University of Southern Queensland

Faculty of Health, Engineering & Sciences

Human Comfort - CFD Modelling to Provide Energy Efficient Air-Conditioning in a Modern Office

A dissertation submitted by

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Abstract

The design philosophy of supplying air conditioning to the modern office layout is a tried and true method with little challenge from the norm. Engineers are taught design rules and guidelines to design an open plan office. This design includes ceiling mounted grilles which work by diffusing cold air across the ceiling which then through natural convection falls down, cooling the whole area from floor to ceiling. While this method works fine and does fulfil the design requirement it is unnecessarily cooling large volumes of air located above people heads which is not required for human comfort conditions. This unnecessary cooling results in a larger cooling demand on the air conditioning system and wasted energy.

This report aims to improve energy efficiency in a modern office by focusing on and comparing a floor based delivery system to that of the more conventional ceiling based. As the floor based system will provide more of a task based cooling system which will focus on cooling around the person and limit the cooling of air in transient areas such as hallways, lobbies and printer areas. People don't congregate in these areas for extended periods of time and will be accepting of slightly higher temperatures than if they were sitting at their desk.

Through Computational Fluid Dynamics (CFD) modelling different ceiling and floor task based air distribution systems have been analysed. The results indicate that a potential energy saving of approximately 15% is realisable by adapting the recommended setpoint of 26.5°C and humidity of 30% to 35% for the office space, which will still maintain acceptable levels of human comfort within the space.

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Limitations of Use

Certification of Dissertation

I certify that the ideas, designs and experimental work, results, analyses and conclusions set out in this dissertation are entirely my own effort, except where otherwise indicated and acknowledged.

I further certify that the work is original and has not been previously submitted for assessment in any other course or institution, except where specifically stated.

C.Higgs

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I would like to thank my family for providing positive criticism on my work throughout the duration of this project. Dr Andrew Wandel for his knowledge and assistance throughout this project, particularly with the Ansys CFD modelling.

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Chapter 1 - Introduction

1.1 Background

Over 70% of a base building offices energy consumption and almost 40% of a working office electrical demand is from providing air-conditioning. In the modern day with such a large push for companies to be carbon neutral and energy efficient more has to be done to reduce this large demand. Air-conditioning is a luxury which only exists to create a more comfortable working environment, it is not a necessity but it aids in work productivity and employee happiness.

Australian standards do not require an office to be at 23-24°C and 50% humidity like most typical offices are set to, it only states that a minimum of 7.5L/s per person of fresh or outside air must be provided (Standards Australia, 2012), while premium offices aiming for GreenStar ratings requires 10L/s in order to gain points on their rating system (Green Building Council of Australia, 2017).

Throughout the day the average person working a desk job spends 5 hours and 41 minutes at their desk (British Psychological Society (BPS), 2012), the other approximately 2 hours is spent either at meetings, lunch, printing, or communicating with fellow employees in close proximity to that person's desk.

Human comfort is somewhat unpredictable, there has been many studies performed by (Humphreys, 2005), (Erlandson et al., 2003) and (Melikov et al., 2005). While many of these studies come to conclusions and recommendations based on sex, age and the metabolism rate of a person, this is generally a guideline at best. Females generally are more temperature sensitive then males which means in an air-conditioned environment they are more likely to feel too cold compared to that of a male in the same conditions. This however doesn't always comply.

An ideal office would have individual controls which could be adjusted by each employer to suit their preferences in task based environments. Studies show a person is upto 10% more productive when they are in a comfortable environment to work in (Dorgan and Dorgan, 2016). This is a main reason air conditioning was introduced initially.

Through the use of CFD modelling this report investigates different methods of delivering conditioned air to more task based situations and reduce air flow to transient spaces in order to save energy in cooling unused spaces in office buildings.

1.2 Idea Initiation

This initial topic arose from working in the building services industry both in a consultant role and on the contractor side. This enabled a great insight into seeing some of the inefficiencies in design aspects. While other industries continue to push the boundaries and challenge conventional design there has been little development in the design concept around providing thermal comfort to typical office spaces.

The current method of delivering air conditioning to an office building involves having either an Air Handling Unit (AHU) or a more local packaged unit (PAC) which is connected via solid and flexible ductwork to an air terminal in the ceiling. This air terminal then diffuses air across the ceiling and utilises natural convection to fall from the ceiling to the people in the office. This method cools the whole space rather than focusing on a specific area. With an average ceiling height of 2700mm a person at their desk sits around 1200-1300mm high, this shows that 1400-1500mm of space above a persons head is being comfort cooled when it is not required to be. This space above a person equates to approximately 55% of the office building being conditioned to 23.5 degrees just because the diffuser positioning. This positioning is used as this is the way an air conditioning system has been designed for the last 100 year, with no one really challenging this design principle.

The focus of this dissertation is to model a range of office, temperature and humidity configurations in order to reduce this wasted energy. By utilising CFD modelling software to investigate different ways to deliver conditioned air directly to work stations as a task based environment, such as the use of floor grilles. The modelling serves to evaluate the ability to condition these localised areas, without introducing issues such as a person feeling cool drafts while sitting in close vicinity to the air terminal. To eliminate any draft feelings, particular attention will be focused around they velocity of conditioned air as it leaves the air terminals.

1.3 How Air Conditioning Works

An air conditioning system which can be seen in Figure 1.1 works by using a cold substance, often a refrigerant such as R410A, and utilises the phase changing of liquid to gas which absorbs the heat by the refrigerant which the evaporates as it collects the heat inside and then condenses to dissipate the heat at the outdoor condenser. The refrigerant flows though pipework and into a series of evaporator coils where warmer air is blown over the refrigerant filled coils, this both cools the air and strips water vapour from the air. The water vapour is collected as condensation formed around the coils within the unit and drained away. This has an effect of cooling the incoming air into a space as well as reducing the humidity of the air, this is particularly important in northern and costal Queensland as well as other tropical climates both in Australia and internationally.

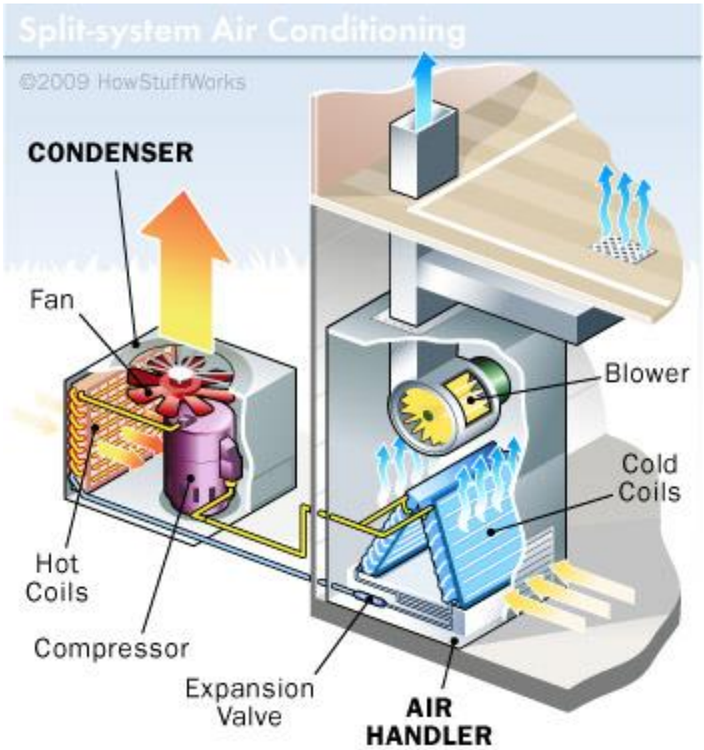

Figure 1.1:Basic Air-Conditioning System (Brain, Bryant and Elliott, 2011)

1.4 Current Energy Saving Methods

There are a number of methods currently used with the aim to reduce energy consumption of air conditioning or providing human comfort to a space, generally these have a reasonable impact of reducing energy consumption. These however are generally systems which need to be installed as the building is being built rather than being able to be integrated with an existing traditional air conditioning system.

1.4.1 Solar powered

There are two forms of solar powered air conditioning that is used, the most common being photovoltaic panels (PV Panels) these panels generate electricity which then powers a traditional air conditioning system. The PV panel works by collecting sun rays which agitate electrons within silicon cells, electrical conductors then capture this current and the output is electricity. This means there is little ongoing cost to run the system after the initial setup. There are a number of disadvantage to this type of system in a commercial environment, firstly the system only runs during sunny periods where the panels can collect the sun's rays, or have a battery setup which requires a sizeable footprint within the building. Additionally, on large office buildings there is not sufficient roof space for enough solar panels to generate the required electrical demand to power the air conditioning systems. This is particularly the case with high-rise office building such is the focus of this project.

The second is by using a solar hot water system and an absorption type chiller. This type of system uses the hot water to regenerate the refrigerant which is often ammonia and has a refrigeration cycle much the same as a standard air-conditioning system except it used the hot water rather that electrical energy to regenerate the refrigerant. This type of system shares similar benefits and problems with a PV solar type system of being that it need a large footprint for the solar panels, which is not possible in a commercial sized situation.

1.4.2 Geo-thermal cooling

Geo-thermal cooling relies on using the thermal mass of the earth to cool air before it enters the space which requires cooling. This type of cooling system takes advantage of the ground being a constant temperature. During summer months, underneath the ground is always colder than the surface temperature. This temperature varies depending on the soil types, depth and the actual location on the earth.

Generally it is easy to find temperature of just below 20°C at a depth of approximately one metre. Colder temperatures are able to be achieved by digging deeper into the earth, but the benefits decrease rapidly after the first metre and a half.

The Geo-thermal system is a fairly simple system, it works by running tube or duct underneath the ground. This duct utilises the heat transfer principles and acts as a heat exchanger between the soil and the air, cooling the air as it is passed though the duct. There is a number of different materials which this duct can be made from but typically brick and cement are used due to their thermal mass properties and little risk to corrosion, rusting or chemical reactions with the soil like some metals would have.

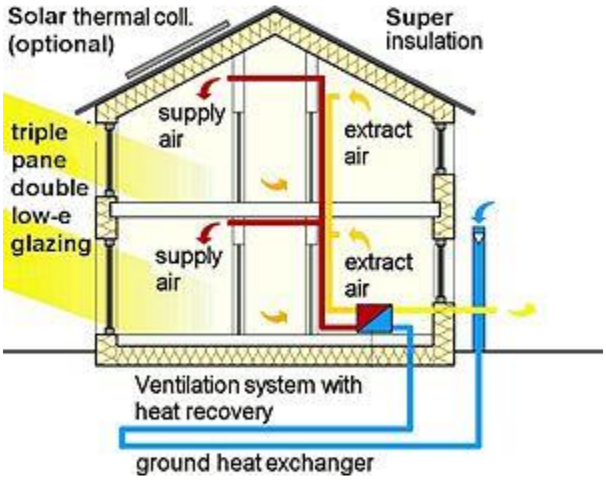

Figure 1.2: Geo-Thermal Cooling System

1.4.3 Heat Exchangers

Heat exchangers are used in a wide array of applications. They typically work in conjunction with an air conditioning system and uses various forms of thermal transfer media. They work by using air that has already been cooled via the air conditioning system, which would otherwise be discharged to atmosphere from exhaust systems such as general and toilet exhaust. The heat exchangers are able to use this air otherwise deemed as obnoxious due to the containment smells and odours by having a solid barrier between the air paths, which does not allow the incoming and outgoing air to mix as in in Figure 1.3.

This conditioned air passes though the transfer media which allows the passing air to absorb the heat energy from fresh outside air passing though the other way. This system acts as a pre-conditioner to the incoming warmer outside air and saves energy by reducing the air temperature before it reaches the air conditioning cooling coil. By pre-cooling the air it reduces the amount of energy the traditional cooling coil in the air conditioning system requires to meet the desired temperature setpoint in the office space.

While heat exchangers have their place in an energy efficient modern office design it is not a standalone system as it relies on having air that has previously been cooled. If the additional cooling coil air conditioning system was turned off, the temperature in the space would gradually rise until it is the same as the outside air temperature. Which during summer time in Brisbane can often be up to and even exceeding 35°C..

Figure 1.3: Heat Exchanger (Ciraldo, 2014)

1.4.4 Variable Air Volume Systems (VAV) with Variable Speed Drive (VSD) Fans

Variable Volume Systems are the most common type of system installed in high rise commercial buildings within Australia (Bhatia, 2012). The system consists of a motorised damper in the main ductwork which opens and closes to maintain a set temperature in the room by reducing the cold airflow to the space once temperature is reached. The system also requires pressure sensors which feed information back to the central air handling unit. These signals then control the main air conditioning fan speed via the variable speed drive. Once the conditioned space reaches the desired temperature the VAV dampers start to close, the fan speed is reduced which enables the energy saving as less fan power is required. When the fan slows down there is a simultaneous effect on the cooling coil as there is less thermal demand is on the cooling coil of the air-conditioning unit, saving further energy.

A variable volume system allows a whole office floor to be run off one main air handling unit rather than multiple smaller units which one otherwise be required. This simplifies the equipment required and is cheaper then installing multiple units. It is a slight more energy efficient design as well.

1.5 Project Aim

This dissertation aims to reduce energy usage by means of varying conditioned spaces inside an open plan office. Computer modelling will be used to determine the ambient space conditions, these conditions will then be input into the human comfort formula to determine acceptable conditions.

While it is not expected that the design philosophy of all office buildings will change to the based on the recommended design layout from this report to become more energy efficient, the aim of this project is to create a number of design guidelines for which the following:

- Recommended design layout, floor or task based layout for the highest energy efficiency
- The required cooling demand per person in watts and volume of airflow (L/s).
- Recommended distance from the grille outlet to seated person for the best distribution of conditioned air.
- The recommended temperature and velocity of the air as it exits the outlet/grille to avoid the feeling of drafts or cold spots.

1.6 Research Objectives

The project is designed to provide detailed analysis of modern office air conditioning designs and alternative solutions with the aim of reducing energy demand required to meet human comfort through using a task based supply system.

The expected outcomes of the project include:

- Identification of wasted conditioned air in the standard modern office design and therefore wasted energy

- A detailed CFD comparison of different design concepts and associated advantages, disadvantages and the possible energy savings for each design.

- Compiled list of design guidelines for a task based air-conditioning system including air terminal locations, air velocities and temperature set points to enable an engineer to design a system in line with the findings from this report.

Chapter 2 - Literature Review

2.1 Introduction

With practically every commercial office in Australia relying on air-conditioning, more efficient engineering designs must be implemented to reduce the energy consumption of modern buildings. This Literature review will focus on three main subjects. Firstly an investigation into current standard air conditioning designs to identify areas of wasted conditioned air and identify possible energy savings design solutions. Secondly these energy saving designs will be investigated further to determine suitability and the effects the designs would have, both positive and negative. Lastly an investigation into current CFD modelling programs to determine their suitability for analysing large office spaces.

"People who are unhappy with temperature, air quality, lighting and noise conditions in their offices are more likely to say that this affects their productivity at work." (Leaman, 1995, p13)

2.2 Background and Current Design

In 1902 the first office air-conditioning system was installed in the Armour Building in Kansas City, Missouri (National Academy of Engineering, 2016). This design system includes many features still used in design today, including individual room thermostats which controlled zoning damper in the ducting to reduce airflow to each room, when it reached set point conditions. Further developments followed quickly thereafter. In 1906 Willis Carrier patented a dew point control which allowed humidity control using refrigerated water sprays, this was further refined by Edward Williams who utilised reheat to lower the humidity.

The Montreal Protocol was signed in 1987, this saw a large change in the use of refrigerants and saw the phasing out of CFC refrigerants, meaning refrigerants such as R-134A, which was first synthesized by Albert Henne in 1936, had to be used in place of CFC's. Five years later saw the first introduction of minimum standards in energy efficiency for commercial buildings introduced, this introduced many equipment testing standard still used today, including Minimum Energy Performance Standard (MEPS) compliance. These standards for the better part only dictate the equipment requirements and covers very little regarding installation design.

While there have been large improvements in equipment efficiencies, refrigerant and design refinement since the first system was installed the principle office designs have remained the same. Air-conditioning being delivered from the ceiling at temperatures of around 18°C with natural convection methods used so the air mixes with the warmer air in the space so it reaches the desired set point conditions of 22-24°C.

The current trend in open plan office design is to have ceiling mounted diffusers which throws the air across the ceiling. This air then drops down due to natural convection as seen in Figure 2.1. This method works effectively in distributing air across the whole room evenly as seen in Figure 2.2. This is ideal for rooms with a high people to floor area ratio, but on a standard office design of 1 person per 10m² of floor area this is cooling down a large amount of unoccupied space and transient areas such as walkways, corners of rooms and space on the opposite side of the desk.

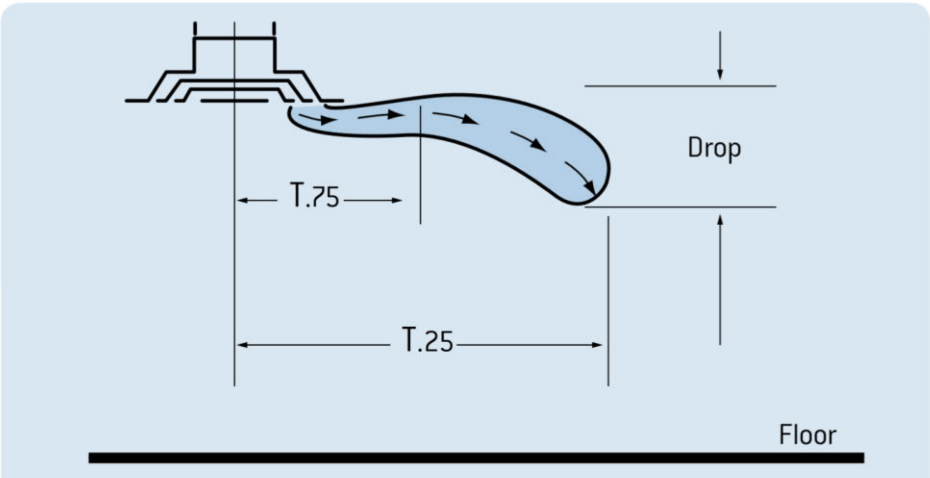

Figure 2.1: Diffuser Flow Path (Holyoake Air Management Solutions, 2013)

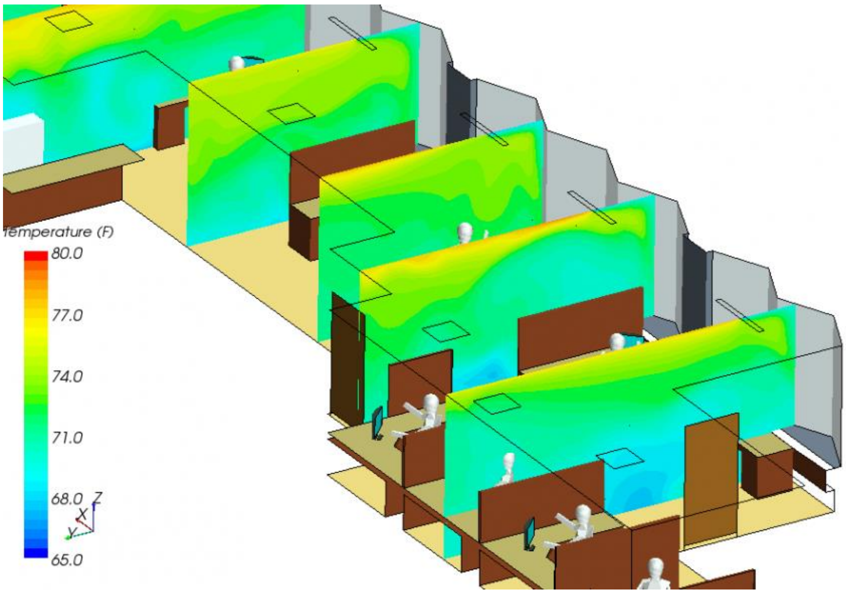

Figure 2.2: CFD Temperature Mapping of an Office Space (M/E Engineering, 2017)

Cooling down all of this air requires a large amount of energy which is wasted when the air conditioning is just operating for human comfort. People spend approximately 5 hours and 40 minutes a day time seated at their desk (British Psychological Society (BPS), 2012). The other time during a working day is spent either at other workers desks, printing, in the staff facilities, at lunch or in meetings, which can often be outside of the office. This means all of the conditioned air above the seated height of 1.5m is generally energy wasted throughout most of the working day. Similarly, for hallways and other transient areas around the office were a worker will spend less than 1 minute in that space.

2.3 Possible Energy Saving Design Solutions

2.3.1 Floor Based Air Terminals

Many floor based air terminal systems currently exist around the world; they were first implemented in Europe and South Africa (Sodec and Craig, 1991). There are two main design methodologies for this type of system, the first utilises ductwork which connects the air conditioning unit to each air terminal with rigid and flexible duct, this is the same method that is done with traditional ceiling designs. The second method involves utlising the raiser floor as a plenum and using localised fans connected to the floor mounted air terminals, this method involves very little ductwork but uses a number of small fans. (Bauman et al., 1994)

There are obvious advantages and disadvantages to both systems; if using the floor void as a plenum, there is no ductwork material needed which saves on material costs, and energy to initially make it. The floor void also doesn't have to allow for large ductwork and coordination of this, resulting in easier build-ability, the downside is the higher ongoing energy consumption from the fans, with the opposite being true for the ducted system.

2.3.2 Work station Based Air Terminals

Work station based air terminals gives the person the ultimate control over their local environment, both Leaman, (1995) and Oseland and Bartlett, (1999) recognise this as one of the key elements for increased productivity, which is an important factor to consider alongside the energy savings.

Leaman ,(1995) analysed results from 11 buildings in the United Kingdom, and data showed that 7 of the 11 buildings showed significant correlation between productivity and perception of control. Leaman ,(1995) and Whitley, et al, ,(1996) both came to the conclusion that lacking environmental control is the most important concern for office occupiers and identified people that have a sense of control over their enviroment feel more productive

Workstation based terminals give the ultimate user control and adjustment for task based air conditioning and suitable for each person's individual comfort settings. Currently an air conditioning system is considered acceptable if 80% of occupants are comfortable. This leaves 20% who may find the conditions too hot or too cold. A task based system would be able to provide a satisfaction rate up to at least 95%.

2.4 Air Pollutants from Humans and Required Oxygen Levels

Air quality is an important factor which needs to be maintained with any air conditioning design, the associated Australian Standard AS1668.2 dictates minimum fresh air of 7.5L/s per person has to be delivered into an indoor space (Standards Australia, 2012). This is important for maintaining acceptable oxygen content in the air.

Additional to this requirement, green building initiatives such as GreenSTAR created by the Green Building Council of Australia have a scoring system which rates building on a number of factors. One of the factors which goes towards gaining a higher score is having additional fresh air coming into the building. The GreenSTAR guideline to achieve points for this criteria is 10L/s per person (Green Building Council of Australia, 2017).

Studies by Dorgan and Dorgan, 2016 highlight the importance of maintaining a high quality of air to avoid health related issues and maintain productivity of the occupants, this is often referred to as sick building syndrome. Many studies have revolved around the sick building syndrome causes and effects (WARGOCKI et al., 2000) performed experiments which focused on the effect in change of air quality with 90 subjects, this study saw a significant drop in productivity over the 90 subjects across all measurable tasks. This was further supported by (WARGOCKI et al., 2000) who performed similar testing across call centres in two different weather climates, Denmark and Singapore, both test cases not only resulted in similar findings to the previous studies they found it exceeded the laboratory based experiments performed by (WARGOCKI et al., 2000).

This indicates how important it is to achieve an acceptable and comfortable work environment. It does not just affect how a person feels it also affects their work output which is important for a company, especially one that may only operate on small profit margins such as call centres. With these types of businesses, a drop in product could see no profit made, or even worse resulting in the company shutting down and loss of jobs.

2.5 Analysis of CFD modelling programs - Ansys vs. Virtual Environment

CFD programs solve numerically the Navier-Stokes equations, i.e. mass, momentum and energy conservation, in a fluid domain, providing detailed information about pressure, speed and temperature at each point (Caciolo, Marchio and Stabat, 2009).

There are two main software packages for CFD modelling, they are Ansys Fluent and Integrated Environmental Solutions – Virtual Environment (IESVE). Both are considered industry standards in different fields both with advantages and disadvantages, IESVE is predominantly used in the building services industry due to its ability to import models from AutoCAD, Revit and Google SketchUp, thus eliminating the re-modelling of the same programs. However (Li, 2015) reports that it does lack the precision when compared with Ansys as indicated in Table 2.1.

Table 2.1 is a comparison of the difficulty level of modelling geometry within each program ranked 1-5 with 1 being the most difficult, While modelling in IES is rated the most difficult of both programs it is able to import Google Sketchup files which simplifies the geometric modelling process significantly.

Table 2.1: Difficulty of 3D Modelling Software (Li, 2015)

	3D Modelling			
	ANSYS Fluent		IES VE - Microflow	
Tools	Design Modeller (Default)	SpaceClaim (collaborate)	Model IT (default)	SketchUp (Plug-in)
Manipulate Difficulty of Interface	3	5	1	4
Degree of Precision	3	5	1	4
Time Spending	3	4	1	5

Another key aspect of CFD modelling is the Meshing capabilities, as this is what the program is actually using to compute the information, each individual meshed section is calculated individually, This means the better the meshing, the more complex it is able to be created and the smaller mesh sizing. This produces the most accurate results.

Table 2.2 is a comparison of meshing performance. It shows that Ansys while being a little more complex to setup is by far the most accurate of the two modelling software. This is important when modelling small spaces and objects in order to achieve the most accurate and reliable results.

Table 2.2: Performance of Meshing (Li, 2015)

Meshing		
	ANSYS Mesh	IESVE Microflo
Manipulate Difficulty of Interface	Complicated	Simple
Degree of precision	High	Low
Time Spending	Intermediate	Fast

As expected, Ansys CFD was indeed highly regarded by most practitioners as comprehensive and accurate. Limitations cited had more to do with the user-software interface and included the lengthy run times of CFD models, steep learning curves of the software, and quality of technical support from software developers (Gandhi, Brager and Dutton, 2014).

2.6 Analysis of Human Comfort

Human comfort is a science unto its own, many theories and formulas have been used over the years such as Fanger, McIntyre's and what is known as SET equations each having their own benefits and shortfalls. The main formula used in Australia is the Fanger as it has been adopted by the three main standards that mechanical building services engineers adhere to; Australian Standards, the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) and the Building Codes of Australia. But even still these standards accepts that 1 in 10 people may still have complaints of being too hot or cold. This is due to a number of items individual to each person, metabolism, work task performed, fitness, body mass, climatization and clothing worn. This is an important detail to consider when it comes to designing a comfort system.

The human body has a temperature range of between 35.8°C to 37.8°C. During various tasks the body generates heat which is than emitted though the skin. Table 2.3 shows the amount of heat generated from the body through various physical activities. This heat produced releases into the room while also changing how the person feels in their current thermal environment.

Table 2.3: Heat Produced Through Various Activities (Cushman-Roisin, 2017)

Activity	Heat produced (in Watts)	Heat produced (in BTUs/hour)
Sleeping	100	340
Light work	200	680
Walking	300	1020
Jogging	800	2720

From using the Fanger formula there is quite a large range which has been determined to be within the 'comfort zone' It ranges from 20% to 80% relative humidity and 20°C to 27°C. As can be seen in the top right portion of the comfort zone for Figure 2.3, as the temperature range increases the humidity percentage decreases. At between 50% to 80% humidity there is a smaller temperature band range which is within this zone, which decreases to until it reaches the maximum humidity of 80%. This means a person will be much more sensitive to small temperature changes at this higher humidity percentage than when compared with humidity factors below the 50% range.

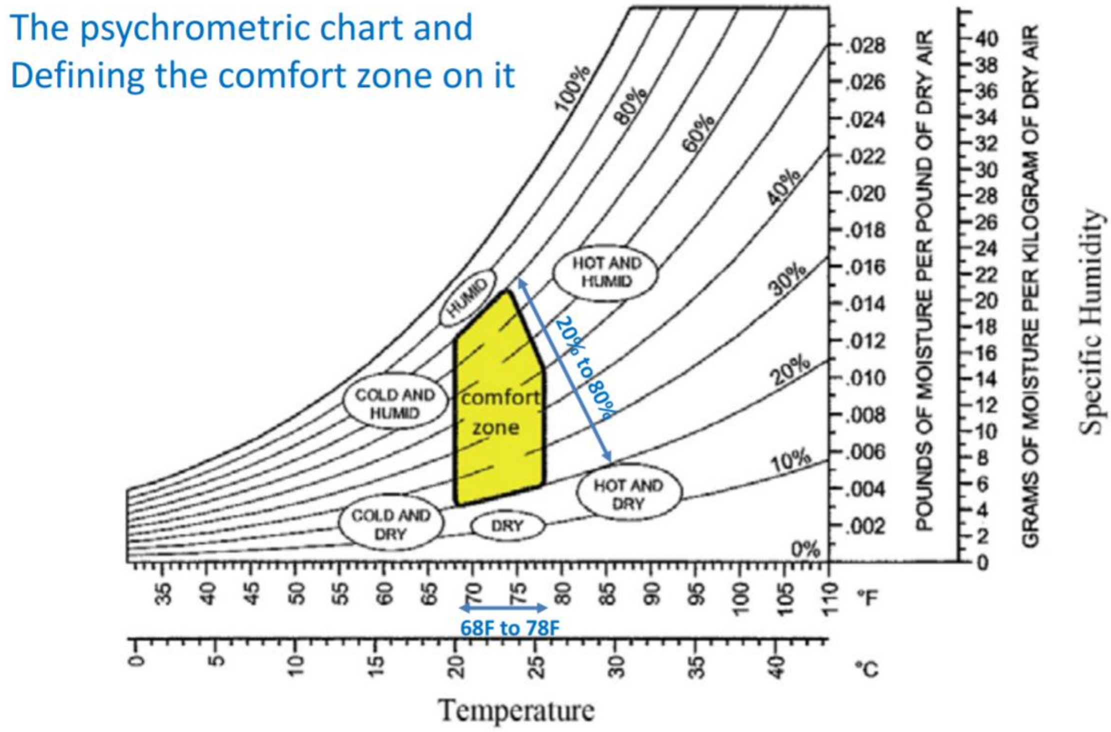

Figure 2.3: Human Comfort - Temperature vs Humidity Psychrometric Chart

(Cushman-Roisin, 2017)

Even within this determined ‘comfort zone’ not all people will be satisfied with the conditions, a small percentage will find the conditions either to hot or to cold for their individual comfort. Because of this ASHRAE developed the Thermal Sensation Scale as a method of measuring peoples comfort within certain conditions. This Thermal Sensation Scale then translates into the Predicted Mean Vote (PMV). PMV is a formula developed by Fanger, (1982) which relies on a number of parameters such as surface temperature of the body while clothed, the clothing ratio and thermal resistance, convection and radiative heat transfer, humidity and saturated humidity ratio as well as some other parameters which are general assumptions and approximations.

The PMV chart Figure 2.4 shows the PMV vs the percentage of dissatisfied people in the thermal environment. The acceptable standard for the PMV is between -0.5 to +0.5, this gives an allowance of 10% of people to not be completely comfortable within the same space at the same conditions.

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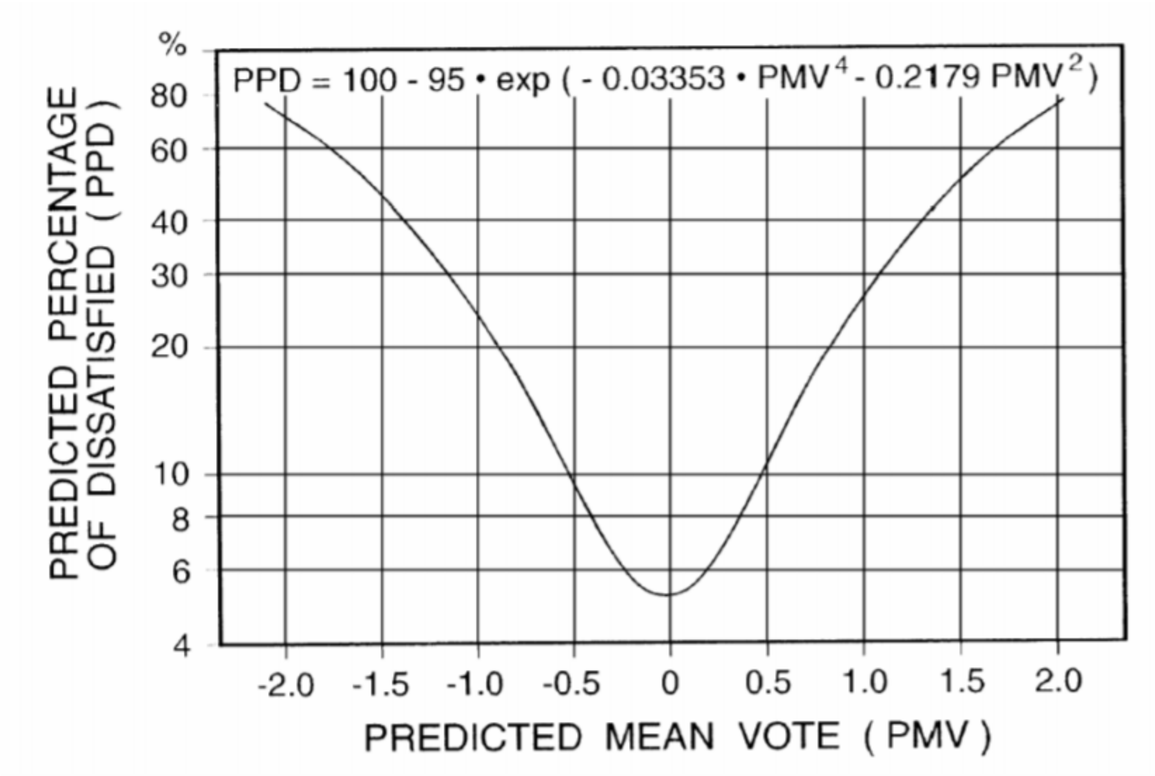

Figure 2.4: Predicted Mean Vote vs Percentage of Dissatisfied People (Colorado, 2005)

The PMV is calculated via a rather complex formula developed by Fanger which can be seen from formula below. This formula gives a fairly accurate indication of how an individual person will find the environmental conditions, it does however still has some limitations such as no allowance for climatization. This would be impossible to formulate a solution for, hence why the 10% dissatisfied factor is accepted.

Fangers Formula:

$$PMV = [0.303e^{-0.036M} + 0.028]\{(M - W) - 3.96E^{-8} f_{cl}[(t_{cl} + 273)^4 - (t_r + 273)^4] - f_{cl}h_c(t_{cl} - t_a) - 3.05[5.73 - 0.007(M - W) - p_a] - 0.42[9M - W) - 58.15] - 0.0173M(5.87 - p_a) - 0.0014M(34 - t_a)\}$$

$$f_{cl} = 1.0 + 0.2I_{cl}\ ; 1.05 + 0.1I_{cl}$$

$$t_{cl} = 35.7 - 0.0275(M - W) - R_{cl}\{9M - W) - 3.05[5.73 - 0.007(M - W) - p_a] - 0.42[(M - W) - 58.15] - 0.0173M(5.87 - p_a) - 0.0014M(34 - t_a)\}$$

$$R_{cl} = 0.155I_{cl}$$

$$h_c = 12.1(V)^{\left(\frac{1}{2}\right)}$$

e $Euler's\ number\ (2.718)$
f_{cl} $Clothing\ factor$
zh_c $Convective\ heat\ transfer\ coefficient$
I_{cl} $Clothing\ insulation$
M $Metabolic\ rate\ \left(\frac{W}{m^2}\right)\ (115\ used\ as\ average)$
P_a $Vapor\ pressure\ of\ air\ (kPa)$
R_{cl} $Clothing\ thermal\ insulaltion$
t_a $Air\ temperature\ (°C)$
t_{cl} $Surface\ temperature\ of\ clothing\ (°C)$
t_r $Mean\ radiant\ temperature\ (°C)$
V $Air\ velocity\ \left(\frac{m}{s}\right)$
W $External\ work\ (assumed = 0)$

Since PPD is a function of PMV, it can be defined as

$$PPD = 100 - 95e^{-(0.3353PMV^4 + 0.2179PMV^2)}$$

2.7 Analysis of Low Humidity Air Conditioning

The optimum humidity range for human comfort is within 35% to 65% relative humidity. A satisfactory range for relative humidity depends on your geographic location (NABERS, 2015) this is due to climatization.

Lowering of humidity can have a number of effects on an environment, both positively and negatively. Reducing humidity below 55% greatly reduces moulds ability to grow (National Asthma Council Australia, 2015) which can cause severe health issues such as asthma and bacterial infections. It also eliminates the ability for Dust mites to survive as they require a rather humid environment. A lower humidity environment also reduces musty and damp smells which can often exist in humidity rich environments.

2.8 Possible Health Risks of low Humidity

Appropriate levels of relative humidity are important within an office environment. Where humidity is too low occupants can experience problems with static electricity, as well as dry eyes, nose, throat or skin. Excess humidity can cause fatigue, increase the rate of ‘offgassing’ of VOCs and formaldehyde from building materials, and can create favourable conditions for the growth of micro-organisms (NABERS, 2015).

2.9 Reducing Humidity with the Air-conditioning

There are a number of ways to reduce the humidity of air before it enters the space which is being served by the air-conditioning unit. Such as the air-conditioning cooling coil itself, dehumidification wheels, electric dehumidifiers and heating coils. They generally all have their own benefits, while others are used because it’s easy to implement with other systems that are either existing within the building or are being installed to serve another main purpose, with the dehumidification being a secondary usage.

2.9.1 Cooling Coils

The cooling coils themselves reduce the humidity of the air as when the air temperature decreases it is unable to hold as much water vapour in the air. The excess water vapour changes from a gas state and into fluid state. The water gets trapped on the cooling coils in the same way condensation forms on a glass of cold water. This water then drips down onto the tray of the air-conditioning unit which is then drained away.

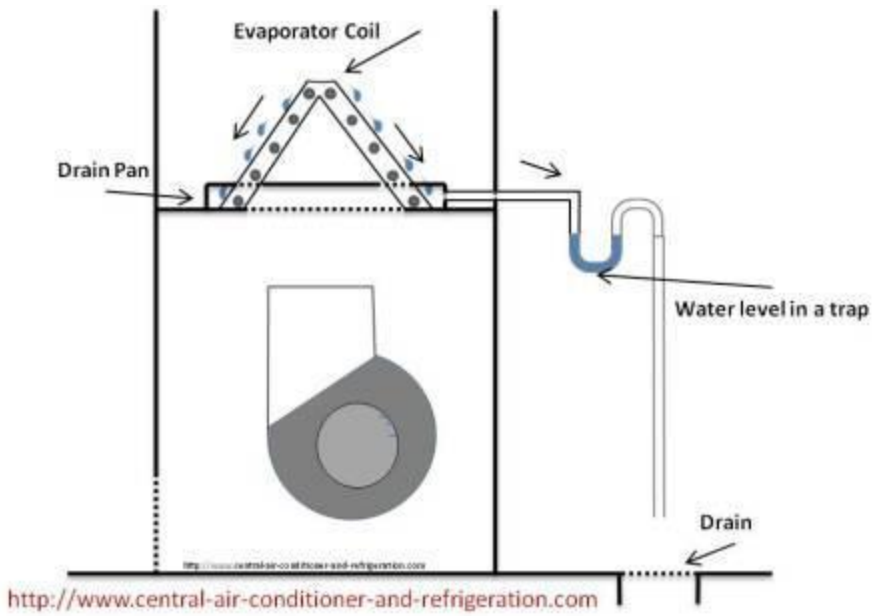

Figure 2.5: Air-Conditioning Coil with Drain Connection (Central-air-conditioner-and-refrigeration.com, 2008)

This is how air-conditioning units work currently, reducing the temperature and humidity at the same time. The limitation to this is that the coil can only reduce the humidity so much without the either being oversized to collect more water vapour as the air passes though, with a standard air conditioning unit this will overcool the air resulting in the space dropping below the desired temperature, this can be avoided by running the cooling at a lower temperature differential to the incoming air. This slows the cooling process down to achieve the desired temperature with the reduced humidity.

This type of system is only suitable to a new install, it would not be cost effective to modify existing air-conditioning units to fit bigger coils, and often this would not even be possible due to space limitations.

2.9.4 Cooling Coils with Re-Heating Coils

Re-heating coils are often used in places where humidity levels are critical, such as hospital operating rooms, manufacturing of electronics, paper and printing plants. There is two main types of heating coils, electric and hot water/ steam. Generally, the hot water or steam option is the most energy efficient, it runs the hot water or steam though coils which the air passes though. This type of system of often used in hospitals and labs where there are boilers or similar plant installed as these types of building also a require steam or hot water to be reticulated throughout the building for medical equipment and various laboratory equipment. Once the steam or hot water has served this equipment it can then be run through the coils, providing, using it in this method requires very little additional energy.

Some general office buildings use boilers to provide hot water to all the levels, this can also be used to serve the re-heating coils, however as the hot water is not recirculated, then there is energy loss associated with this, as the water either needs to be heated to a higher temperature initially, so at the hot water outlet it is still at a desired temperature or there will be a slight reduction in temperature at the final outlet, if this is deemed acceptable.

The electric heaters have a row of heating elements which can be seen in Figure 2.6. These elements heat up from electrical input and warm the back to the correct temperature after the coiling coil, the same way the hot water/steam coils work. These electric coils have a rather large power draw which makes then less than ideal when creating a system focused on energy efficiency. There is a lot of duct heaters installed in modern building currently, in their current arrangement they are generally used for heating in winter rather than as part of a humidity system. The current building code (NCAA) section J dictates minimum energy efficiency levels for plant and equipment. It states that these electric heaters are only allowed to heat air to 7°C above the air before the coil. While this generally would not be an issue if it was used as an energy re-heat as part of a dehumidification system, there is better options available.

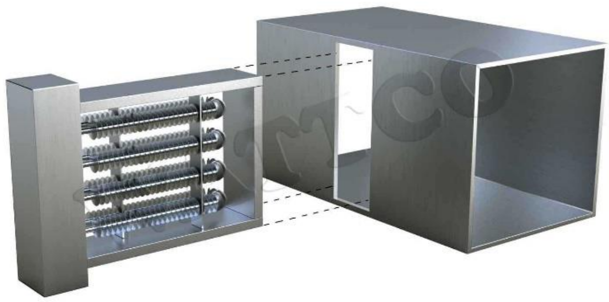

Figure 2.6: Duct Heaters (Wattco, 2017)

2.9.2 Dehumidification Wheels

There is a large amount of research being done into dehumidification wheels and different configuration options which use different types of media. This can be broken up into two main types, being solid or liquid. Some of the liquid use a thermal liquid membrane (Yang et al., 2017), and are generally more complicated when compared to the solid desiccants.

Solid desiccants are more popular because they are easier to manufacture and operate.

They can consist of Silica gel, zeolite and a ranger of other materials. These work by attaching the desiccant material to a honeycomb base which can be seen in Figure 2.7. This honeycomb base is a wheel which turns within the unit, it had two phases which enables it to work. The adsorption or dehumidification phase where the humid air is passed though the honeycomb web, where water is adsorbed and collected by the materials. The regeneration or desorption phase is where exhaust air from the building is blown throw the wheel, the air the adsorbs the moisture and removes it from the dehumidification wheel.

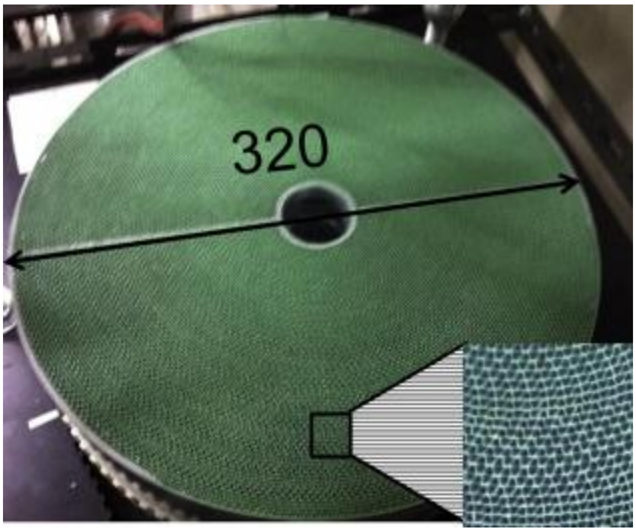

Figure 2.7: Front View of a Desiccant Dehumidification Wheel (Tsujiguchi, Osaka and Kodama, 2017)

Studies by (Cai et al., 2017) found that these systems can work without external heat source, and that the entire system can be driven by the exhaust heat of the compressor except for very small electric energy consumption. This means that there is very little energy added to a traditional air-conditioning system, with the exception of needing a small motor to drive and turn the wheel. This makes then an excellent choice to be used in energy saving applications, reducing the work the coiling coil has to do.

2.9.3 Electric Dehumidifiers

An electric dehumidifier works independently to all other systems and has its own cooling refrigeration cycle much like an air conditioner to remove moisture from the air. It also has a heater to then re-heat the air, this means it is still reliant on electric re-heat for bring the air back to its desired temperature. These dehumidifiers generally work as a standalone system as it has its own cooling coil it is basically doubling up, performing the same work as the cooling coil for the main air conditioning system is already doing. This doubling up and electric re-heat makes this dehumidifier the worst potential option to be used for an energy efficient system and should only be used in specific circumstances where extreme humidity controls are important.

Figure 2.8: Comercial De-Humidifier (Sylvane, 2017)

Chapter 3 - Methodology

3.1 Overview

This chapter serves to outlines the methodology of the parametric study of human comfort in a modern office. The main process of this dissertation comprises of CFD modelling. This involved creating a geometric model of a space with various parameter inputs in the model to map the airflow, temperature and humidity. These conditions are what the projects main focus is on, the effect of varying input conditions to establish a conformable working environment. Once the geometric model is established it will not be modified except for air diffuser positioning within the space.

3.2 Model Selection

The focus of this research is a typical modern office fitout, this means generally an open plan style fitout with desks in rows and minimal singular person offices. This type of office design generally has a number of meeting rooms located on the floor, however this rooms will typically have a dedicated AC unit and only run when the room is occupied, therefore this has not been included with the scope of this project.

A typical office building has been selected for this modelling which can been see in Figure 3.1. This floorplan was selected due to the majority of it being open plan style layout. It has nice even rows of desk and the building itself is rectangular. This simplifies the model geometric model which needs to be created.

Figure 3.1: Typical office floorplan

The final model created was a 10m x 6m space with a 2.7m ceiling and desk space for 6 people, a representation of this layout can be seen in Figure 3.2 as the Australian Standard AS1668.2 states 1 person per 10 square metres for a commercial office building.

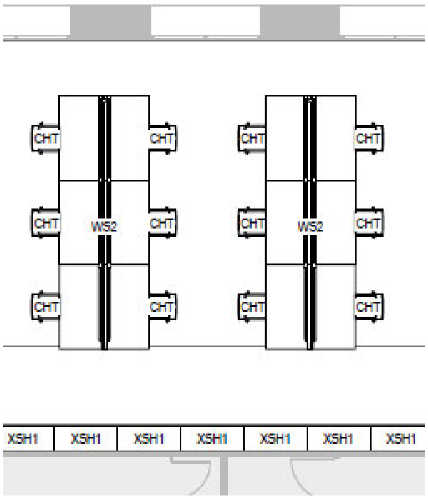

Figure 3.2: Simplified CFD model layout

3.3 Modelling Technique

For the analysis to be performed the geometric model was originally created using Autodesk Revit due to the prior knowledge and 3D objects available to use. The model was then exported and imported into ANSYS, as the models geometry was quiet complex it was then modified within ANSYS to remove a lot of detail which was not required such as draws and handles. Once the model was refined the inlets and outlet diffuser positions were added for both the ceiling and floor mounted diffusers.

3.4 Fluid Domain

Once the main geometric models were finalised the model was imported into the Fluent package within the ANSYS program. To accurately simulate the space thermal loading was given to the walls of the space to simulate external heat loading from the sun and outside ambient conditions.

3.5 Mesh Setup

After the geometric model of the office space was created the model was imported into the meshing program. As the meshing is what the CFD program performs the calculations on it was important that this process was done accurately as any of the results would be determined by the quality of the mesh.

Once the meshing was established a trial run of the analysis was done to check for any issues relating to the mesh and to check if any alteration needed to be performed. Once the mesh was deemed acceptable a Grid Independence Study was undertaken to validate the solution and the setup of the model.

The ANSYS analysis system used to perform the analysis was the CFX, the physics preference used was CFD and the solver preference used was CFX.

3.6 Global Mesh Sizing Control

Once the physics settings were setup for the mesh, the sizing features that were considered for meshing are; Relevance and Relevance Center, Advanced Size Functions (ASF), Smoothing, Transition & Span Angle Center. The relevance would be the main items to be considered.

The coarsening of the mesh is determined by the relevance, by using the relevance settings the mesh could be adjusted and fine-tuned to increase and decrease the meshing sizing, which in turn increases and decreases the models accuracy. The sliding scale within the relevance center allows to adjust the mesh. It has a range of -100 to 100. To achieve a coarser mesh the slide should be moved to the negative side of the scale, the benefit to this is a faster calculation and processing time to achieve the results but with some loss of accuracy. For the particular analysis. Alternatively, the mesh could be modified under the relevance centre which had three options; Coarse, Medium and Fine. These options had similar effect as the sliding scale.

Due to the nature of the modelling and analysis performed for this study a high level of detail was not required as the model incorporated a space of approximately 160m^3. Airflow paths did not need to be modelled with any large precision or down to the centre metre. Because of this and the interest of keeping the models computing time down the course mesh was deemed to be acceptable.

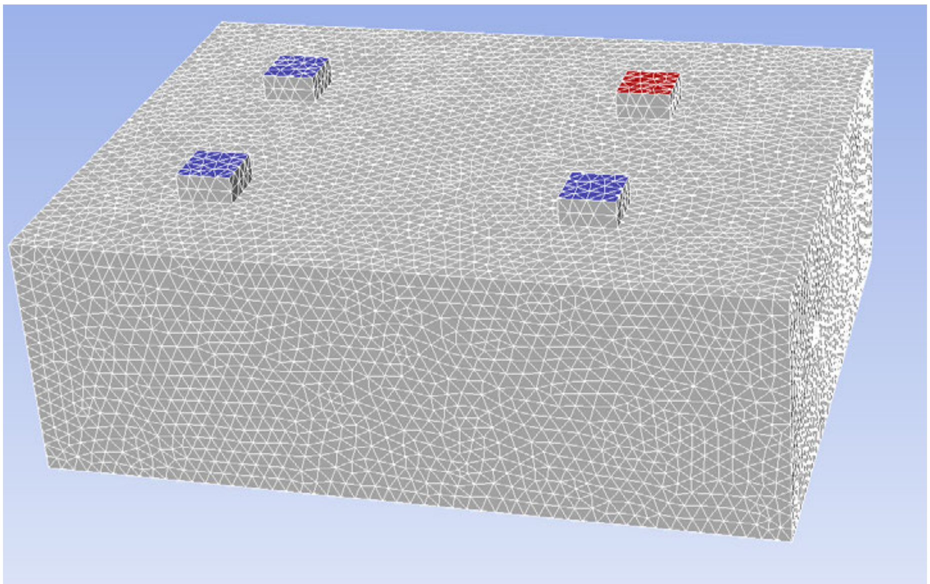

Figure 3.3: CFD Meshing

3.7 Humidity Modelling

A critical aspect of this CFD analysis was the humidity modelling, this had to be modelled as water vapour and added into the input air stream entering the space. Adding water vapour into the CFD modelling has a specific process which needs to be followed as ANSYS does not have an option to input a humidity percentage to the incoming air stream.

The following outlines the steps which need to be followed in order to accurately model water vapour and therefore adding humidity into the incoming are stream to simulate a real office situation.

Firstly under the models tree select ‘Species (Species Transport)’ then on the drop down menu for ‘Mixture Material’ select mixture-template. Then click OK to exit.

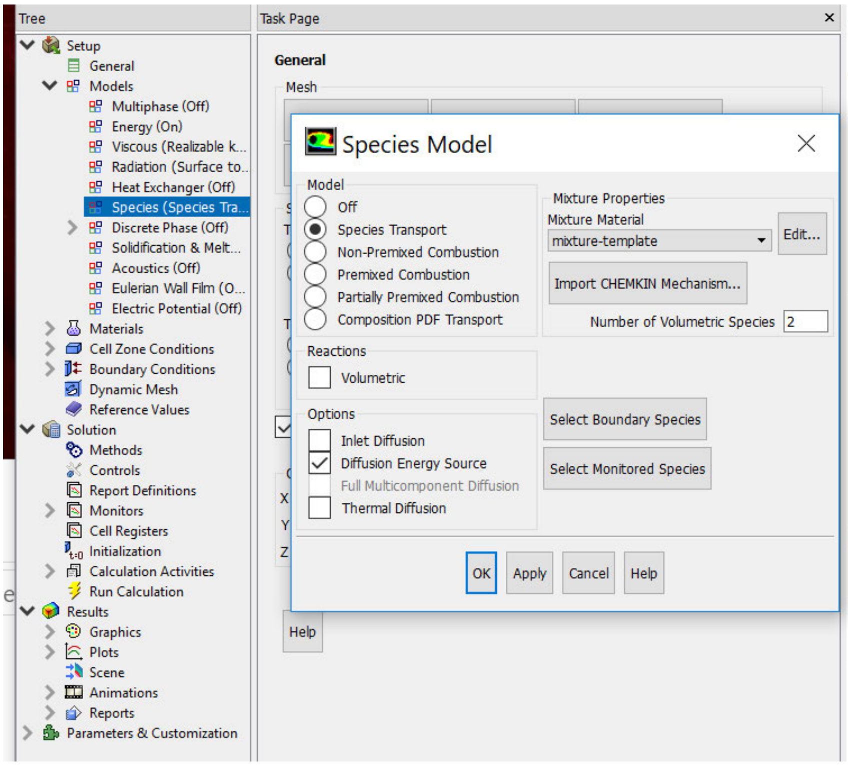

Figure 3.4: Species Model

Next select ‘mixture-template’ under the Materials then Mixture tree. Select the ‘Fluent Database’ as per Figure 3.5.

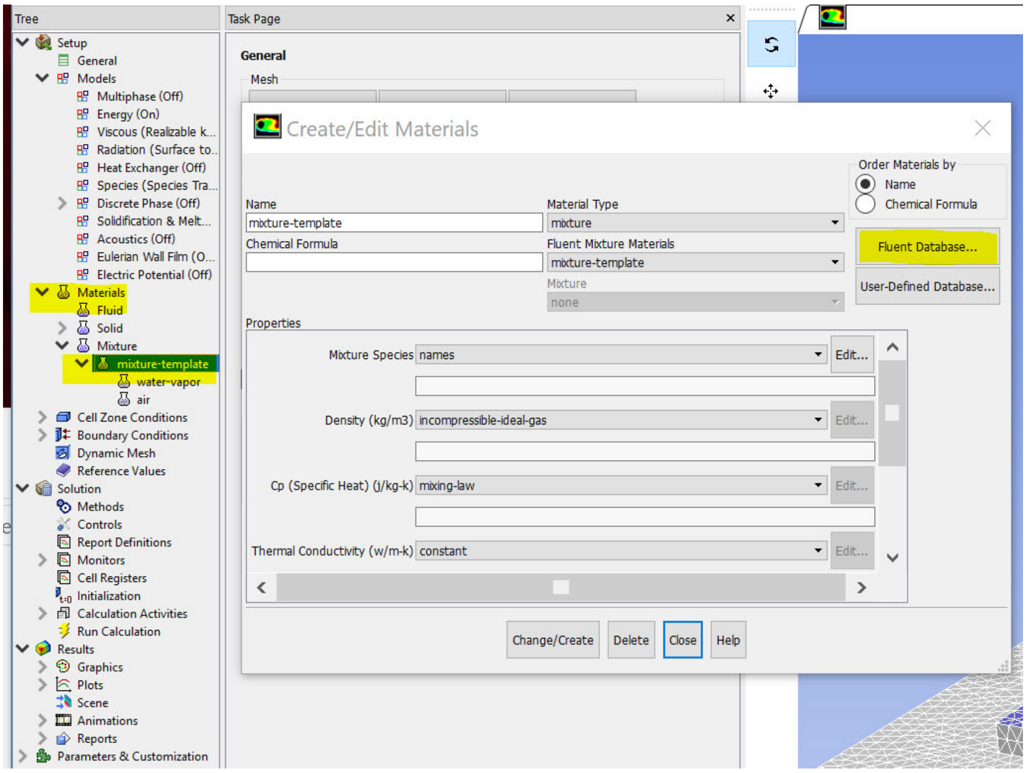

Figure 3.5: Fluent Setup - Create Materials

Once the Fluent Database Materials box pops up, change the 'Material Type' to fluid and then select air and water-vapour (h2o) as per Figure 3.6 and 3.7.

It is important that Air is added first or ANSYS will use a base of water vapour rather than a base of air. This means that the incoming fluid will be water vapour with only minimal amount of air.

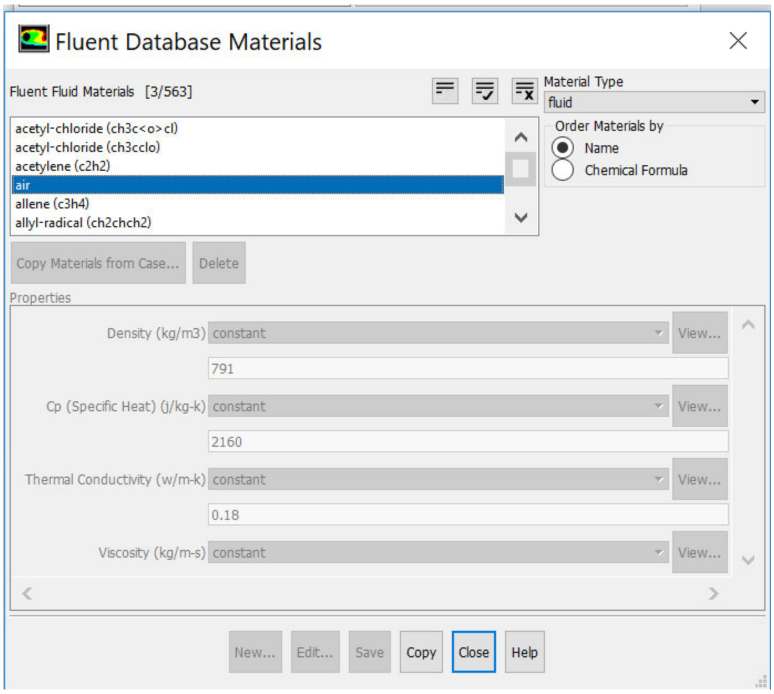

Figure 3.6: Adding air as mixed material

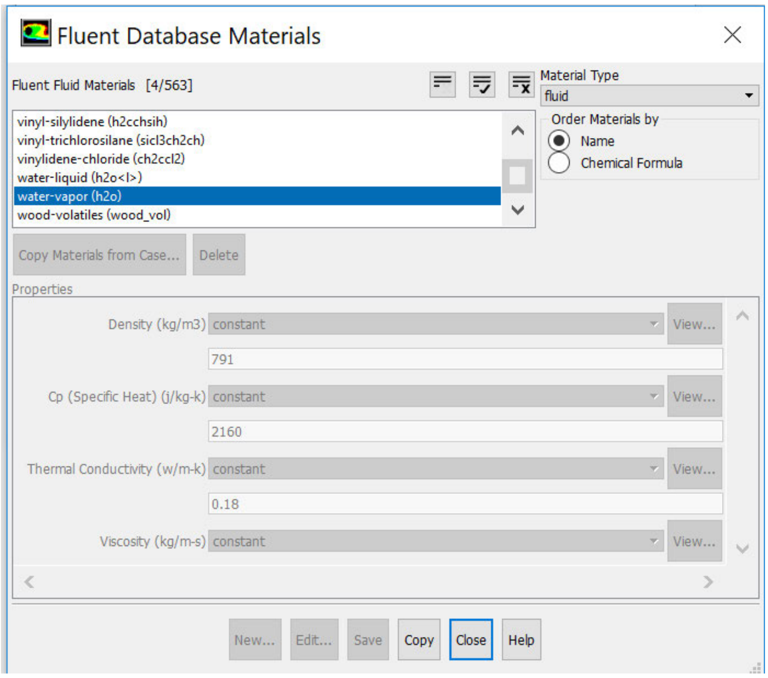

Figure 3.7: Adding water-vapour (h2o) as mixed material

Once that process has been done then the water vapour needs to be added to the inlets. Under the 'Boundary Conditions' tree select your inlets and add the incoming conditions as normal. Under the Species tab ass h2o as either a species mass fraction, alternatively tick the box and specify the h2o in mole fractions.

If this box lists air, rather than h2o or if the modelling results show humidity well over 100% the air and water-vapour have been added in the wrong order. Repeat the previous step but reverse the order which materials were added to correct this.

For the modelling performed as part of this research 0.005 & 0.008 Mole Fractions was used.

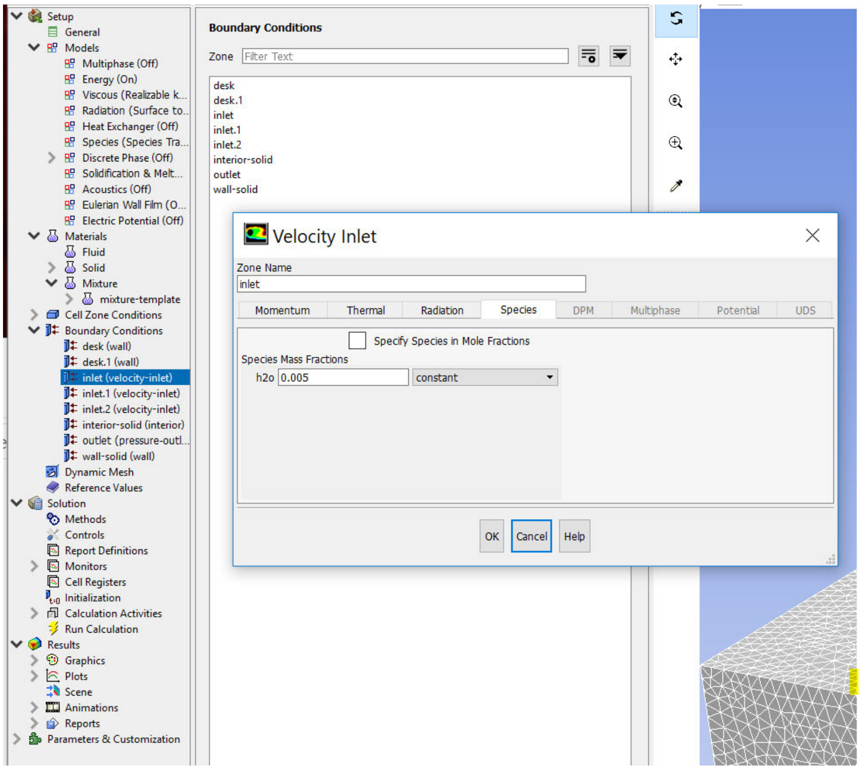

Figure 3.8: Setting water-vapour mass fraction inputs

Once the modelling and analysis had been run to view the relative humidity a contour needs to be set up. Select ‘Contours’ under ‘Results’ tree and select species under the ‘Contours of drop down menu refer to Figure 3.9. Select Relative Humidity on the second drop down menu, select the surfaces to display, which would generally be a plane that has been created. Once this is done click display. The relative humidity will be show as a contouring colour plot as a percentage.

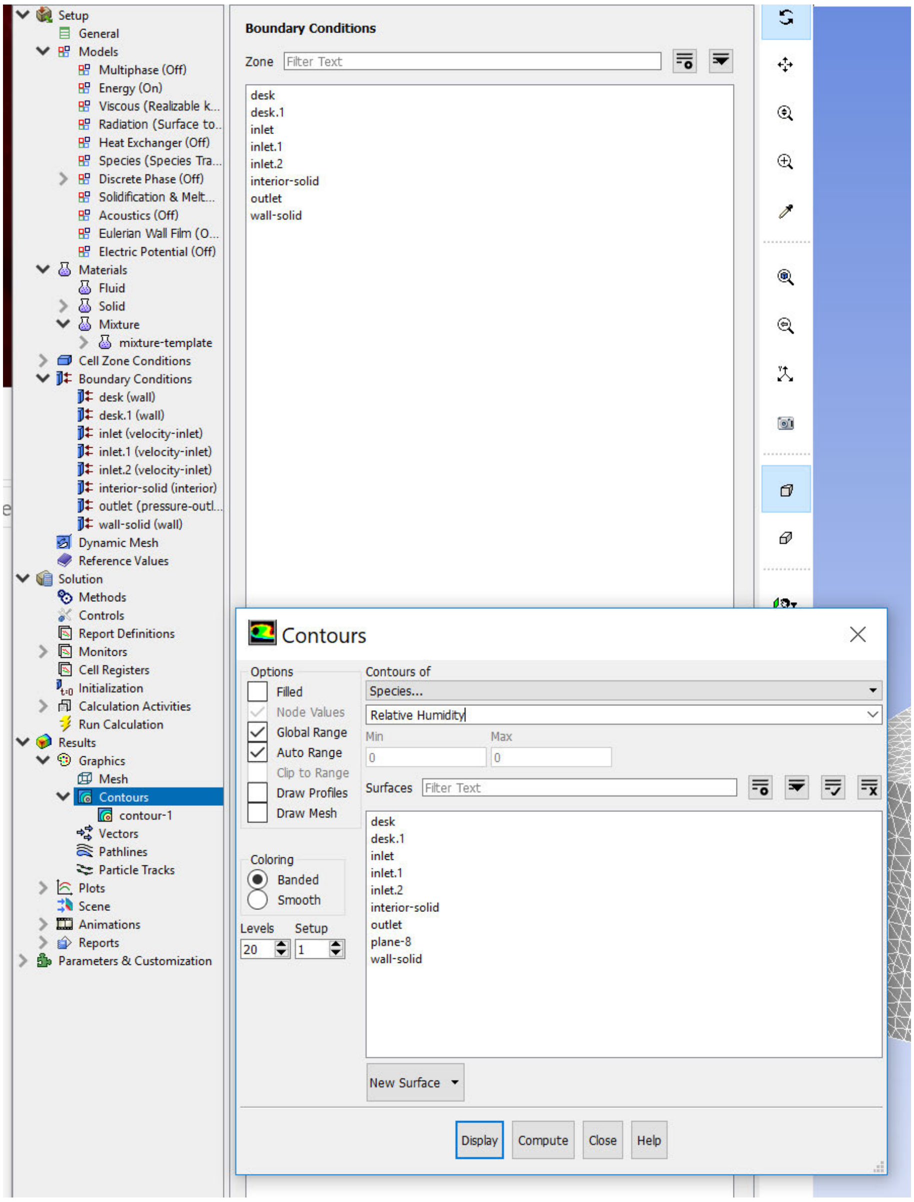

Figure 3.9: Creating contours to display humidity

3.8 Fluent Parameters

Two models were created with identical geometry except for the inlet locations. These models ran with the same temperature and water-vapour input ranges.

The temperature was modelled in 2°C increments from 16°C to 26°C. These increments give a good range for analysis and results for comparison.

The water vapour was modelled at 0.003, 0.005 and 0.008 mass fractions, this resulted in a range of humidity within the space from 18% upto 55%. As the current standards dictates a 50% relative humidity, modelling above this humidity level is not required for this project, the focus is particularly around the 25-40% humidity range.

3.9 Review of Information

As a result of the literature review two methods of cooling shall be investigated. Both floor based and workstation based systems shall be investigated.

There needs to be a high focus on the supply of fresh air into the office space to avoid the likes of sick building syndrome, as this is a major issue and can affect the health of occupants both short term and long term.

3.10 Resource Requirements

The following resource analysis, Table 3.1 outlines equipment and licencing requirements for the project. To ensure the project can be budgeted according if required.

Table 3.1: Project Resource Analysis

Item	**Quantity**	**Source**	**Cost**
Computer	1	Owned	Owned
Ansys CFD Software	1	USQ (Licence through VPN)	Borrowed
Apache Camel	1	Workplace	Borrowed
Excel	1	Owned	Owned
Word	1	Owned	Owned
Cloud Storage	1	Dropbox	Nil
		Total	Nil

As the majority of resources required for this project are already owned, or have a means to source them without any foreseeable cost outlay, there is no financial limitation to this project.

The main threat to the viability of the project would be the Ansys CFD software and the Computer. If the program was to corrupt any modelling files or the computer was to develop issues and lose critical data or progress. To avoid any potential issues all files will be backed up and stored remotely through the use of personal cloud storage. If he computer was to have a failure then very little progress would be lost and work could continue on an alternative computer once the files were retrieved from the cloud storage.

3.11 Consequential Project Effects

The project is to be completed with a thorough understanding of the standards set by the Engineers Australia and all relevant building standards, particularly;

- AS 1668.2-2012: The Use of Ventilation and Air-conditioning in Buildings, Mechanical ventilation in buildings, Part 2.
- Building code of Australian, NCC 2016 Volume One. In particularly Section J, Minimum standards for energy efficiency in a building.
- ASHRAE – American Society of Heating, Refrigerating and Air-Conditioning Engineers
- Engineers Australia Code of Ethics

3.11.1 Building Standards

Within Australia all buildings and equipment must be manufactured and built to comply with all relevant building codes and Australian Standards. All commercial buildings must be inspected by a qualified engineer, inspector or approved tradesperson, and once the inspection is satisfactory a certificate of compliance is then issued.

The certificate of compliances relevant to this projects field are known as Form 15's and Form 16's. The Form 15 is completed by a qualified engineer who has reviewed the design of the mechanical air-conditioning system, and certifies that it complies with all current building codes and Australian Standards. The Form 16 is completed by a representative of the mechanical installer, it certifies what they have installed both compliance with the design the engineer has issued to them as well as the relevant building codes and standards.

Because of this stringent certification process all of the relevant Australian Standards must be adhered to for the duration of this project for it to be a valid accepted solution within the building services engineering industry.

3.11.2 Ethics

In a similar manor to the building standards there are certain standards and engineer must hold themselves to at all times. These are known as the Code of Ethics published by Engineers Australia. The key aspect of the ethics relevant to this research paper is accurate and truthful reporting of information and data found both though research in the literature review and with the modelling that has been performed as part of this project.

3.12 Risk Assessment

Due to the nature of this project largely being focused around data collection and computer modelling there will be very minimal exposure to any physical risk besides general workstation ergonomics. However, there is potential for risk in both data collection and modelling, if either were to fail this would leave a large gap within the project and results.

Table 3.2: Project Risk Assessment

0 – 5 = Low Risk 6 – 10 = Moderate Risk 11 – 15 = High Risk 16 – 25 = extremely high unacceptable risk		Severity of the potential injury/damage				
		Insignificant damage to Property, Equipment or Minor Injury **1**	Non-Reportable Injury, minor loss of Process or slight damage to Property **2**	Reportable Injury moderate loss of Process or limited damage to Property **3**	Major Injury, Single Fatality critical loss of Process/damage to Property **4**	Multiple Fatalities Catastrophic Loss of Business **5**
Likelihood of the hazard happening	Almost Certain **5**	5	10	15	20	25
	Will probably occur **4**	4	8	12	16	20
	Possible occur **3**	3	6	9	12	15
	Remote possibility **2**	2	4	6	8	10
	Extremely Unlikely **1**	1	2	3	4	5

The following hazards will be managed and contingencies will be put in place to mitigate any major issues with the project which would hinder completion of this study;

- Workstation ergonomics
  Due to the projects nature, a number of hours will be spent both in the modelling and writeup phases of this project. Correct seating position, monitor heights and palm rests should be used to avoid any repetitive injuries or spinal stiffness.
  Likelihood – 2, Injury potential – 3. Combined risk score – 6

- Loss of data or access to required programs
  As previously discussed backing up of data onto a cloud based storage server is important to minimise the potential to loss of data and risk to not completing the project. Retailing access to the required programs is also important, This risk is mitigated through the use of VPN software to enable remote login to license servers at USQ and use the required program remotely.
  Likelihood – 3, damage potential – 2. Combined risk score – 6

3.13 Quality Assurance Plan

In order to ensure a high level of quality data was collected a number of targets were set. The most important aspect of this project was ensuring that the CFD modelling was complete and producing accurate results. To ensure this, a review process of the CFD model was setup and reviewed by another mechanical engineer. The modelling output was also sent to the project supervisor which was reviewed. These comments were then incorporated into the model to improve the accuracy of the final results.

3.14 Heat load

As part of both Ansys CFD and the Camel modelling heat loads have been incorporated into the design. For the Ansys model the focus was on the internal heat loading, such as people and equipment. As Camel is one of the industry standard heat load calculation programs it was chosen to be used rather than relying solely on Ansys, which takes longer to setup different materials with U-Values and solar loading positions. Calculations for the Camel heat load incorporated both internal and external solar loading on the building.

The design parameters have been based around available weather information for Brisbane, Queensland, Australia. With standard design conditions, based on averaged summer temperature during January in the middle of the day. The weather data is from the Amberly weather station and was sourced from the Bureau of Meteorology and Apache Camel environmental weather data, this can be viewed in Figure 3.10.

COOLING OUTDOOR DESIGN TEMPERATURES (C)

(DB - DRY BULB WB - WET BULB MC - MOISTURE CONTENT g/kg)

		JAN	FEB	MAR	APR	MAY	JUN	JLY	AUG	SEP	OCT	NOV	DEC
8AM	DB	27.3	27.3	27.3	25.0	20.6	16.8	18.0	19.9	26.3	27.3	27.3	27.3
	WB	22.8	22.8	22.8	20.7	18.7	15.6	16.4	15.9	18.1	20.5	22.3	22.8
	MC	15.6	15.6	15.6	13.6	12.8	10.6	11.1	9.6	9.6	12.3	15.0	15.6
9AM	DB	28.3	28.3	28.3	26.0	21.6	17.8	19.0	20.9	27.3	28.3	28.3	28.3
	WB	23.0	23.0	23.0	21.0	19.1	15.9	16.8	16.2	18.4	20.8	22.6	23.0
	MC	15.6	15.6	15.6	13.6	12.8	10.6	11.1	9.6	9.6	12.3	15.0	15.6
10AM	DB	29.6	29.6	29.6	27.3	22.9	19.1	20.3	22.2	28.6	29.6	29.6	29.6
	WB	23.4	23.4	23.4	21.4	19.5	16.4	17.2	16.7	18.8	21.2	23.0	23.4
	MC	15.6	15.6	15.6	13.6	12.8	10.6	11.1	9.6	9.6	12.3	15.0	15.6
11AM	DB	30.6	30.6	30.6	28.3	23.9	20.1	21.3	23.2	29.6	30.6	30.6	30.6
	WB	23.7	23.7	23.7	21.7	19.8	16.7	17.6	17.1	19.2	21.5	23.3	23.7
	MC	15.6	15.6	15.6	13.6	12.8	10.6	11.1	9.6	9.6	12.3	15.0	15.6
NOON	DB	31.6	31.6	31.6	29.3	24.9	21.1	22.3	24.2	30.6	31.6	31.6	31.6
	WB	23.9	23.9	23.9	22.0	20.1	17.1	17.9	17.4	19.5	21.8	23.5	23.9
	MC	15.6	15.6	15.6	13.6	12.8	10.6	11.1	9.6	9.6	12.3	15.0	15.6
1PM	DB	32.9	32.9	32.9	30.6	26.2	22.4	23.6	25.5	31.9	32.9	32.9	32.9
	WB	24.3	24.3	24.3	22.3	20.5	17.5	18.3	17.8	19.9	22.1	23.9	24.3
	MC	15.6	15.6	15.6	13.6	12.8	10.6	11.1	9.6	9.6	12.3	15.0	15.6
2PM	DB	33.9	33.9	33.9	31.6	27.2	23.4	24.6	26.5	32.9	33.9	33.9	33.9
	WB	24.5	24.5	24.5	22.6	20.8	17.9	18.7	18.2	20.2	22.4	24.1	24.5
	MC	15.6	15.6	15.6	13.6	12.8	10.6	11.1	9.6	9.6	12.3	15.0	15.6
3PM	DB	34.9	34.9	34.9	32.6	28.2	24.4	25.6	27.5	33.9	34.9	34.9	34.9
	WB	24.8	24.8	24.8	22.9	21.1	18.2	19.0	18.5	20.5	22.7	24.4	24.8
	MC	15.6	15.6	15.6	13.6	12.8	10.6	11.1	9.6	9.6	12.3	15.0	15.6
4PM	DB	33.9	33.9	33.9	31.6	27.2	23.4	24.6	26.5	32.9	33.9	33.9	33.9
	WB	24.5	24.5	24.5	22.6	20.8	17.9	18.7	18.2	20.2	22.4	24.1	24.5
	MC	15.6	15.6	15.6	13.6	12.8	10.6	11.1	9.6	9.6	12.3	15.0	15.6
5PM	DB	32.9	32.9	32.9	30.6	26.2	22.4	23.6	25.5	31.9	32.9	32.9	32.9
	WB	24.3	24.3	24.3	22.3	20.5	17.5	18.3	17.8	19.9	22.1	23.9	24.3
	MC	15.6	15.6	15.6	13.6	12.8	10.6	11.1	9.6	9.6	12.3	15.0	15.6

Figure 3.10: Outdoor design temperatures

The internal design parameters for both Ansys and Camel were kept the same to maintain reliable results. This required a selection of a typical office layout. Within this layout various equipment and furniture was modelled in the space in line with the design standards set out by AS1668.2. This includes the following:

- Lighting load of 15W/m2.
- 1 person per 10m2 with 80W Latent and 80W Sensible heat gain per person
- 150W per computer with one computer per person.
- 7.5L/s of fresh outside air per person

As the geometry modelled was a 60m² room, 6 people were modelling within the space, this gave an internal heat load of approximately 2.2kW once heat gain from the people, computers and the warming incoming fresh air.

Data in the upper panel on this screen is used in the calculations. Data in the lower panel (below Glass Number) is optional and is only to assist users with selection of appropriate values in the upper panel. The Glass Number is also used in BEAVER and is inserted in the Beaver LOADS data when 'loading' a CAMEL file.

Click column number to display where window is used

	1	2	3	4	5	6	7
Window Type	1	2	3				
Height (mm)	1500	2500	1500				
Width (mm)	1000	920	920				
U-Value	4.8	4.8	4.8				
Shade Factor	0.2	0.2	0.2				
Frame S.Fact Correction	1	1	1				
Internal Shading	NO	NO	NO				
Glass No							
U Value for BEAVER							
U Value for CAMEL							
Shade Coeff. for BEAVER							
Shade Coeff. for CAMEL							
Int Solar Att Coeff.							
Frame U Value Corr'n							

double click to toggle

double click to transfer U Value or Shade Factor to above

Modified Storage Load Factor

Figure 3.11: Screen capture of Camel window fabric U-values

	1	2	3	4	5	6
Wall Type	ext	int	roof			
U-Value	2.7	2.5	1.2			
Surface Density	250	100	20			

Figure 3.12: Screen capture of Camel wall fabric U-values

AHU		Zone				Room		Floor Area (m²)	Ceiling Height (mm)	Storage Mass (kg/m²)	Infil AC/Hr	Vap gain (kW)	Outside Air		Minimum S/A		Supply Duct Gain			Connected to Return Air Room
No.	AHU Title	No.	No. off	Air Dis'n	Thermostat Location (SZH&C, RCHP and Evap. Only)	Room Title	No. off						Units	Value	Units	Value	% Heat Gain	% Leak Loss	Ext (kW)	
1	AHU1	1		LOAD		Front	1	60	2700	250	0		l/s per person	7.5						

Figure 3.13: Screen capture of Camel geometric inputs

AHU		Zone No.	Room Title	Ex-pos	Height (mm)	Width (mm)	Shad Sch	% to R/A	Wall/ Roof		Windows / Skylight							Adjacent Shading				
No.	Title								Type	Ab-sorp	Type	No.	Dir	Shad Sch	Betwn (mm)	V-off (mm)	H-off (mm)	Dist (m)	Height (m)	Width (m)	L Shift (m)	Depth (m)
1	AHU1	1	Front	N	3000	6000			ext	0.5												
				E	3000	6000			ext	0.5	2	3	H		50	200	100					
				W	3000	5500			ext	0.5	2	4	H		50	200	100					

Figure 3.14: Screen capture of Camel solar loading external walls

AHU		Zone No.	Room Title	People						Lights						Sensible					Latent				Steam			
No.	AHU Title			Units	Load	Sched. No.	% RA	% for Heating	Activity	Units	Load	Sched. No.	% RA	% for Heating	Light Type	Units	Load	Sched. No.	% RA	% for Heating	Units	Load	Sched. No.	% RA	Units	Load	Sched. No.	% RA
1	AHU1	1	Front	No.	6	1			3	W/m²	15	3			FLR													

Figure 3.15: Screen capture of Camel internal heat loads

Chapter 4 - CFD Modelling

As part of this study three main variables of interest which were adjusted for the CFD modelling and one additional variable which was required to be modified as a result of one of the main variables. The main variables of interest to the project included;

- Ambient Temperature
- Relative Humidity
- Grille Diffuser Positioning

As the air diffuser positioning was modified to from a ceiling based grille to a floor based grille, the flow rate and therefore the velocity of air exiting the grille was required to be adjusted. This was to avoid air exceeding 0.2m/s when coming into contact with a person as this would cause the person to feel a draft of air which would alter their comfort levels, making them feel colder than another person in their general vicinity but outside of the draft zone.

4.1 Ambient Temperature

The air temperature is the most important variable in the human comfort equation, it requires the air to be between 20°C and 28°C. Anything outside this small temperature band and a person will find the environment uncomfortable, feeling either hot or cold.

4.1.1 Ceiling Diffuser Position

The current standard design temperature setpoint for an office space is 23.5°C with the air supplied from the ceiling. This is achieved by delivering approximately 18°C air from the diffusers once the air exits the diffuser at a velocity of approximately 1.5m/s which then due to this velocity disperses across the ceiling as which can be seen in Figure 4.1 where smoke has been added into the air stream in order to make this visible. Once the velocity of the air dies away the air is left to fall to the floor, mixing with the warmer air within the conditioned space and displacing it through natural convection.

Figure 4.1: Air flow from a ceiling mounted diffuser

This process can be seen replicated by the CFD modelling of the space at these same conditions, 18°C input air at 1.5m/s for Figure 4.2. The modelling of the space also shows a very uniform temperature between 23°C and 24°C. This indicates the model is showing accurate results as the temperature across the space is uniform as expected from using a diffuser located on the ceiling.

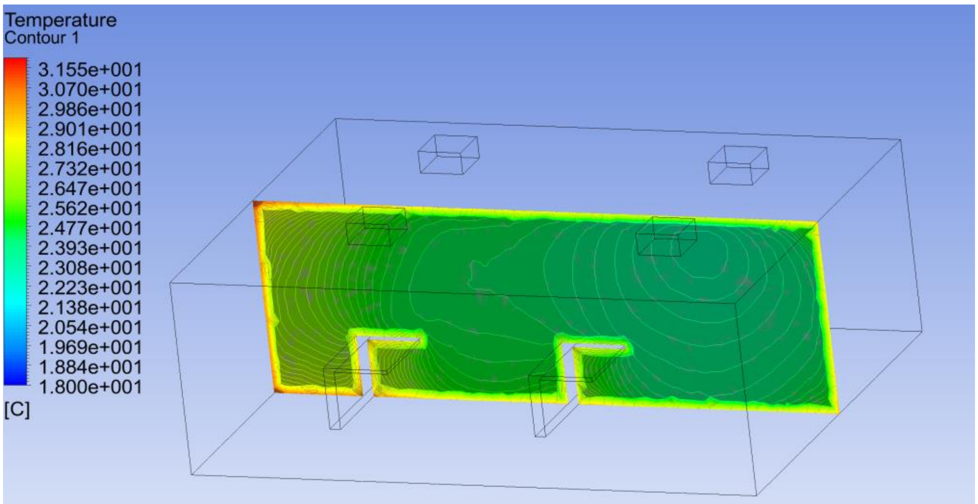

Figure 4.2: Temperature CFD Results - Ceiling based 0.005 mass fraction, 18 degrees

With the air temperature exiting the diffuser raised to 26°C per Figure 4.3. This increases the space temperature to approximately 27°C to 29.5°C through most of the office space. However, there is a development of some hot and cold spots were the cooler air is starting to pool, and less mixing of air is taking place. With the temperature raising to a level above 28°C it puts the temperature outside of the acceptable human comfort zone.

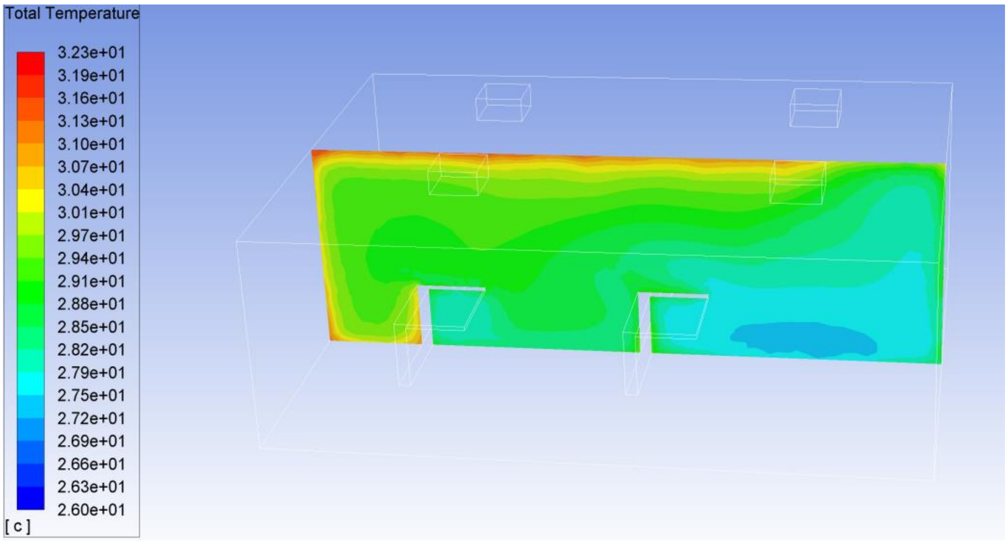

Figure 4.3: Temperature CFD results - Ceiling based 0.005 mass fraction, 26 degrees

As the 26°C air exceeded the human comfort range the incoming air was changed to 22°C per Figure 4.4. The results of this saw the temperature of between 25°C and 27°C through the whole office, with the lower end of the range at the lower 1m of the office space. This creates an environment where the temperature is within the acceptable range.

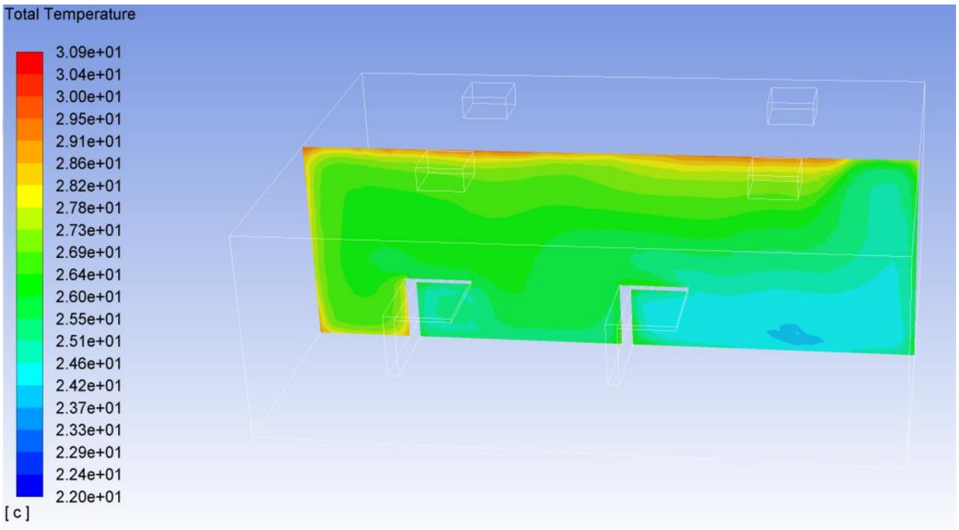

Figure 4.4: Temperature CFD results - Ceiling based 0.005 mass fraction, 22 degrees

While the offices temperature has increased which will result in the reduction of the air conditioners energy requirement, there is still a large amount of air above a seated persons head height. This results in wasted energy cooling this upper level of the open plan office.

4.1.2 Floor Diffuser Position

In order to further reduce this redundant energy usage, a floor based system was modelled with the aim to create a more distinct layering or pooling of cooler conditioned air around the desk and at this level. This is where a floor based system can be utilised to minimise the energy wastage. For a direct comparison, the space has been modelled at the same temperatures as the ceiling based diffusers, however due to the grille positioning the airflow exiting the grille has been reduced from 200L/s to 45L/s this gives a velocity at the grille of 1m/s exiting the grille.

Figure 4.5 has been modelled with 18°C incoming air. The pooling of cooler air is clearly visible around the workstation area, with warmer temperatures as you get further away from the workstation. This clearly demonstrates that by moving the diffuser positioning then we can achieve a more tasked based air distribution. The air around the seated position for this supply temperature is approximately 19°C, this is below the acceptable temperature range of comfort.

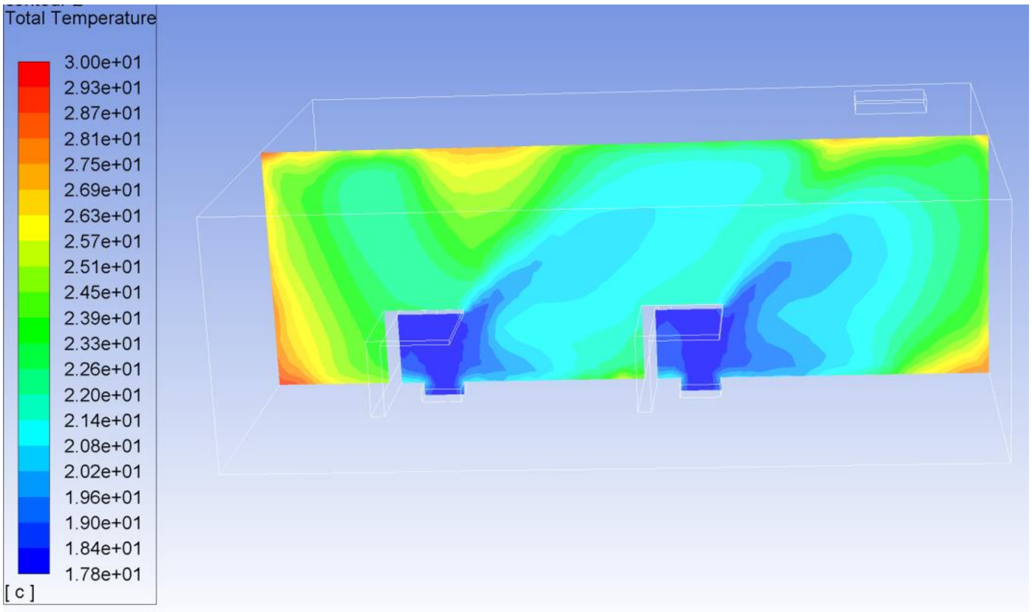

Figure 4.5: Temperature CFD results - Floor based 0.005 mass fraction, 18 degrees

Figure 4.6 again shows a larger temperature range compared to the ceiling located grilles of 23°C to 28°C. There is clear laying or temperatures, with approx. 23.5°C air located around the seated desk position with air in the other transient areas reaching the 26.5-27°C range. These temperatures are all located within the human comfort zone.

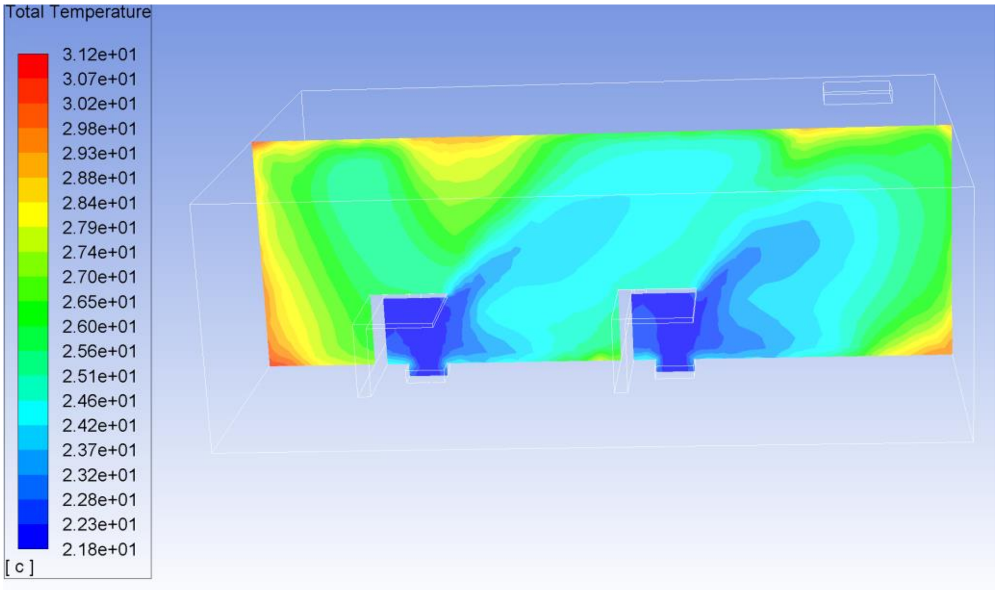

Figure 4.6: Temperature CFD results - Floor based 0.005 mass fraction, 22 degrees

4.2 Humidity

Humidity is the second most important variable in the human comfort equation, and the second main variable of focus for this research. The humidity its what makes the air feel almost thicker and stuffy. It can make a space feel at a much higher temperature than it actually is if they humidity is high enough. The current standard design condition if 50% relative humidity. This modelling will be aiming for a humidity range of 30% to 35%

4.2.1 Ceiling Diffuser Position

The first analysis has been run using an input of 0.005 mass fraction of water vapour to air. Figure 4.7 shows the results of the modelling, this model achieves a nice range of 25-35% humidity with the lower end of this being towards the outer boundary of this geometric model.

Ideally the whole space should remain above the 30% humidity range to avoid and of the possible negative effect such as dry and irrigated eyes, dry skin etc as mentioned previously. As this model is a small section of an entire office, a large space will mean these lower humidity spots which are located around the boundary of the model will be limited to just around the perimeter of the building. Due to solar rays coming through the windows, workstations are seldomly positioned right against the windows of a building so this mitigates the issue.

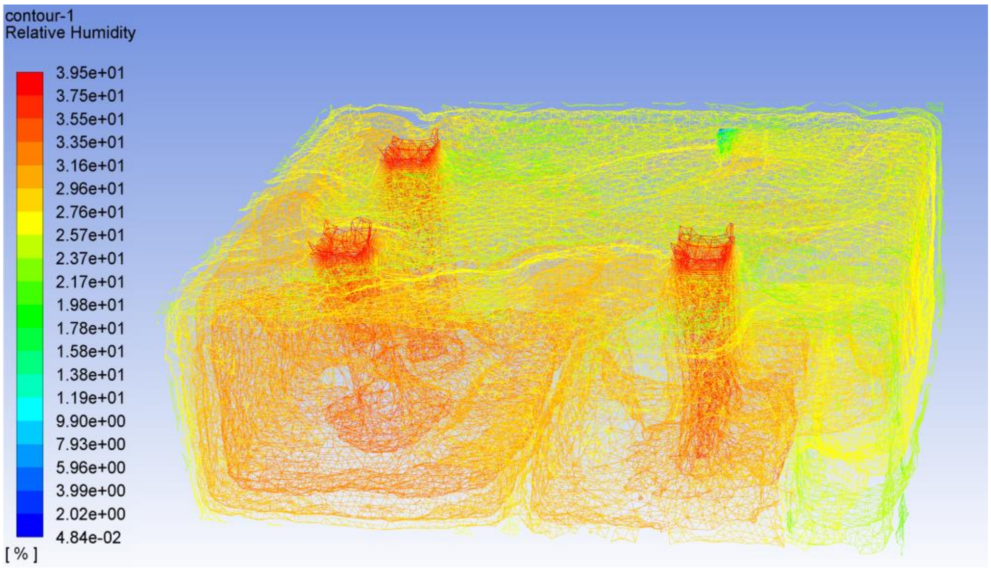

Figure 4.7: Humidity CFD results - Ceiling based 0.005 mass fraction, 18 degrees

The same mass fraction has been modelling, except this time using the 22° incoming air, the results can be seen from Figure 4.8. The humidity percentage can see a significant drop even though the same quantity of water vapour has been inputted into the space. This is due to colder air having a lower saturation level. This results in the air needing more water vapour to remain at the same relative humidity as the temperature increases.

The humidity range has been reduced to 20%-25% as a result of the air being 4°C warmer. This demonstrates that at a higher temperature setpoint, less water vapour need to be removed from the air in order to achieve a lower humidity level than at that lower air temperature. The less water vapour that is required to be removed from the air the less energy that is required for the system to meet the desired design conditions.

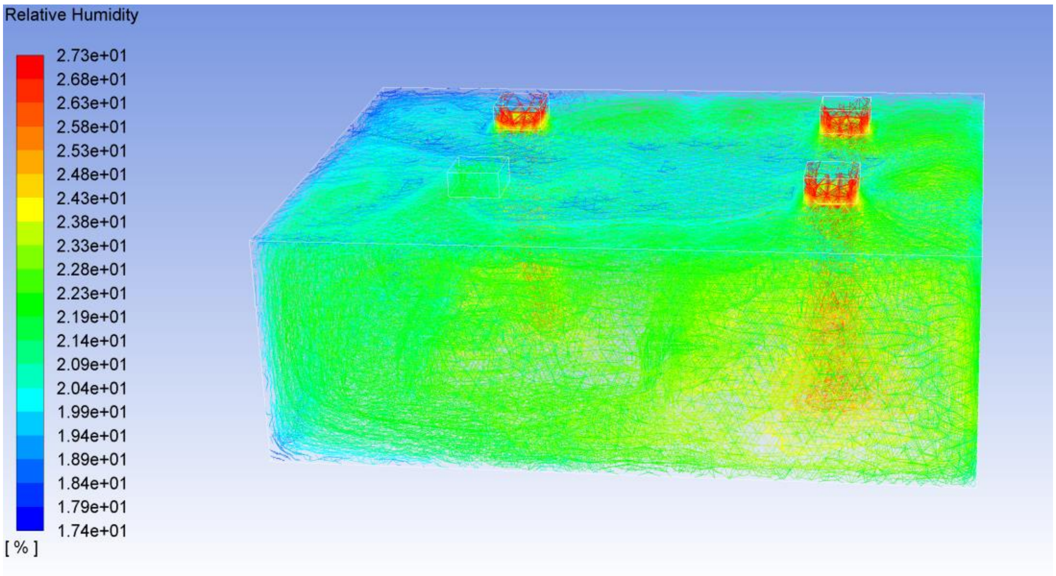

Figure 4.8: Humidity CFD results - Ceiling based 0.005 mass fraction, 22 degrees

4.2.2 Floor Diffuser Position

The same conditions were modelled using the floor based diffusers as per Figure 4.9. This showed results generally in line with the findings of the equivalent ceiling located diffusers, the humidity range was slightly higher due to the proximity of the workstation to the grille, with this still at approximately 30%, which is right on the ideal level of humidity of what is aiming to be achieved.

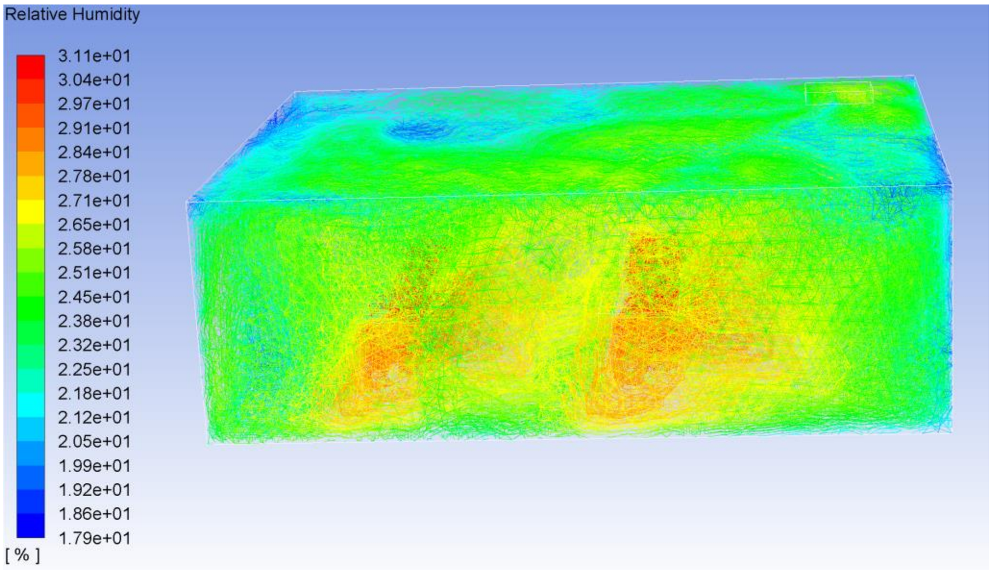

Figure 4.9: Humidity CFD results - Floor based 0.005 mass fraction, 22 degrees

Because of these two previous results, the water vapour mass fraction was increased to 0.008. This resulted in the space around the workstations sitting as approximately 45% relative humidity, with the areas away from the workstations showing a range of 30% to 40%. These relative humidity ranges are all within the acceptable human comfort zone.

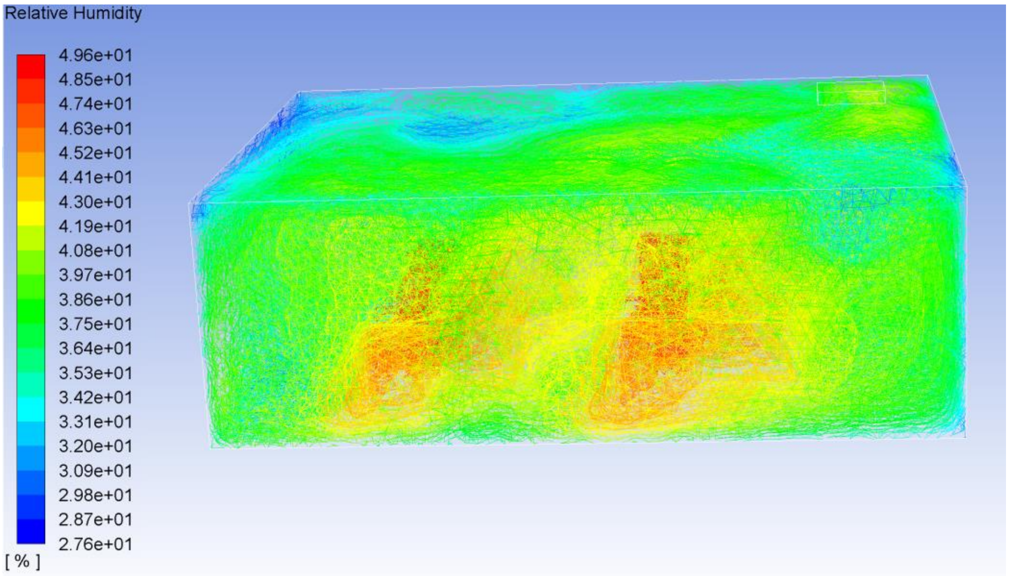

Figure 4.10: Humidity CFD results - Floor based 0.008 mass fraction, 22 degrees

Further modelling with larger temperature and water vapour input ranges can be found as part of Appendix A. These have been omitted from the main report as the results were either outside of acceptable human comfort limits or they were in line with the results mentioned previously.

Chapter 5 – Analysis and Results

As the modelling is complete and has demonstrated that delivering a higher air temperature at a lower humidity is feasible design solution for a modern open plan office, the data from the modelling has to be input into the human comfort equation. As the Predicted Mean Vote, formula developed by Fanger is the most accepted formula by the relevant standards including ASHRAE and AS1668.2, this is the formula used to evaluate the human comfort levels.

A calculation on the heat load associated with the modelling results will also be conducted using Apache Camel software to calculate the potential energy saving due to this reduced heat load.

5.1 Human Comfort

The predicted mean vote for human comfort has been graphed to demonstrate the comfort region matching with the CFD modelling from chapter 4. The shaded section demonstrates the acceptable 'human comfort zone' This has been calculated using the PMV formula. While the red circle indicating the exact data point which has been input from the CDF modelling. For human comfort to be met the PMV formula needs to result in an answer between -0.5 and +0.5.

All calculations have been performed with the same variables except for ones which are being evaluated. The constant variables are;

- Metabolic rate - 1.1 met. This is equivalent to seated, stationary typing or writing.
- Clothing level – 0.61 SSU. This is equivalent to a smart casual business dress code, typical of Brisbane. This includes Trousers or a below the knee skirt, long sleeved shirt, underwear and enclosed footwear.

As a control test Figure 5.1 has been calculated using the current standard design conditions of 23.5°C air, 50% humidity and 0.05m/s air velocity across a person. It results in a PMV value of -0.34. This is the value which people working within the majority office buildings will be experiencing currently what they have become conditioned too.

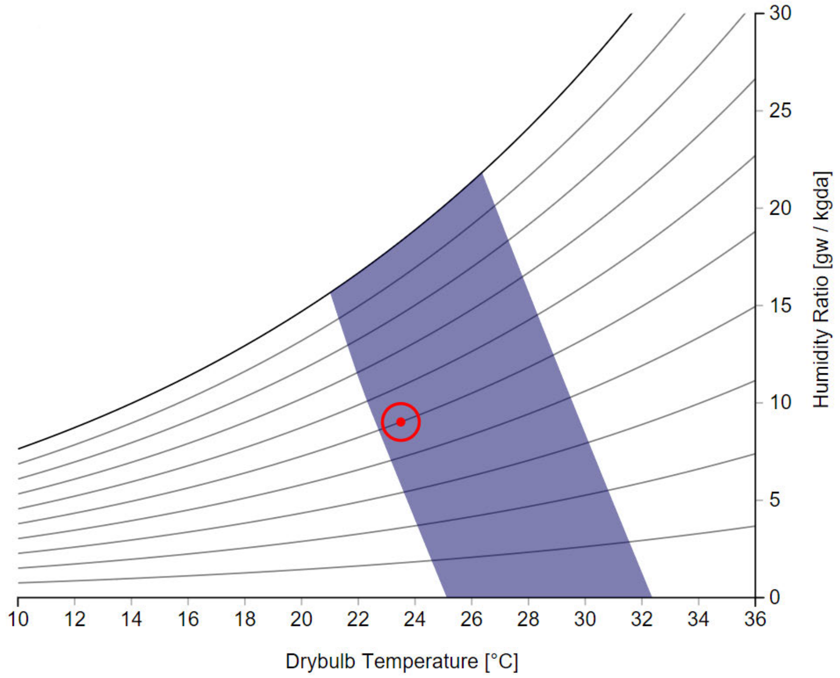

Figure 5.1: Human comfort - 24 degrees, 0.05m/s air velocity, 50% Humidity, PMV = -0.34, PPD = 7%, Feeling = Neutral

The following Figures 5.2, 5.3 and 5.4 have been graphed using the results of incoming air of 22°C with water vapour mass fraction of 0.008 as the modelling results look to fit best within the human comfort zone and best satisfy the aim of this research.

Firstly, the conditions closest to the outlet is graphed in Figure 5.2. This is the location where a person will be situated and be working up to eight hours a day. The modelling shows this zone with the approximate conditions of 23.5°C air with 0.15m/s velocity across the person and a relative humidity of 48%. This situation results in a PMV value of -0.44. This is within the acceptable human comfort standards, but it is noted that it is close to the lower limit. This suggests while considered acceptable, the grille locations should be considered carefully at time of design and done in accordance with the architectural workstation locations.

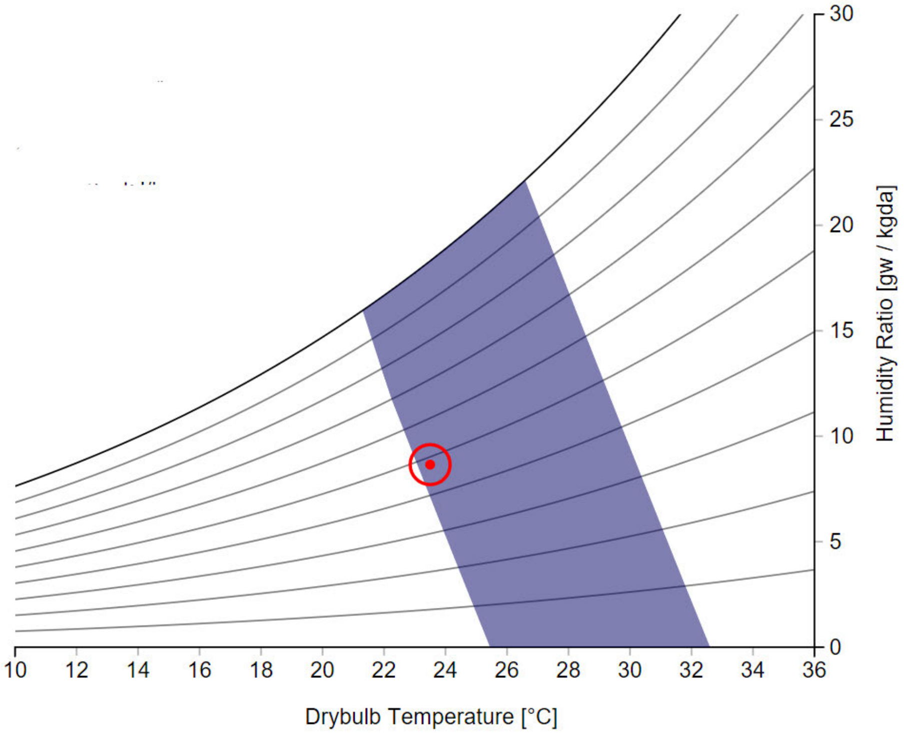

Figure 5.2: Human comfort - 23.5 degrees, 0.15m/s air velocity, 48% Humidity, PMV = -0.44, PPD = 9%, Feeling = Neutral

Figure 5.3 has been selected at a distance of approximately 1.5 metres away from the workstation, this is a distance where work colleagues may gather for impromptu meeting nearby one person's workstation or a social talk. The approximate conditions are 25.5°C with a velocity of 0.1m/s and 40% humidity. This situation results in a PMV value of 0.16. This is in the middle of the acceptable human comfort range and presents no issues.

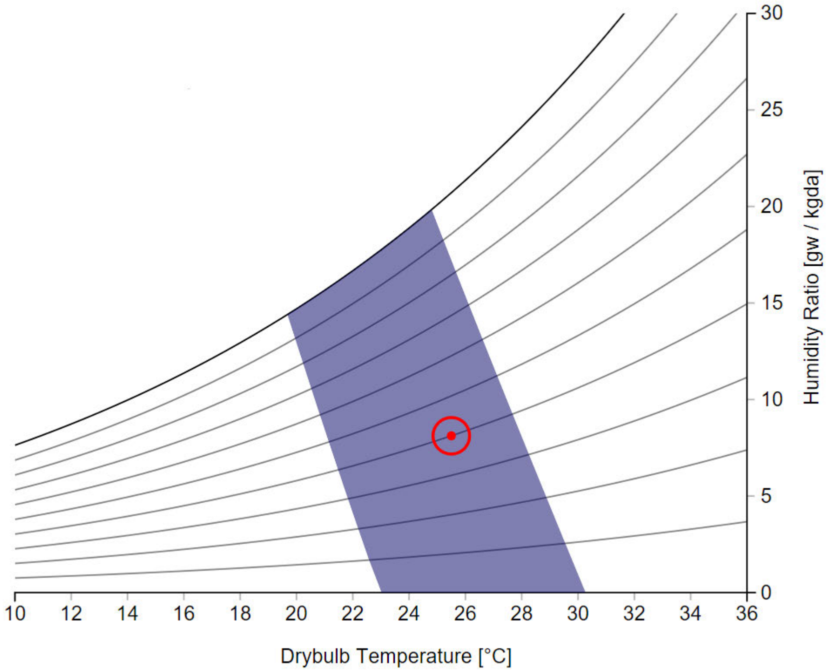

Figure 5.3: Human comfort - 25.5 degrees, 0.1m/s air velocity, 40% Humidity, PMV = 0.16, PPD = 6%, Feeling = Neutral

Lastly, a distance of approximately 3.5m from the workstation was selected for Figure 5.4. This distance was selected for two main reason, air diffusers are typically installed 6 metres apart as they have a 3 metre throw range for the air exiting the diffuser, this makes this distance the maximum that a person would be from an air diffuser at any given time. It also gives a good indication of the thermal conditions at transient spaces, such as hallways and printer areas. The approximate conditions are 26.5°C with a velocity of 0.08m/s and 36.5% humidity. This situation results in a PMV value of 0.49.

While the PMV value is on right on the upper limit of acceptable human comfort, this will be limited areas around the office, such as hallways and printers. These are areas where a worker would spend less than one to two minutes in, time enough to collect some printing or walk to the office facilities or a co-workers desk.

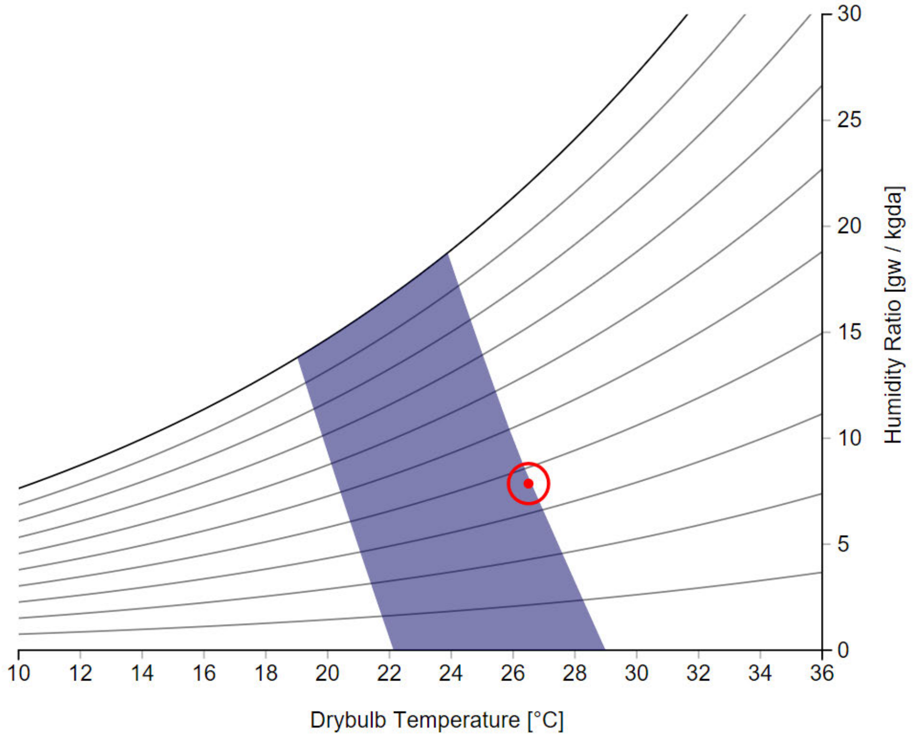

Figure 5.4: Human comfort - 26.5 degrees, 0.08m/s air velocity, 36.5% Humidity, PMV = 0.49, PPD = 10%, Feeling = Neutral

5.2 Energy Savings

With the increase in temperature setpoint of the workspace the energy required to cool the space is reduced as the temperature differential is reduced. Because of this reduction the required capacity of the air conditioning units is also reduced, this means smaller air conditioning unit it able to be used which saves cost on the procurement of the equipment at the installation stage as well as ongoing power usage.

With all modern air conditioning equipment being either an inverter type or stages compressors means that existing units that are currently installed will also be able to reduce their energy usage with the reduced cooling capacity as they will not be required to operate at 100% capacity. This means little to no modification of existing equipment will be required to existing plant and equipment. The only exception to this will be if the existing cooling coil cannot achieve the reduced humidity requirement. In situations where this is the case, a simple passive energy recovery unit, or humidity absorbing filter media will be installed into the existing system which will result in minimal ongoing cost.

The following heat loads have been calculated with the use of Apache Camel software based on the same geometrical model used as part of the Ansys CFD modelling. This program uses solar loading from weather data based on localised weather station monthly averages which have been recognised by the Australian Standards. It also requires U-value inputs for all building fabric materials such as walls and windows.

The data used to calculate the following heat loads has been set out in section 3.14 Heat load.

ACADS BSG Program

CAMEL

Version Number 5.10.5B

ACADS BSG advises that the program CAMEL is intended to be used only by persons who are proficient in its use and application and that these results should be verified independently. The results must not be used without acceptance of the ACADS-BSG's License Agreement for this program.

AHU SUMMARY - COOLING

At Time of Peak Grand Total Heat (GTH)

TITLE	NO. OFF	S/A l/s	OUT/AIR l/s	OUT/AIR %	GTH kW	GTSH kW	COIL CDB	ENT CWB	COIL CDB	LVG CWB	PRECON NO.
AHU1	1	286	45	16	5.36	4.17	25.4	18.3	13.3	12.7	

AHU SUMMARY COOLING SUPPLEMENTARY DATA

Note 1: at time of peak AHU adjusted sensible heat
2: increased air quantity or reduced leaving coil CDB are alternatives

Title	Time Peak GTH	Adj Sens kW	Time Peak Adj Sens	Adj Sens kW	GTH kW	AQ l/s	% var	Lvg CDB	Diff CDB
AHU1	Peak adjusted sensible occurs at same time as peak GTH								

Figure 5.5: Heat load at current standard office conditions

ACADS BSG Program

CAMEL

Version Number 5.10.5B

ACADS BSG advises that the program CAMEL is intended to be used only by persons who are proficient in its use and application and that these results should be verified independently. The results must not be used without acceptance of the ACADS-BSG's License Agreement for this program.

AHU SUMMARY - COOLING

At Time of Peak Grand Total Heat (GTH)

TITLE	NO. OFF	S/A l/s	OUT/AIR l/s	OUT/AIR %	GTH kW	GTSH kW	COIL CDB	ENT CWB	COIL CDB	LVG CWB	PRECON NO.
AHU1	1	237	45	19	4.59	3.52	27.7	20.2	15.4	14.7	

AHU SUMMARY COOLING SUPPLEMENTARY DATA

Note 1: at time of peak AHU adjusted sensible heat
2: increased air quantity or reduced leaving coil CDB are alternatives

Title	Time Peak GTH	Adj Sens kW	Time Peak Adj Sens	Adj Sens kW	GTH kW	AQ l/s	% var	Lvg CDB	Diff CDB
AHU1	Peak adjusted sensible occurs at same time as peak GTH								

Figure 5.6: Heat load at proposed office conditions

Table 5.1: Comparison of heat loads

Room Temperature Setpoint (°C)	Air off Coil (°C)	Cooling Requirement (kW)	Sensible Cooling Requirement (kW)	Airflow (L/s)
23.5	18	5.36	4.17	286
26.5	22	4.59	3.52	237

As can be seen from Table 5.1 there is a reduction of just under 15% of cooling demand by increasing the setpoint temperature in line with the results from section 5.1 Human Comfort. This is a significant energy saving once this is scaled up to a full-size office floor plan. A typical office floor can consist of 800m² lettable area and a cooling demand up to 125kW. This means an energy reduction of 25kW per level is possible.

Table 5.2: Hourly Cost of Air Conditioning at Various Setpoints

Cooling Capacity	21°	22°	23°	24°	25°	26°	27°
2.5kW	$0.15	$0.14	$0.12	$0.11	$0.10	$0.10	$0.09
5kW	$0.38	$0.35	$0.31	$0.29	$0.27	$0.24	$0.22
10kW	$0.83	$0.76	$0.68	$0.62	$0.57	$0.51	$0.46
15kW	$1.32	$1.21	$1.08	$1.00	$0.93	$0.84	$0.75
20kW	$1.81	$1.66	$1.48	$1.38	$1.29	$1.16	$1.04
25kW	$2.30	$2.11	$1.87	$1.77	$1.65	$1.49	$1.34
50kW	$4.75	$4.36	$3.85	$3.69	$3.45	$3.11	$2.79
80kW	$7.69	$7.06	$6.23	$6.00	$5.61	$5.05	$4.54
100kW	$9.65	$8.86	$7.81	$7.53	$7.05	$6.35	$5.71
125kW	$12.10	$11.11	$9.79	$9.46	$8.85	$7.97	$7.17

Based on 27c/kWh usage charge.

Based on an energy saving of what use to be a 125kW system this reduces to a 100kW system which results in a potential energy saving of 21,900 kWh and a cost saving of $5,913 per annum based on a 10-hour running time per day. If this adopted throughout the whole building, this equated to 657,000 kWh with a cost saving of $177,390 based on a 30-storey office building.

5.3 Recommendations

The results of the modelling had been plotted against the energy saving for Figure 5.7. The human comfort zone marked in yellow sits between the 30% and 50% humidity lines and between 23.5°C and 26.5°C. For the best balance between energy efficiency and human comfort, the office setpoint conditions should be set right where the cooling load demand line comes into contact with the 30% humidity line.

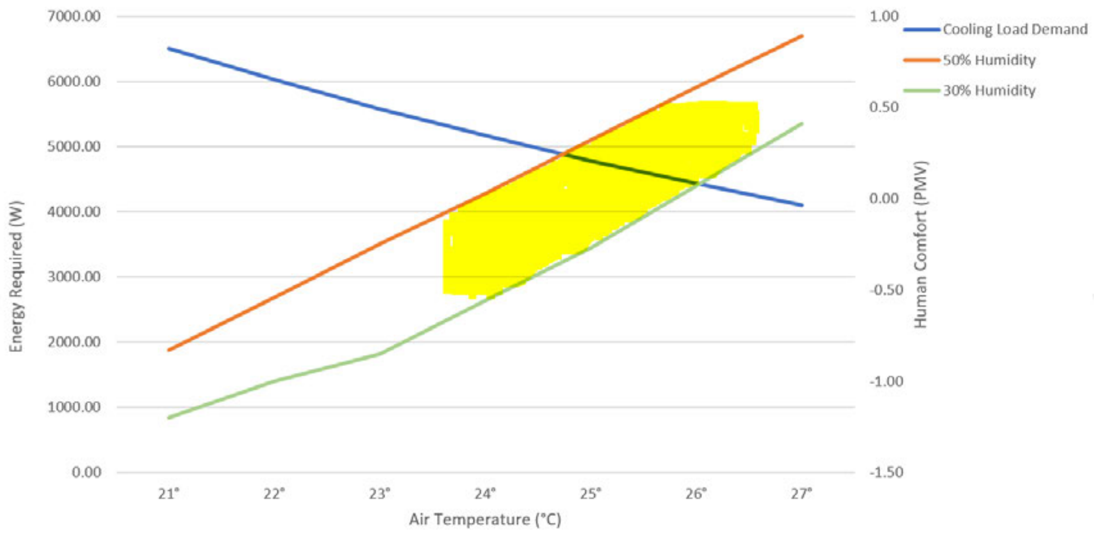

Figure 5.7: Energy Saving vs Human Comfort

This gives an ambient space temperature of 26°C at 30% relative humidity. In order to achieve these space conditions, the off coil air temperature should be set to between 21.5°C to 22°C with a water vapour mass fraction on 0.008 entering the space as the CFD modelling has indicated.

Chapter 6 - Conclusion and Future Work

6.1 Conclusions

This study progressed through a number of stages as set out by the Project Specification in appendix A. The project progress through all of the stages and results were achieved and found to be reliable. The first stage of the dissertation was to collect data and information though a literature review process, this process highlighted important information such as relevant Australian Standards for air conditioning and ventilation design and the best way to go about producing the CFD modelling. It also highlight some potential issues and risks involved with lowering the humidity levels, which has to be considered.

Once this information was collected the project moved onto the next stage of the CFD analysis. This analysis involved modelling a geometric object which resembles an open plan office, then different air temperatures and water vapour levels were tested to see the impact this would have on the conditions inside the space. Once this data was collected it was input into a human comfort equation and graphed to give an indication on how a person within the space would find the comfort levels.

The results showed that acceptable human comfort levels could still be maintained with an increase in temperature to 26.5°C and between 30% to 35% relative humidity. This increase saw a potential energy saving of approximately 15%. With project calculations this could see energy savings of 657,000kWh at a cost saving of $177,390 per annum

Further work should be undertaken to validate the human comfort levels in a real-world environment.

6.2 Future Work

Continuation of the project work would be to test the results in a real-world environment by setting up a controlled office environment running the air conditioning system both at recommended levels found from this project as well as variables outside of the recommendations while monitoring the internal conditions as well as collecting human feedback above their individual comfort.

The results should be then correlated with the CFD results with a direct comparison of the variables to validate both the CFD modelling and the PMV calculations. Due to the fact that 1 in 10 people will feel slightly warm or cool within a space even while the ambient air is within the PMV acceptable comfort zone it would be recommended to have a minimum of 15 people participating in the study, this gives an allowance to eliminate 1 or 2 outliers and maintain a 90% satisfaction rate. If a larger sample group is able to be used this will produce more reliable results, however the cost implications will be high to modify or setup an office area to accommodate a large sample group.

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Appendices

Chapter A – Project Specification

ENG4111/4112 Research Project

Project Specification

For: Callan Higgs

Title: Human Comfort – Reinventing Typical Modern Office Design to Provide Energy Efficient Air-conditioning.

Major: Mechanical engineering

Supervisors: Dr Andrew Wandel

Enrolment: ENG4111 – EXT S1, 2017 ENG4112 – EXT S2, 2017

Project Aim: To develop a more energy efficient method of delivering air conditioning to a modern office for human comfort.

Programme: Version 1, 7th March 2017

1. Review existing studies focused around human comfort levels and task based air conditioning.
2. Examine existing Australian standards and Building Codes for performance requirements and applicable standards which must be adhered to for design.
3. Review current office designs and identify areas where conditioned air is wasted. Perform a staff survey if required to identify any issues with an existing design
4. An analysis of the best type of system supply and airflow paths using CFD analysis modelling
5. Investigate and analysis of delivering different temperature and humidity levels of conditioned air. Establish a balance between improving energy efficiency and maintaining human comfort.
6. Incorporate these findings into the CFD model and refine the simulation.
7. Compile the results and form a series of recommendations for improving the current design philosophy.

If time and resources permit:

1. Calculate energy savings over a 6 month to year period
2. Explore options to modify existing systems to improve energy efficiency using the findings from the above recommendations.

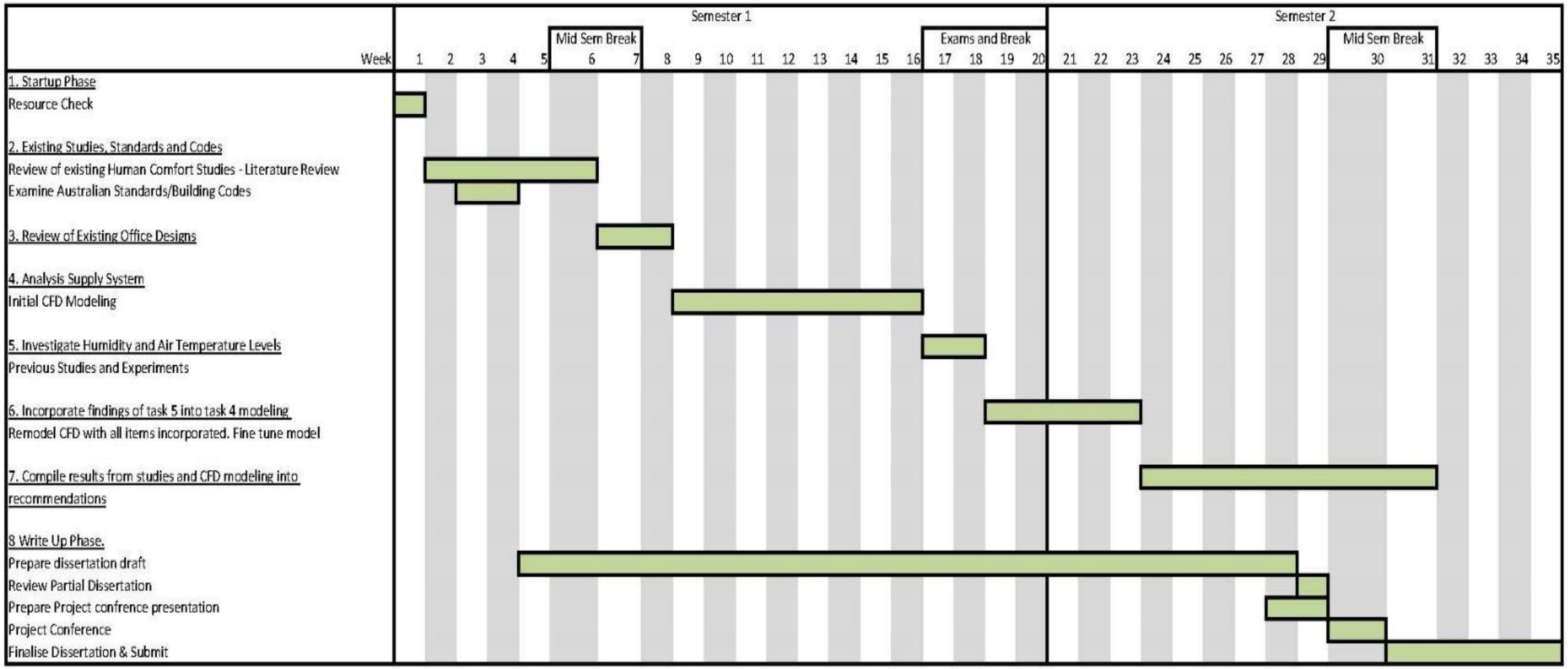
Chapter B - Project Schedule

The project schedule is given below. It incorporates the following targets and milestones:

- Project start on Week 1, Semester 1 and ends Week 35

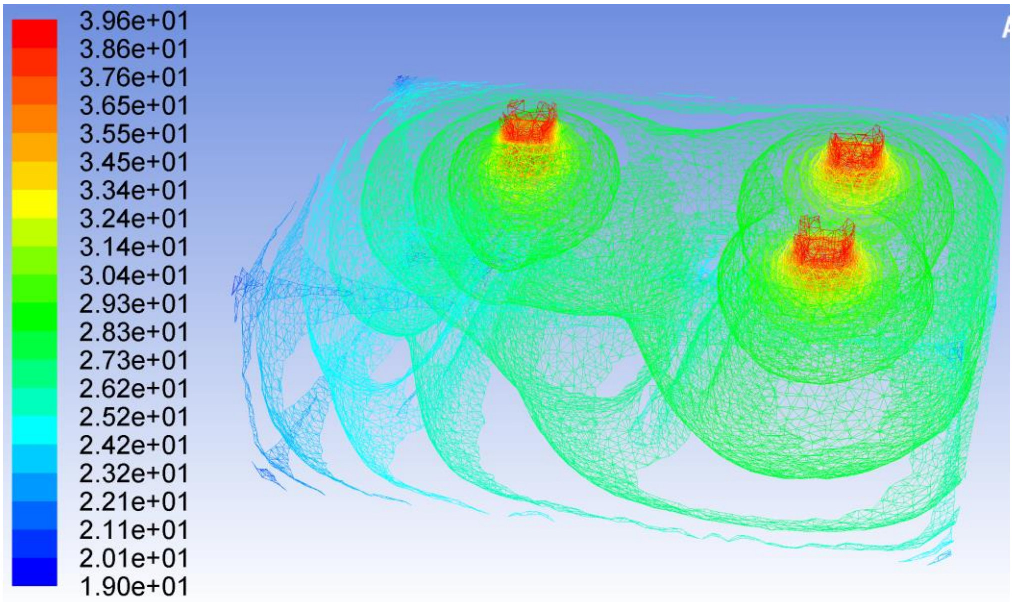
- ENG4903 Project Conference is included in the schedule as a presentation needs to be prepared for this, I have also allowed 2 week prior to the conference for preparation

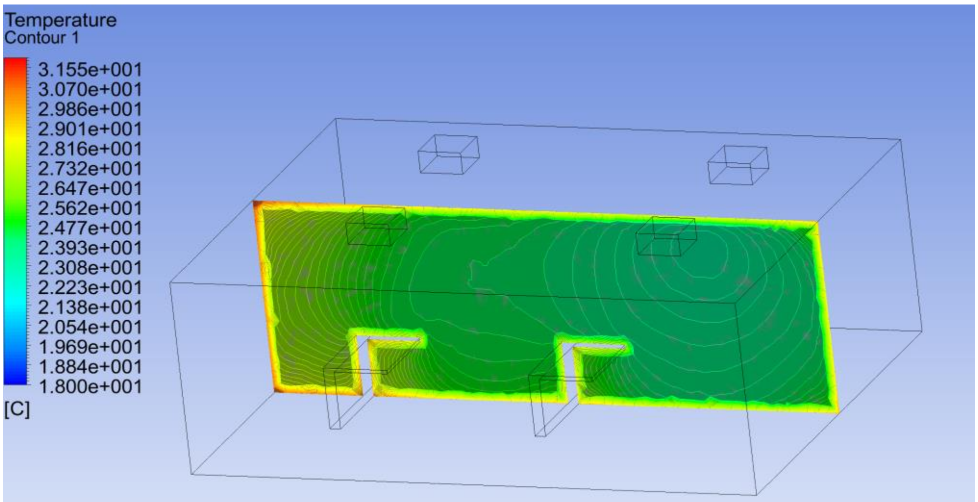
- Data analysis and dissertation write-up will be an ongoing continuous process during the whole year as I produce information from data collection and CFD modelling.

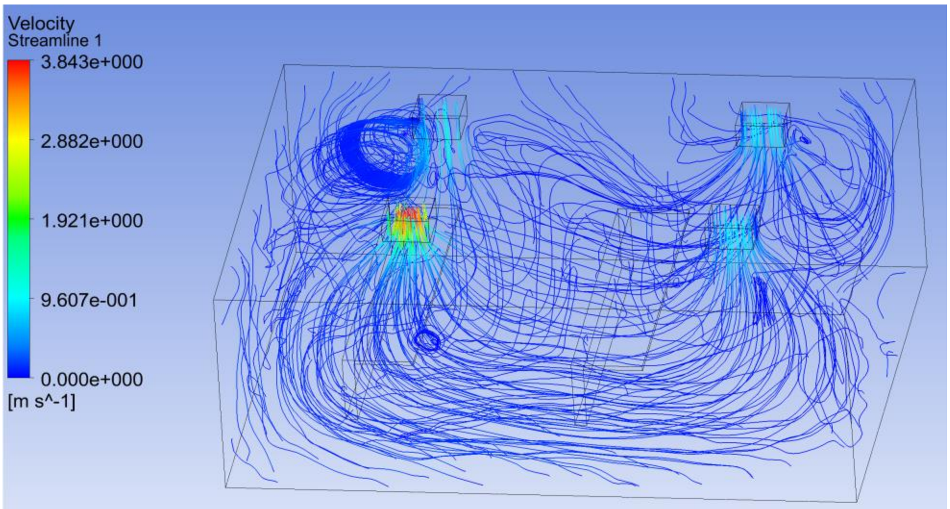

Semester 1
Semester 2
Mid Sem Break
Exams and Break
Mid Sem Break
Week
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31 32 33 34 35
1. Startup Phase
Resource Check
2. Existing Studies, Standards and Codes
Review of existing Human Comfort Studies - Literature Review
Examine Australian Standards/Building Codes
3. Review of Existing Office Designs
4. Analysis Supply System
Initial CFD Modeling
5. Investigate Humidity and Air Temperature Levels
Previous Studies and Experiments
6. Incorporate findings of task 5 into task 4 modeling
Remodel CFD with all items incorporated. Fine tune model
7. Compile results from studies and CFD modeling into recommendations
8 Write Up Phase.
Prepare dissertation draft
Review Partial Dissertation
Prepare Project confrence presentation
Project Conference
Finalise Dissertation & Submit

Chapter C - CFD Modelling

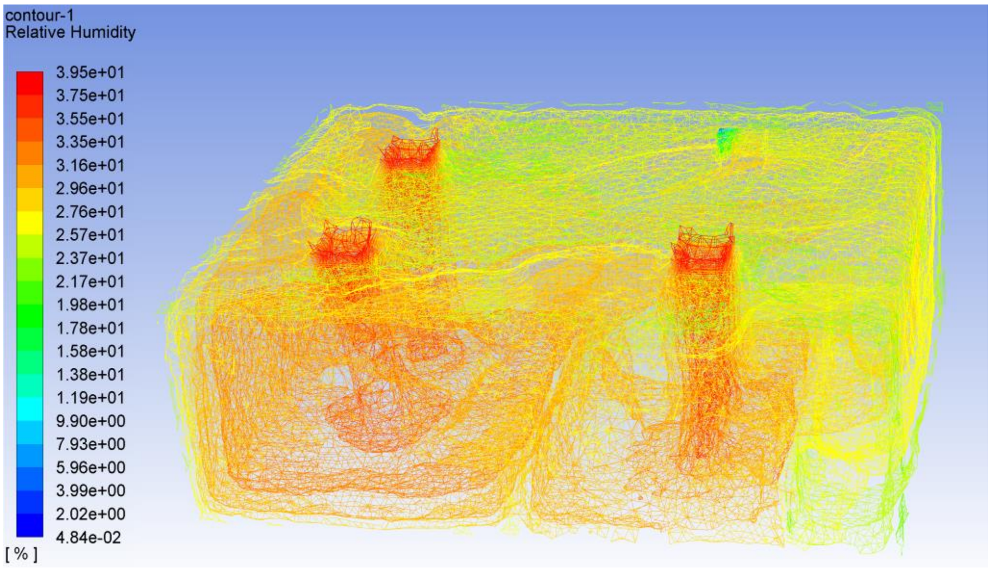
Model 1 – Ceiling based 0.005 mass fraction, 16 degrees – Humidity, Temp & Velocity Steams

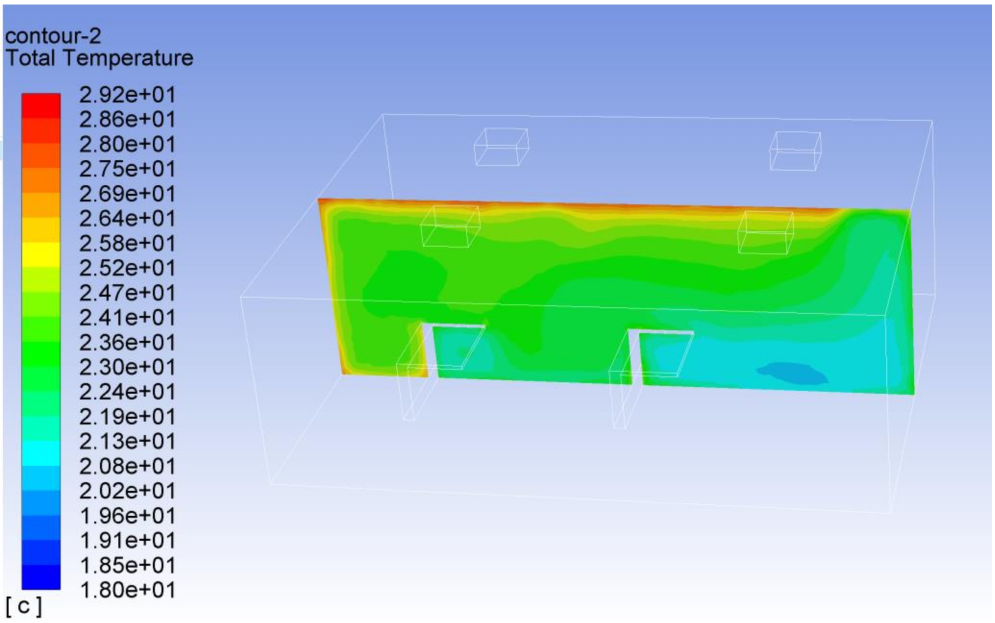


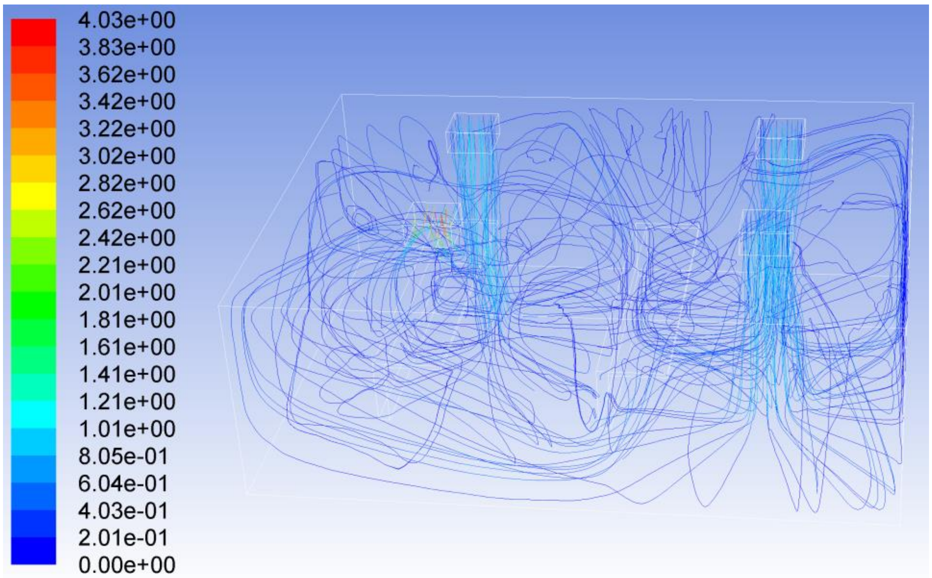




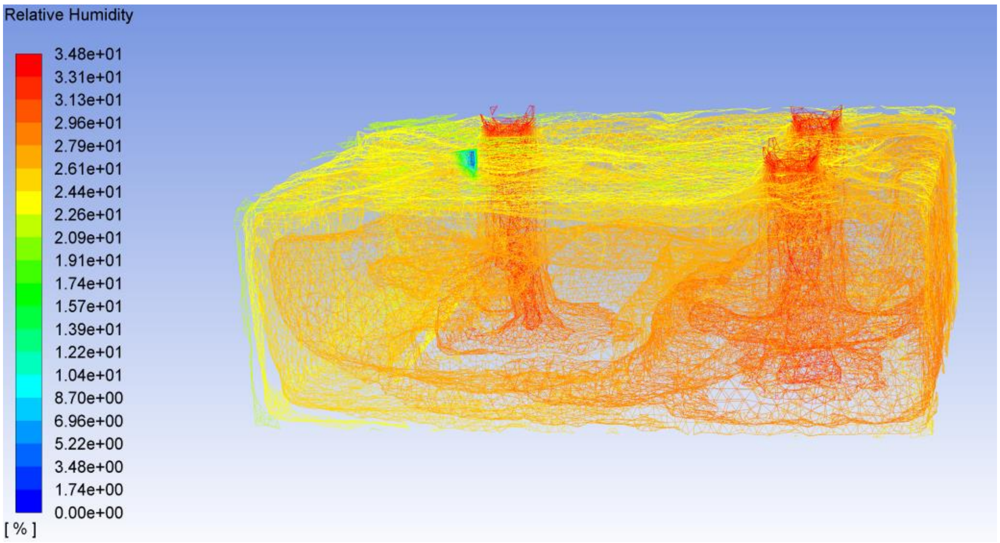
Model 2 – Ceiling based 0.005 mass fraction, 18 degrees – Humidity, Temp & Velocity Steams







Model 3 – Ceiling based 0.005 mass fraction, 20 degrees – Humidity, Temp & Velocity Steams


Relative Humidity
3.48e+01
3.31e+01
3.13e+01
2.96e+01
2.79e+01
2.61e+01
2.44e+01
2.26e+01
2.09e+01
1.91e+01
1.74e+01
1.57e+01
1.39e+01
1.22e+01
1.04e+01
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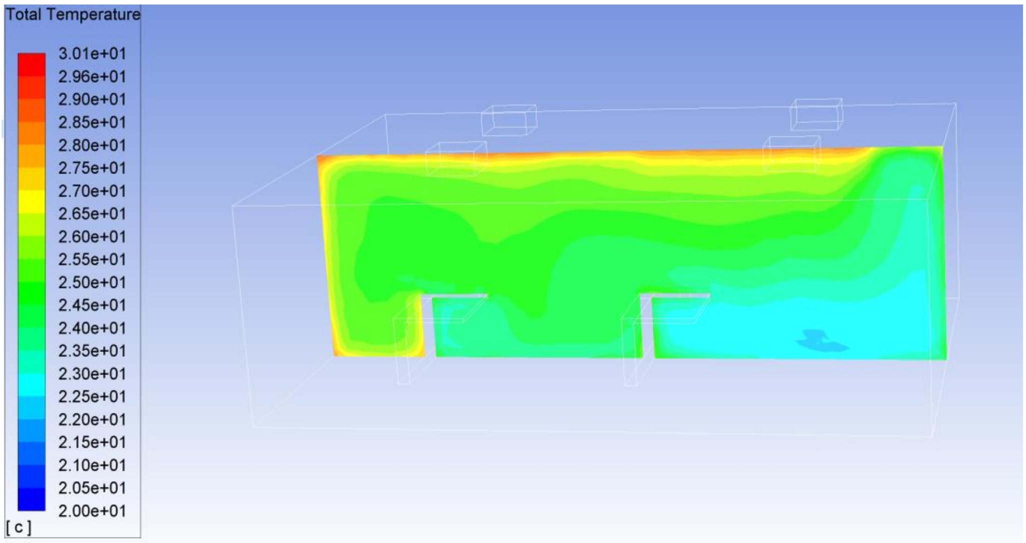
5.22e+00
3.48e+00
1.74e+00
0.00e+00
[%]


Total Temperature
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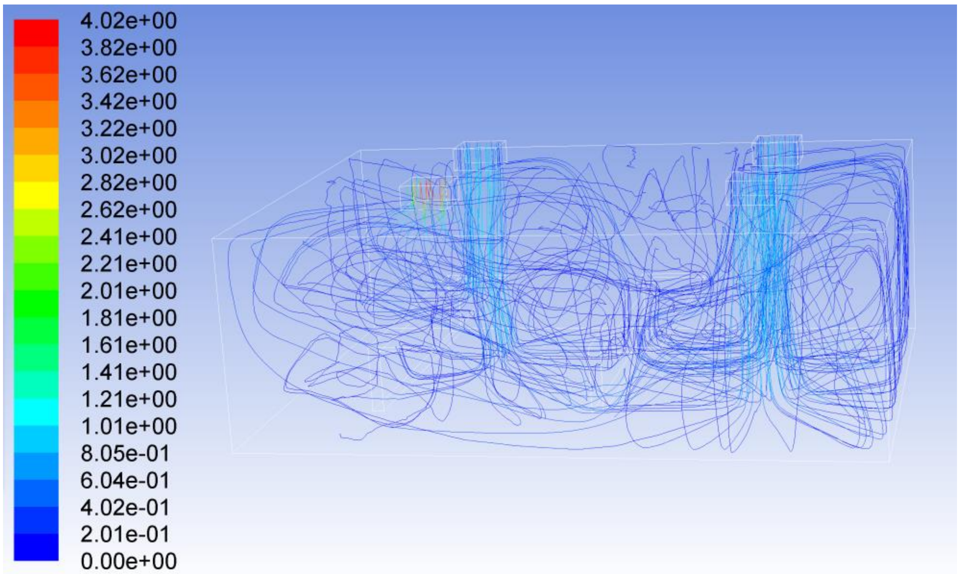
2.96e+01
2.90e+01
2.85e+01
2.80e+01
2.75e+01
2.70e+01
2.65e+01
2.60e+01
2.55e+01
2.50e+01
2.45e+01
2.40e+01
2.35e+01
2.30e+01
2.25e+01
2.20e+01
2.15e+01
2.10e+01
2.05e+01
2.00e+01
[c]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3.82e+00
3.62e+00
3.42e+00
3.22e+00
3.02e+00
2.82e+00
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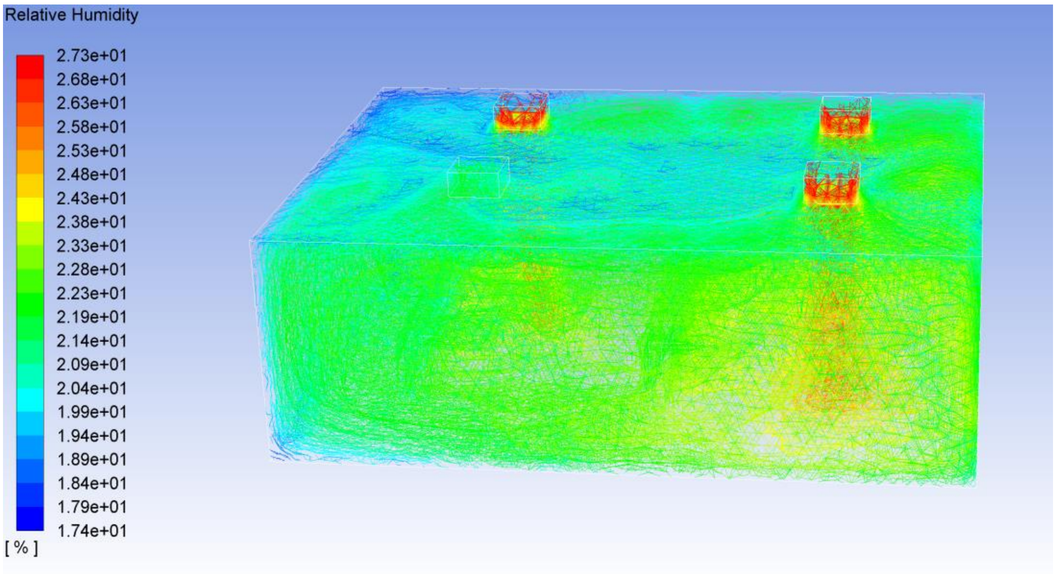
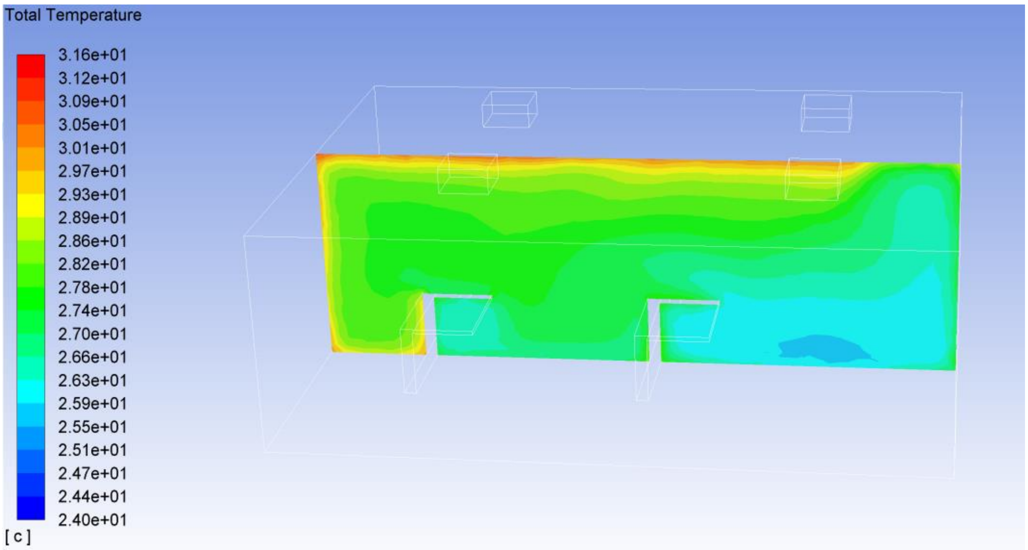
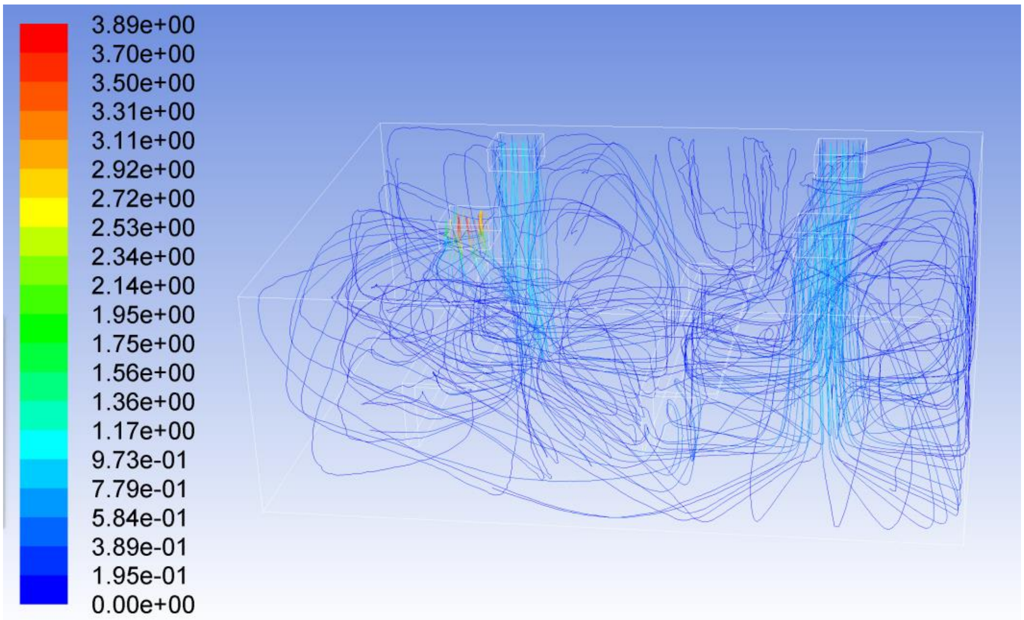
2.41e+00
2.21e+00
2.01e+00
1.81e+00
1.61e+00
1.41e+00
1.21e+00
1.01e+00
8.05e-01
6.04e-01
4.02e-01
2.01e-01
0.00e+00

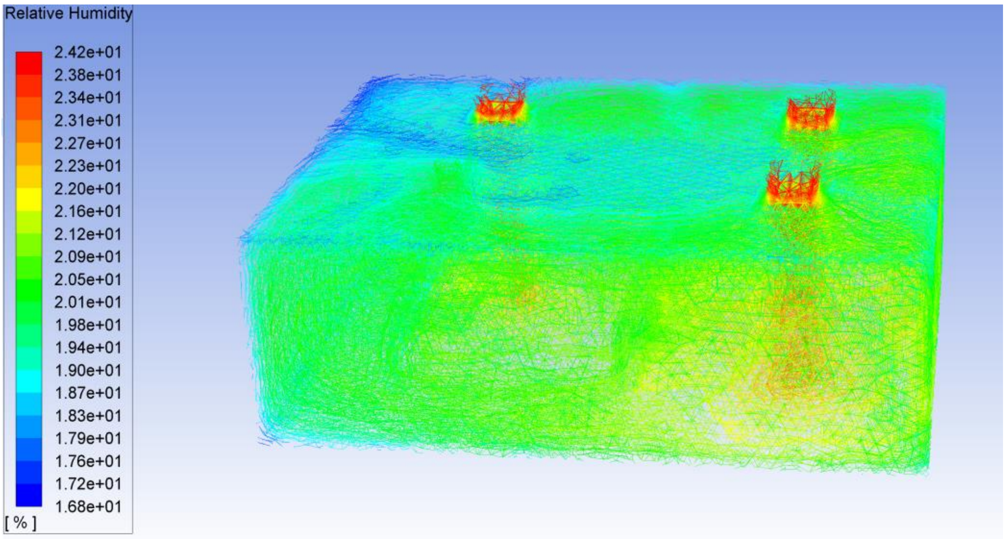
Model 4 – Ceiling based 0.005 mass fraction, 24 degrees – Humidity, Temp & Velocity Steams

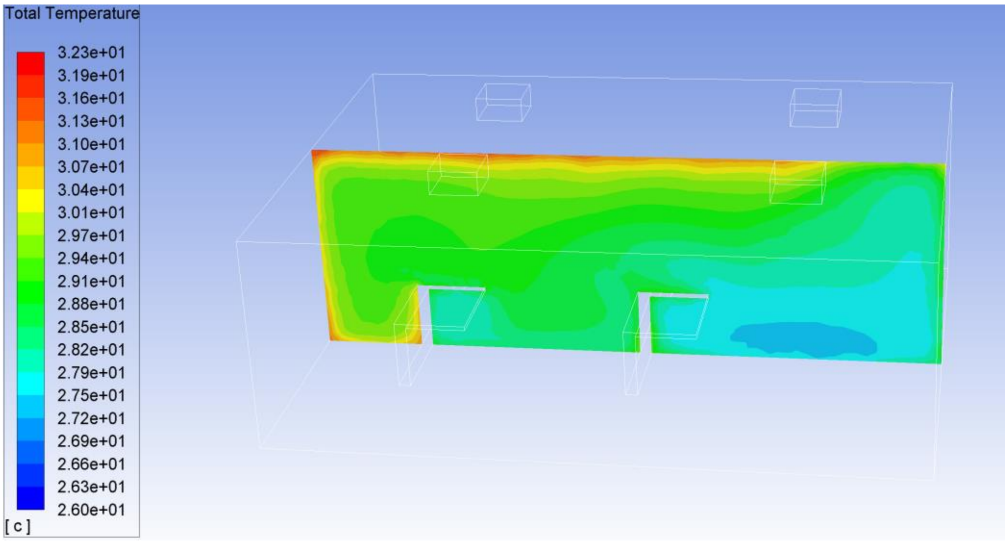


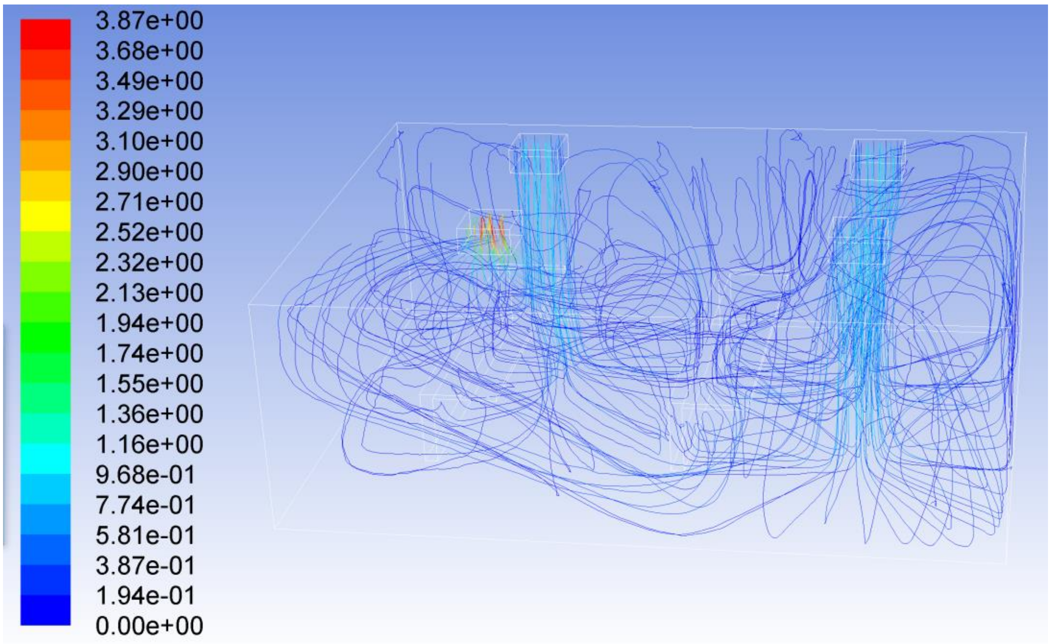




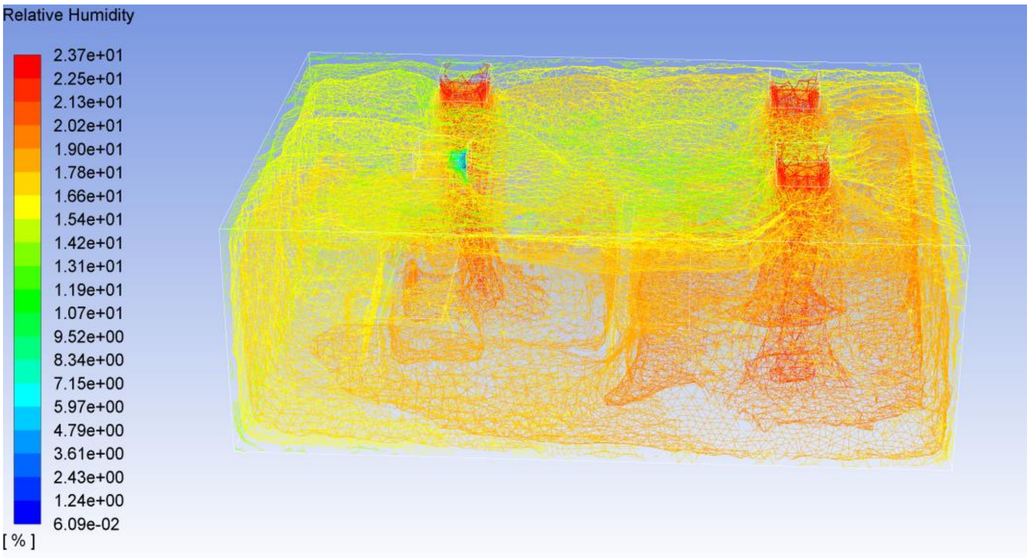
Model 5 – Ceiling based 0.005 mass fraction, 26 degrees – Humidity, Temp & Velocity Steams

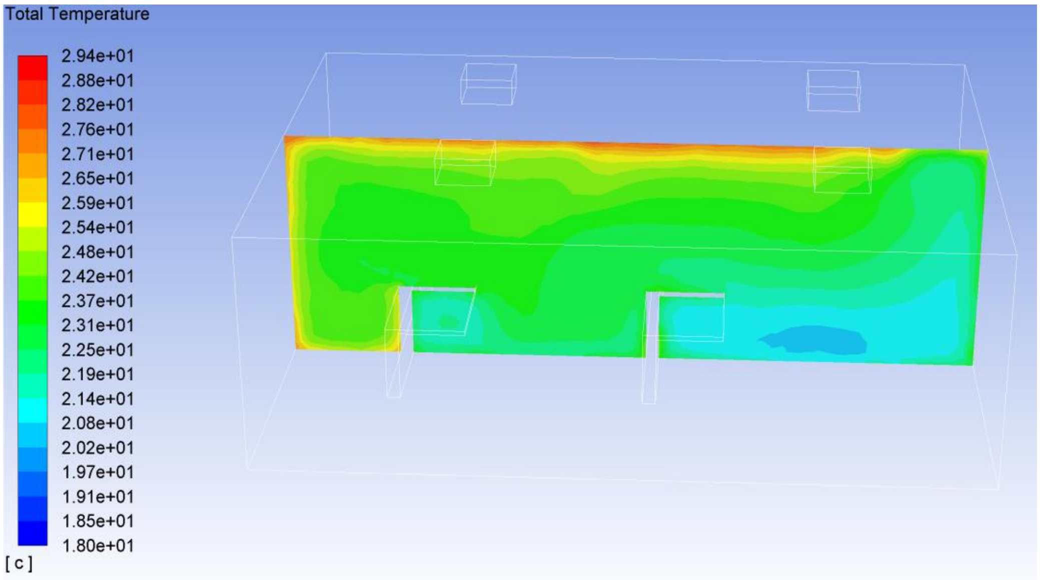






Model 6 – Ceiling based 0.003 mass fraction, 18 degrees – Humidity, Temp & Velocity Steams


Relative Humidity
2.37e+01
2.25e+01
2.13e+01
2.02e+01
1.90e+01
1.78e+01
1.66e+01
1.54e+01
1.42e+01
1.31e+01
1.19e+01
1.07e+01
9.52e+00
8.34e+00
7.15e+00
5.97e+00
4.79e+00
3.61e+00
2.43e+00
1.24e+00
6.09e-02
[%]


Total Temperature
2.94e+01
2.88e+01
2.82e+01
2.76e+01
2.71e+01
2.65e+01
2.59e+01
2.54e+01
2.48e+01
2.42e+01
2.37e+01
2.31e+01
2.25e+01
2.19e+01
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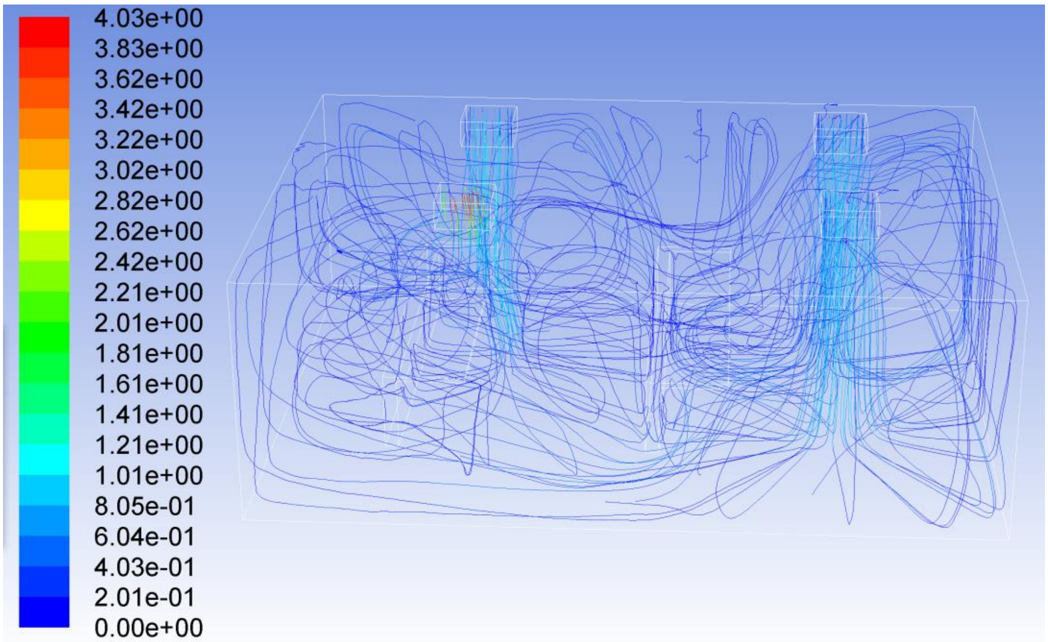
1.80e+01
[c]


4.03e+00
3.83e+00
3.62e+00
3.42e+00
3.22e+00
3.02e+00
2.82e+00
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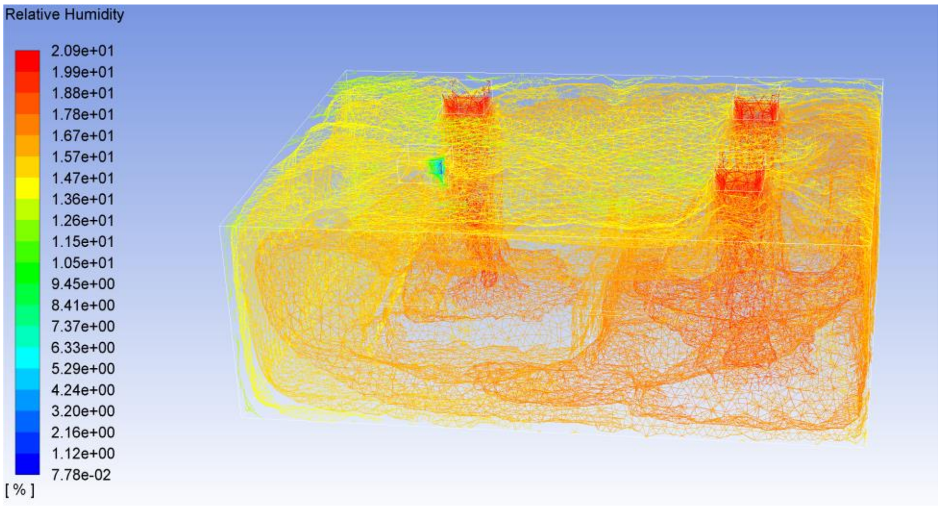
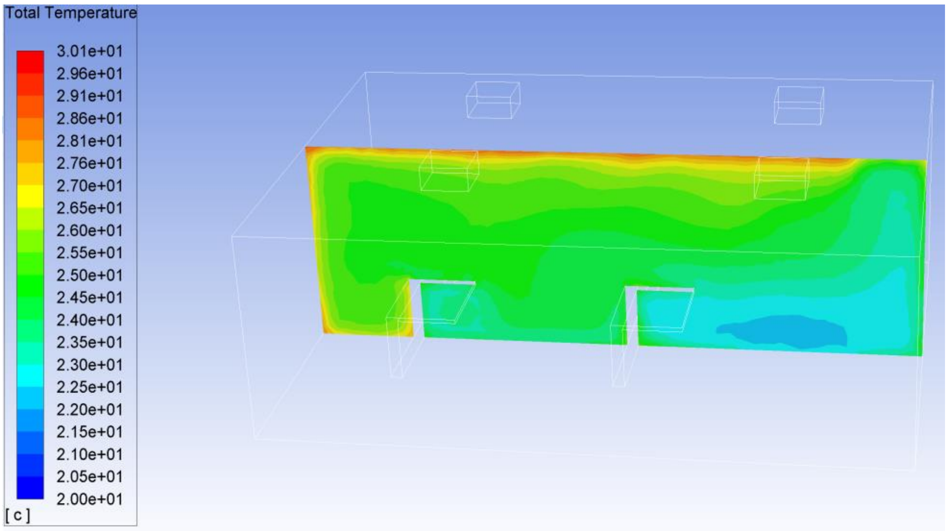
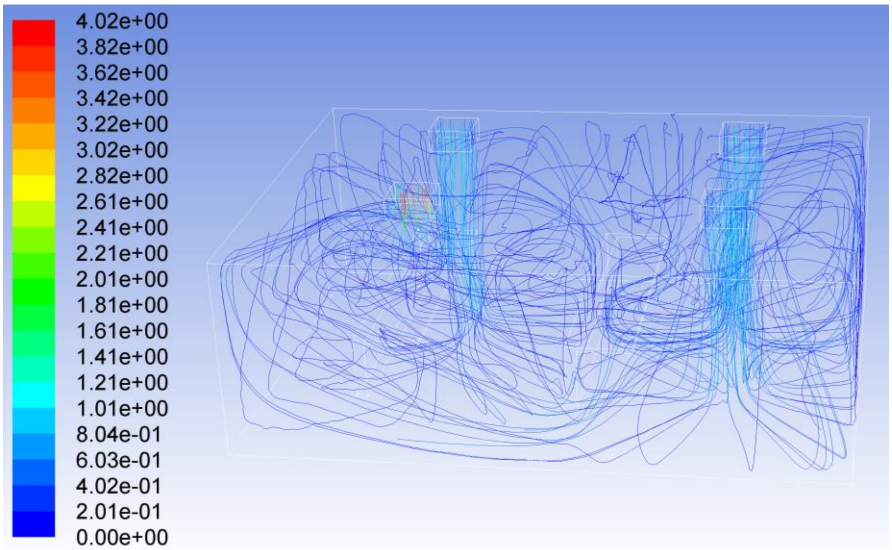
2.42e+00
2.21e+00
2.01e+00
1.81e+00
1.61e+00
1.41e+00
1.21e+00
1.01e+00
8.05e-01
6.04e-01
4.03e-01
2.01e-01
0.00e+00

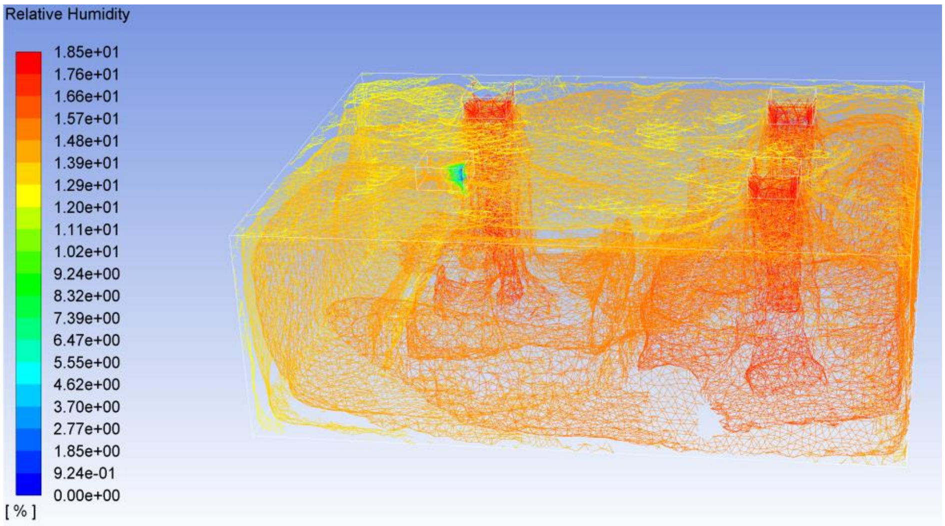
Model 7 – Ceiling based 0.003 mass fraction, 20 degrees – Humidity, Temp & Velocity Steams

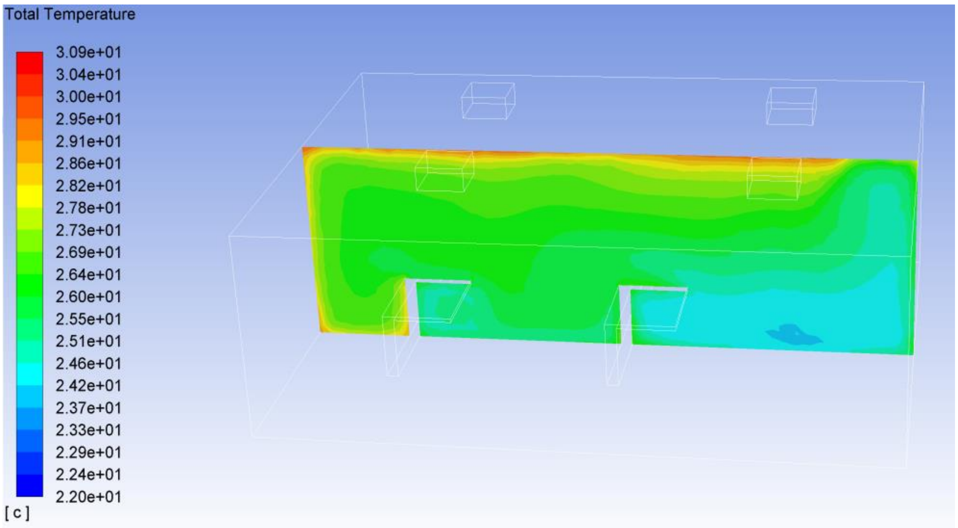


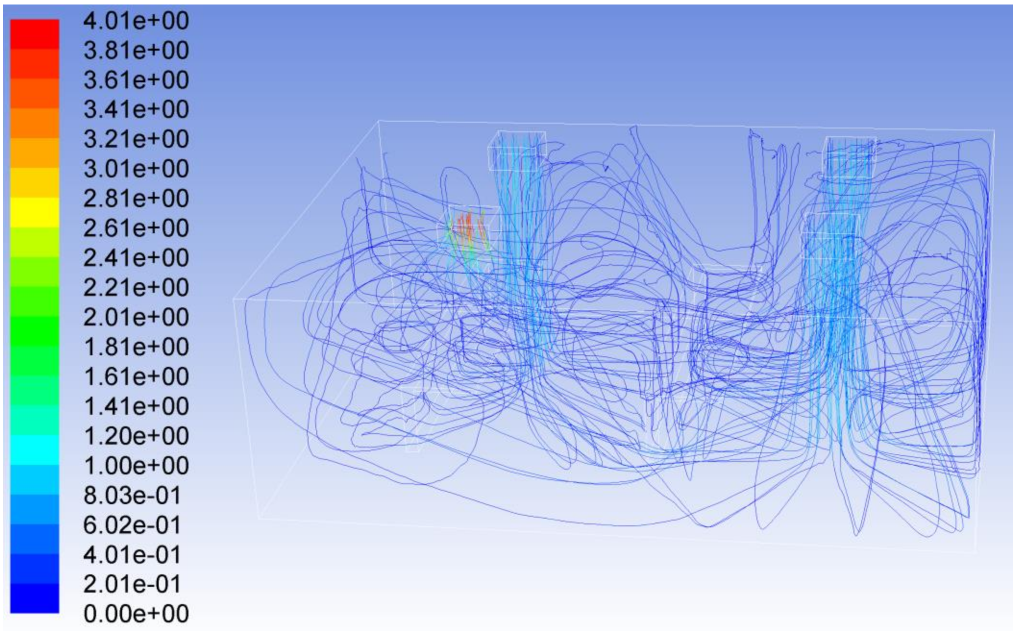




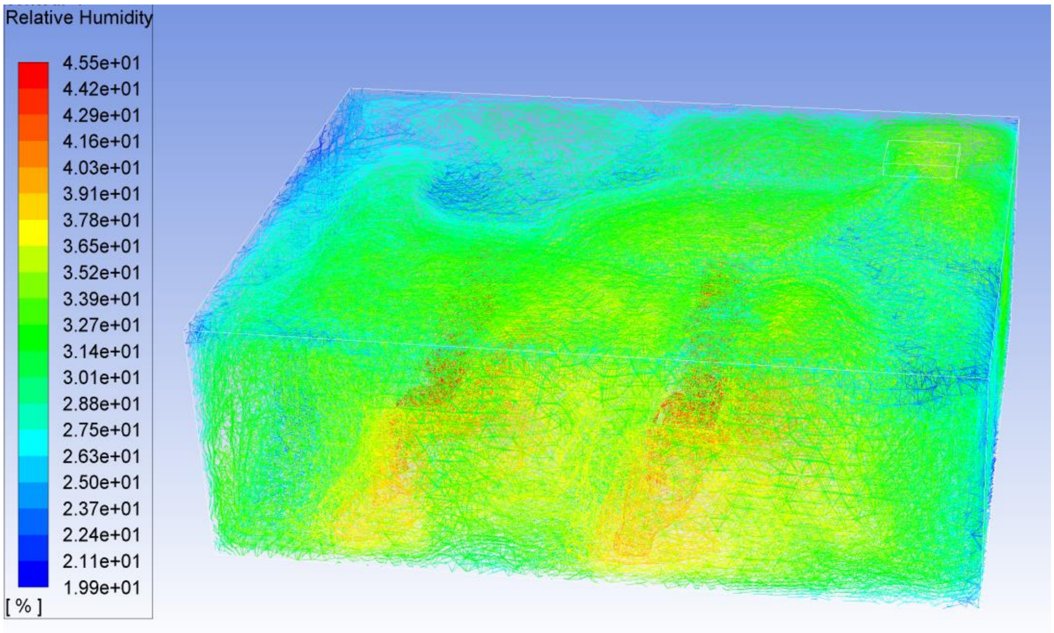
Model 8 – Ceiling based 0.003 mass fraction, 22 degrees – Humidity, Temp & Velocity Steams

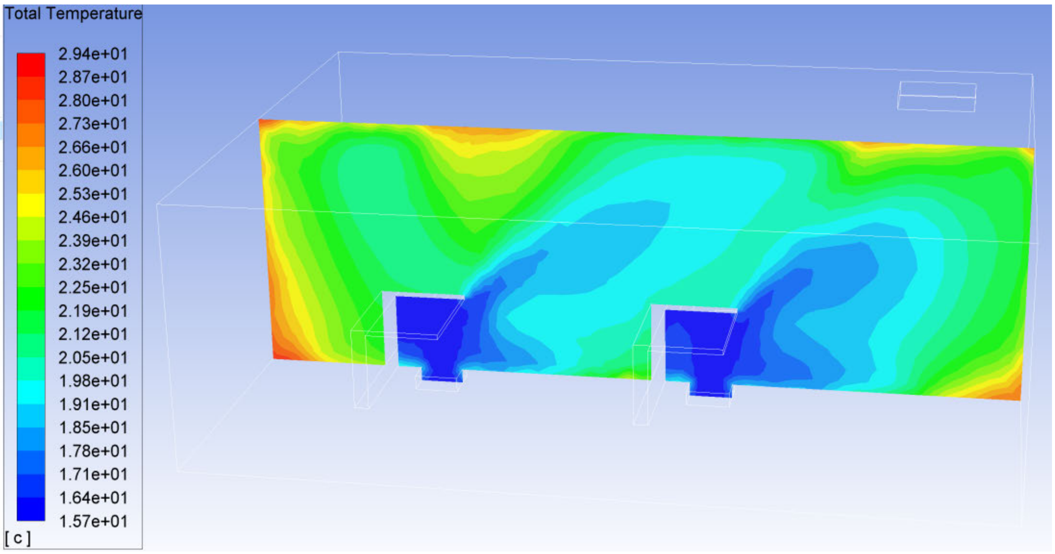




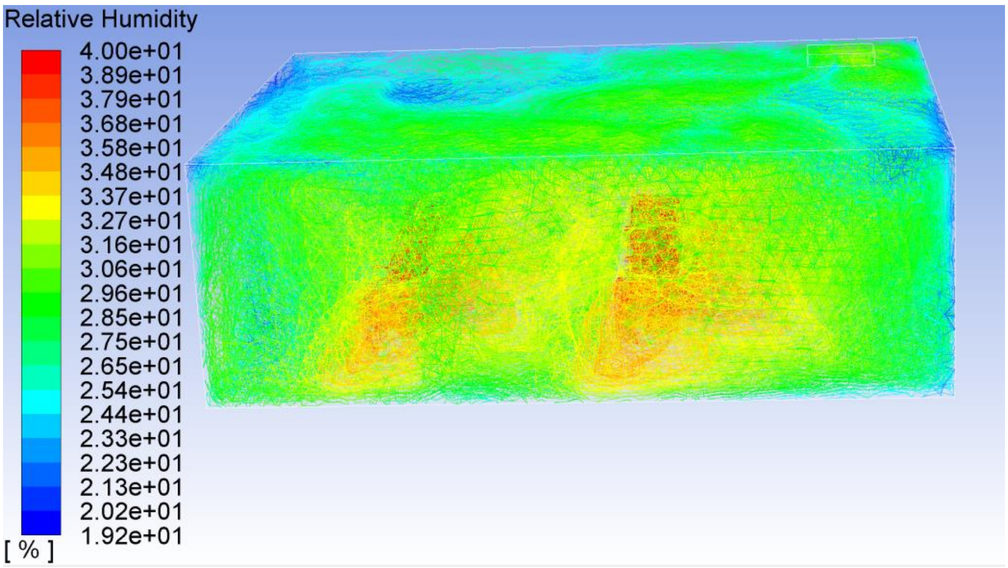


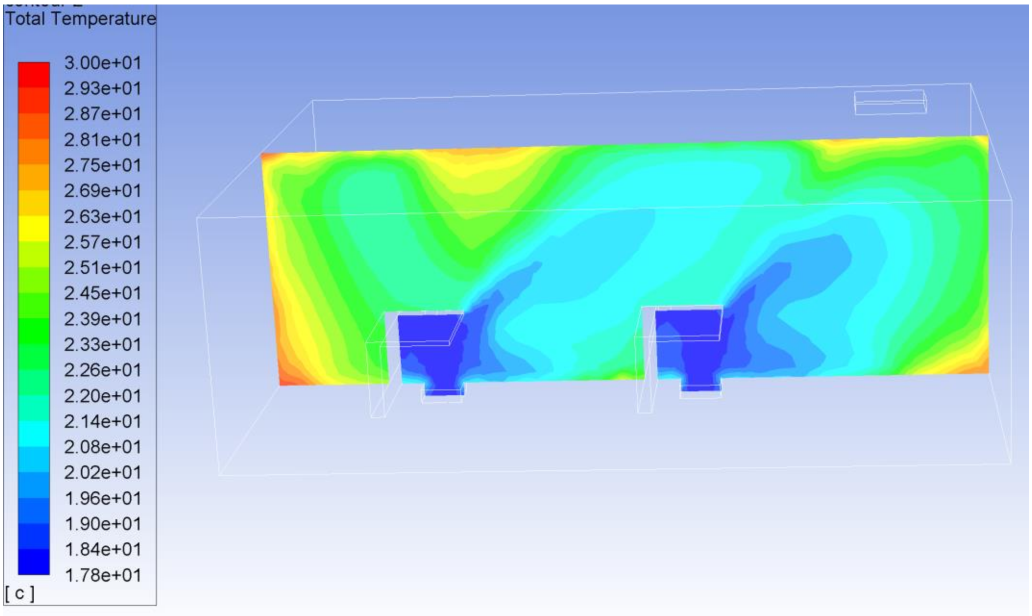
Model 9 – Floor based 0.005 mass fraction, 16 degrees – Humidity, Temp & Velocity Steams



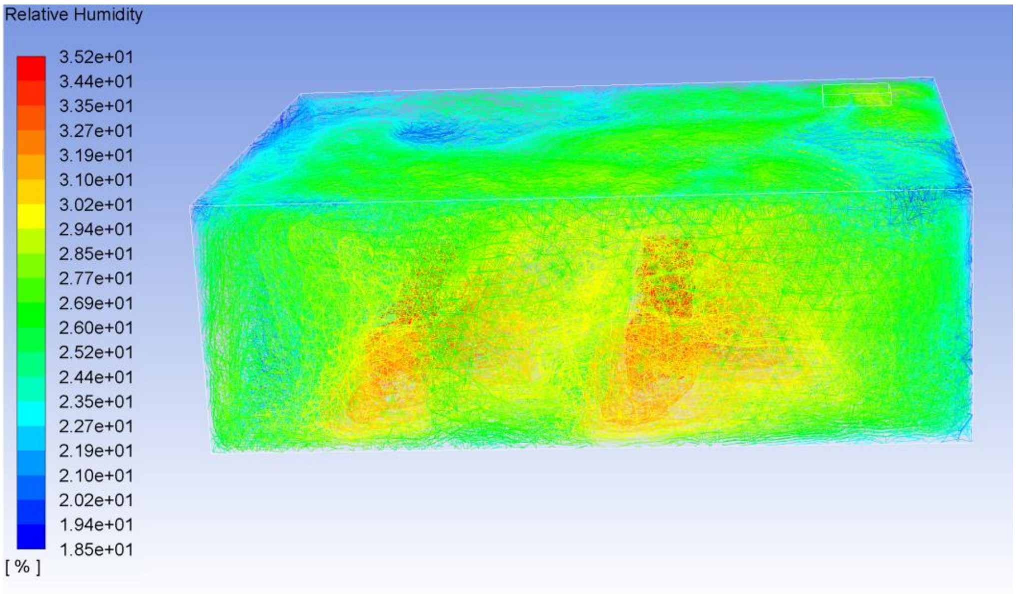


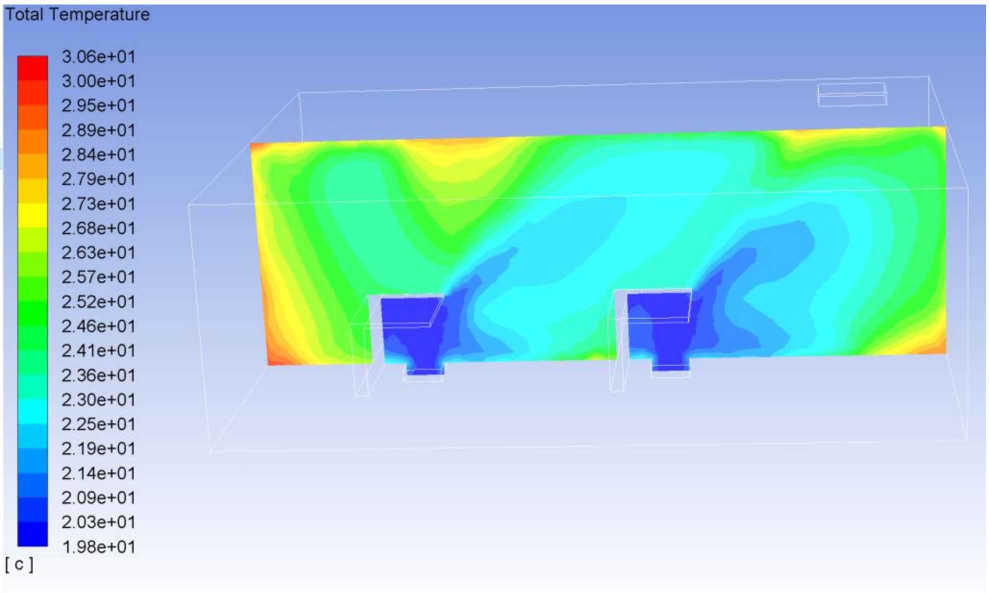
Model 10 – Floor based 0.005 mass fraction, 18 degrees – Humidity, Temp & Velocity Steams



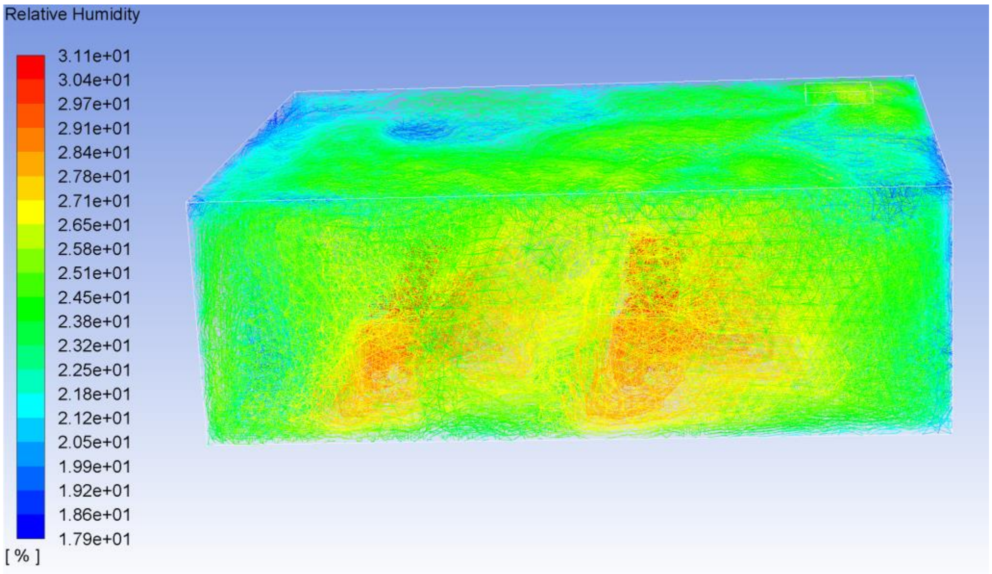


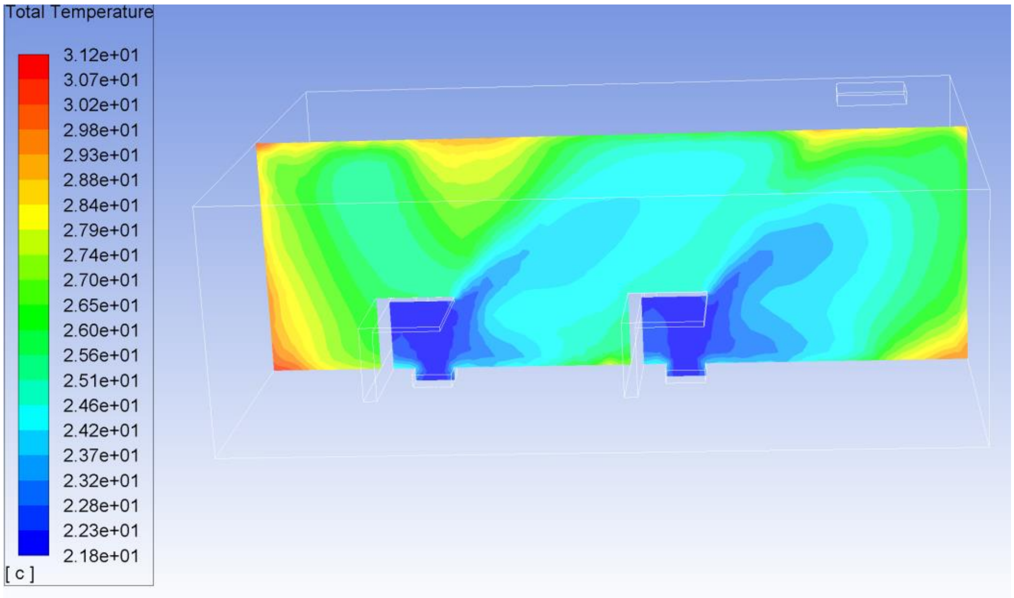
Model 11 – Floor based 0.005 mass fraction, 20 degrees – Humidity, Temp & Velocity Steams



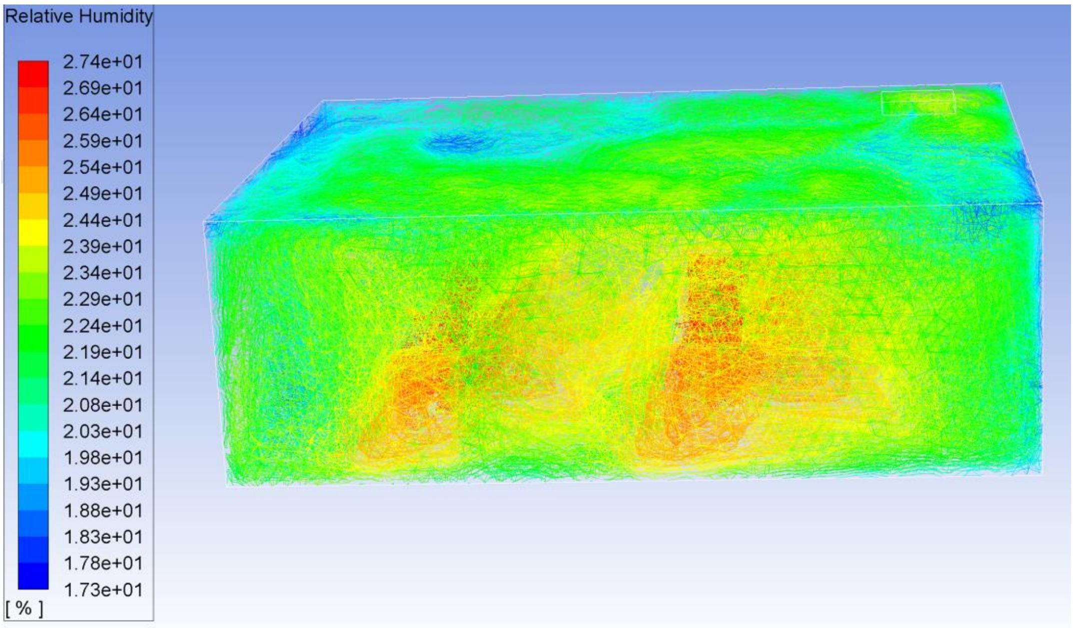


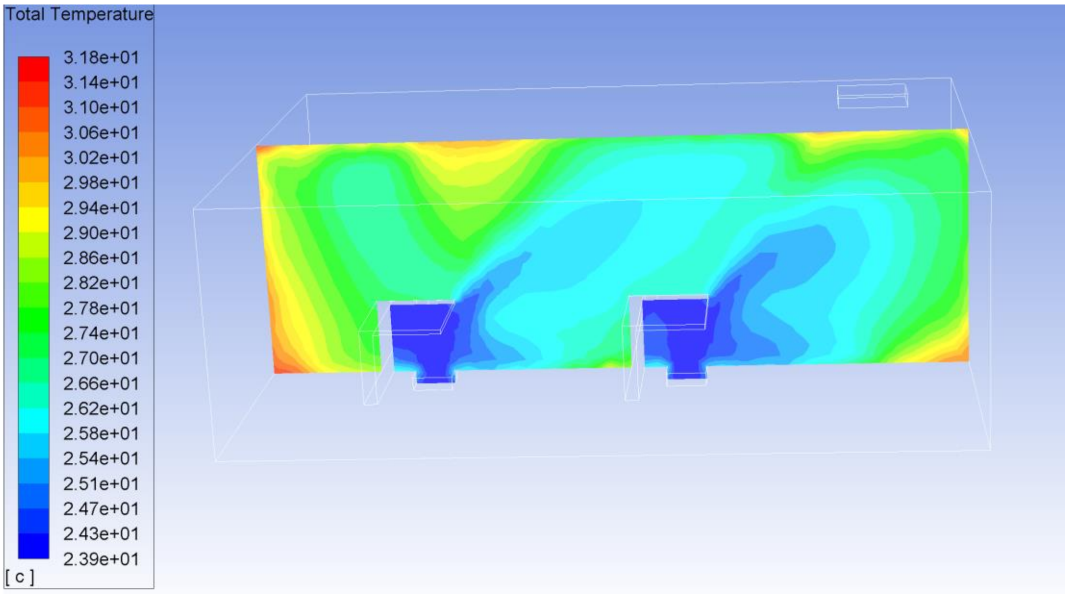
Model 12 – Floor based 0.005 mass fraction, 22 degrees – Humidity, Temp & Velocity Steams



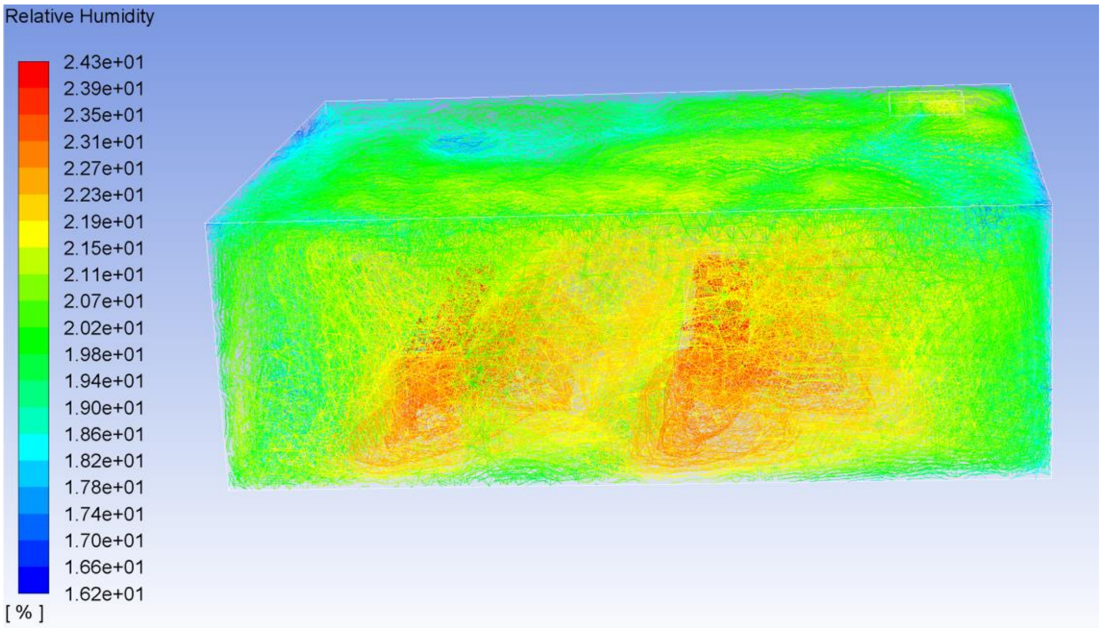


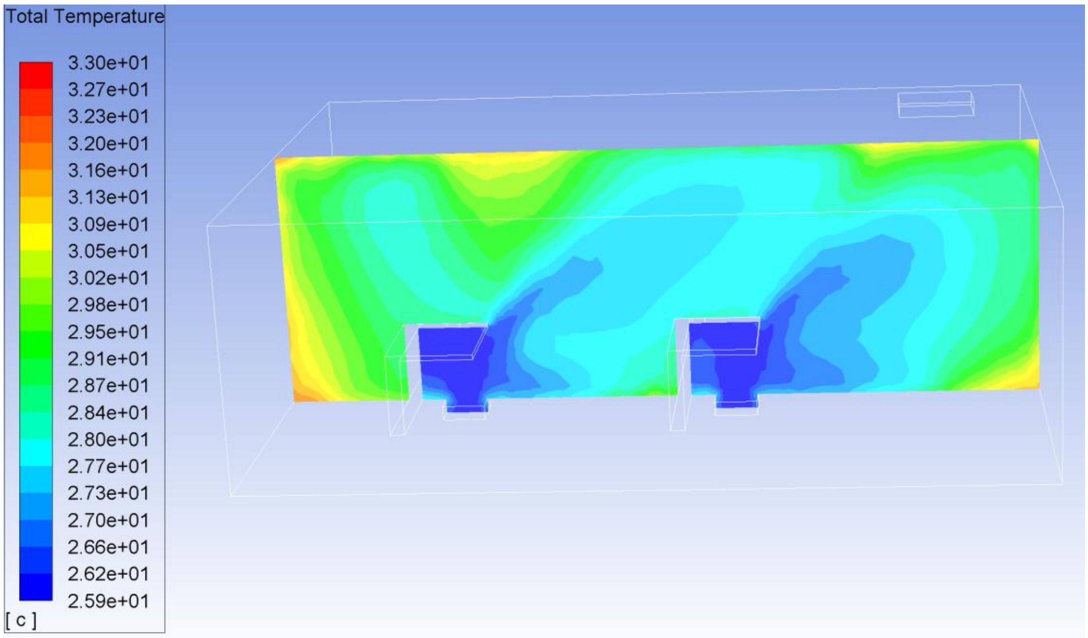
Model 13 – Floor based 0.005 mass fraction, 24 degrees – Humidity, Temp & Velocity Steams



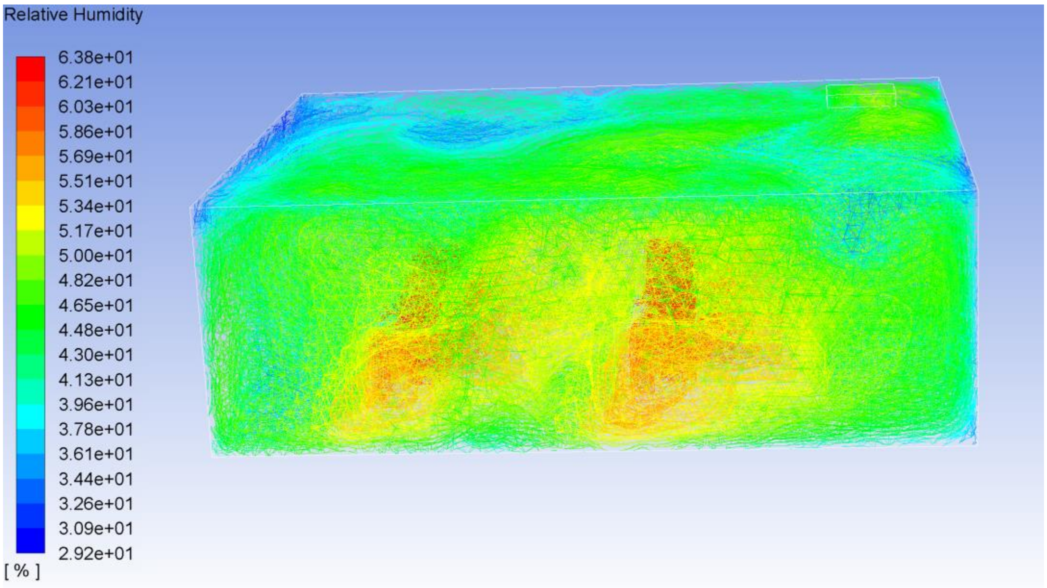


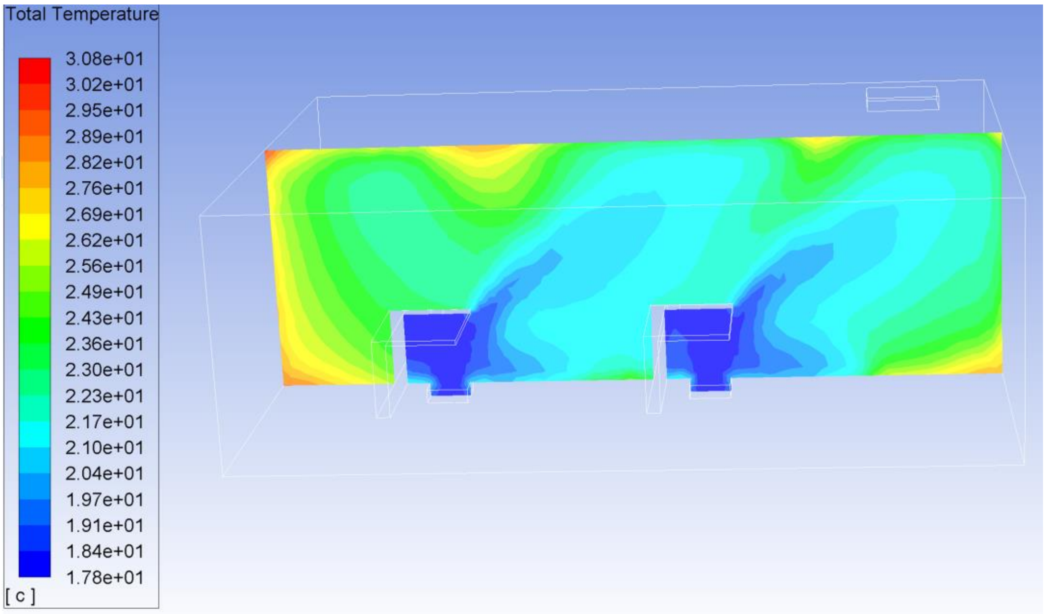
Model 14 – Floor based 0.005 mass fraction, 26 degrees – Humidity, Temp & Velocity Steams



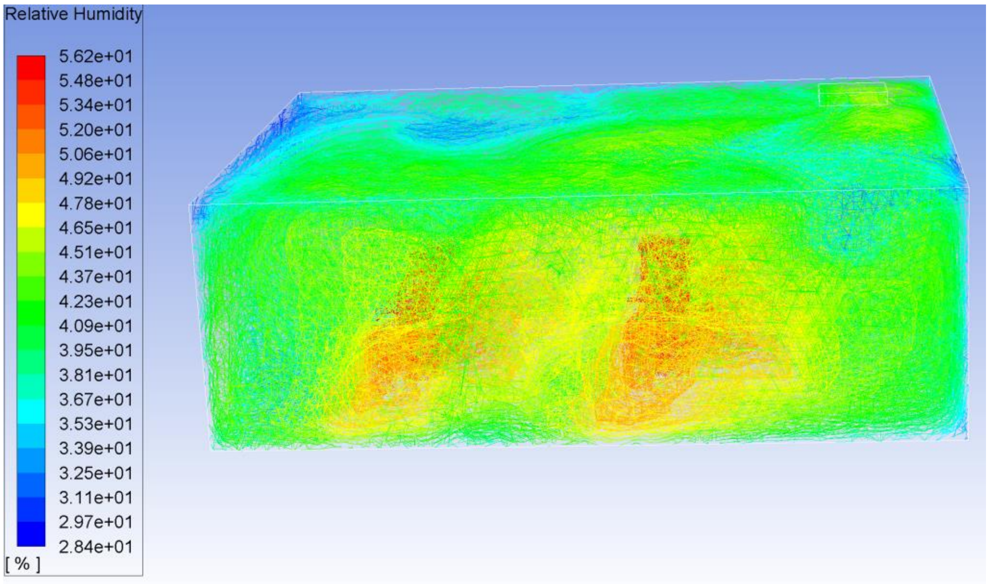


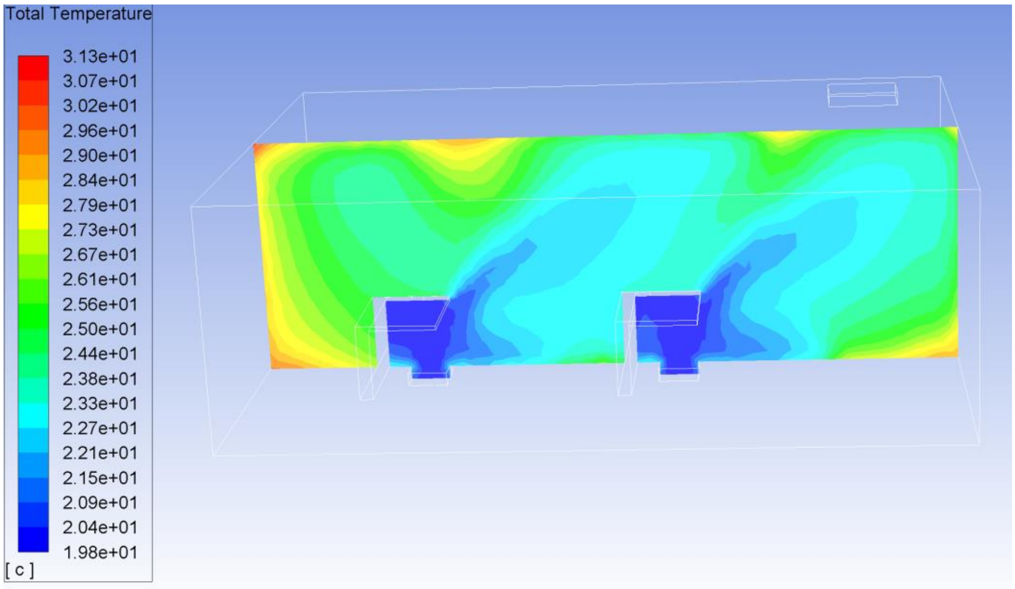
Model 15 – Floor based 0.008 mass fraction, 18 degrees – Humidity, Temp & Velocity Steams



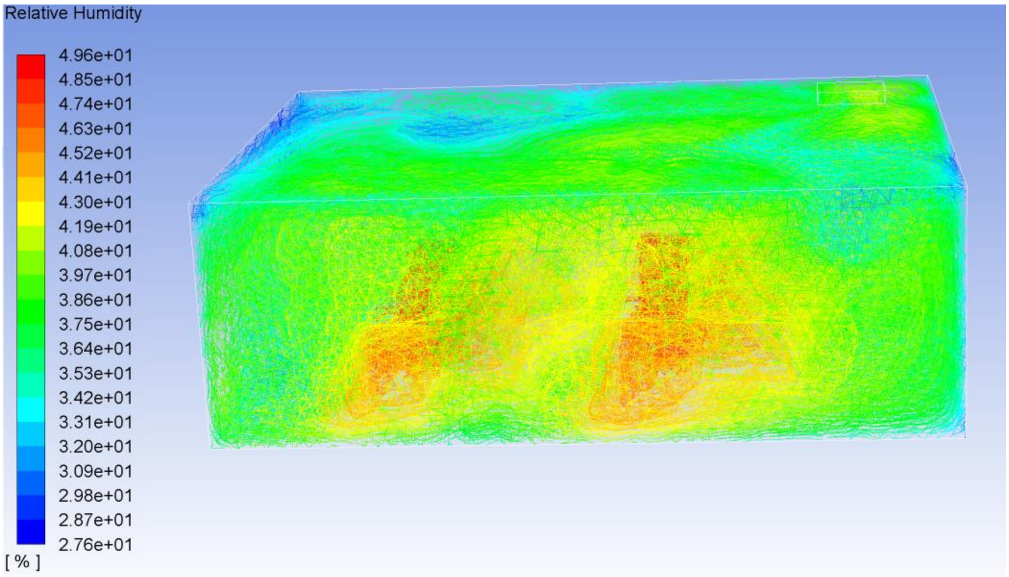


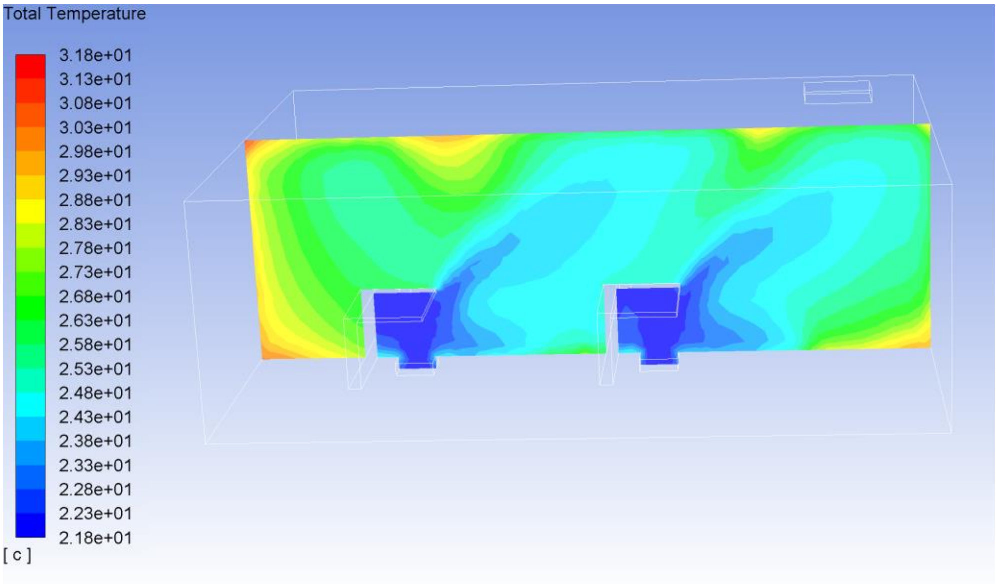
Model 16 – Floor based 0.008 mass fraction, 20 degrees – Humidity, Temp & Velocity Steams



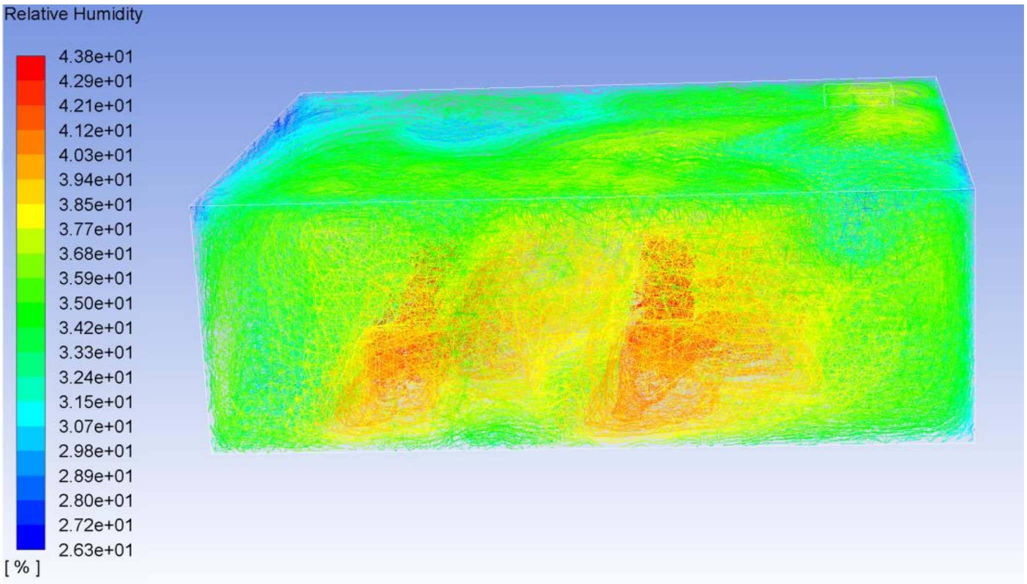


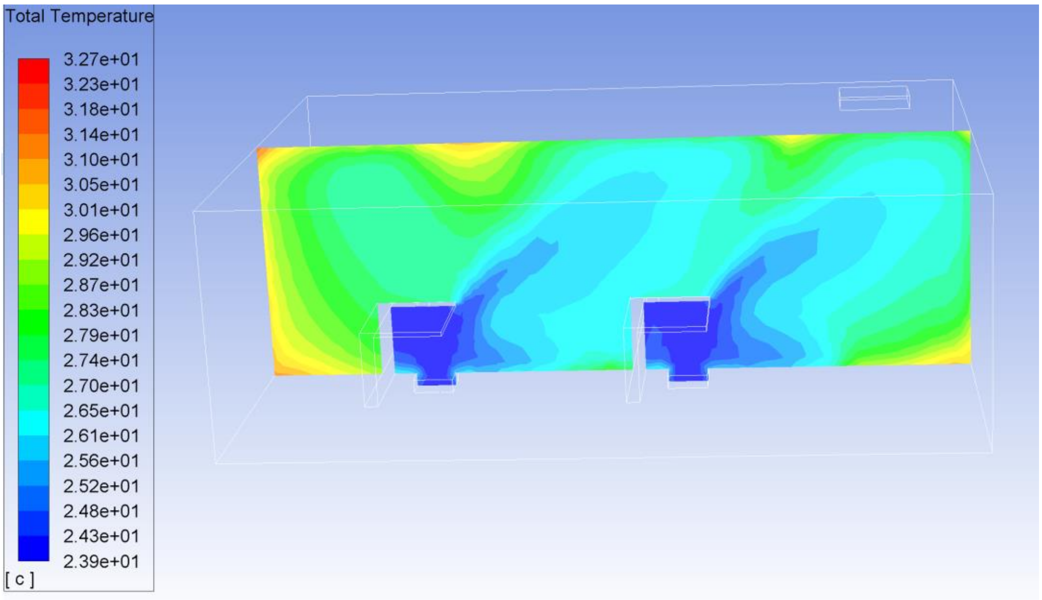
Model 17 – Floor based 0.008 mass fraction, 22 degrees – Humidity, Temp & Velocity Steams



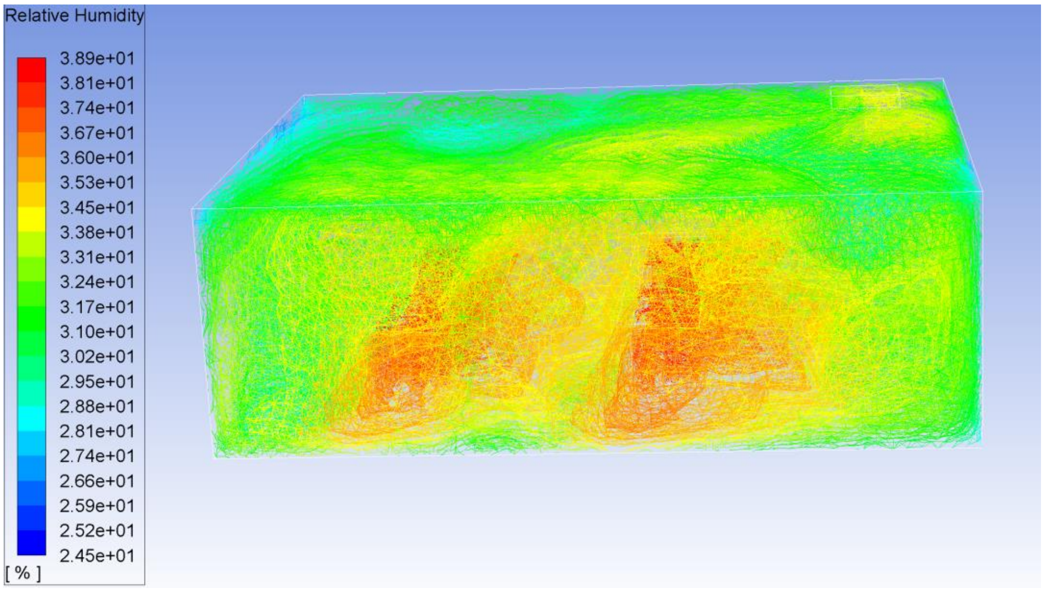


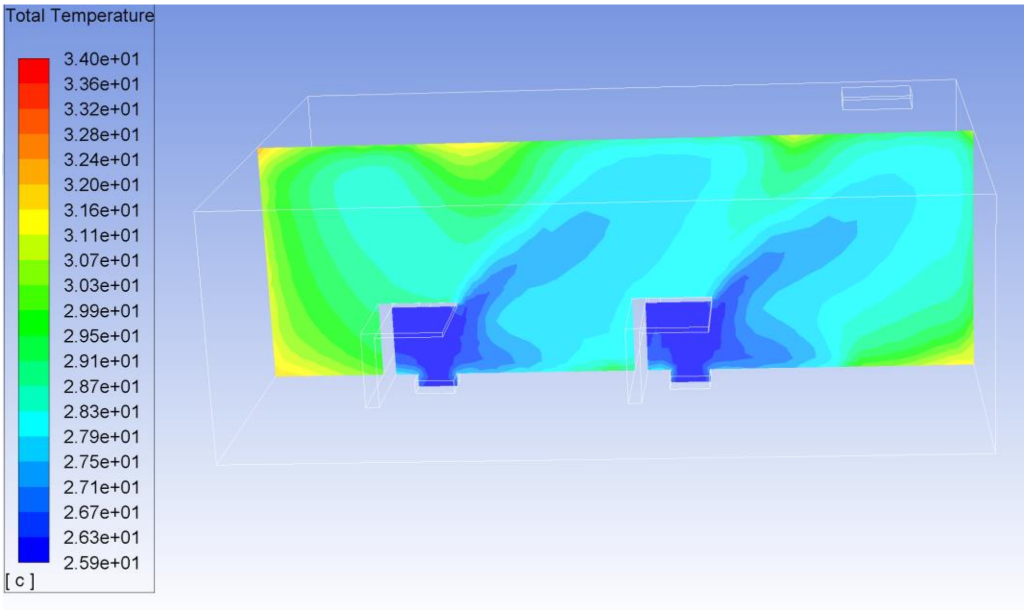
Model 18 – Floor based 0.008 mass fraction, 24 degrees – Humidity, Temp & Velocity Steams





Model 19 – Floor based 0.008 mass fraction, 26 degrees – Humidity, Temp & Velocity Steams

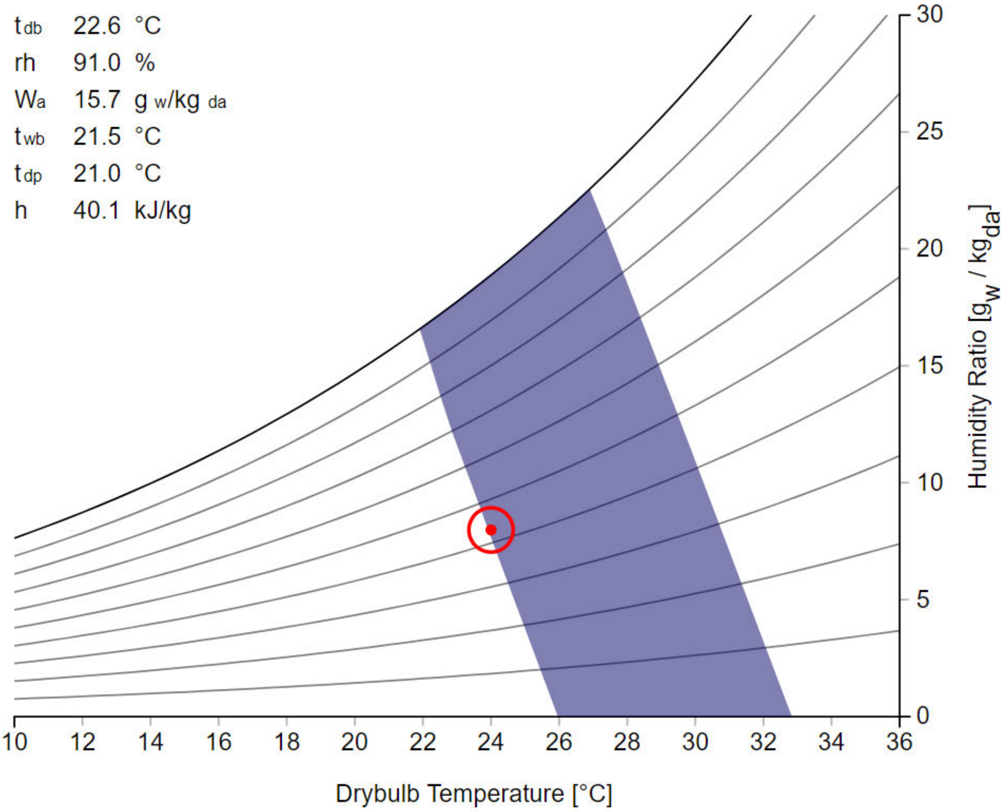



Total Temperature
3.40e+01
3.36e+01
3.32e+01
3.28e+01
3.24e+01
3.20e+01
3.16e+01
3.11e+01
3.07e+01
3.03e+01
2.99e+01
2.95e+01
2.91e+01
2.87e+01
2.83e+01
2.79e+01
2.75e+01
2.71e+01
2.67e+01
2.63e+01
2.59e+01
[c]

Chapter D – Human Comfort Calculations

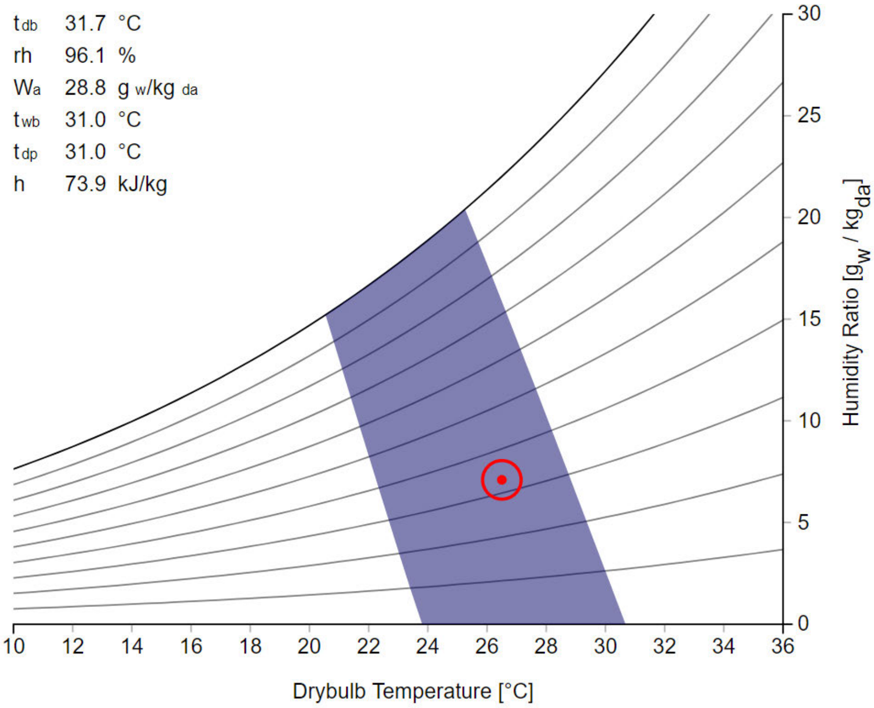
24 degrees, 0.2m/s air velocity, 43% Humidity

PMV = -0.49, PPD = 10%, Feeling = Neutral



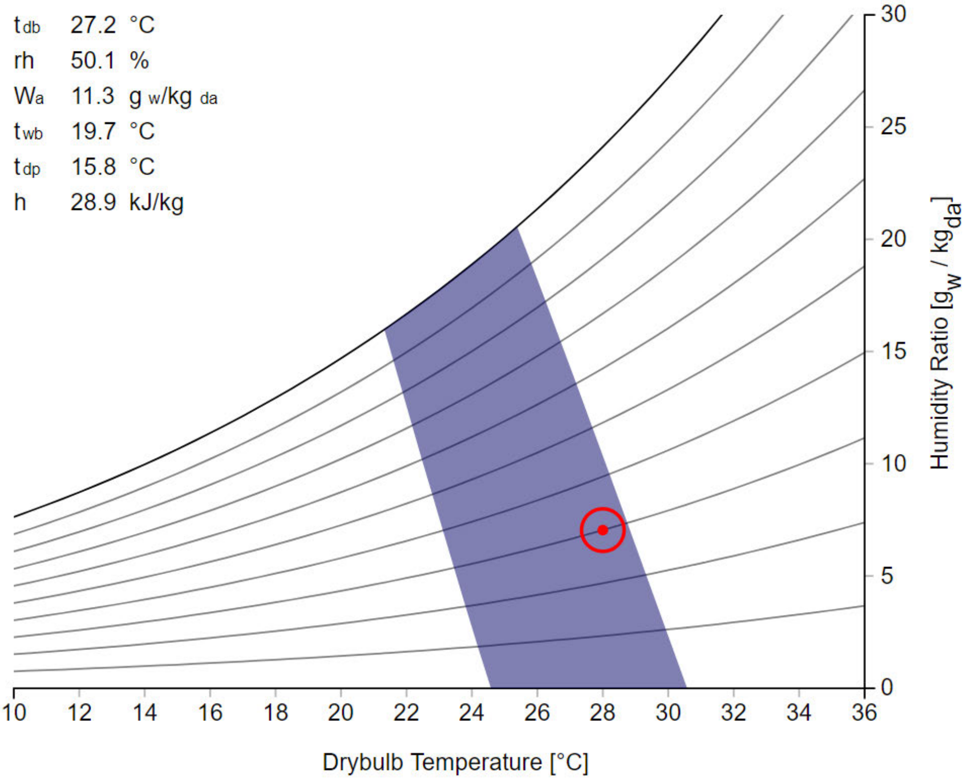
26.5 degrees, 0.2m/s air velocity, 33% Humidity

PMV = 0.16, PPD = 6.2%, Feeling = Neutral



28 degrees, 0.2m/s air velocity, 30% Humidity

PMV = 0.36, PPD = 8%, Feeling = Neutral



29 degrees, 0.2m/s air velocity, 30% Humidity

PMV = 0.68, PPD = 15%, Feeling = Slightly Warm