$

$$t_e = -\frac{0.15k}{\varepsilon * \log(r)}$$

5.2.3 Mist Injection and Droplet Sizes

Pressure swirl atomizer is used to inject water droplets on the continuous stream (incoming hot air). In fluent, to create an array of nozzles or pressure swirl atomizers, positions of the nozzles need to be specified rather than building a physical structure of nozzle that saves a lot of meshing time and converge the solution quicker. Point properties for the nozzles are specified in the following table 5.1. The total number of nozzles is 30 and is fixed for all the cases to ease of the simulation. Placement of nozzles is uniform in the simulation domain as shown in figure 5.2. Nozzles are placed at 0 degree angle by assuming that there is no leakage and dripping from the nozzle. Half symmetry model is analyzed as a result of that half number of nozzles (30/2 = 15) are taken into the consideration. Nozzles are placed 2 ft away from the inlet and directed into the incoming air stream so the moisture has the greatest mixing opportunity with the air as it turns around and flows towards the discharge. The mass flow is the same at each injection location, i.e., 1/30th of the total droplet mass flow rate. The evaporation efficiency of the nozzle is assumed to be 80%. For more details follow the figure A.1 from appendix A.

Table 5.1: Point Properties of the Pressure Swirl Atomizer

Pressure Swirl Atomizer	
Flow Rate	16 lbs/hr
Injection Diameter	0.00015 m
Spray Half Angle	50 degree
Pressure	1000 psi
Azimuthal Start Angle	0
Azimuthal Stop Angle	360 degree
Sheet Constant	12
Ligament Constant	0.5
Atomizer Dispersion Angle	6
Number of Particle Streams	60

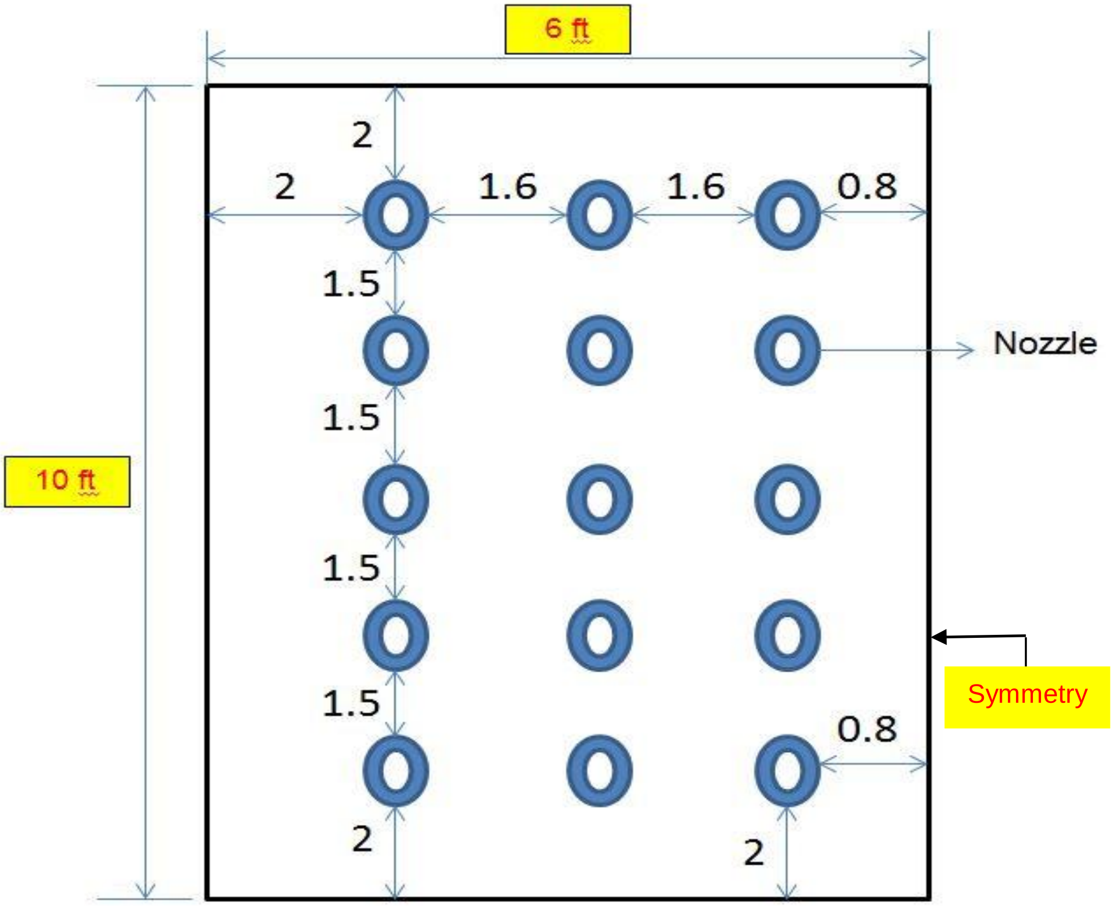

Figure 5.2: Nozzle Placement

The boundary condition of droplets at walls is assigned as “reflect”, which means the droplets elastically rebound off the wall once reaching the wall. A more complex model is undertaken to determine if the droplets breakup, rebound, or are trapped by the wall when they hit the wall. At the outlet, the droplets just simply flee/escape from the computational domain.

Since the evaporation rate is also strongly related to the droplet size, the effect of different droplet sizes on cooling performance is investigated in this study. For this study, impact-pin IP-16 (Mee fog nozzle) is used to generate the mist. The non-uniform droplet size distribution is given in fig 5.3 and detailed values are provided in Table 5.2. This distribution gives an average diameter of d10= 12.33µm, d20=15.58 µm, d30=17.63 µm, and d32=22.53 µm. This can achieved in fluent by point properties described in table 4.1.

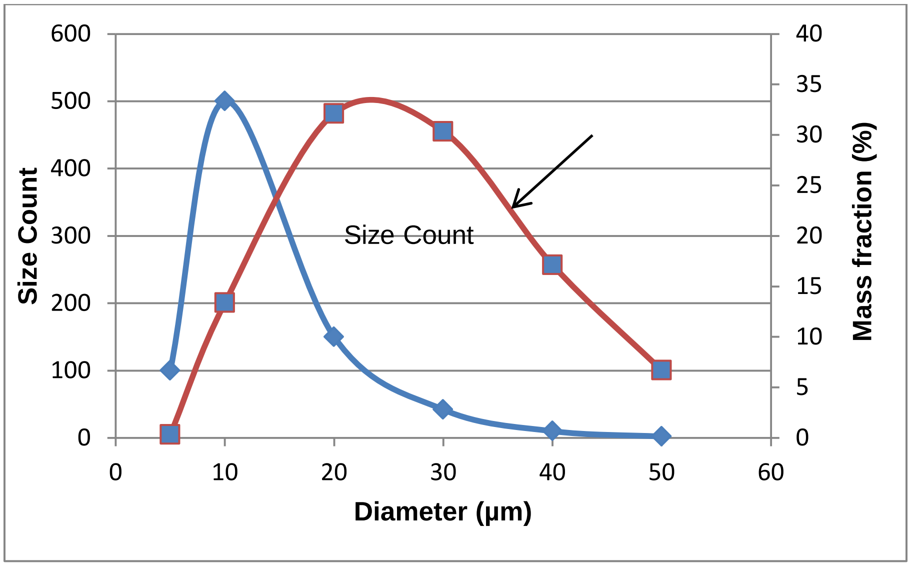

Figure 5.3: Distributed Droplet Size From Mee Fog IP-16 [34]

Table 5.2: Droplet Size Distribution

Diameter (µm)	5	10	20	30	40	50
Droplet Count	100	500	150	42	10	2
Mass Fraction (%)	0.33	13.38	32.12	30.35	17.13	6.69

5.2.4 Boundary Condition

Based on the water requirements according to the ambient conditions and by keeping number of nozzle fixed (30 for all cases), inlet velocity varies for all the cases. Value for inlet velocity is varies from 0.8 m/sec to 3 m/sec. The inlet conditions of turbulent intensity are 5 percent and 10 for turbulent viscosity ratio. The flow exist (outlet) is assumed to have a constant pressure. The backflow, if any, is set to ambient temperature. Mass fraction of water depends on relative humidity and is calculated according to following equation.

$$RH = \frac{P_{partial\ pressure\ of\ water-vapor}}{P_{saturation\ pressure\ of\ water-vapor}}$$

$$m_{water-vapor} = \frac{0.621 * P_{partial\ pressure\ of\ water-vapor}}{101325 - P_{partial\ pressure\ of\ water-vapor}}$$

The sidewall is non-slip (velocity is zero at the wall) and is assumed to be adiabatic.

5.2.5 Meshes and Convergence

Figure 5.4 shows the grid structure of x-y plane. Total elements number of the mesh is around 0.5 million. A converged result can be reached after iteration proceeds alternatively between the continuous and discrete phases. Five iterations in continuous are conducted between two iterations in the discrete phase. A typical converged result renders mass residues of 10-2, energy residue of 10-6, and momentum and turbulence kinetic residues of 10-4. Typically 5000 iterations are needed to obtain a converged result, which takes about 7 to 8 hours on a PC with 4 core processor of 3.4 GHz.

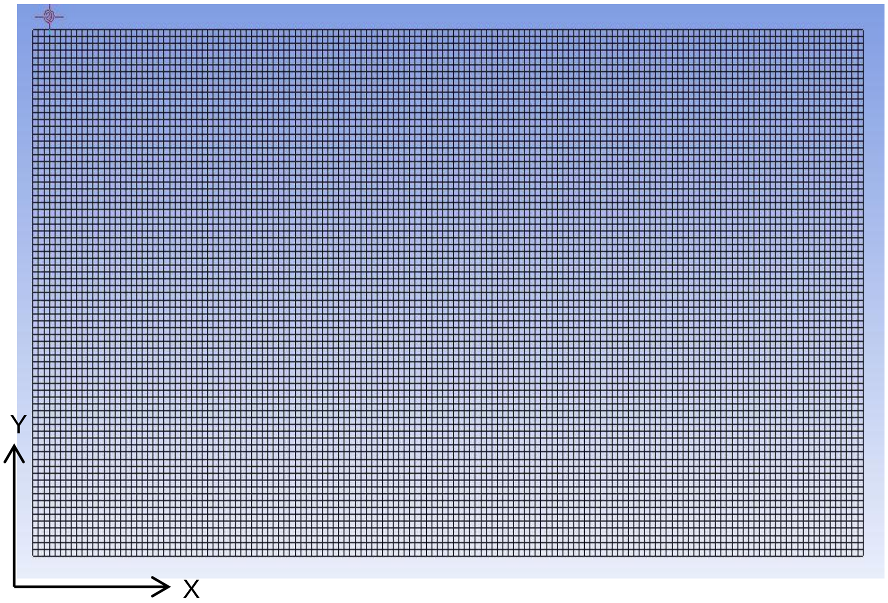

Figure 5.4: X-Y plane of Grid Structure

5.3 Results and Discussion

The results of the evaporative zone are shown in the figures 5.5 and 5.6. Figure 5.5 show that the temperature distribution in the container and the ambient condition in this case is 37.77°C (100°F) with 10% relative humidity and the droplet diameter distribution in this is 5μm to 50μm. The temperature at the center core is lower because of the smaller droplets and higher near the inlet region and close to the wall. The reason is that the injections are displaced away from the wall on purpose. In this way, the frequency of liquid deposit on the wall surface can be minimized.

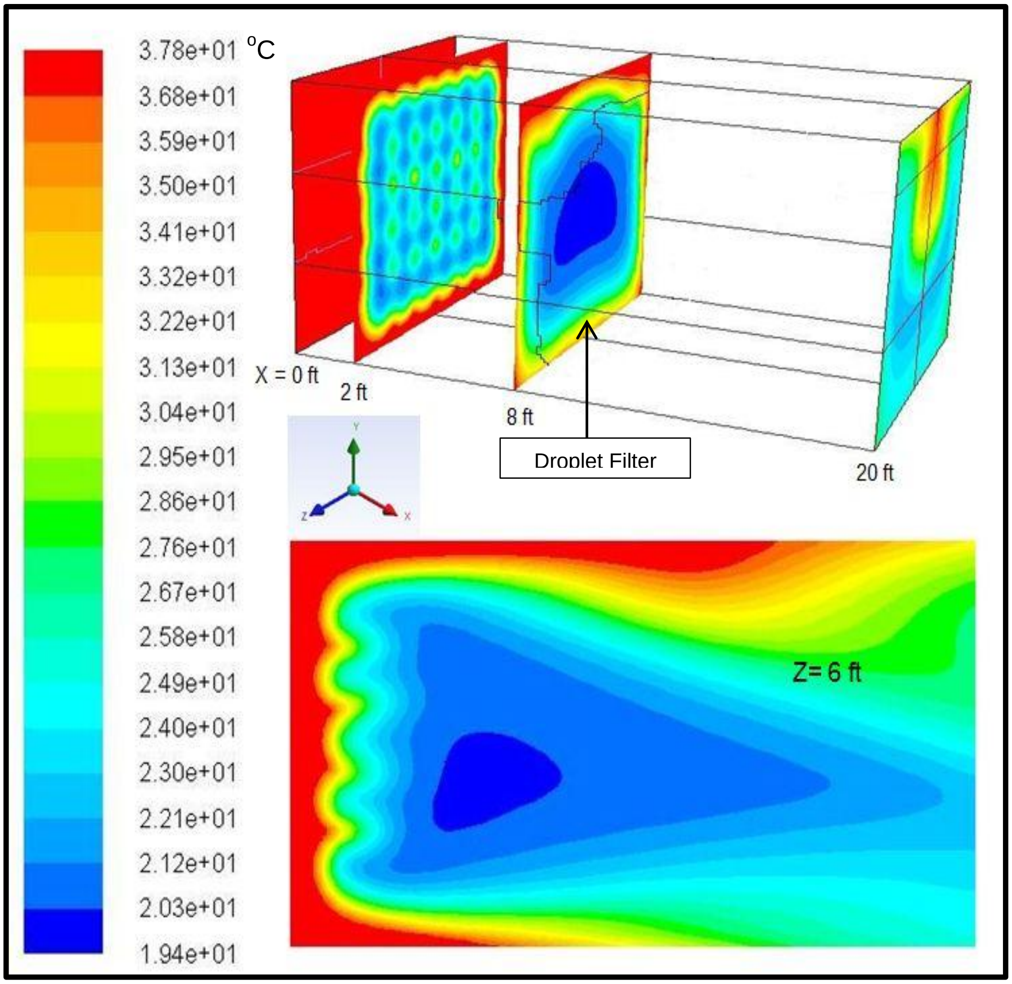

Figure 5.5: Temperature Contour for 158 FPM

The velocity of the incoming air is 158 FPM (0.8 m/sec), which is lower and gravity influence on particles, thus non-uniform temperature distribution achieved as shown in figure 5.4. Figure 5.5 shows the uniform temperature distribution, the inlet velocity for this case is 500 FPM and therefore gravitation effect is negligible on particles. In this study, behavior of various water temperatures, different humidity level and distribution of various droplet sizes are studied.

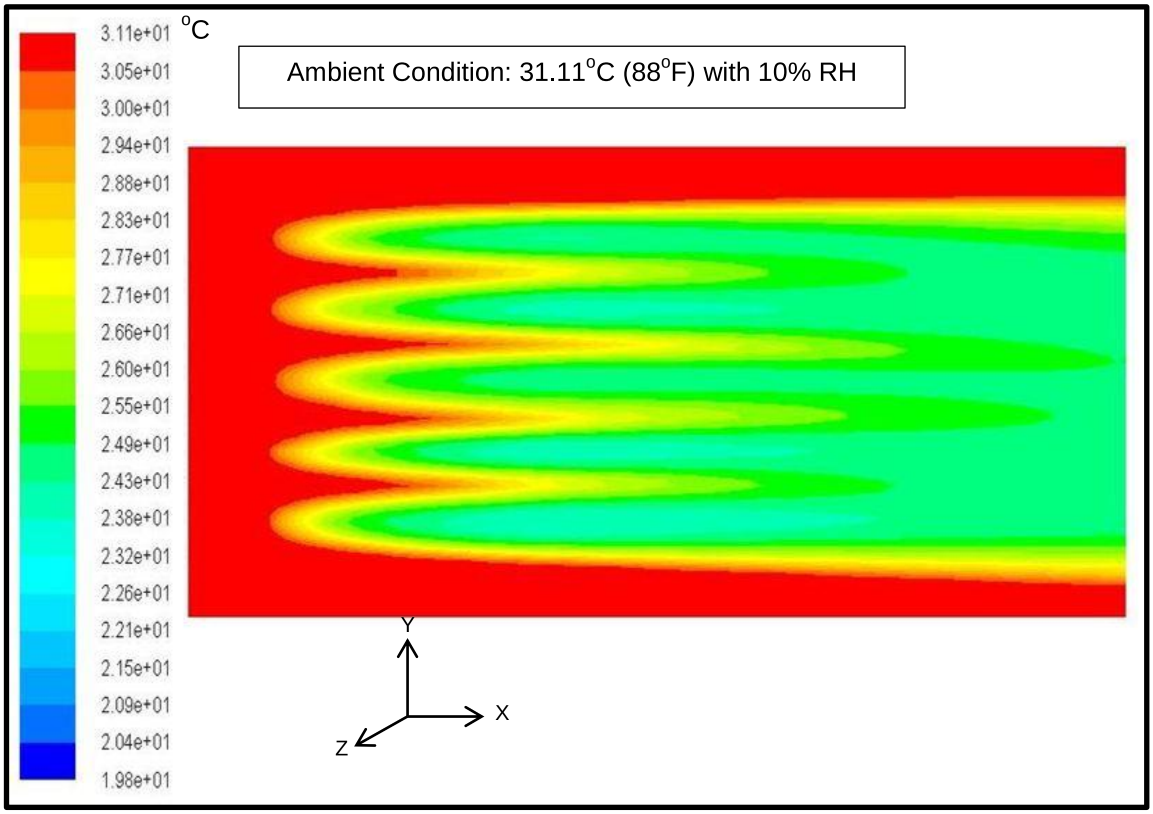

Figure 5.6: Temperature Contour for 500 FPM

5.3.1 Water Temperature

Distribution of droplet diameter is also depending on the temperature of the water. As the temperature of the water increased, water becomes softer. At the high temperature, surface tension (cohesive forces among water molecules) of the water will decrease and that helps the water to be soft thus creates more fine particles. Table 5.3 and shows the comparisons of different water temperature ranges from 20°C (68°F) to 30°C (86°F) with different ambient conditions. Result shows that, there is not a significant drop in temperature even at higher water temperature.

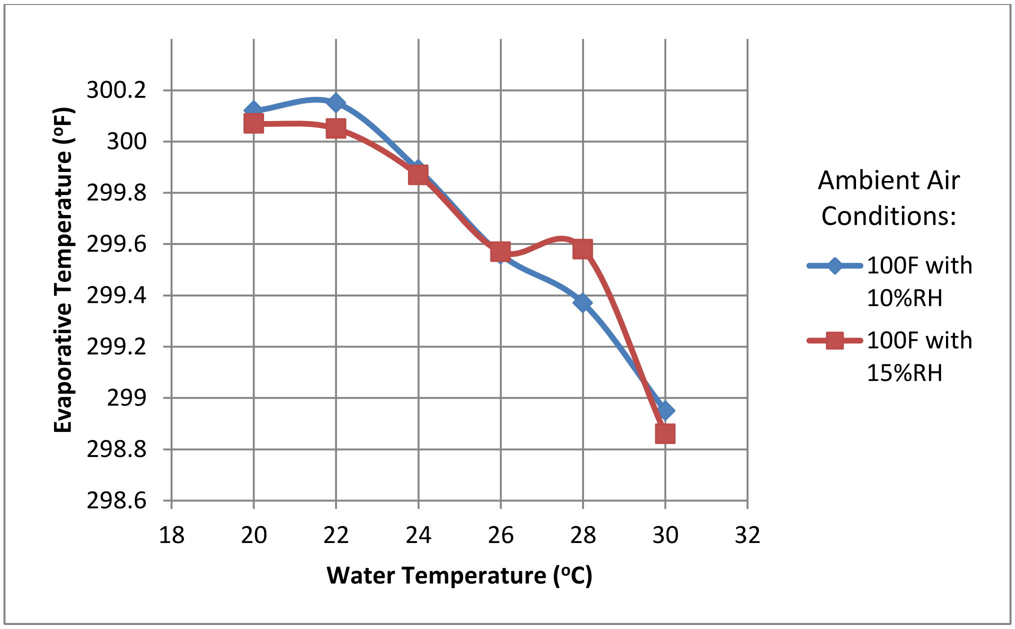

Figure 5.7: Comparison of Various Water Temperatures

Table 5.3: Water Temperature Comparison

	Water Temperature (°C)	20	22	24	26	28	30
Evaporative Air Temperature (°F)	100°F with 10% RH	300.12	300.15	299.89	299.56	299.37	298.95
	100°F with 15% RH	300.07	300.05	299.87	299.57	299.58	298.86

Figure 5.8 shows the temperature contour comparison for water temperature at 20°C and at 30°C for 37.77°C ambient air with 10 % RH and the temperature distribution in both cases is almost same.

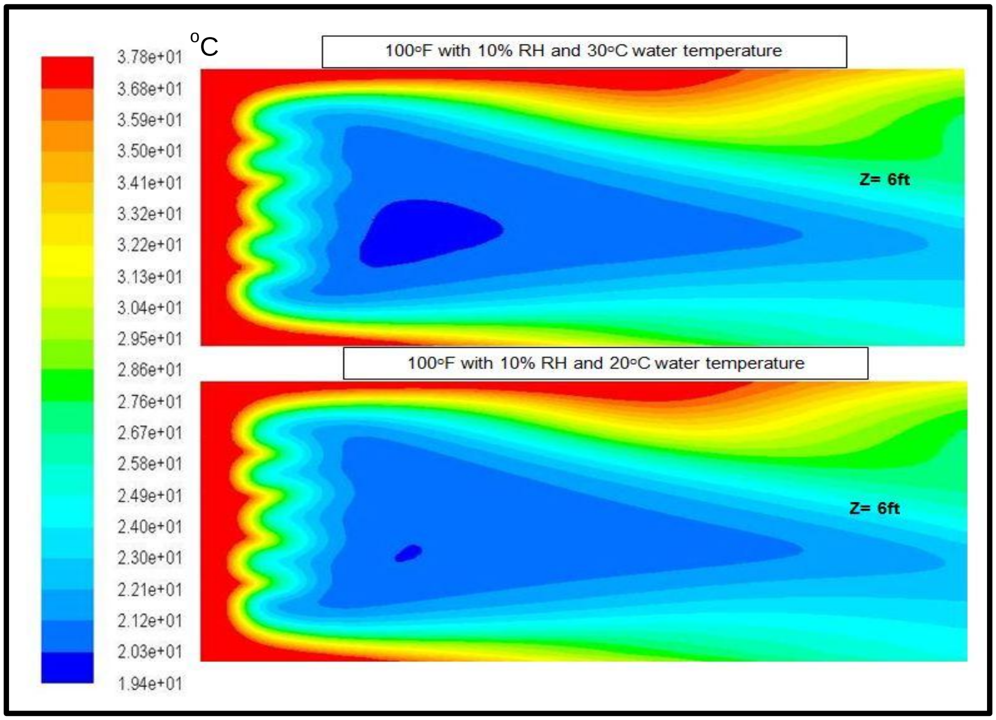

Figure 5.8: Temperature Contours of 20°C and 30°C Water Temperature

5.3.2 Effect of Relative Humidity

The effect of relative humidity is shown in fig 5.9, which clearly indicates that fog cooling becomes more effective when the humidity decrease. Table 5.4 presents the relative humidity comparison between Psychrometric Chart and computational analysis at 100°F. The temperature at 0% humidity can evaporates faster than the temperature at 15 percent humidity as shown in figure 5.9. The relative humidity increases rapidly to 100% after droplet injection.

Table 5.4: Relative Humidity Comparison

Case	Psychrometric Chart RH	Computational RH
1 (15% RH)	48.00%	49.86%
2 (10% RH)	39.00%	43.53%
3 (5% RH)	29.00%	31.82%

Table 5.5 shows that by assuming 80% evaporation efficiency, fog cooling can bring the temperature down to the ASHRAE recommended the operating temperature range even in harsh environment such as 100°F with 5% RH.

Table 5.5: Comparison of Temperature at Droplet Filter Location

Case	Psychrometric Chart Temperature	Computational Temperature
1 (15% RH)	27°C	26.91°C
2 (10% RH)	27°C	27.35°C
3 (5% RH)	27°C	27.74°C

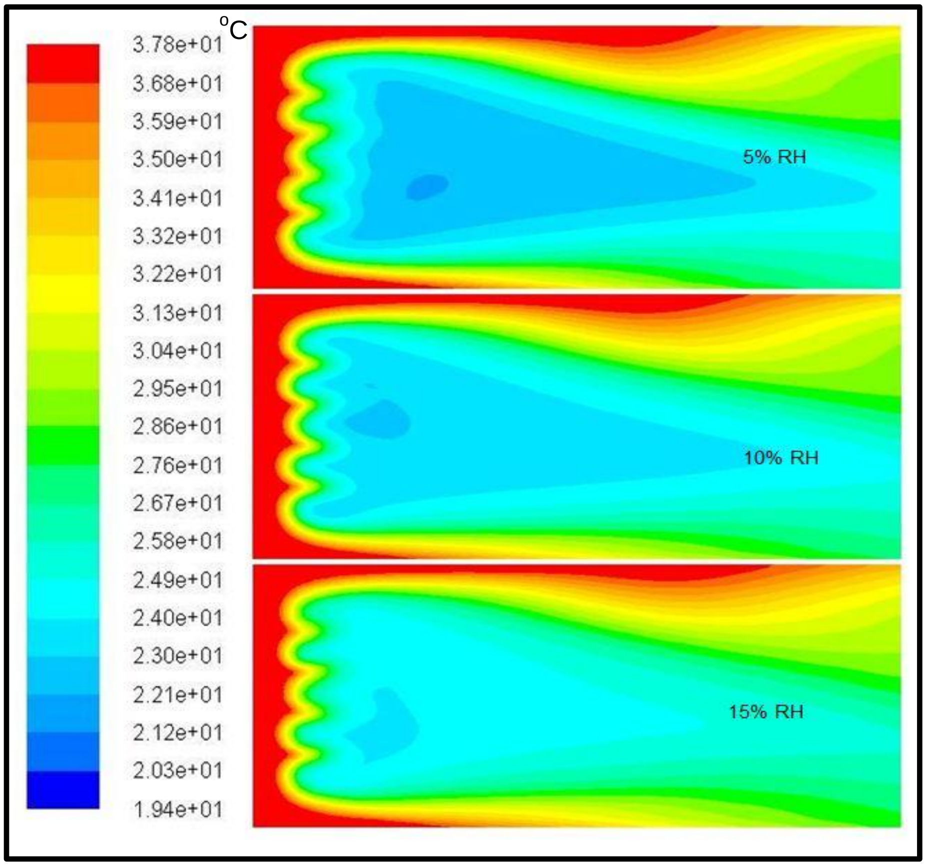

Figure 5.9: Temperature Contour of 5%, 10%, and 15% RH

5.3.3 Effect of Droplet Size

In real life application injected droplet size is not a single value that influence on the investigation of non-uniform droplet size distribution. Figure 5.10 shows comparison of the temperature contours for 5µm to 50µm droplet size distribution and 50 µm to 100 µm droplet size distributions. Table 5.6 presents the droplet size distribution inch cases according to the DV90. That means in case-1 90% of the water volume in the spray is less than or equal to 17µm droplet diameter and while in case-2 droplet diameter is 73 µm or less. The temperature field for these two cases reflects the two major characteristics of different droplet size. First, the overall temperature reduces slowly due to the presence of large droplets. Secondly, the temperature at the center area of the outlet reaches the saturated temperature faster than outside due to the small droplets.

Table 5.6: Droplet Distribution (DV90)

Case 1		Case 2	
Min Diameter (µm)	5	Min Diameter (µm)	50
Mean Diameter (µm) (DV90)	22	Mean Diameter (µm) (DV90)	73
Max Diameter (µm)	50	Max Diameter (µm)	100

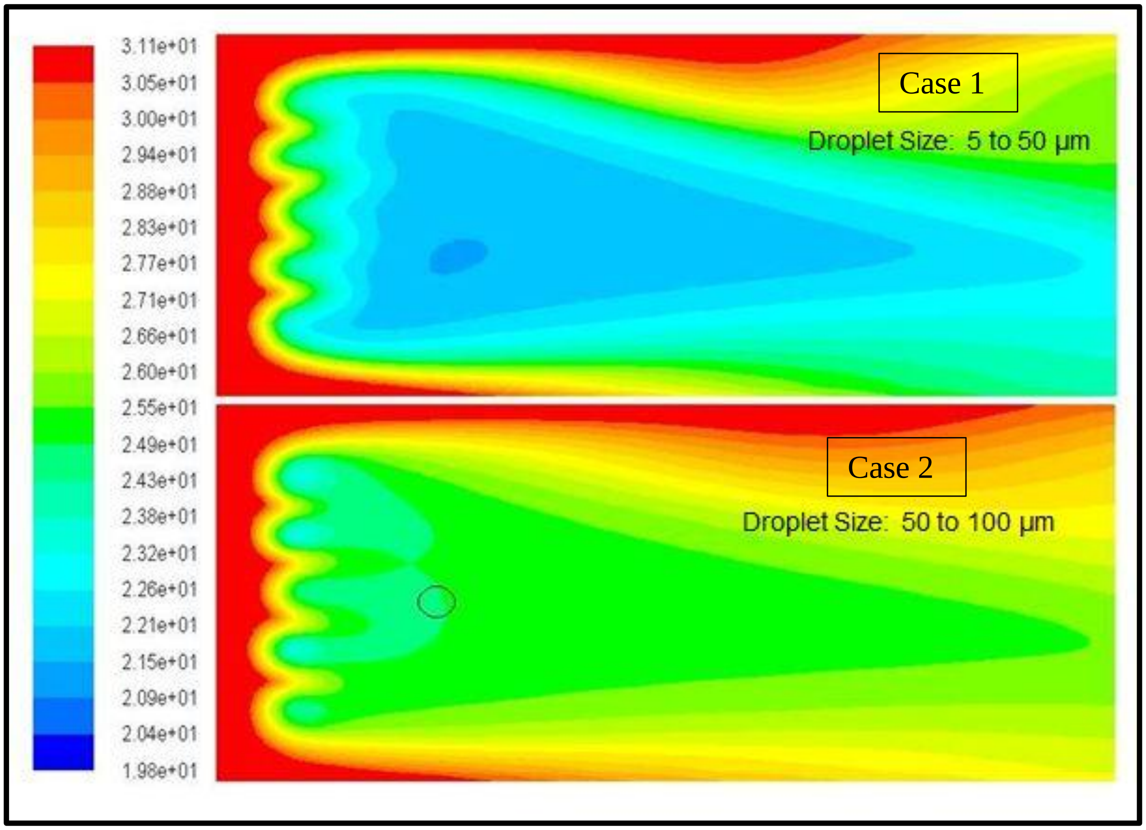

Figure 5.10: Temperature Contour for Case 1 and Case 2

5.4 Conclusion

To investigate the performance of the evaporating cooling zone in the Air-side economizer, numerical simulations are performed in this work. Fundamental geometry, a straight duct is selected for the numerical simulation of the container. The effect of the water temperature, relative humidity and droplet distribution on fog cooling is examined. The conclusions are:

- Numerical simulation provides a detailed local temperature distribution resulted from fog-cooling process in a container.
- CFD simulation shows that, fog cooling can achieve 80% evaporating efficiency and evaporation mostly occurs within 6 ft from the injection of water droplets having diameter of 22µm (DV90).

- It is true that at higher temperature, water becomes soft and thus easy to breakup. However, IP-16 nozzle provides sufficient pressure for disruption of water which provides finer droplet distributions even for water at lower temperature. Therefore, effect of water temperature on evaporation cooling is negligible.
- CFD proves that at lower humidity, rate of the evaporation is faster than the higher relative humidity. Because at lower humidity, air has capacity to absorb more moisture contain. Fog cooling not only cool down the temperature but also it increases the humidity level which is clearly seen from table 5.4.
- Simulation with the fine droplets, ranging from 5 μm to 50μm, shows that evaporation rate at the center core is faster than the outer region because the presence of smaller particles. Evaporation rate is lower for the large particles compare to the small particles.
- CFD proves that if ambient temperature condition is suitable for evaporative cooling, then a substantial cooling can achieve through a fog cooling (adiabatic cooling) without using any refrigeration units. Thus it reduces significant cooling cost.

5.5 Future Work

Particle distribution has a significant impact on evaporation rate. Nozzle angle is one of the important parameter for the particle distribution. Therefore, effect of various nozzle angle such as 30, 45, 60 degree on particle distribution will be analyzed. In this analysis, the effect of droplet filter is totally ignored which might be increase the pressure drop of incoming air resulting in increased power usage of the blower. So the effect of droplet filter on pressure drop need to be analyze. Also future work, include the analysis on types of the water because water is one of the key parameters for the evaporative cooling.

APPENDIX A

EVAPORATION EFFICIENCY

Calculating Evaporation Efficiency:

Evaporation Efficiency is defined as the percentage of the total water that evaporates before being captured on the Droplet Filter. For instance, 80% evaporation efficiency means that 80% of the sprayed water evaporated and entered the air stream as humidity while 20% was captured on the Droplet Filter and drained away. In other word, evaporation efficiency is defined by:

$$E = \frac{T_{1DB} - T_{2DB}}{T_{1DB} - T_{1WB}}$$

Where, T_1 = inlet temperature

T_2 = Exit temperature of evaporative cooler

DB = dry bulb

WB = wet bulb

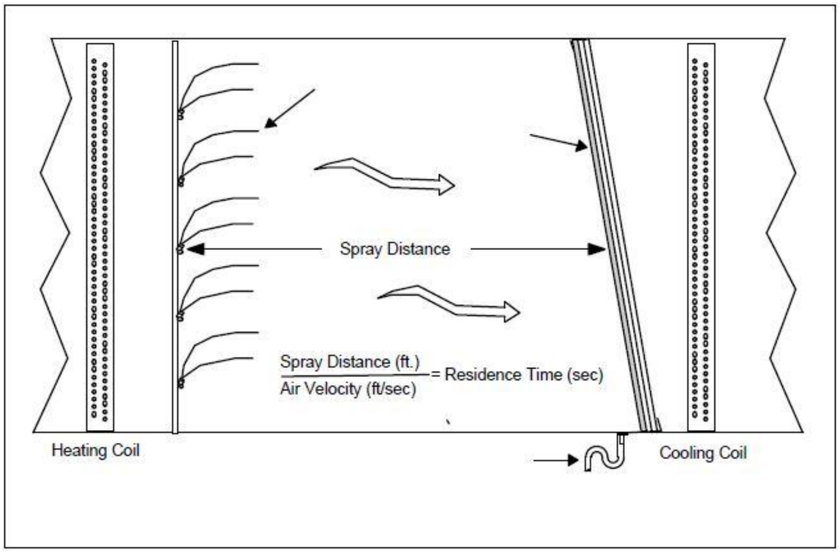

Figure A.1: Spray Distance [34]

The amount of water that will evaporate before being collected on the Droplet Filters depends also on the residence time of the droplets in the air stream, the size of the droplets, the entering air humidity and temperature and the water temperature. The spray distance and airflow velocity determine the average residence time.

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BIOGRAPHICAL INFORMATION

Niket Shah received his Bachelor’s Degree in Mechatronics Engineering from G. H. Patel College of Engineering and Technology, V.V.Nagar, India in June 2008. He completed his Master of Science degree in Mechanical Engineering at the University of Texas at Arlington in May 2012.

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

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

Niket also worked as a co-op at Cummins Filtration Inc. During the course of the co-op, he primarily focused on CFD analysis of rectangular panel and cylindrical panel filters, validation of rectangular panel and cylindrical panel tools, market research on natural gas engine filters. He is a member of Phi Kappa Phi (ϕKϕ), ASHRAE, and Surface Mount Technology Association (SMTA).