CHARACTERIZATION OF VERTICALLY SPLIT DISTRIBUTION-WET COOLING MEDIA USED IN DATA CENTERS

by

MULLAIVENDHAN VARADHARASAN

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I would like to thank my family, who always wish me to succeed in my career goals, for providing me this beautiful and invaluable life, filled with so much love and affection.

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Abstract

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Mullaivendhan Varadharasan, MS

The University of Texas at Arlington, 2017

Supervising Professor: Dereje Agonafer

Data Centers houses substantial number of information technology (IT) equipment like computer servers and storage modules associated with various electronic components which consume high volume of electricity. The IT equipment in data center housing keeps dissipates heat energy as it is constantly running day and night. To keep the data center environment under thermally control and to favor the reliability of electronic components, we need to adopt a cooling technique which aids the module level cooling, with due consideration of the size of the data center and its geographical location.

One of the adopted cooling technique in data center thermal management is direct evaporative cooling (DEC). In this DEC, warm air interacts with cold water and losses its sensible heat, thereby the temperature of the air be lowered and its relative humidity be increased.

Evaporative Cooling Pad or Wet Cooling Media is a rigid media in DEC technique, which plays a role to make air-water interaction more efficient. This thesis is focused on investigation on performance characteristics of a vertically split wet cooling media which has separate water distribution setup, this type of staged wetting gives more control on relative humidity (RH) as well as temperature.

In this study, commercial designing and CFD tools are used to design the wet cooling media and simulate the conditions for the test. I have used equal and un-equal two split configurations to test wet cooling media to check which configuration favors the control. Apart from relative humidity and temperature, other parameters of interests are pressure drop across the media and saturation efficiency of the rigid media. Each split configuration is further tested for different wetting, for equal configuration the media has been tested for 0%, 50% and 100%, similarly for unequal configuration the media has been tested for 0%, 33%, 66%, and 100%. The CFD model is further validated with the team's previous experimental data and the results are plotted for comparison on control over inlet RH and temperature to the data center housing.

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Chapter 1

Introduction

Data Centers

The increasing dependence on information technology in various fields ultimately needed large computing and storage capacity, which accompanies with switches, power distribution units, uninterrupted power supply and cooling units. Data Center houses all these IT equipment and other necessary units, this consumes large electricity power and dissipates heat energy at the same rate. IT equipment are designed by the manufacturers in such a way that it dissipates its heat out of its vicinity with the help of in-built module level fans and cold plates.

Figure 1-1 Facebook Data Center in North Carolina [1]

Data Center can either be a single large facility which house everything in to it or a standalone unit which is called modular data center (MDC), which doesn't include

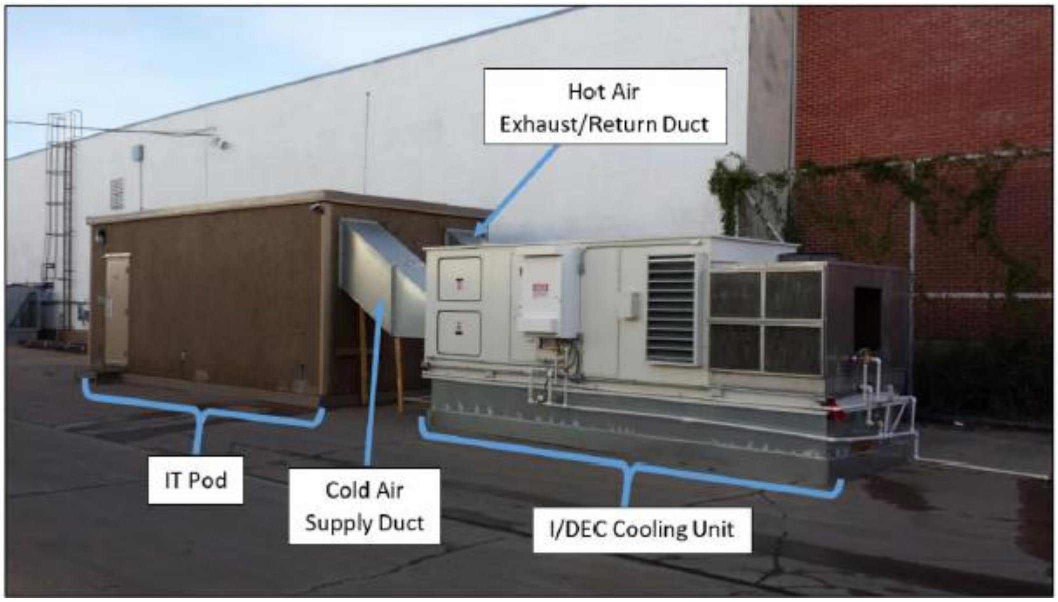

Figure 1-2 Modular Data Center [2]

cooling unit in to it. Modular Data Centers are employed where the portability efficiency of the unit becomes necessary.

The above figure shows the research modular data center located at Mestex facility in Dallas. In this MDC, cooling unit and cooling towers are located outside the MDC, the cold-air is constantly supplied in to the MDC to keep its environment under control.

Evaporative Cooling

Evaporative cooling is a widely-adopted technology used in data centers to control its environment effectively. Evaporative cooling has two different classifications, one is in-direct evaporative cooling and other one is direct evaporative cooling. Data center environment should be controlled under the allowable ranges suggested by American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE). To maintain within the allowable, range the outlet air condition of the cooling unit should be capable of achieving within the that particular range.

Table 1-1 2011 ASHRAE Thermal Guide Lines [3]

Classes (a)	Equipment Environmental Specifications							
	Product Operations (b)(c)					Product Power Off (c) (d)		
	Dry-Bulb Temperature (°C) (e) (g)	Humidity Range, non-Condensing (h) (i)	Maximum Dew Point (°C)	Maximum Elevation (m)	Maximum Rate of Change(°C/hr) (f)	Dry-Bulb Temperature (°C)	Relative Humidity (%)	Maximum Dew Point (°C)
Recommended (Applies to all A classes; individual data centers can choose to expand this range based upon the analysis described in this document)								
A1 to A4	18 to 27	5.5ºC DP to 60% RH and 15ºC DP						
Allowable								
A1	15 to 32	20% to 80% RH	17	3050	5/20	5 to 45	8 to 80	27
A2	10 to 35	20% to 80% RH	21	3050	5/20	5 to 45	8 to 80	27
A3	5 to 40	-12°C DP & 8% RH to 85% RH	24	3050	5/20	5 to 45	8 to 85	27
A4	5 to 45	-12°C DP & 8% RH to 90% RH	24	3050	5/20	5 to 45	8 to 90	27
B	5 to 35	8% RH to 80% RH	28	3050	NA	5 to 45	8 to 80	29
C	5 to 40	8% RH to 80% RH	28	3050	NA	5 to 45	8 to 80	29

Direct Evaporative Cooling

In this direct evaporative cooling, warm air will be made interacting with the cold water, so that the hot air loses its sensible heat, thereby decrease in temperature and increase in RH happens. At the meantime, the passing air's enthalpy will be balanced by the latent heat of water vapor. This process takes advantage of the latent heat of water, which helps bringing down the temperature of air. Since the enthalpy is balanced in this process, it is an adiabatic process. Mass of the passing air gets increased with the addition of water vapor and the mass of the water is getting decreased. This cold supply air can't be recirculated inside the environment, since it gets saturated.

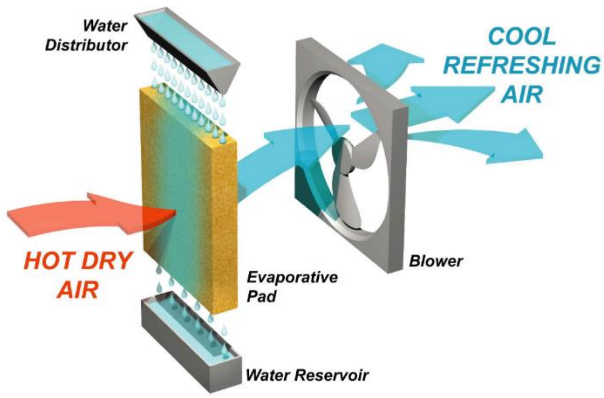

Figure 1-3 Direct Evaporative Cooling [4]

In-direct Evaporative Cooling

In this in-direct evaporative cooling technique the primary air, which could be

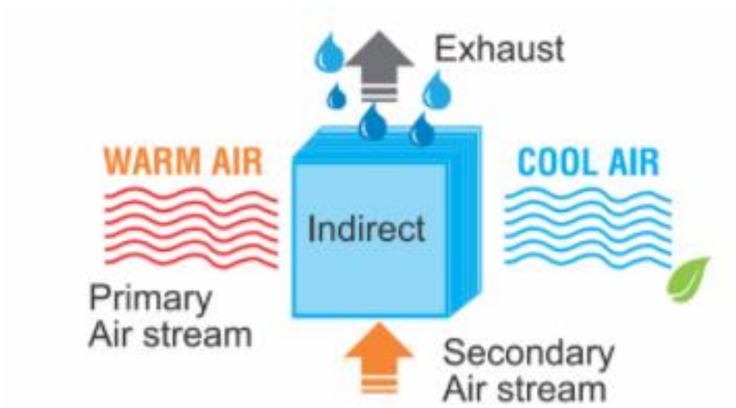

Figure 1-4 In-direct Evaporative Cooling [5]

recirculated inside the data center environment, is cooled in-directly by the heat exchangers with the help of secondary air which gets cooled by direct evaporative cooling. The relative humidity of the primary air won't get changed in the entire process and the primary can be recirculated many times unlike the direct evaporative cooling. In addition, this cooling technique can be applied to hot and humid outside conditions.

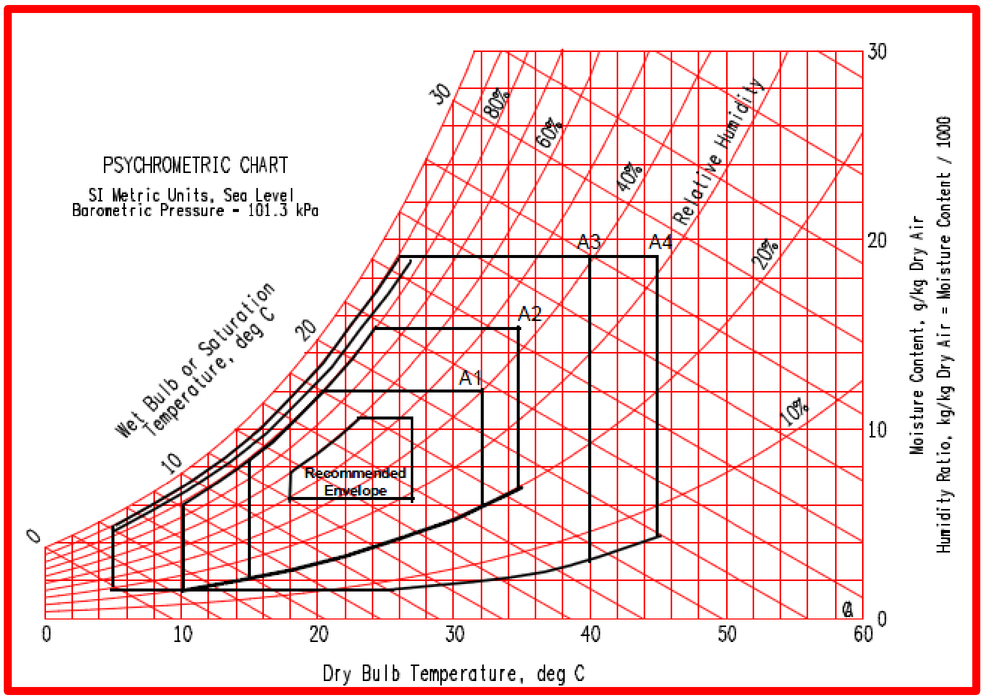

Figure 1-5 ASHRAE Environmental Classes [3]

The above psychrometric chart shows the various recommended envelopes by ASHRAE.

Evaporative Cooling Pads

Evaporative Cooling Pads or Wet Cooling Media is a corrugated rigid media pads used in direct evaporative cooling technique to facilitate air-water interaction more effectively. These media pads are made of varied materials like aspen fiber, glass fiber and cellulose. Out of these cellulose and glass fiber medias are widely popular in data center cooling units. There are number of important parameters associated with media pads, which are

i. thickness of the media
ii. flute angle
iii. material of the media
iv. surface area of the media

Other two key performance factors taken in to consideration are

i. static pressure drop
ii. saturation efficiency

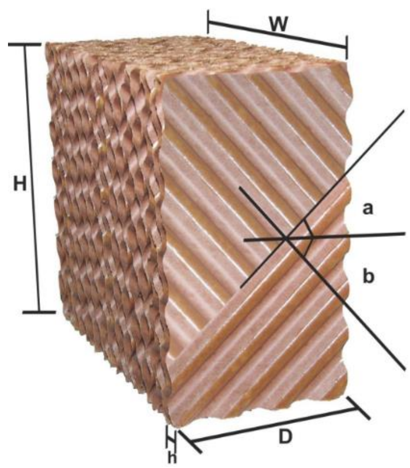

Figure 1-6 Evaporative Cooling Pad [6]

Pressure drop is the difference between the average static pressure at the inlet and outlet of the duct.

Saturation efficiency is calculated using the correlation,

$$\eta = 100 \times \frac{t1 - t2}{t1 - ts}$$

Where,

η – *Saturation Efficiency, %*

$t1$ – *Entering Air Temperature, °C*

$t2$ – *Leaving Temperature, °C*

ts – *Saturation Temperature, °C*

Staged System

Evaporative Cooling Media pads are modified in to different split configuration in order improvise control over the water usage, moisture added to the inlet supply air and over the cooling effectiveness of media. This type of modification made on the water distribution system helps achieving specific needs of the data center cooling.

There are three different staging techniques,

i. Horizontal Split Distribution
ii. Vertical Split Distribution
iii. Series Distribution

All these three-different configurations have its own advantages, the horizontal split distribution unit help utilizing water effectively with over provisioning or under provisioning. If the media pads are staged on top of each other with only one water distribution header at the top, then at times it may evaporate before it reaches the bottom of the media or the water may flow in excess rate. Either situation is not preferable, so in the horizontal split configuration, the water distribution is setup every 6 ft of the media, so that the water can be supplied in the right amount for evaporation. In the vertical split distribution system, the media are split into number of sections and with separate water distribution headers, which allows easy on and off control. This configuration will be effective in usage when we need humidification control over the evaporation process, as per ASHRAE recommendation, RH should be within 28% to 60%, which means to get higher temperature drop we can’t exceed the upper RH limit. When this becomes necessary, the vertical split distribution helps control the relative humidity added to the supply air at the same time temperature drop can also be controlled using the same. The third configuration, which is media in a series. In this configuration, relatively low thickness media are placed in series to get higher cooling effectiveness or saturation efficiency, the trade off in this configuration is the pressure drop.

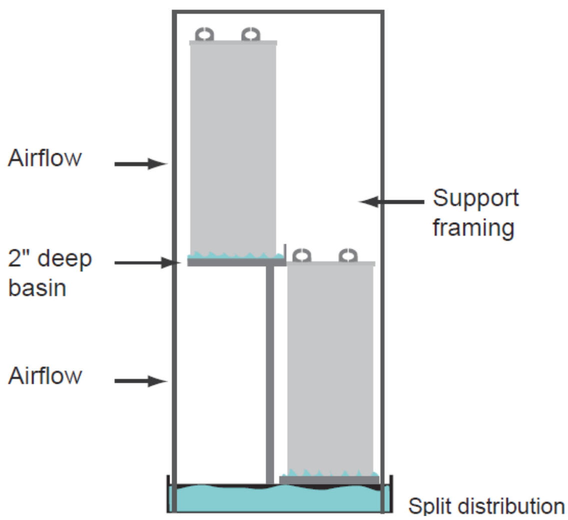

Figure 1-7 Horizontal Split Distribution [8]

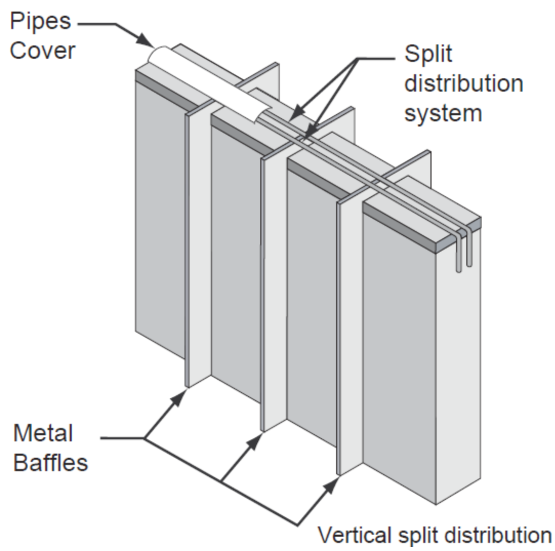

Figure 1-8 Vertical Split Distribution [8]

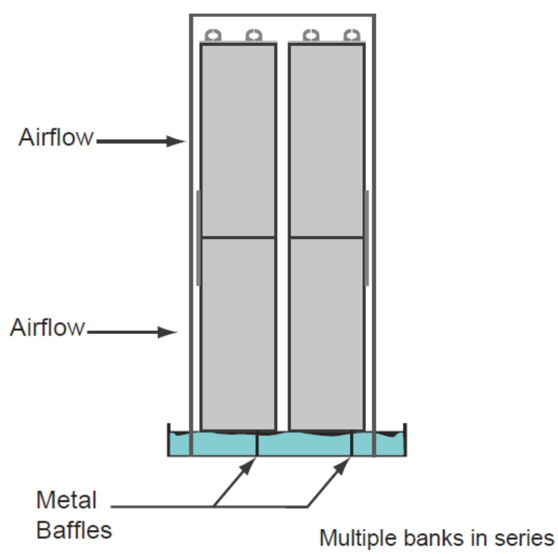

Figure 1-9 Series Distribution [8]

Chapter 2

Overview on Wet Cooling Media Experiment & Results

Experimental Set-up

Wet cooling media has been tested on an Air-Flow bench to find its performance characteristics. In addition to the air-flow bench a three-test duct has been fixed to the air flow bench where in the wet cooling media has been placed at the middle duct and provided with single water distribution unit. Air-flow bench is connected to the blower to provide required air flow through the wet cooling media, the speed of this centrifugal blower is controlled and varied to get necessary flow rate. Flow rate calculations are made using the known nozzle diameter and using the static pressure drop across it. Static pressure has been collected at three different location one before the nozzle and one after the nozzle and one after the wet cooling media test duct. Second pair of pressure sensors were used to calculate the pressure drop across the wet cooling media.

A set of 9 RF Code sensors are placed each in-front of the wet cooling media

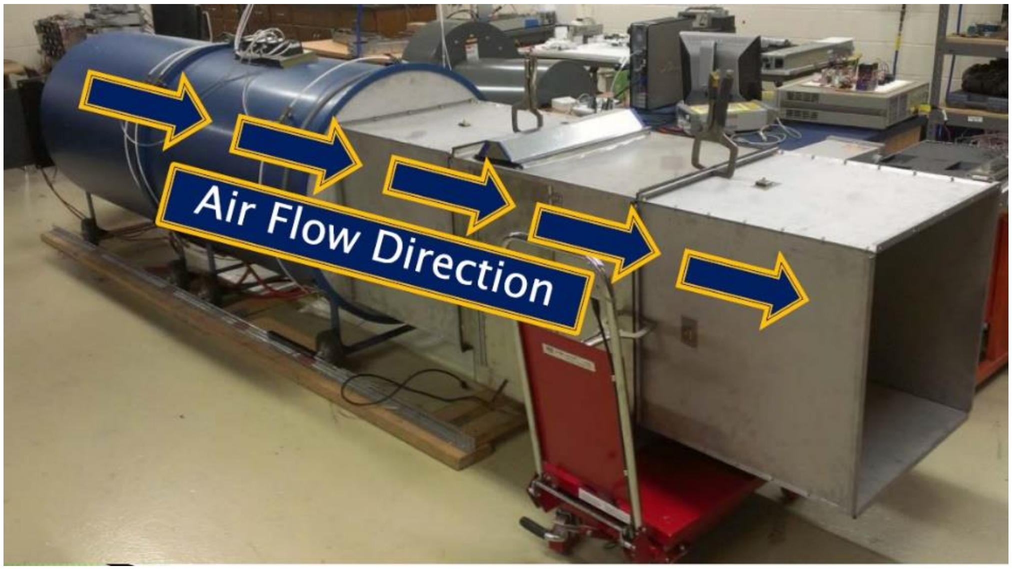

Figure 2-1 Air Flow Bench Set-up [2]

and after the wet cooling media in a plastic mesh, and the relative humidity values and temperatures are monitored continuously using the average values. A water pump is fixed inside the middle duct’s sump to supply water over the media through the distribution tray and a float valve is fixed to regulate the level inside the sump. The water flow rate with this pump is a fixed one with respect to the media manufacturer’s specification.

In this experimental testing, different media has been tested with varied flute angle like 45°×15° and 30°×30°, varied thickness like 12 in and 8 in, and varied materials like cellulose media and glass fiber media.

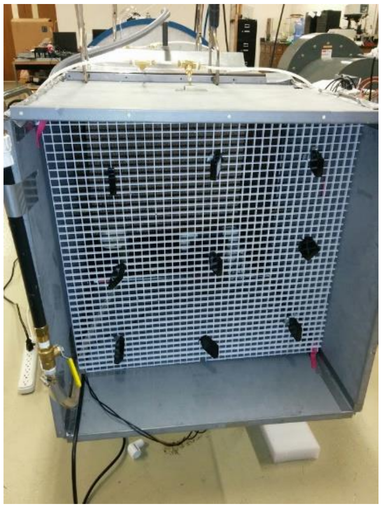

Figure 2-2 RF Code Sensors

The above figure shows the outlet end of the duct set-up with the RF code sensors attached to the plastic mesh to record the outlet temperature and RH values of air.

Figure 2-3 Wet Cooling Media

The above figure shows side view of the wet cooling media placed inside the middle duct with a small door way to fix and remove media inside the duct. The top portion is where the water distribution header goes to supply water over the media.

Experimental Results

The experimental test results are reported and published by the team in order to characterize the wet cooling media to understand its performance and to compare with manufacturer's claim. This experimental test was planned to use and validate with different analytical and CFD simulation models.

For specific flute angle, thickness and material combinations, the media has been tested for different air flow rates with the constant water flow rate over the media. First, the media has been tested for dry run condition, which means there is no water flow rate over the media. After introducing the water flow rate, gradual increase in number of air flow rates has been introduced and results were recorded. This gives us a system resistance curve and the saturation efficiency curve against different air flow rates.

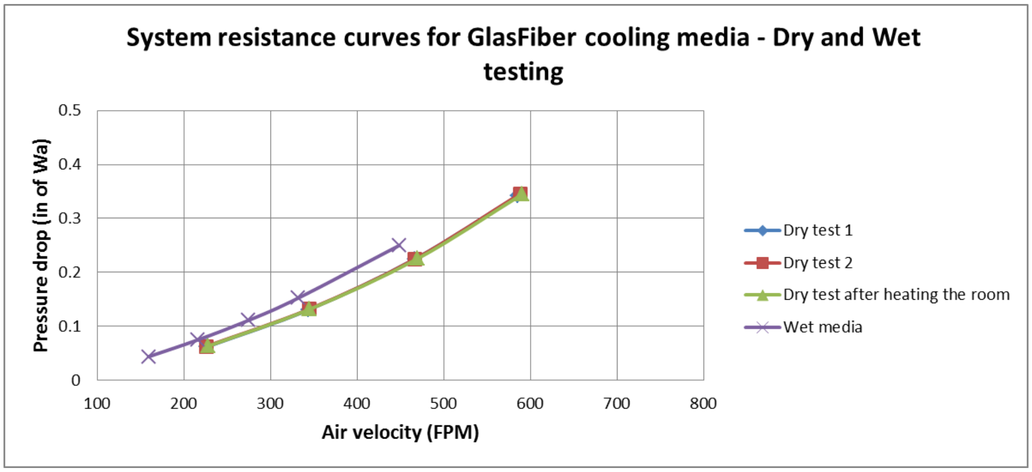

Figure 2-4 Sytem Resistance Curve – Experiment [7]

The above figure shows the pressure drop against the different air flow rates for the 12 in thick GLASdek media. Both the dry run and 100% wet run are plotted for comparison. In this we can see that the pressure drop for dry run is lesser than the wet run tests.

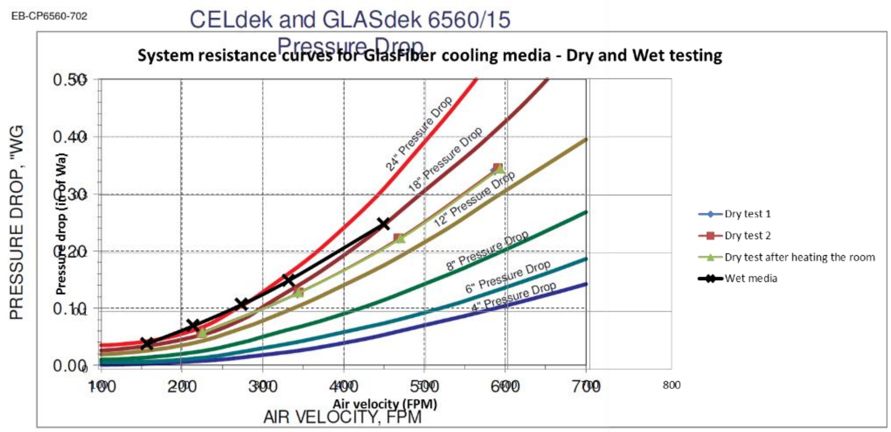

Figure 2-5 System Resistance Comparison [7]

This above figure shows the comparison of test results with the manufacturer data of pressure drop for 12 in thick wet cooling media.

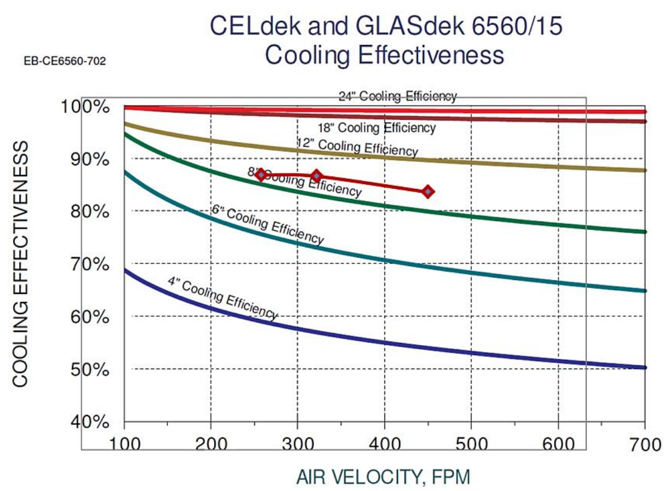

Figure 2-6 Cooling Effectiveness Comparison [7]

This above figure shows the comparison of experimental test results with the manufacturer data of saturation efficiency for 12 in thick wet cooling media. The experimental test results clearly shows the increase in air velocity reduces the efficiency gradually.

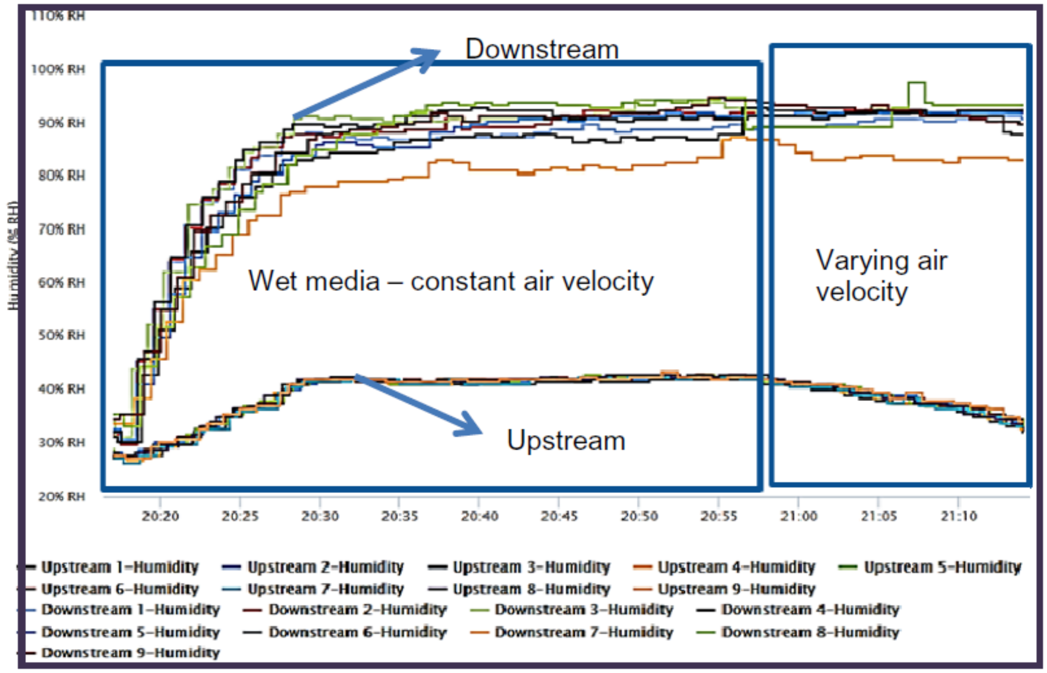

Figure 2-7 RF Code Sensor Readings [7]

The above figure shows the upstream and downstream RH values for a constant air flow rate. The downstream RH value increases from 32% to 90% RH during the wetting phase.

Chapter 3

CFD Simulation and Results

Objective of CFD Simulation

The main objective of this CFD analysis is to simulate a test condition on a vertically split wet cooling media to see the control over relative humidity and the temperature drop when it is necessary. As we have seen in the previous experimental work, the control over humidification is less possible, since we always wanted to keep the water flow rate constant over the media. Other option to control the relative humidity is to keep switching off and on the water flow over the media frequently to introduce dry air, this methodology is not advisable since it creates scale at faster rate on the media and increases its weight, which may even lead to collapse. So, the other viable option is staging the wetting of media.

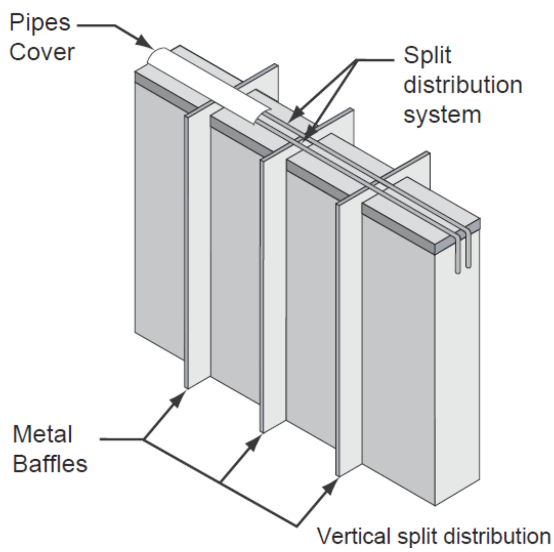

Figure 3-1 Vertical Split Distribution [7]

In this CFD analysis I have modeled the media with two equal and un-equal sections and I simulated the test condition which is similar to the experimental work. The main difference is, now it has two different water distribution sections.

Equal Configuration – Wetting Percentages

- 0% (dry)
- 50% wet
- 100% wet

Un-equal Configuration – Wetting Percentages

- 0% (dry)
- 33% wet
- 66% wet
- 100% wet

Geometry and Mesh of the Wet Cooling Media

The wet cooling media geometry is created using the SolidWorks designing tool for the 12-inch-thick GLASdek media with 45°×15° configuration and the heigh of the media is 12 inch. The air channel and water channel are designed and patterned to get the rigid media, with the consideration of metal baffle which separates it in to two sections. The domain has also been created around the rigid media to mimic the duct in the experimental test.

The SolidWorks model is then imported to the ANSYS Design Modeler and the enclosure option is introduced to the duct. At this point, the two-section media has two duct adjoined together, which are duct_left and duct_right. The size of the duct depends on the equal or un-equal configurations.

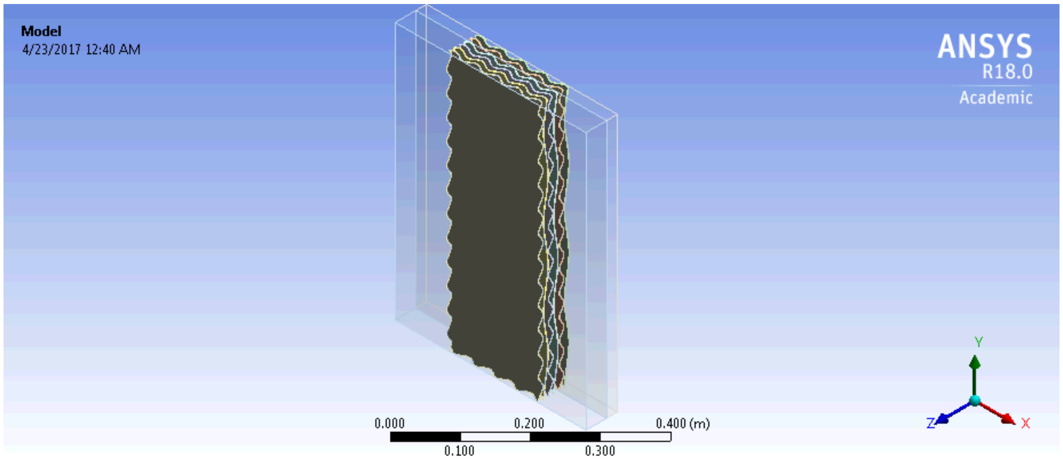

Figure 3-2 Un-equal Geometry

The above figure shows the wet cooing media geometry for an un-equal configuration. With consideration of the number of mesh elements and computational expenses, the geometry is simplified to a lower width compared to the experimental one, but at the mean time the left and right portions are sectioned proportionally. The named sections are created at this point, where the min_x of the duct is inlet to the media and the max_x is the outlet to the media.

The mesh has been generated in the ANSYS Mesh, with the curvature sizing function and zonal mesh refinement. For the equal configuration, the number of elements are around 2.49 million and for the un-equal configuration it is around 3.59 million. For maximum utilization of processing capacity, the number of CPU usage has been increase almost to the maximum.

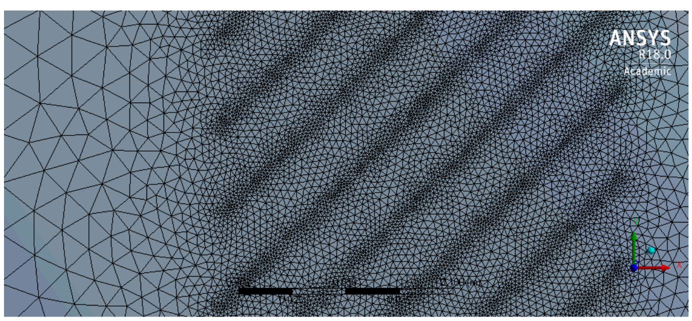

Figure 3-3 Mesh Density

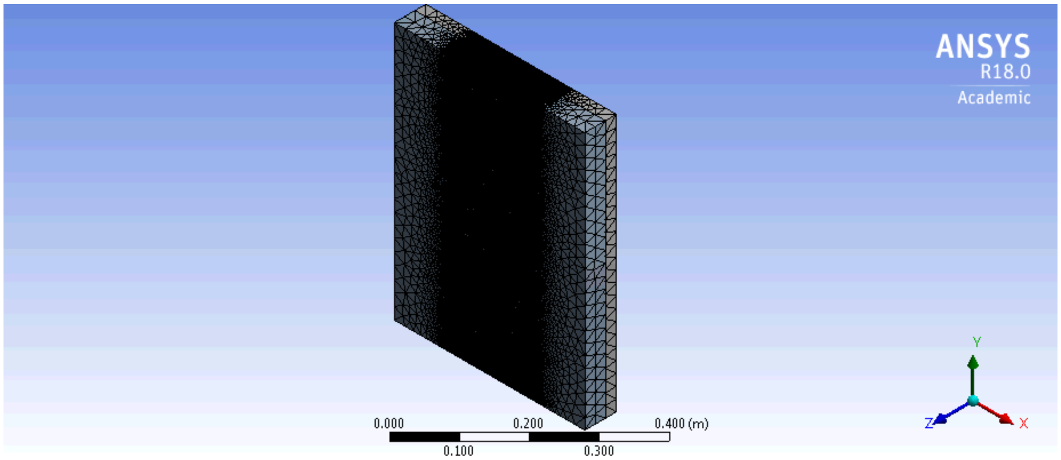

Figure 3-4 Mesh

Boundary Conditions

The following is the inlet condition are specified to the air flow entering the duct and the water flow over the media in ANSYS Fluent. For the constant water flow rate and for the constant temperature and RH conditions of air inlet, the air velocity has been varied to find out its trend and to compare with the experimental data. The number of velocity inputs has been increased from the experimental to get high accuracy.

Inlet Conditions:

- Temperature – 27 °C
- Velocity Range – 1.27 to 3.3 m/s (increment of 0.25 m/s)
- Relative Humidity – 35%
- Mass Flux of Water – 9 $kg/m.s^2$
- Hydraulic Diameter – 0.2517 m
- Reynolds Number – $[2.41 - 5.4] \times 10^4$

Model Set-up

It is a pressure based, steady problem set-up with the gravitational force is considered on negative Y direction. Energy model and Viscous k-epsilon model has been used with the enhanced wall treatment. Viscous k-epsilon model has been used, since the Reynolds number falls in to the turbulence region. Eulerian wall film has been switched on to introduce the water flow over the media, the mass flux value of water has been specified. Species transport has been used to introduce moisture in the air inlet.

Under the cell zone conditions, duct has been considered as the fluid with mixture template of air and water and the media has been given the properties of glass fiber.

Model Setup:

- General – Steady, Pressure Based with Gravity on
- Energy
- Viscous Model: Standard $k - \varepsilon$ with Enhanced Wall Treatment
- Species Transport
- Eulerian Wall Film

Contour Plots

The following contour plot and vector profile across the wet cooling media gives an overview of what exactly is happening in terms of relative humidity, temperature, pressure and velocity. The following contour plots are taken for a velocity at 2.54 m/s and at 100% wet condition.

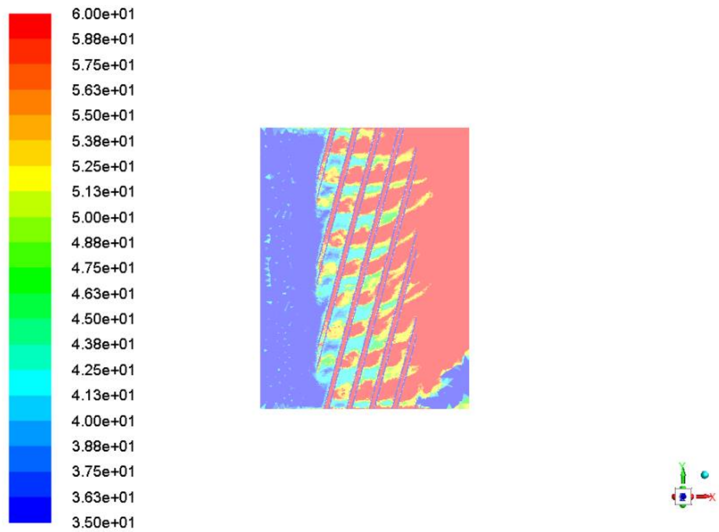

Figure 3-5 Relative Humidity Contour

The above contour plot shows the change in relative humidity across the media, here the air flows from the left to the right. As the air flows through the media the moisture is getting added as it interacts with the water, which is flowing over the media.

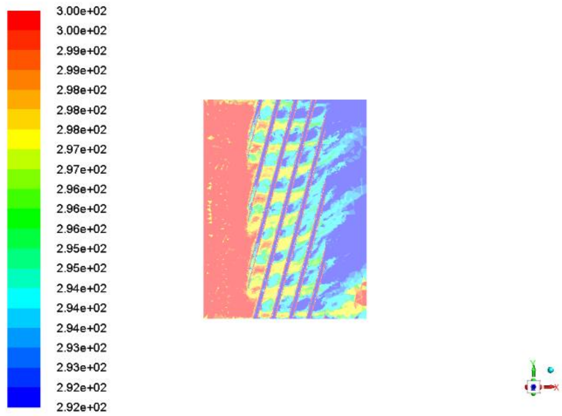

Figure 3-6 Temperature Contour

This contour plot shows the temperature change across the wet cooling media. As the air flow from the left to right, due to the loss in sensible heat, air losses its temperature. The overall drop in temperature we see is 8°C.

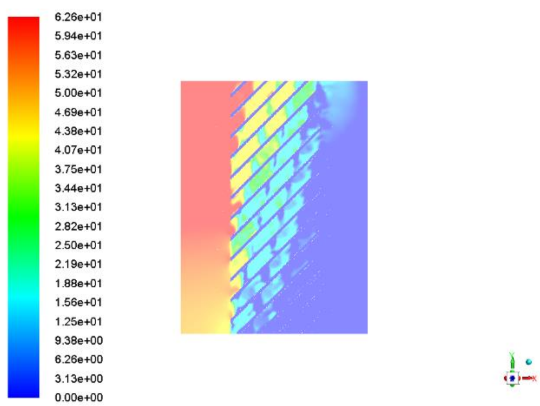

Figure 3-7 Pressure Contour

This contour plot shows the pressure change across the wet cooling media. As the air flows from the left to the right, there is a drop in pressure. The total drop in pressure for this region is about 62 Pa.

Results

The CFD results are plotted for system resistance, saturation efficiency, temperature change and relative humidity change against the number of inlet air velocity values, for all the combinations of wetting percentages and split configurations.

The CFD model for vertical split distribution system is validated with the experimental result using the system resistance curve and saturation efficiency curve for both 0% i.e. dry run and for the 100% wet run for the GLASdek media.

The following two plots shows the pressure drop for different velocity inlets and as the velocity increase from 1.24 to 3.3 m/s, the pressure drop is also increasing for both dry and wet conditions. The pressure drop for wet run is more than the pressure drop for the dry run.

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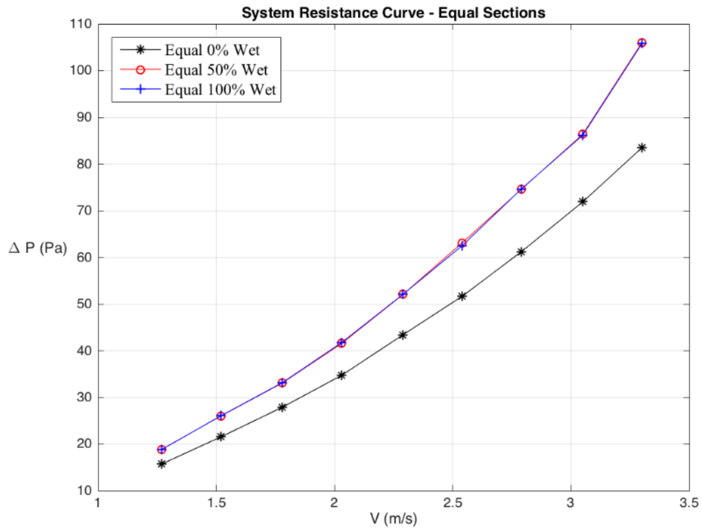

Figure 3-9 System Resistance Curve Equal Sections

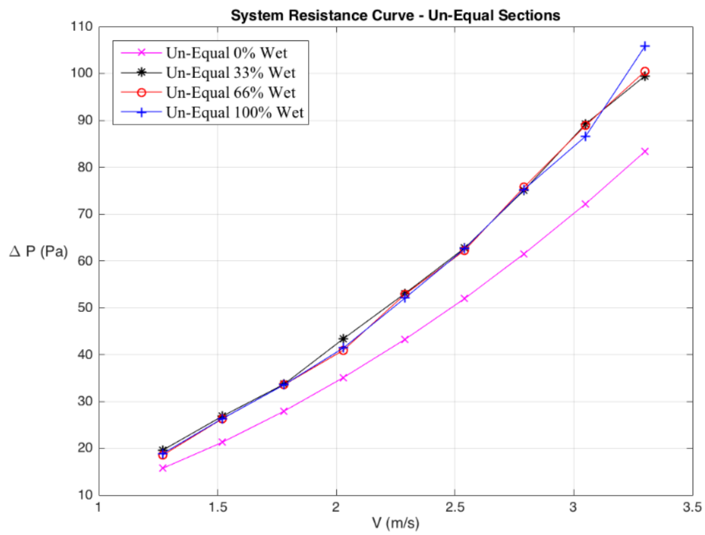

Figure 3-8 System Resistance Curve Un-Equal Sections

The following two plots shows the saturation efficiency for different velocity inlets and as the velocity increase from 1.24 to 3.3 m/s, the saturation efficiency is decreasing for all the wet conditions. Here the values are plotted only for wet conditions since there won't be any temperature drop for dry run to calculate saturation efficiency.

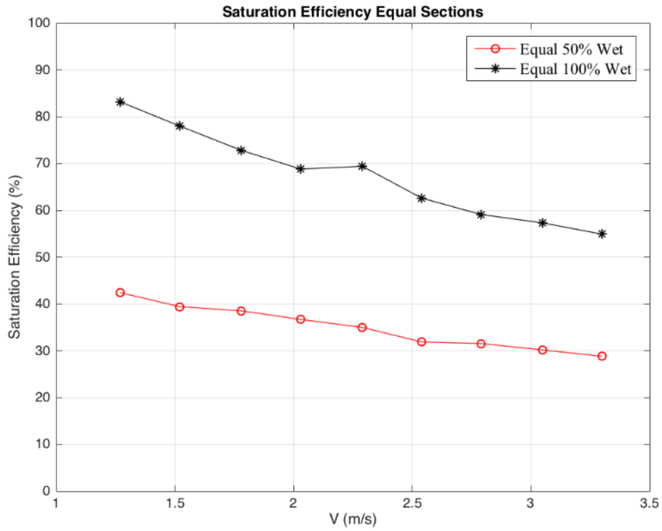

Figure 3-11 Saturation Efficiency Equal Sections

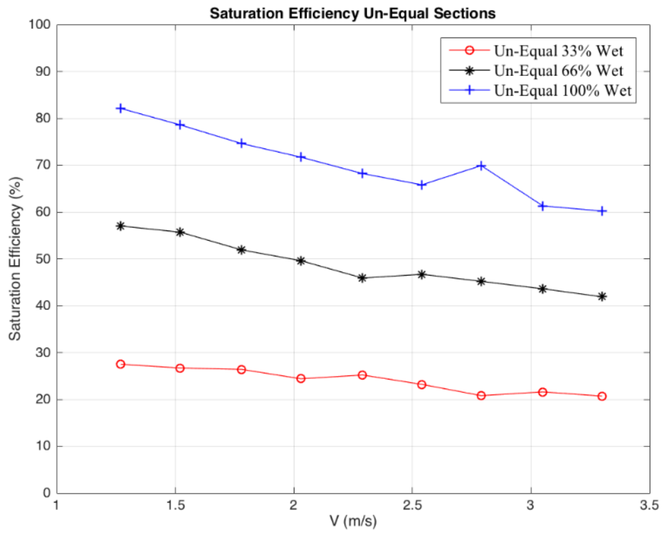

Figure 3-10 Saturation Efficiency Un-Equal Sections

The following two plots shows the change in temperature for different velocity inlets and as the velocity increase from 1.24 to 3.3 m/s, the temperature is decreasing for all the wet conditions. Here the values are plotted only for wet conditions since there won't be any temperature drop for dry run.

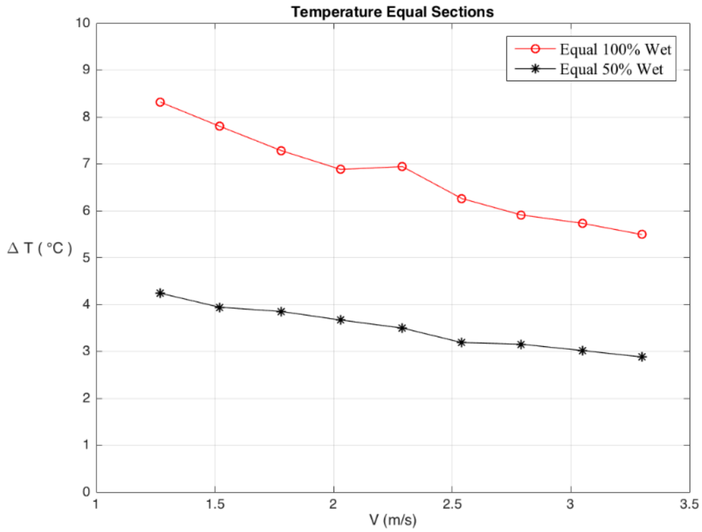

Figure 3-13 Temperature Equal Sections

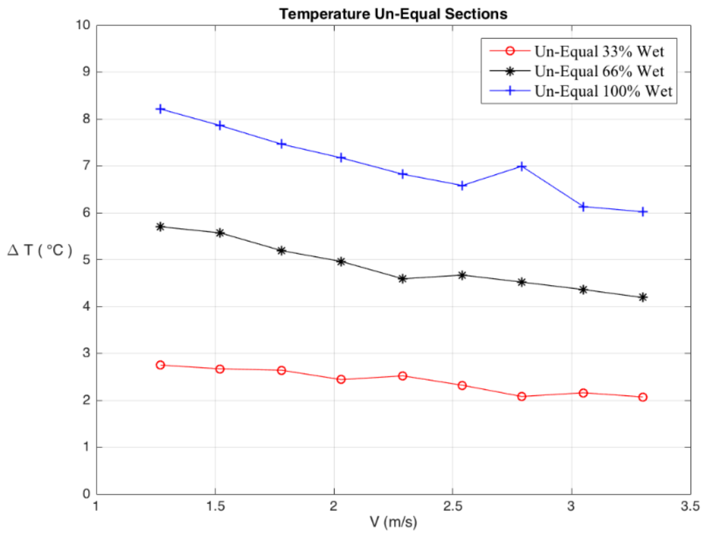

Figure 3-12 Temperature Un-Equal Sections

The following two plots shows the change in relative humidity value for different velocity inlets and as the velocity increase from 1.24 to 3.3 m/s, the RH value is decreasing for all wet conditions. Here the values are plotted only for wet conditions since there won't be any addition of moisture in dry run. This test result clearly shows the control on water distribution staging gives control over relative humidity.

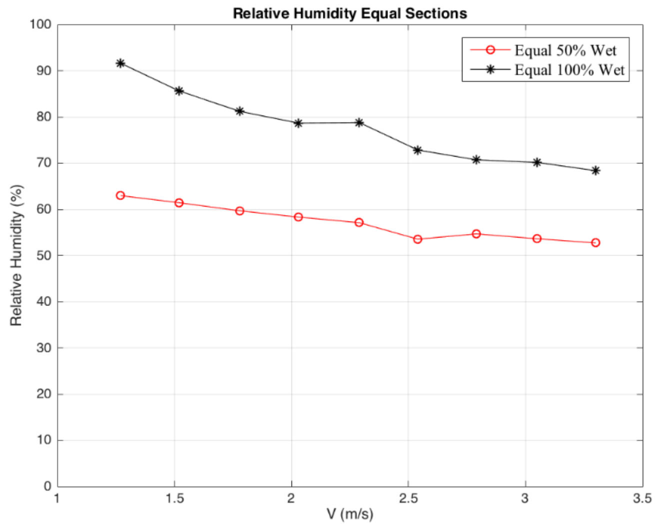

Figure 3-14 Relative Humidity Equal Sections

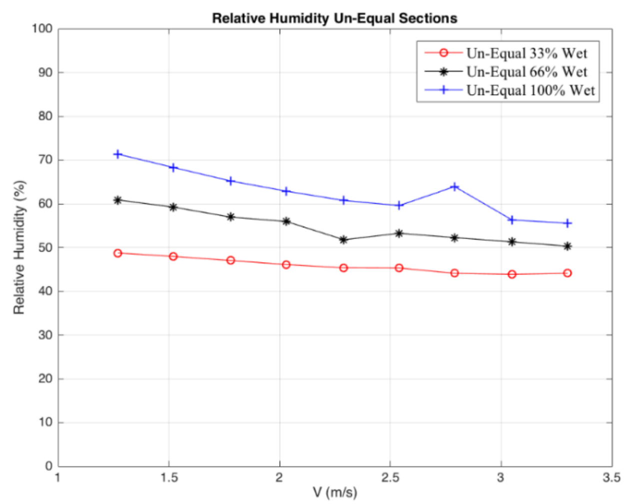

Figure 3-15 Relative Humidity Un-Equal Sections

The following plot shows the change in relative humidity for different velocity inlets ranges from 1.24 to 3.3 m/s. The three curves here are the readings taken from the left and right section of the media as well the 100% wet media. The black curve represents the average RH value calculated only at the right-side section (66%) of the media and the blue curve is similarly for left side section (33%), unlike the previous data which averages out for entire outlet area.

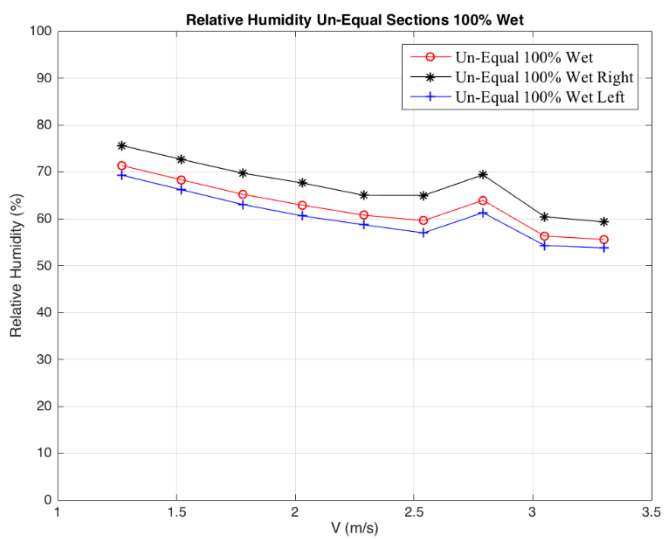

Figure 3-16 Relative Humidity Un-Equal Sections 100% Wet

Chapter 4

Conclusion

The vertical split distribution model has been successfully created and validated with the previous experimental results for dry and 100% wet runs. The objective of this CFD simulation has been achieved by getting results for all combinations of split distribution with equal and un-equal configurations.

The change in relative humidity and the temperature drop has been carefully reviewed and interesting results are found. This control on relative humidity and temperature greatly helps the data center environment to be run inside the ASHRAE's allowable range of relative humidity and temperature upon implementing the vertical split distribution system. This ultimately increase the reliability of the IT equipment and minimize the cost associated with it.

The comparison of two configurations showed the un-equal configuration has better control on relative humidity than the equal configuration. This clearly shows when the vertical split configuration is implemented for any number of staging, it would be beneficial, if the sections are un-equal.

Chapter 5

Future Work

- The CFD simulation can be extended to experimental work.
- The scale formation due to on and off can be investigated experimentally.
- The same test can be repeated for different flute angles and for different thickness.
- The CFD simulation for horizontal split distribution and series distribution can be done.

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Biographical Information

Mullaivendhan Varadharasan is from a town Pattukkottai, India. He has completed his high school in Pattukkottai and has completed his Bachelor of Engineering in Mechanical Engineering from Nehru Institute of Engineering and Technology, Coimbatore affiliated to Anna University Chennai in June 2013.

He decided to pursue higher education and joined the University of Texas at Arlington for his graduate studies in Mechanical Engineering in Spring 2015. He joined the EMNSPC research group in the following summer and worked on various projects on Data Center Thermal Management. He has also worked as a Graduate Teaching Assistant for Electronic Packaging Courses and for Thermal Engineering Course at UT Arlington. In April 2017, he has successfully defended his master's thesis and graduated with Master of Science degree in Mechanical Engineering.