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Approved by Major Professor(s): Ali Razban and Jie Chen

Approved by: Sohel Anwar 02 / 25 / 2016

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# ENERGY OPTIMIZATION OF AIR HANDLING UNIT USING $CO_2$ DATA AND COIL PERFORMANCE

A Thesis

Submitted to the Faculty

of

Purdue University

by

Arash Edalatnoor

In Partial Fulfillment of the

Requirements for the Degree

of

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I would like to dedicate this thesis to my parents and my brother Amin for their always love and support.

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## ABBREVIATIONS

| | |
|---|---|
| V | Voltage |
| I | Current |
| R | Resistance |
| Q | Heat transfer rate |
| $\dot{x}$ | Mass flow rate of a fluid |
| $C_p$ | Specific heat |
| T | Temperature |
| $\rho$ | Density |
| C | Flow rate |
| $\beta$ | Fan % speed |
| $\alpha$ | Max coil capacity flow rate |
| $\dot{q}$ | Theoretical flow rate through the coil |
| h | Specific enthalpy |
| $\omega$ | Relative humidity |
| P | Final parameter |
| $T_x$ | Initial twelve bit number |

# ABSTRACT

Edalatnoor, Arash. M.S.M.E., Purdue University, May 2016. Energy Optimization of Air Handling Unit Using $CO_2$ Data and Coil Performance. Major Professors: Ali Razban and Jie Chen.

Air handling unit systems are the series of mechanical systems that regulate and circulate the air through the ducts inside the buildings. In a commercial setting, air handling units accounted for more than 50% of the total energy cost of the building in 2013. To make the system more energy efficient and reduce amount of $CO_2$ gases and energy waste, it is very important for building energy management systems to have an accurate model to help predict and optimize the energy usage and eliminate the energy waste. In this work, two models are described to focus on the energy usage for heating/cooling coils as well as fans for the air handling unit. Enthalpy based effectiveness and Dry Wet coil methods were identified and compared for the system performance. Two different types of control systems were modeled for this research and the results are shown based on occupancy reflected by the collected $CO_2$ data. Discrete On/Off and fuzzy logic controller techniques were simulated using Simulink Matlab software and compared based on energy reduction and system performance. Air handling unit located in the basement of one campus building is used for the test case of this study. The data for model inputs is collected wirelessly from the building using fully function device (FFD) and pan coordinator to send/receive the data wirelessly. The air handling unit modeling also is done using Engineering Equation Solver EES Software for the coils and AHU subsystems. Current building management system Metasys software was used to get additional data as model inputs. Moving Average technique was utilized to make the model results more readable and less noisy. Simulation results show that in humid regions

where there is more than 45% of relative humidity, the dry wet coil method is the effective way to provide more accurate details of the heat transfer and energy usage of the air handling unit comparing to the other method enthalpy based effectivness. Also fuzzy logic controller results show that 62% of the current return fan energy can be reduced weekly using this method without sacrificing the occupant comfort level comparing to the ON/OFF method. Air quality can be optimized inside the building using fuzzy logic controller. At the same time system performance can be increased by taking the appropriate steps to prevent the loss of static pressure in the ducts. The implementation of the method developed in this study will improve the energy efficiency of the AHU.

# 1. INTRODUCTION

## 1.1 Problem Statement

Nowadays, engineers are focusing on preserving the environment by performing advanced research and experiments in the field of energy efficiency. Researches have shown buildings consume around 41% of total energy and 73% of electricity portion of energy generated in the US. [1] (Figure 1.1 shows the overall energy usage by buildings in the US also the amount HVAC energy usage for buildings). On the other hand energy efficient and smart buildings seem to be the future of architectural designs. Many researches have been done to find and achieve a tradeoff level between overall energy consumptions and also occupant comfort level in buildings. [2] Lack of accuracy in number of occupants prediction and energy models have caused a large amount of energy waste in the buildings. Indoor air temperature, air quality, and indoor illumination are three main factors considered as comfortable level in the buildings. [2, 3]

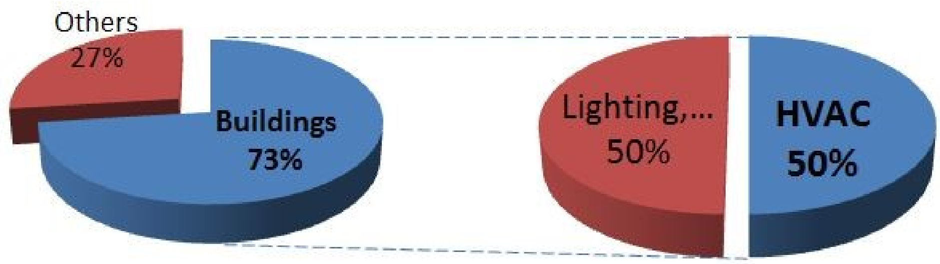



Fig. 1.1. Building energy usage in US [1]

Considering overall amount of energy usage by buildings and also the importance of comfortable air level in buildings for occupants, it is very important to come up with a best design and modelling in air handling units (AHU) for the buildings. In order to improve the performance of Air Handling Units, an accurate model should be built that can predict the energy usage of the building at the same time provide a good system performance for AHU. This thesis is intended to develop such models for improving energy efficiency of AHU through simulations.

## 1.2 Previous Work

### 1.2.1 Modeling Approaches

Many studies have been done on the modeling and performance of AHU in the past. The vast majority of buildings have been using on-board sensors and software to monitor the general building performance. For example, they collect small amount of data and conduct a basic analysis on system performance over a period of time. Most of these models have assumptions based on first and second law of thermodynamics. These models often can be a very useful and quick solution to efficiency but they are not necessarily optimal design for the building AHU system. The majority of the models is not comprehensive and only provides quick solutions for each part of the system, which in overall may not improve the system performance much. [4]

There have been also different approaches in order to get the model behaviors for different HVAC components. One of the methods for example is focused on mathematical modeling of components. This method uses a different order polynomial results and representations to get the best fit and minimum modeling error for each component. Modeling in these cases is mostly based on system inputs and outputs without focusing on meaning of the system. When the data is taken from the outside of the fitted data range, it can lead to an inaccurate results. [5] Another method uses a complete mechanistic model of the system, which makes it very hard to adopt the model to different systems and buildings. Also, this detailed information is not always easy to find within the system components. There have been other researches of semi-mechanistic modeling technique, which ended up with better results on small air conditioning systems. However, these models were not able to adopt easily to more complex systems, such as whole air handling units. [5] Also, many different control techniques have been used in different researches, such as Model Predictive Control, Evolutionary Algorithm, Evolutionary Programming, and PID controllers. These control where mostly used to regulate the temperature inside the house and keep the temperature below/above the user limits. [6, 7] However, most of these models do not completely cover all climate conditions and do not provide a general solution for bigger buildings. Therefore, the listed models can only be adopted to specific systems and are not robust enough to improve performance on different systems.

On making accurate models, other researchers used data driven approach, white box (knowing details) and also combination of non-physical and physical methods. In general, data driven approach uses the data which was collected in different conditions and then again as mentioned in [5] it uses statistical methods, such as linear regression and best data fit to find the rules and relationship for the air handling unit. These models are quick and simple approach, but not necessarily an accurate one. Because once the data falls out of the fitted line then results can be completely inaccurate. Also this approach is known as fault detection method that uses the input and output of the system. It calculates the error of the system and uses it to make the model more accurate and robust. [6]

Also, white box model has the details of mechanical system that is called Fully Mechanistic Modeling. This method of modeling makes it very hard to measure and find all the system parameters. Most of the time this parameters are not available and on the other hand it is very hard to adapt them with any new system or air-handling units. Also this method of the system modeling is an opposite what was explained in black box modeling, since black box modeling is only based on the details of mechanical system. Governing equations and systems behavior have been investigated using white box method and are described in different research materials. Figure 1.2 shows three general modeling approaches. [7]

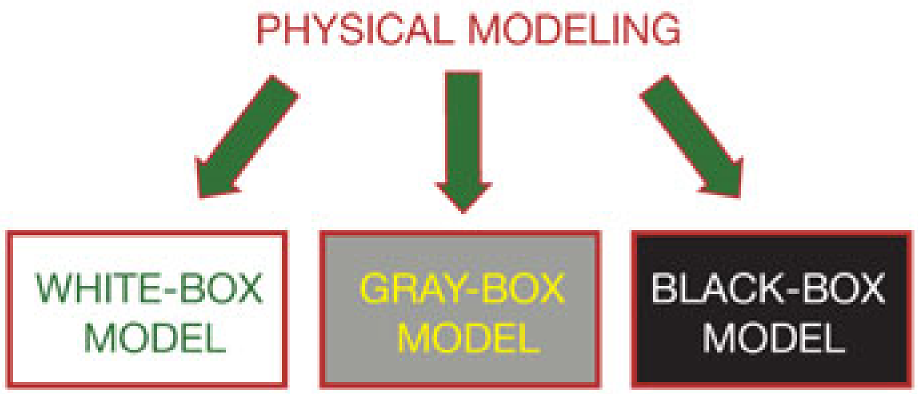



Fig. 1.2. Different modeling approaches [7]

Grey box is also called semi-mechanistic model. This method uses some details of the mechanical model and governing equations. Using these equations and inputs for the model this method calculates the output of the system. This method can conclude more robust results since it can adapt easier to different scenarios. The measurements can always be used as a feedback for the system and make the model more accurate or more compatible with different conditions. Many researches have been done using this method and validating the prediction of the model. Many HVAC systems have been using this method to predict their systems behavior. This method has advantages over white box and black box modeling mostly because of robustness and compatibility with different conditions. Also next section will focus more on previous work which have been done to make AHU more energy efficient. [8]

### 1.2.2 Modeling Approaches with Energy Efficiency Focus

In general, researches about energy performance in buildings started in the 1970s. With the rise of prices in oil and gas industries many nations started to look for new ways in using energy sources. Many energy protocols and regulations come in to place from government, which mainly focuses on energy efficiency and energy performance.

Many of these regulations have limitations of trustworthy benchmarking data since they do not provide detailed energy cost calculations. For example, ASHRAE in 2007 started to release standardized procedures for energy efficiency. These methods usually provide measuring and comparing solutions rather than detailed information since mentioned modeling only uses set of rules comparing to the controlling models/software models. [9]

There were other studies in energy efficiency areas that are more involved with changing the building or system settings. For example, resetting or changing the static pressure set points in the building, which can end up to 5% energy savings [10]. Also, other strategies are focusing on the peak and off-peak hours to rest the chilled water temperature in off peak hours to reduce the cost of chilled water (Gidwani 1984). Studies such as replacing valves and variable speed drives will reduce the cost of equipment retrofits, have been done to perform more energy efficiency actions. Most of these studies only show specific ways of savings that can be implemented in unique cases. [10]

Study from Elleson (1933) was focusing on the cost of different subsystems in air handling units. This research is mainly comparing different designs on terminal units. Parallel and series terminal units have some advantages over each other. Parallel terminal units use less energy since there would be less fan energy required to run through the ducts comparing to series terminal units. In fact, Elleson result shows that parallel terminal units can save from 24% to 47% on fan energy consumption (because of less fan energy usage as stated before). This study can only be used for the seasonal solutions and it is mostly energy saving for the cold air. [11]

In the other research from 1986 done by Leslie and Mazzucchi, who argues two major approaches for better energy performance analysis in buildings. These two methods are forward and inverse modeling. Forward modeling is about predicting the behavior of the system using simulation tools on hourly, monthly, or yearly basis. Inverse modeling is mostly collecting the data history of the building and try to match them together at every time of the year. Inverse models are quick and effective solutions, it also leads to better savings. Inverse model method was used in studies, such as Claridge et al. 1992, Haberl et al. 1998. In other words combined invers and forward modeling can be considered as grey box model as it was discussed earlier. [9]

Mentioned techniques and strategies may be able to improve the functionality of the whole air handling unit system. In many cases such techniques are specific to seasonal and partial solutions. Also some of these techniques are system specific and they are not robust enough to be easily adapted to other air handling units or in other buildings. More importantly, majority of the previously described works do not target the energy modeling based on the overall energy cost in buildings. This issue would be resolved in this study. This work would include modeling and analysis of AHU focusing on energy consumption in whole air handling unit. Based on energy consumption of most energy consuming subsystems, there would be more sufficient information to provide for users and show the consequences of their actions on total energy cost in the building.

### 1.2.3 Air Handling Units Simulation Tools

Nowadays, using computers and variety of available tools makes it easier for engineers to come up with more accurate designs and models for complex systems. Air handling units and HVAC systems have been under such attention that many companies started building automation tools. Commercial companies and also governmental agencies have presented different simulation tools on the market. One of the very common tools is DOE-2, which is free to use and many researches have used it in the past. This tool was developed by “JJH associates” and “Lawrence Berkeley National Laboratory” (LBNL). Also, this work was sponsored by US department of energy (DOE). Another tool is called eQUEST that comes from the same publishers and it is also free. eQuest has more friendly interface and is primarily used for buildings energy usage. The tool does not require a lot of training for an engineer but at the same time provides a high level output and results of modeling and energy usage in general [12]. eQuest has mostly the details of system design while DOE-2 focuses on cost functions and simple outputs/inputs from the system. Same kind of analysis also can be done with other software, such as Trane. However, Tranes most focus is on HVAC in details but not the whole air handling unit. This software also helps engineers to compare building standards with major energy efficient certificates. Trane can calculate ventilation, air quality, and many other standards of the existing building with major standard organization such as American Society of Heating Refrigeration and Air Conditioning (ASHRAE) or LEED certifications from US Green Building Council. Figure 1.3 shows an example of simulation tool for AHU and air flow inside the duct and AHU mixing box. [13–15]

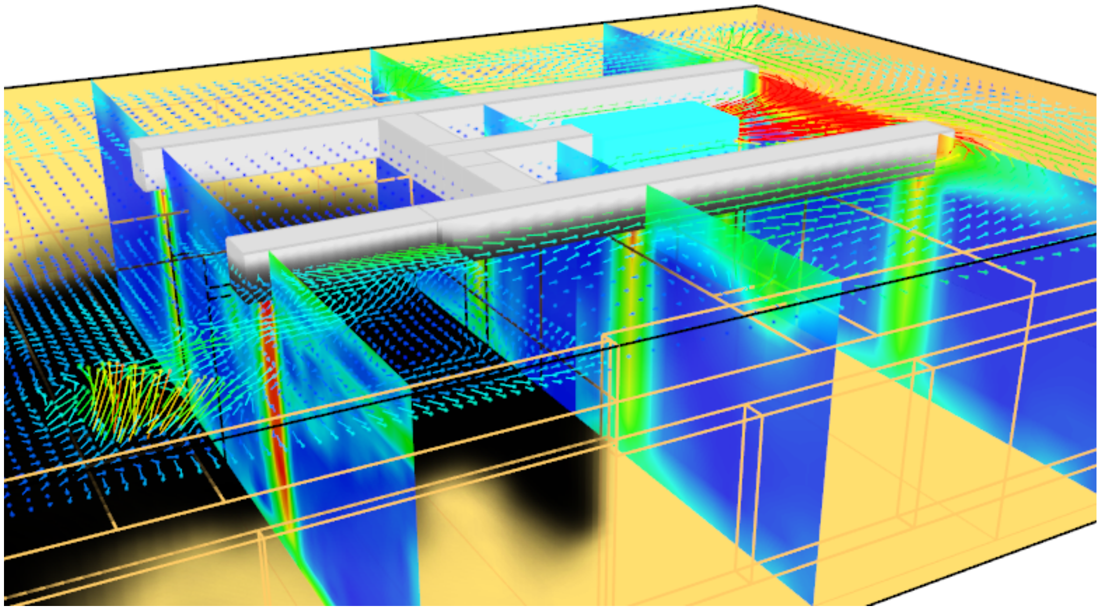


Fig. 1.3. Air handling unit, mixing box air flow simulation example. (Courtesy of Comsol CFD)

Energyplus software is also one of highly used simulations tools for buildings. This software can be used by engineers, architects, and researchers for all air handling units. These mentioned software are highly dependent on building inputs, but neither of them have deeply focused on thermodynamic functionalities. Figure 1.4 from national renewable energy laboratory shows a software chart for device simulations, such as air handling unit.

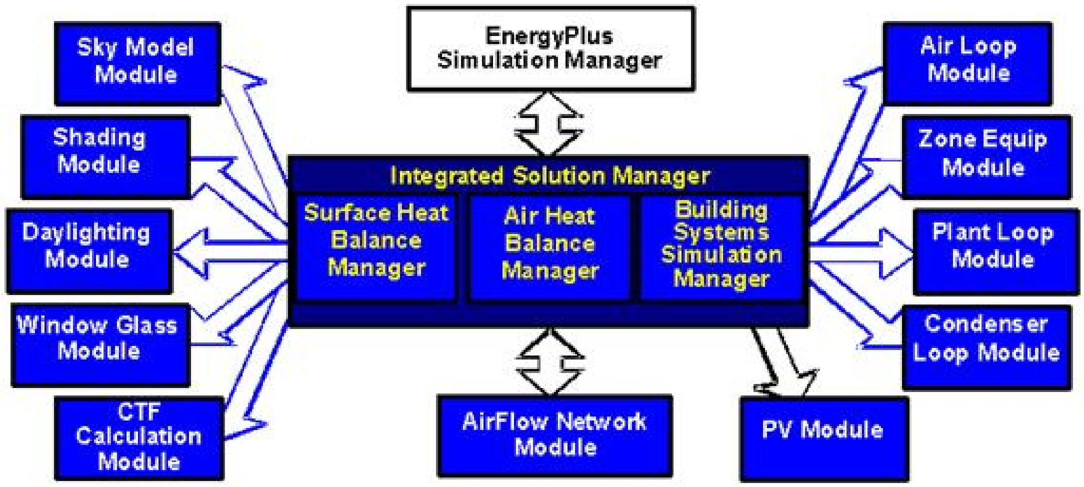



Fig. 1.4. Energy plus simulation chart (Chart from NREL EnergyPlus)

There are other coding and programming software like Matlab that can come very handy while using energy calculations for buildings. Engineering Equation Solver (EES) is another programming language which focuses on high level thermodynamic equations. One of the advances of this software that it has included all the thermodynamics libraries within the software, so it can automatically relate the characteristics of different parameters to their thermodynamics values. EES also generates plots and does check units. It has functionality of making Macro programming, therefore one can write all logic equations and use macro programming to run the whole code simultaneously calling for thermodynamic properties. [16]

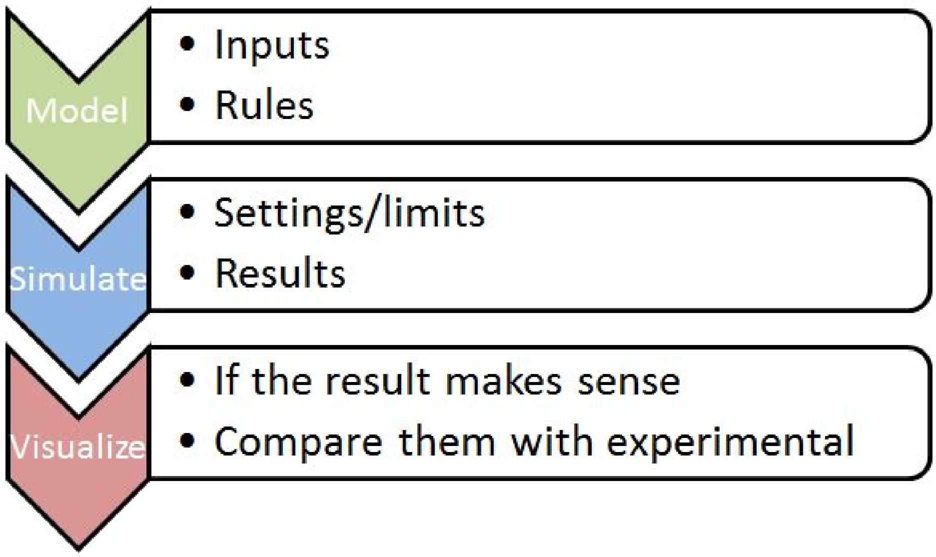



Fig. 1.5. Modeling and simulation flow chart

Figure 1.5 above shows the logic sequence of using simulation tools. The input of simulation tool like EEs can be a building air handling unit model. Using inputs and governing questions, this tool will provide us a visualization of the model. [17]

### 1.2.4 Control Strategies

There are different approaches in controlling the air handling unit systems. Different researches were performed on resetting sensor settings such as variable air volume boxes and discharge air temperatures. Dynamic modeling of air handling unit systems, which has been described in the following reference [18, 19] uses orientated modeling platform, named as Modelica-based. This model based only uses input and output of the system so it does not consider what is inside the modeling system. The optimization is done based on eliminating the error between input/output. Also, various type of controllers have been used the air handling units, such as proportional-integral-derivative (PID) loop feedback mechanism. PID controller has been used mostly in black box models which uses only input and output of the system. Using constant gains in PID controller the model can predict the error of the system and finally updates system parameters such as supply temperature, fan speed and etc. Disadvantage of PID controllers is that the design parameters are constant and they cannot be adapted by every systems. It is good to use this type of control for subsystems of Air Handling Units but not as overall system modeling. Working with multiple input-outputs and more complicated systems make the PID controller very difficult to program. [20, 21]

Most of air handling units work is based on different number of sequences. These sequences and controls can be adjusted by threshold for certain values. There are many sensors that send data to these controls. These sensors get tripped based on pre-defined threshold. Decoupling methods have been described in the following Ref [22]. Generally there are two types of static and dynamic decoupling controls. For example, static decouplers have constants and steady state process but since these values are fixed the control performance will not be satisfactory. In opposite way dynamic decouplers need more details in modeling but at the same time the output for these systems are more accurate and trustworthy. [23–25]

### 1.3 Objectives

The goal of this thesis is to make the air handling unit more efficient without scarificing the comfort level. If there is unnecessary energy waste in the system they would be addressed and removed while keeping the same or more advanced system performance. Achieving this goal and finding the unnecessary waste in the system would be accomplished by system software modeling and validation.

Making the correct modeling is performed by thermodynamic law, mathematical and logical equations. Meanwhile, there are statistical techniques applied to get rid of outliers and make the model more representable. Later in this study, different models will be implemented on air handling unit. Data will be collected through the sensors in the building in order to interpret the model.

Simulation tools such as Matlab, Simulink, and Engineering Equation Solver have been used to make the model more accurate and validate it with existing experimental data. Coil performance has been analyzed and statistical analysis has been used to make the thermodynamic and mathematical models more compatible. Based on the experimental data, different models would be validated and different energy reductions and control strategies would be recommended. Two different coil performance modeling have been introduced and validated. Methods of energy reduction have been introduced using $CO_2$ data measurement and automation of demand ventilation for air handling unit. Fuzzy logic controller has been made to show the energy reduction of mechanical system and system performance improvement.

In the end, validated models have been compared in terms of total energy consumption, occupant comfort level, and system performance. Performance data will be followed by conclusions and discussions in the final section of this study.

## 1.4 Thesis Information Order

In the next chapter there will be information of modeling types which have been used in this work, the rationale for why these methods were chosen, also general information of air handling units, components and controls. There would be two different models explained along with the demand control validation method for energy savings on the air handling unit. Chapter 3 has included information on data collection, the type of sensors have been used, and where they were installed. The information on the test facility used was presented, which included associated specifications, location and etc. The important areas are the current configuration of air handling unit and automation system. The information regarding wireless receiver for sensors data and Modbus network in general will be explained afterwards.

Chapter 4 will include details of thermodynamic and mathematical modeling of air handling unit. Each individual part of air handling unit box will be explained in terms of thermodynamic equations. In this research specific type of controller has been used that will be explained in Chapter 5 and software associated with this modeling. Chapter 6 will present information about the results and validations of thermodynamic model for each individual method and part of air handling unit. There were different statistical methods, which have been used in this research, they are explained in Chapter 7. Results and comparison from the control is included in Chapter 8 and final conclusions and recommendation will be covered in Chapter 9.

# 2. MODELING AND METHODS

## 2.1 Goal and Targets

The ultimate goal of this thesis is to make the air handling unit more energy efficient and increase the system performance in terms of total energy consumption without sacrificing the occupant comfort level. This work has been done by using one of school campus buildings and implementing different sensors. These sensors are connected to a wireless network through the school network to ease the process of recording the data and using sensors as the inputs to the system/model. The wireless system also allows controlling the buildings energy usage from offsite locations using the sensor data information passed to the software model. Sensors location has been researched to get the ultimate data recording. Also the wireless devices have been researched so that it proves its good connectivity and accuracy during data transmission. Software coding has been done for data collection and software connections to the main server. $CO_2$ sensors also were placed to get the amount of air quality and required ventilation for the building.

There were different software used in this research for data collection and modeling purposes. Filezilla has been used to collect the data from sensors to the server. Metasys software from Johnson Control was used to visualize and temporary store the data.Matlab software has been used to make the mathematical and logical sequences for the data. Matlab Simulink was used to make the $CO_2$ simulations and power output controllers. Also Engineering Equation Solver (EES) has been used to make the thermodynamic model of air handling units. EES software was chosen mostly because of available built in thermodynamic charts and functions libraries within the software. The professional version 9 of EES was acquired for the research work within the school. There are multiple advantages for using EES system. This software automatically re-orders the equations to get the fastest solution. There are over 1200 substances and built-in functions for different materials and thermodynamic properties. Another advantage of ESS software is Macro commands, which allows the user to write scripts. These scripts allow loops and other different functions, logics. Different software can be called through macro commands for example Excel file in order to modify and store the test results. [26]

Using software and making models for the system, results were compared to experimental data. Also different thermodynamic models were compared and discussed through this work. Data validation has been done by working on real time data from the system and Metasys software. Most important part of this work was working on data validation and tuning in the data to make the most accurate model. Errors between models have been discussed to get the accurate data validation.

Statistical analysis have been made to make the data more readable and useful for comparison, such as moving average method to low pass filter the data for avoiding sensors spikes and deviations between different models have been analyzed. In the end, $CO_2$ data was analyzed and a controller has been introduced to reduce the unnecessary energy consumption of the air handling unit. Figure 2.1 in explains the overall sequence of modeling and methods to perform energy savings strategies.

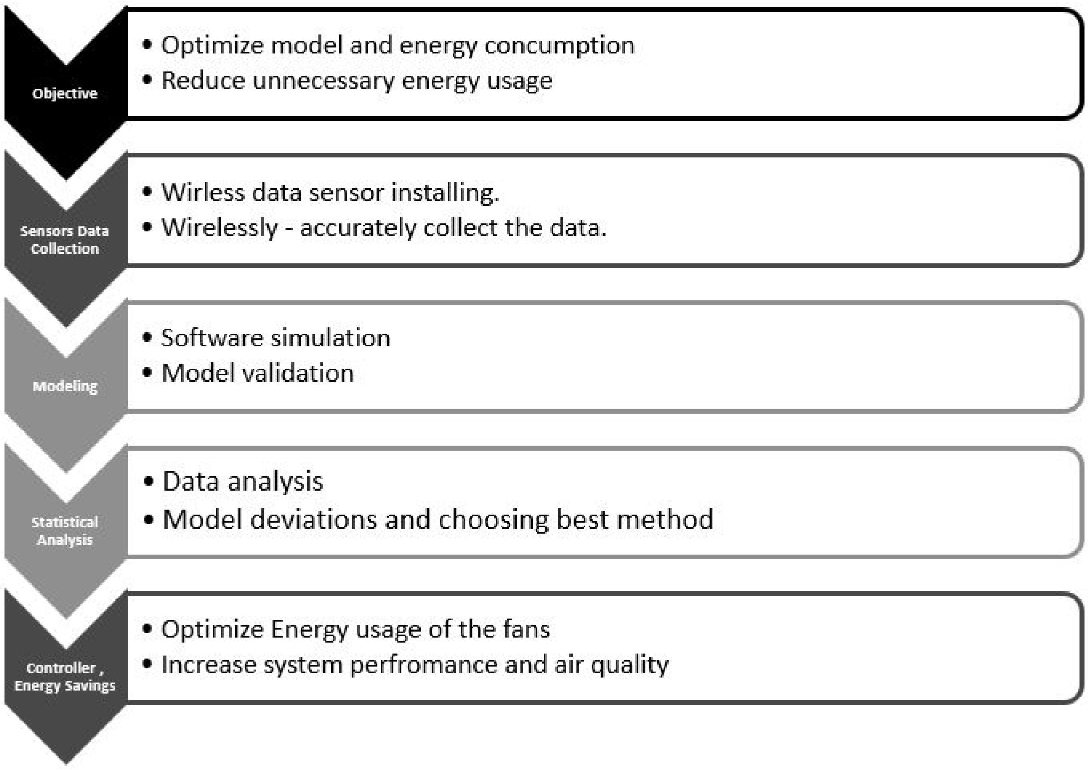



Fig. 2.1. Methodology flowchart

## 2.2 What is Air Handling Unit?

Air handling unit systems are the series of mechanical systems in order to regulate and circulate the air through the ducts inside the buildings. Air handling units include equipment such as fans, filters, dampers, different sensors, and coil that are inside the heating ventilation and air conditioning system (HVAC). Air handling units always have a main unit, which can be placed on roof of the building or inside the mechanical rooms for bigger buildings. Figure 2.2 shows a typical air handling unit system in medium size building, where yellow parts represent different components of air handling unit for this particular building.

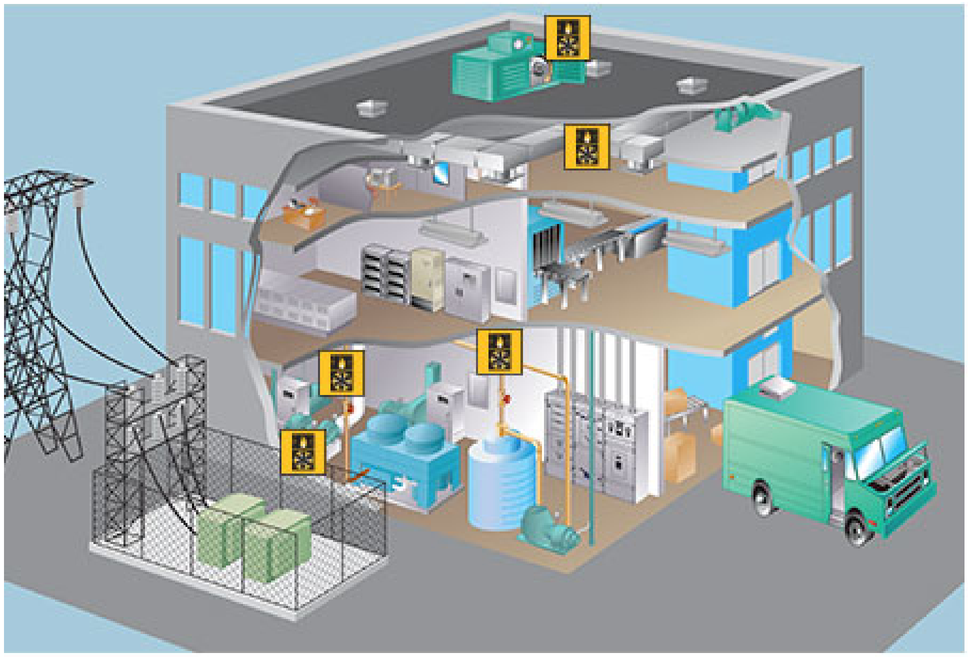


Fig. 2.2. Typical air handling unit system [27]

In a typical air handling unit system there is a boiler for providing steam for heating purposes and also chilling water system for providing chilled water for cooling. In this research the facility is purchasing these two materials from the city. So in the test building the general system does not have boiler and chiller but these materials are being sent to the building from the city. Also the purpose of this thesis is more to focus on coil units and making an accurate model for it. Figure 2.3 shows a particular coil unit.

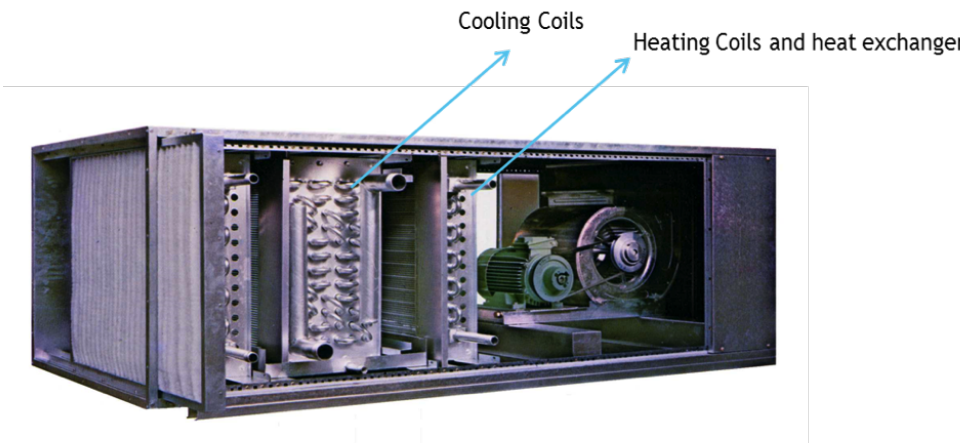



Fig. 2.3. AHU coil units

As its shown in Figure 2.3 cooling coil would pass chilled water and heating coil would pass steam so the air that is flowing can get certain amount of heat or removing heat. There are heat exchangers in which move air accordingly through the coils. From the very left in the Figure 2.3 the air flows in will get passed through the filter and enters in humidifiers. After that air hits the cooling and heating coils. On the right side there is a supply fan inside the unit which provides enough differential pressure in order to force the air through the unit.

Fresh outside air comes in to the system Figure 2.4 would enter the mixing box and pass through the coil units. Return air and Exhaust air are also shown in the figure. Dampers allow certain amount of return and outside air to get in though the system. Also there is a building automation system available to control all the commands and also monitor the data from the sensors inside the unit. In the following sections of this thesis there will be more information about the EMS or how energy management system works. Current energy management system from this air handling unit is Johnson control Metasys system.

### 2.2.1 Air Handling Unit Components

Current air handling unit includes parts shown in Figure 2.4. The simple picture of this air handling unit includes return fan, supply fan, dampers, heating, and cooling coil At the end, supply air would be sent to variable air volume boxes where there are 36 VAV boxes existing in current test facility. Current VAV boxes as shown in Figure 2.5 which is a single duct variable air volume component.

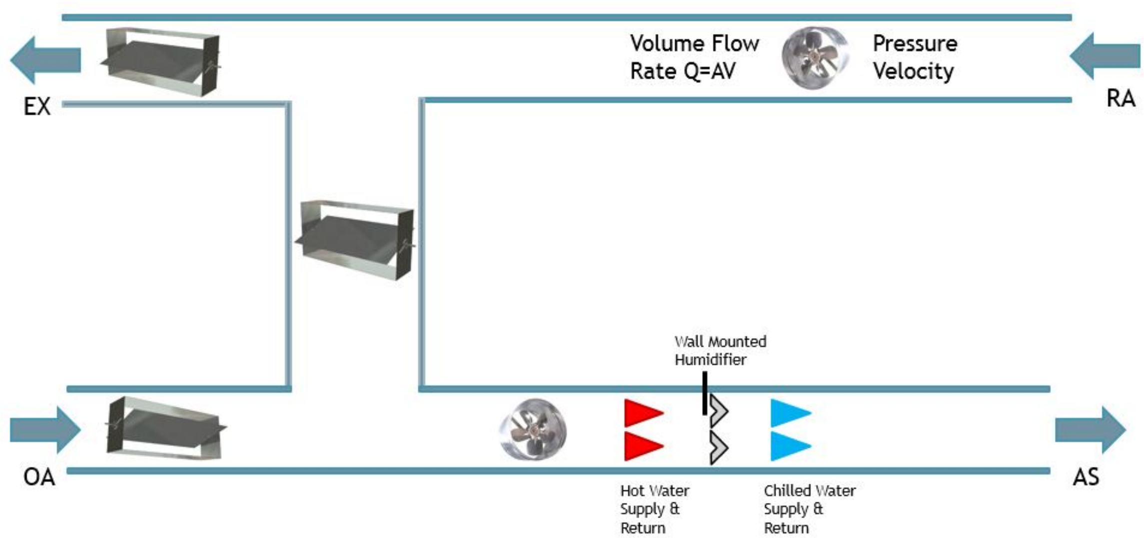



Fig. 2.4. AHU schematic diagram

Variable air volume boxes are part of air handling units that supply air flow with slightly variable air temperature to each zone. One of the advantages of using variable air volume boxes is that the control for each zone will be more precise, since each vav box has the ability to change the air temperature. There are different VAV box types available. Figure 2.5 shows a typical VAV box, which is also currently being used in this test building. This VAV box is referred as single duct VAV box.

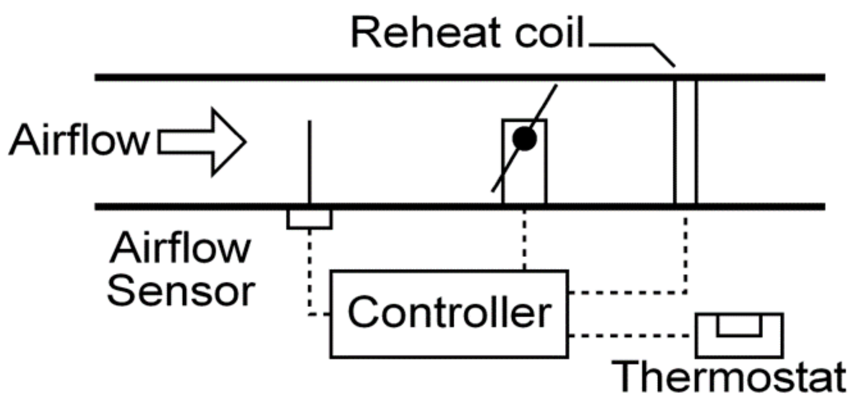



Fig. 2.5. Single duct VAV box (Courtesy of Johnson Control, Inc)

Figure 2.6 is showing other type of variable air volume box. The advantage of this VAV box is that the box has an extra fan that can provide more air to build enough fresh air for each zone.

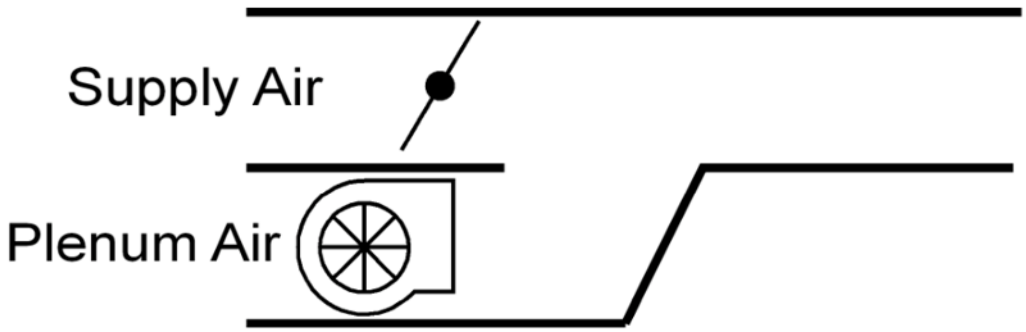



Fig. 2.6. Dual duct VAV box (Courtesy of Johnson Control, Inc)

### 2.2.2 AHU Energy Usage

This research mainly focuses on major energy usage components of air handling units. These parts, such as fans, use a lot of electricity power to keep the static pressure positive inside the ducts. Also heating and cooling coils are major energy consumers of AHU. This thesis provides detailed information on these parts and provides solutions on how to reduce energy usage and to peak best model for different conditions.

## 2.3 Modeling and Parameter Selection

Parameter selections in this work were mostly based on energy usage. Most of the energy in air handling units is being used by boiler and chillers. In our case the building is purchasing steam and chiller water from the city. Parameters also were selected based on how important is their role on energy consumption and occupant comfort level. One of the important subsystems that consumes a lot of energy and affects the $CO_2$ level, ventilation, and occupant comfort is the fan. Figure 2.7 shows a typical centrifugal fan which has been used in the air handling unit.

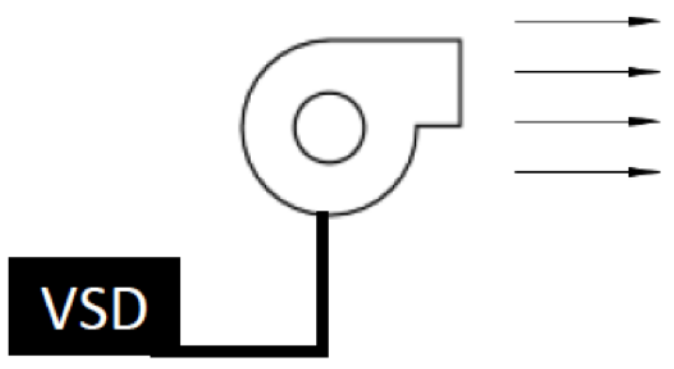



Fig. 2.7. Typical centrifugal fan

The inputs to this subsystem are air and electricity. Electricity is used as the energy to increase the static pressure and air flow inside the duct. Also VSD or variable speed drives are implemented in some of the fans in order to control the speed of the fan and air flow inside the duct. In the current air handling unit setup the supply fan has an active VSD.

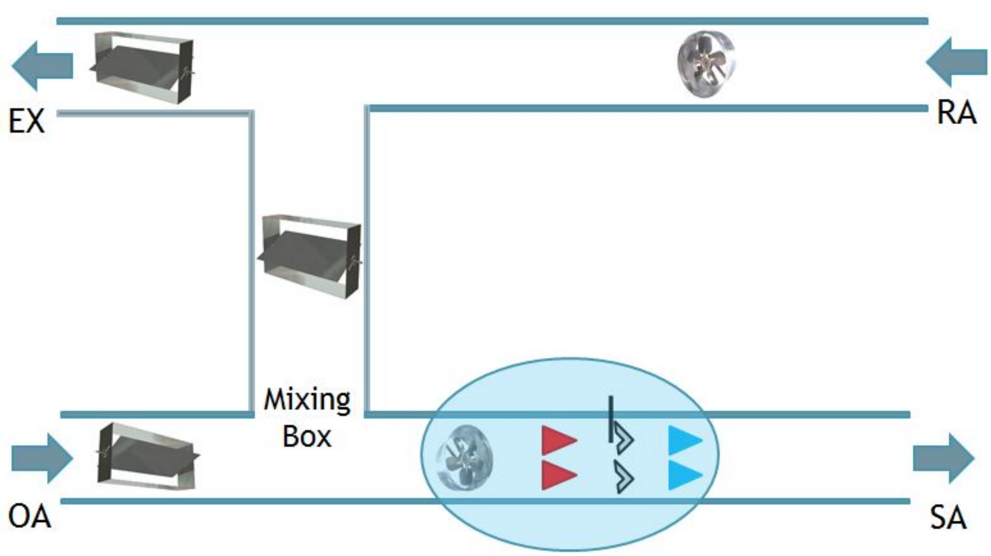



Fig. 2.8. Modeling focus in AHU

As it is shown on Figure 2.8 modeling in this thesis have been focused on the AHU unit, preheat, cooling coils, and the fan. Figure 2.9 also shows how the heat exchanger inside the air handling unit is setup. As it is shown on the figure the inputs to the system are obviously air from the duct, chilled water supply, and hot water or steam supply. The outputs of the heat exchanger are supply air, chilled water return, and hot water (steam) return.

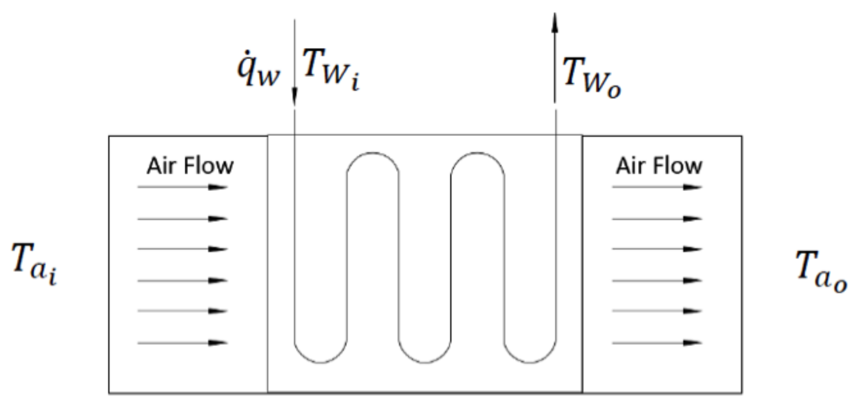



Fig. 2.9. Heating and cooling coils Input/Outputs heat exchanger in AHU

The more detailed information of system inputs/outputs is described on Figure 4.3 for AHU flow diagram. For better understanding on how these two are being used will help to make the usage more efficient and reduce the waste. On the other hand, fans use a lot of electricity/energy to keep the positive static pressure in the ducts. If fans are not working efficiently and are turned on without any reasons it will end up with a lot of energy waste. These items have been identified as most energy consumers inside the air handling unit. Both, model and results, will present how to avoid energy waste and make a better use of them later in this thesis.

### 2.3.1 Dry/Wet Coil Method

Cooling and heating coils are cross-flow heat exchangers in most common air handling units. In cross-flow heat exchangers heating and cooling is provided to the air from the steam and chilled water. Also dehumidification and humidification is done through these heat exchangers. For example, if the cold side and chilled water temperature is lower than the dew point of air, during the heat exchange water in the air starts to condensate. Therefore, there would be less moisture in the air.

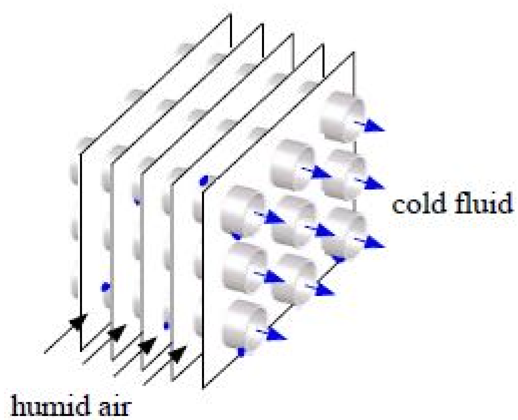



Fig. 2.10. Condensation on the coils [28]

To get the best results from the heat exchangers, it should have very thin layers and also large surface so it could exchange the maximum amount of heat. Most of the heat exchangers are made out of multiple tubes and rows versus finned coils in order to force the air between the cold and hot sides as shown on Figure 2.10.

As it was mentioned before in this research there were two methods discussed for air handling unit coils. The first method is called dry and wet method approach that basically divides the heat exchange between cold and hot to two different sections as dry and wet. Second method is also described based on Psychometric chart and saturated line for air and water, which will be explained later. Psychometric chart shows the physical and thermodynamic properties of gas-vapor mixtures (Figure 2.11).

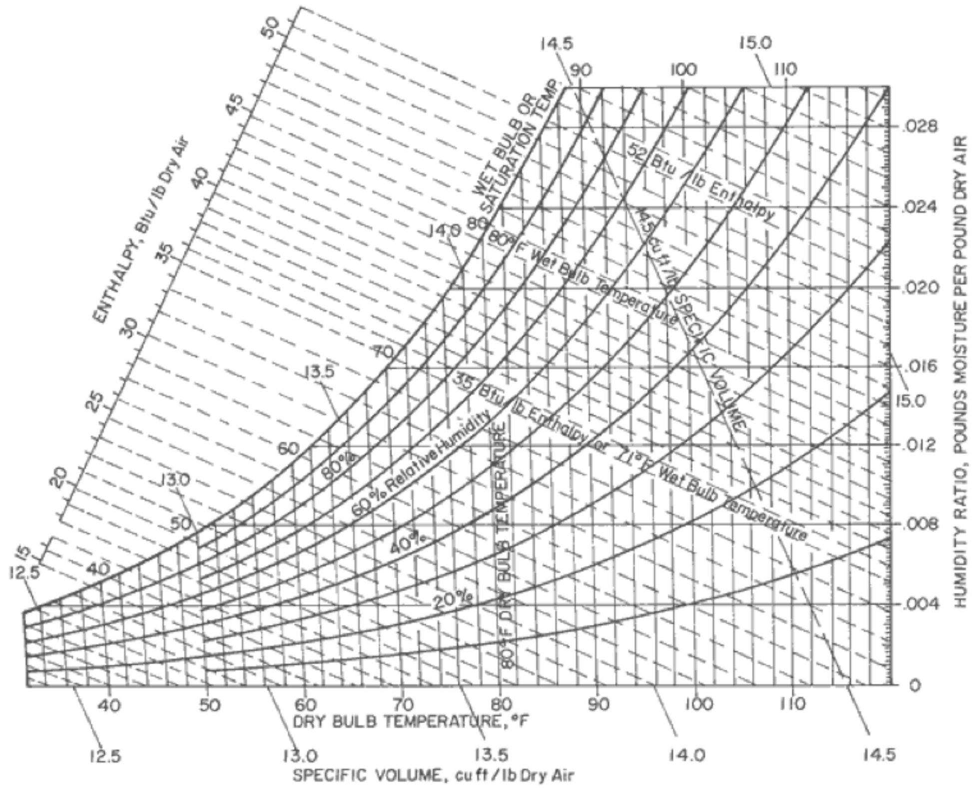



Fig. 2.11. Psychometric chart (Carrier)

Dew points and saturation temperature are shown on figure above. Dew point is basically the temperature that water vapor reaches at the saturation level. From this point if heat is removed from air for it will condensate the amount of water in the air since it reached the saturation level. Also in this example the process of dry and wet coil methods can be shown on Psychometric charts as well as in enthalpy based effectiveness method. In this specific example consider air enters the coil with temperature of 25 degrees Celsius and also leaves the coil with temperature of 7 degrees Celsius. If this condition happens in relative humidity of 42 percent then the path for dry and wet coil method can be shown below.

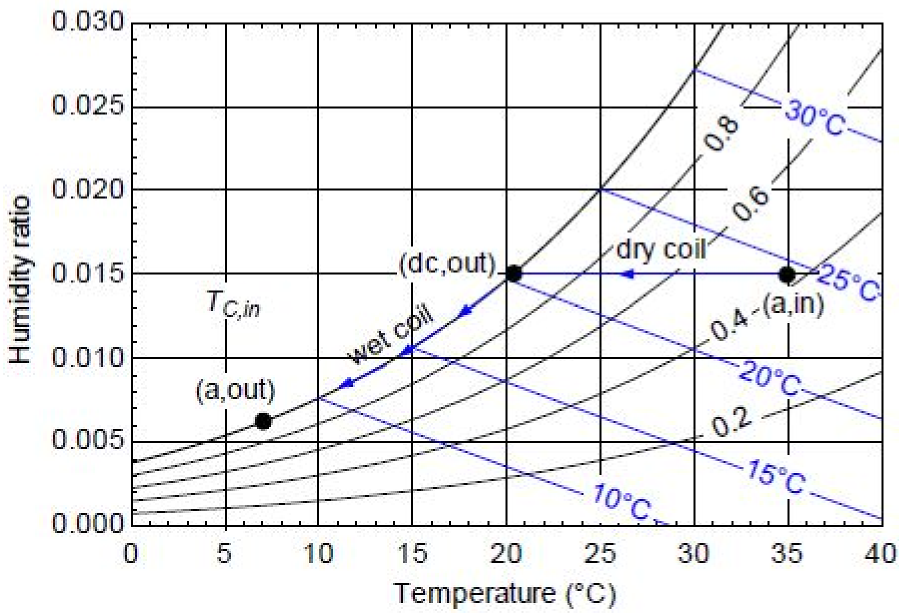



Fig. 2.12. Dry and wet coil method dehumidification process [28]

So, on Figure 2.12 as it is shown in dry coil part only the temperature of air reduces until it reaches the saturation line as it was discussed in psychometric chart section. In the first part there wont be any dehumidification as in this method is assumed. Once the air gets to its dew point the dehumidification process starts and it will enter to the wet coil part. In first part during dry coil as its shown in Figure 2.12 the humidity ratio of air stays the same. As it enters the saturated line and wet coil part the dehumidification starts.

The wet coil analysis allows calculating two heat exchanger values for dry and wet coil approaches. The advantageous of this method is the amount of dehumidification can be specified in terms of heat exchange values. But also, when the air that enters in the coil does not have high humidity ratio, this method might not be accurate enough to calculate the dehumidification amount. This is the expected results and it will be more discussed in results and conclusions section.

### 2.3.2 Enthalpy Based Effectiveness

So in contrast with wet dry coil method enthalpy based on effectiveness assumes the coil is partially or fully wet, which means there is always dehumidification happening along the process. But in fact, the air that is closer to the fans and heat exchanger areas faces more heat transfer and dehumidification, but also some air may not touch the heat exchange areas and somehow skip it through the path.

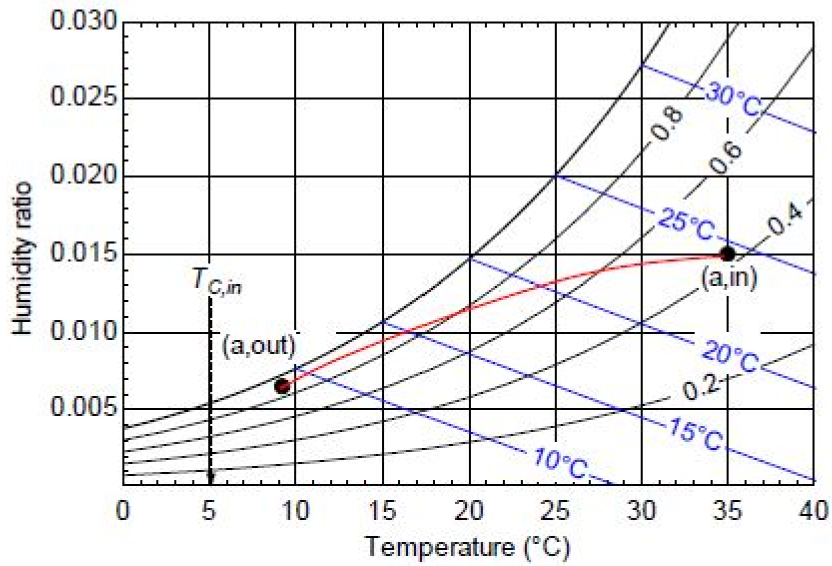



Fig. 2.13. Actual air heat exchange process [28]

Figure 2.13 shows in reality what would be the actual heat exchange process where there would be a smooth change of humidity ratio throughout the coils. But also in enthalpy based effectiveness its assumed that this heat exchange process if straight line of change in enthalpy values of the air so it does not consider the amount dehumidification and humidification as two separated regions.

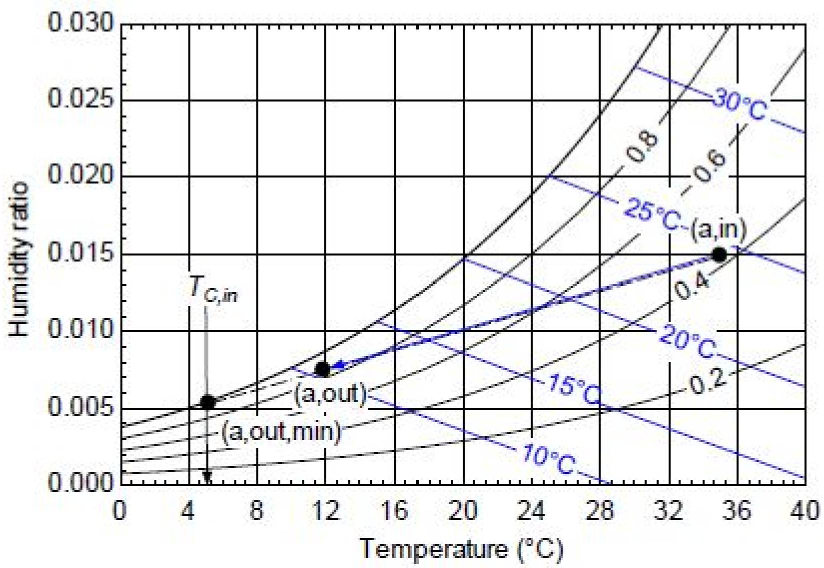



Fig. 2.14. Enthalpy based effectiveness air heat exchange process [28]

Figure above 2.14 shows how the enthalpy based effectiveness approach is based on air heat exchange process. Using energy balance equations the amount of total heat transfer and water vapor can be calculated.

## 2.4 Demand Control Ventilation $CO_2$ Based

Also another focus of this research is reducing energy consumption of the fans by calculations based on $CO_2$. Since the indoor air quality is very dependent on the number of people inside the building and also more importantly is based on their activities. This method can give us accurate predictions of energy usage for the fans. Using this method we can also reduce energy waste by reducing unnecessary ventilation inside the building. Fresh air and good quality air is necessary inside the school buildings. So this research concentrates on calculating the required demand and power for the fans based on sensor data that have been mounted inside various locations in building to calculate $CO_2$ values.

## 2.5 Design of Experiment

Three main methods have been discussed to model the energy efficiency and energy consumption of the air handling unit subsystems in the building. This section explains what parameters and predictors have been used to validate the models. In the first two thermodynamic models the focus on the model validation was more on humidity ratio and inlet temperature as the main factors to compare the models. Inside the heat exchanger the main air properties that change significantly are temperature and humidity ratio, since humidification and temperate raise happens through the heating coil. This condition also applies in cooling coil where air reaches its saturated temperature and enters the de-humidification part. The purpose of this research is mostly focused on the energy cost aspect of modeling. So the result sections and models variation are discussed based on the amount of heat exchange in each model. Later on this heat exchange amount (or energy) can be transferred directly to cost depends on energy value in each region or city. The $CO_2$ modeling focus was mostly based on ppm values in the air for carbon dioxide. $CO_2$ numbers are the indicators of the amount of fresh air presented in the room, building or etc. So amount of ventilations needed in the building is calculated and compared based on different allowed $CO_2$ limits explained in Section 6.3 and specifically in Table 6.3.

## 2.6 Statistical Analysis

After working on models and getting results, it was decided to work on some data polishing. Not all the results were readable and reliable as (refer to figure actual modeling result), especially while working with all different units and different software. There is couple of different statistical analysis performed in this research, such as moving average method, histogram analysis, data deviation and comparison. Two major methods are explained below.

### 2.6.1 Moving Average Method

This analysis is basically a calculation in mathematics and physics used to show the general trend of the data sets. This method works based on the series of averages for different subgroups of the full main data sets. Moving average method is also a great tool on financial applications that allows users to see the trend change in the datasets. [29–31]

This research has used moving average method to smooth the data from the modeling and to get the trend of heat transfer calculations rather than just looking at the spikes and invalid single data points in the modeling.

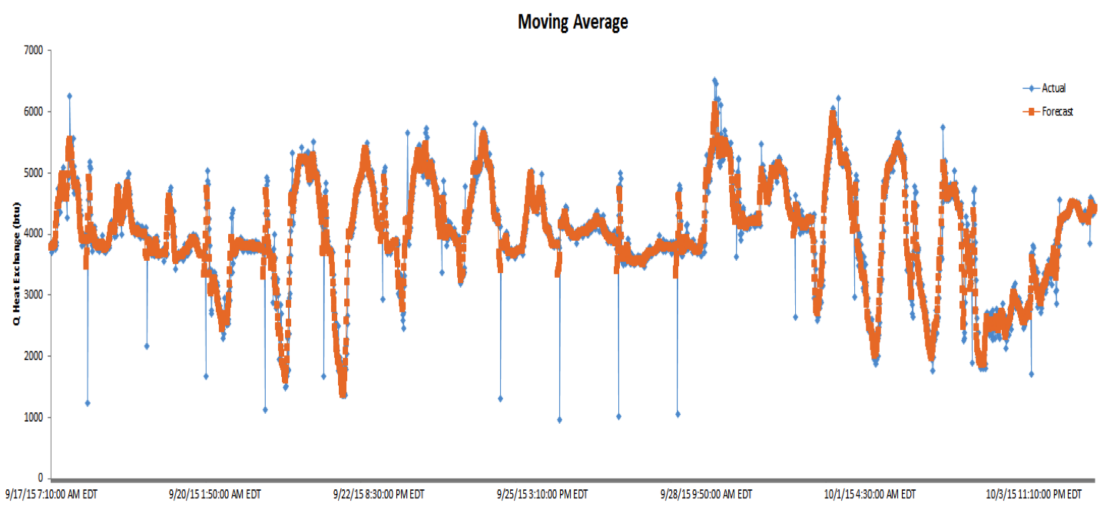



Fig. 2.15. Moving average method

For example, Figure 2.15 shows the difference between the actual datasets and forecast values for the data sets. In this case forecast data sets are consecutive average of 5 actual data points. In other words every 5 different data points were averaged and plotted as the forecast. In this way we can avoid extreme picks in the data set and as you can see the forecast shows more the actual trend of values. In this research this method was used to compare the trend of coil performance modeling on two different methods. One is dry wet coil method and the other is enthalpy based effectives. These two methods were compared with the actual experimental values using moving average method. Moving average method helped to focus more on the trend of modeling rather than details of spies in this work. It was also useful for data comparison after performing moving average method since it smooths the data. Figure 2.16 shows the actual results from modeling. You can identify single invalid data points in this modeling that looks like spikes. By comparing Figures 2.16 and also 2.17 one can easily realize the advantages and improvements of using moving average method. Figure 2.16 includes a lot of data spikes and out of correct range data but Figure 2.17 provides smooth data graph and the overall trend.

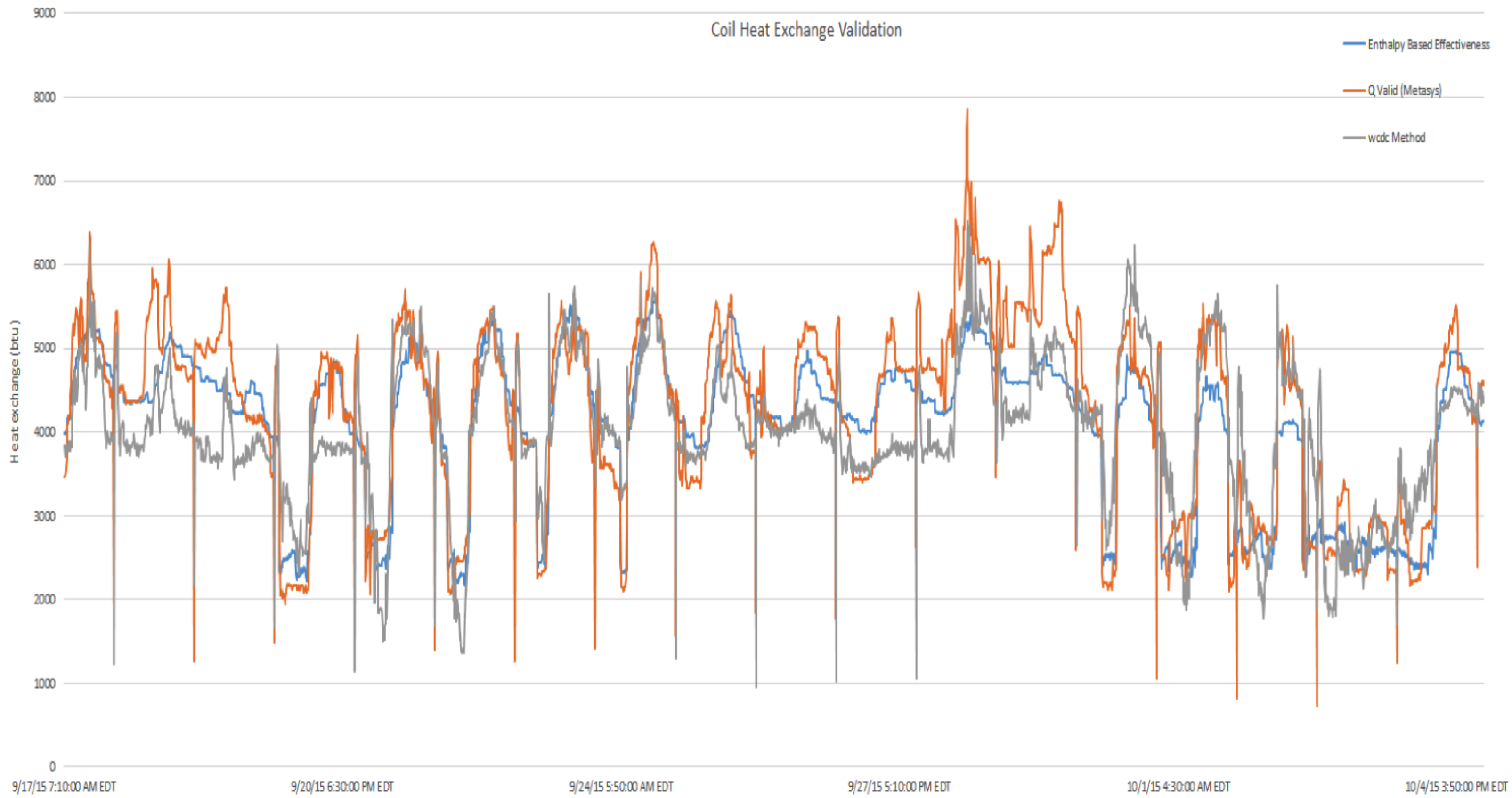



Fig. 2.16. Actual modeling results

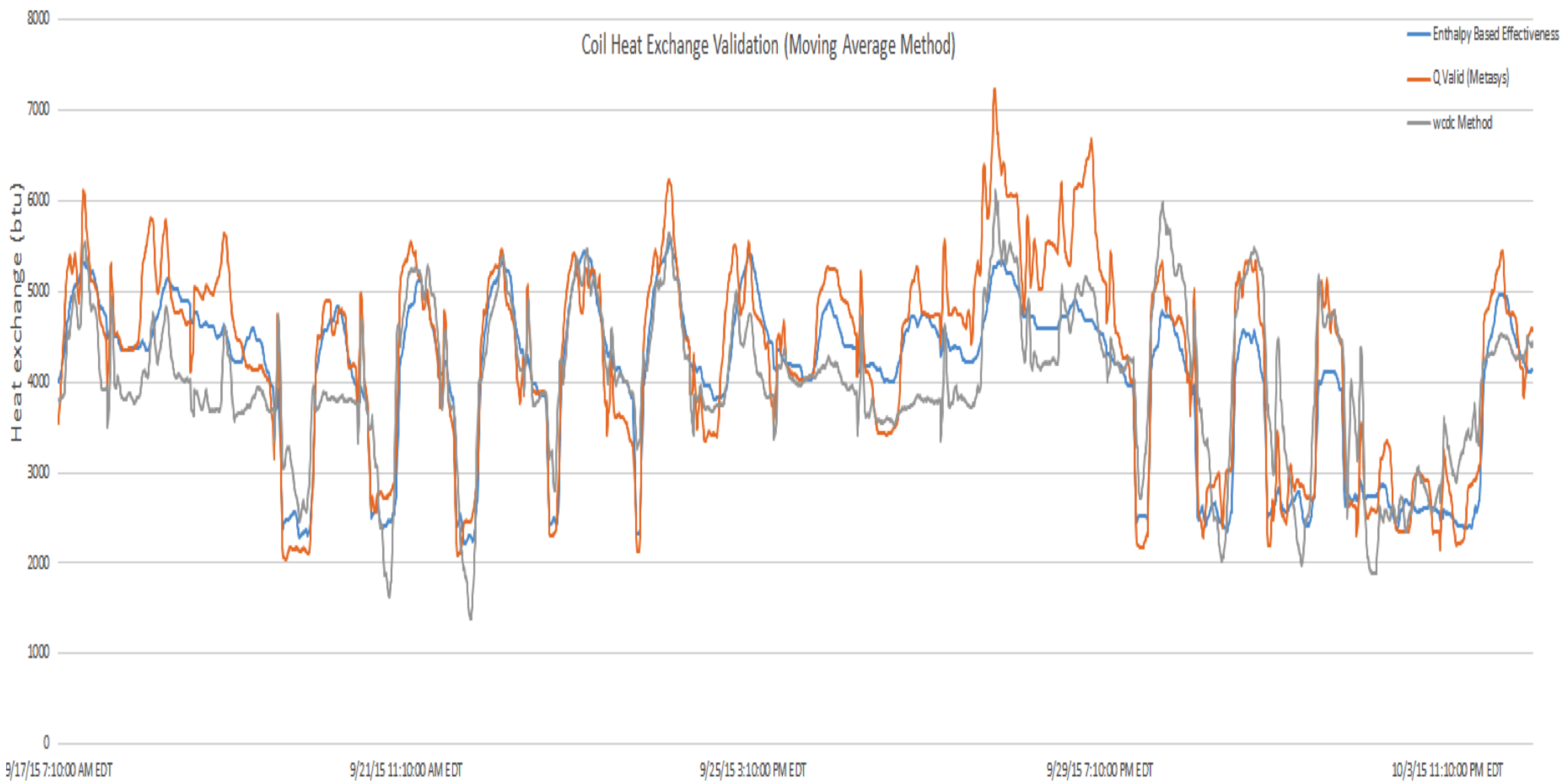



Fig. 2.17. Modeling results using moving average method

### 2.6.2 Model Deviations

Error was calculated between two models by using model deviations analysis. Deviation simply gives us the difference between two models. There are many tools that can help us performing this action for large datasets. The standard deviation tool in Excel gives an indication of how much data is spread out for each data set. Also, an error function can calculate quickly what are the differences and big gaps between each model. This research has used Excel software to compare multiple datasets and present the results as its shown in Figure 6.2.

$$\sigma = \sqrt{\frac{1}{N}[(x_1 - \mu)^2 + (x_2 - \mu)^2 + ... + (x_N - \mu)^2]} \tag{2.1}$$

$$\frac{ApproximateValue - ExactValue}{ExactValue} \times 100\% \tag{2.2}$$

# 3. SENSORS AND DATA COLLECTION

## 3.1 Experiment Goals

The goal of this chapter is to explain how general system is currently working. Later on how data was collected wirelessly and what type of data collection was needed within the scope of this research.

## 3.2 Test Facility

Currently, the test case for this research is the facility located in the Engineering/Technology (ET) building of the School of Engineering and Technology at IUPUI. Building has 31,957 square feet with 4 floors including basement and it was built in 1969. The current air handling unit is located in basement inside the mechanical room.

## 3.3 Floor Layout

Figure 3.1 shows the facility layout.

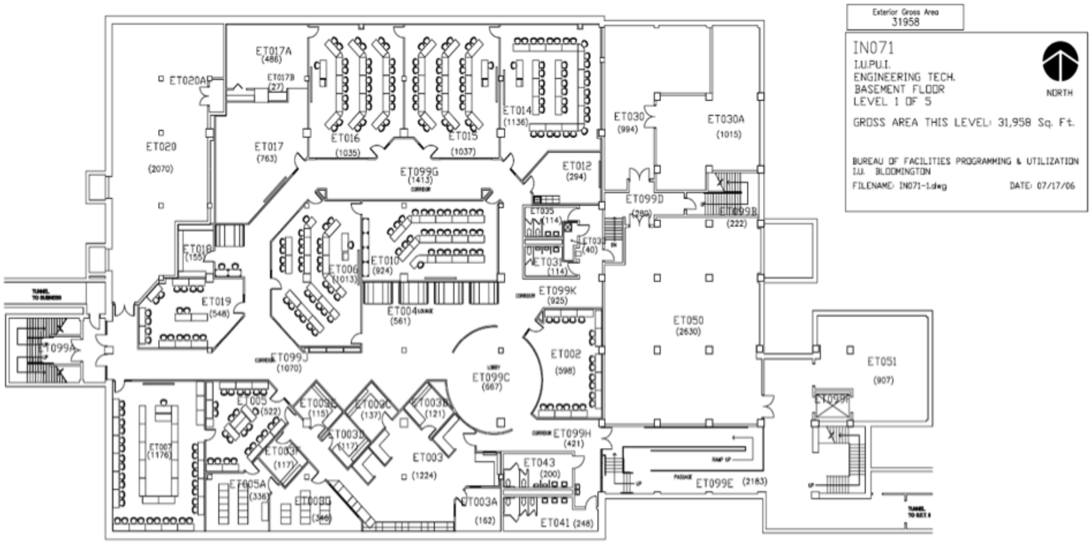



Fig. 3.1. Facility floor layout

## 3.4 Current AHU Design Specifications

Specific design parameters are listed in Table 3.1.

## 3.5 VAV Terminal Unit Specifications

Also specifications for all the design VAV boxes are included here in Table 3.2.

## 3.6 Building Automation System

ET building uses the automation system made by Johnson Control company. The software is called Metasys building management system. This software also has an online version through the Metasys Launcher application which can be reached and connected from anywhere using internet and specific IP settings. Metasys allows the

Table 3.1.
AHU Design Specifications

| Components | Specifications |
|---|---|
| Preheat Coil | Surface Area: 40 sq. ft<br>Rows:1<br>MBH (Mega BTU per hour):733 |
| Cooling Coil | Surface Area: 40 sq. ft<br>Rows:6<br>MBH (Mega BTU per hour):796 |
| Supply Fan | Min OA CFM: 5000<br>Supply CFM: 17000<br>Horsepower:25<br>External Static Pressure:3 in. WC |
| Return Fan | Supply CFM: 17000<br>Horsepower:15<br>External Static Pressure:1.75 in. WC |

user/users to view different system settings and sensor functioning with their current properties.

Metasys also has the functionality to work with field controller to perform some operator commands on the system. In the current research the access to the Metasys system was limited to only view certain data on Air handing unit coils and few more equipment, which was good enough within the scope of this work.

Table 3.2.
VAV terminal unit specifications

| Terminal Units | Model no | D CFM | Min CFM | Max CFM | MBH | GPM | Rows | LAT |
|---|---|---|---|---|---|---|---|---|
| TB-01 | DESV-10 | 1000 | 600 | 0.5 | 29.2 | 2.0 | 2 | 100 |
| TB-02 | DESV-10 | 1000 | 600 | 0.5 | 29.2 | 2.0 | 2 | 100 |
| TB-03 | DESV-10 | 1000 | 600 | 0.5 | 13.9 | 2.0 | 2 | 75 |
| TB-04 | DESV-10 | 1000 | 600 | 0.5 | 13.9 | 2.0 | 2 | 75 |
| TB-05 | DESV-10 | 1000 | 600 | 0.5 | 13.9 | 2.0 | 2 | 75 |
| TB-06 | DESV-05 | 300 | 300 | 0.5 | 6.5 | 1.0 | 2 | 75 |
| TB-07 | DESV-07 | 500 | 500 | 0.5 | 10.9 | 1.0 | 2 | 75 |
| TB-08 | DESV-07 | 500 | 500 | 0.5 | 10.9 | 1.0 | 1 | 75 |
| TB-09 | DESV-8 | 700 | 400 | 0.5 | 8.7 | 1.0 | 1 | 75 |
| TB-10 | DESV-07 | 500 | 500 | 0.5 | 10.9 | 1.0 | 1 | 100 |
| TB-11 | DESV-07 | 500 | 500 | 0.5 | 10.9 | 1.0 | 1 | 75 |
| TB-12 | DESV-07 | 500 | 500 | 0.5 | 10.9 | 1.0 | 1 | 75 |
| TB-13 | DESV-09 | 800 | 600 | 0.5 | 13.0 | 2.0 | 1 | 75 |
| TB-14 | DESV-09 | 700 | 600 | 0.5 | 10.9 | 1.0 | 1 | 75 |
| TB-15 | DESV-10 | 500 | 500 | 0.5 | 10.9 | 1.0 | 1 | 75 |
| TB-16 | DESV-07 | 500 | 500 | 0.5 | 10.9 | 1.0 | 1 | 75 |
| TB-17 | DESV-08 | 600 | 400 | 0.5 | 8.7 | 1.0 | 1 | 75 |
| TB-18 | DESV-08 | 600 | 400 | 0.5 | 8.7 | 1.0 | 1 | 75 |
| TB-19 | DESV-09 | 800 | 600 | 0.5 | 13.0 | 2.0 | 1 | 75 |
| TB-20 | DESV-10 | 500 | 500 | 0.5 | 10.9 | 1.0 | 1 | 75 |
| TB-21 | DESV-08 | 750 | 400 | 0.5 | 8.7 | 1.0 | 1 | 75 |
| TB-22 | DESV-08 | 750 | 400 | 0.5 | 8.7 | 1.0 | 1 | 75 |
| TB-23 | DESV-09 | 700 | 700 | 0.5 | 34.1 | 2.0 | 2 | 100 |
| TB-24 | DESV-10 | 925 | 700 | 0.5 | 34.1 | 2.0 | 2 | 100 |
| TB-25 | DESV-10 | 375 | 375 | 0.5 | 8.1 | 1.0 | 1 | 75 |

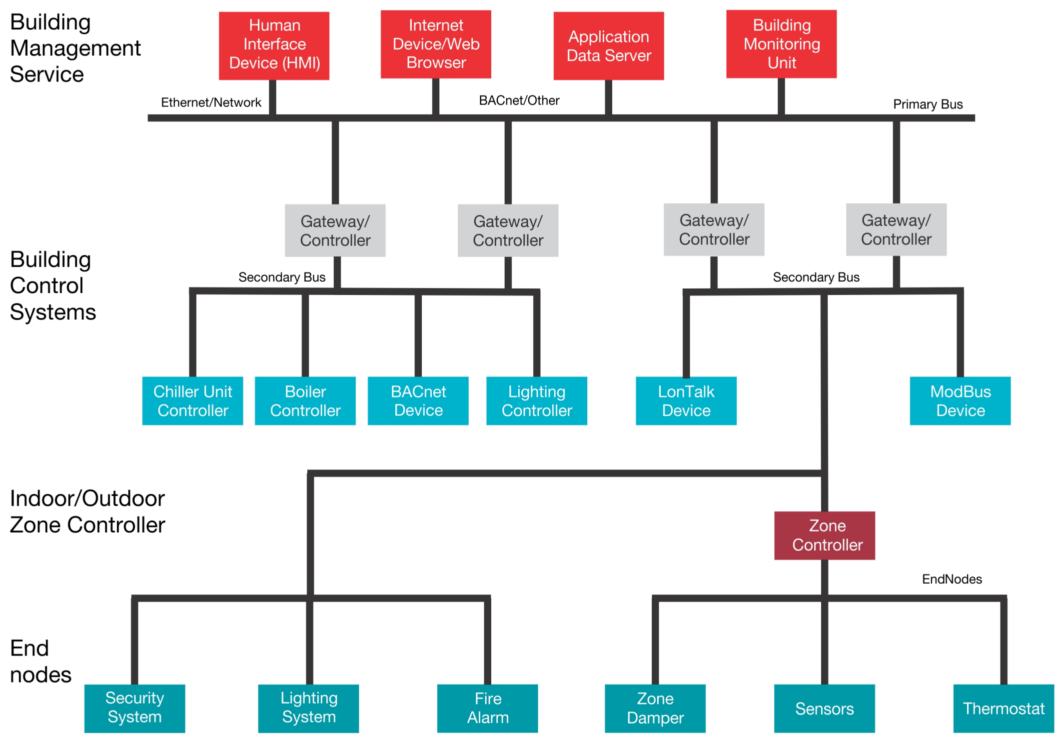



Fig. 3.2. Example of current building network (Wikipedia)

The architecture components and communication structure of Metasys are shown in Figure 3.2. Information from primary BUS can be sent and received through the system. Building management service has the functionality of changing all overall settings on the system but after that it would come down to building control system that would be Metasys software and simple commands for different units.

### 3.6.1 AHU List of System Inputs

Table 3.3 shows the inputs and outputs of the AHU that serves the ET basement. Some of the inputs and outputs are used for simulation.

### 3.6.2 Sensor Types

Averaging temperature sensors have been used to measure CHR-T, MA-T, PH-T and DA-T, they are available in Table 3.4.

### 3.6.3 Sensor Locations

Sensor locations are displayed in Figure 3.3 show the screenshot of the current system through the Metasys software. The figure also displays sensor locations and some roughly values of sensors.

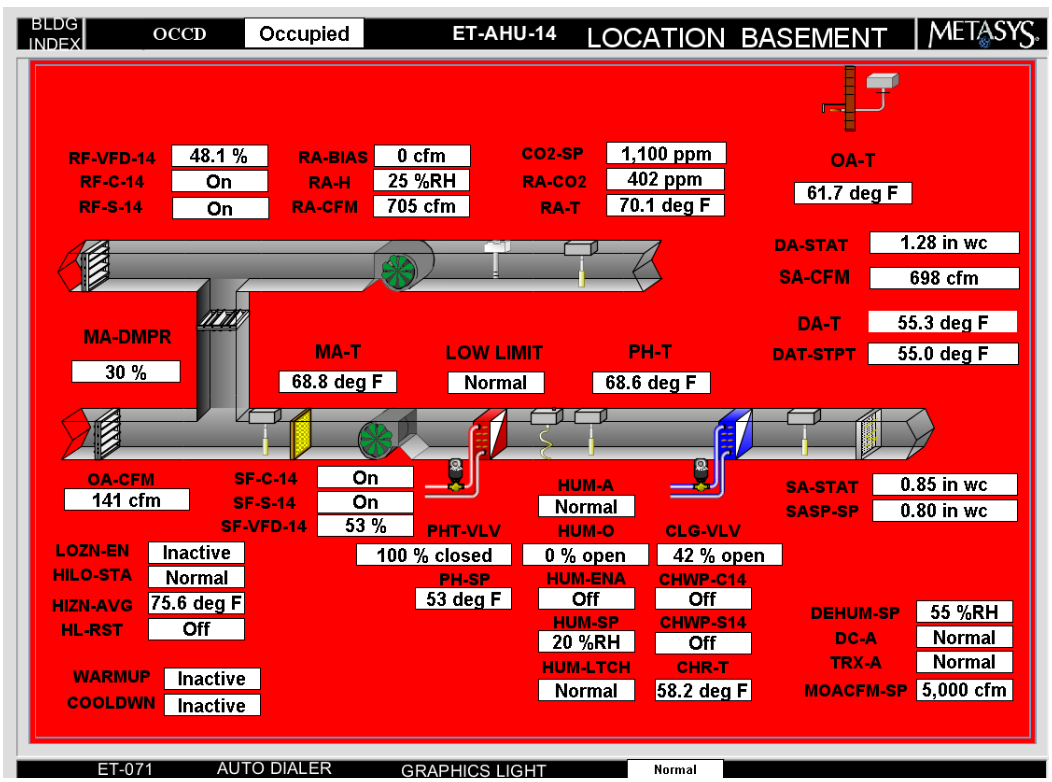



Fig. 3.3. Sensor locations of the AHU (Metasys Johnson Conrtol)

### 3.7 Wireless Data Receiver

This research also has used wireless data system to collect $CO_2$ data in the basement. A fully functional device FFD was used to collect the information and connect to sensors using ZigBee network system. Also the $CO_2$ sensor is connected to this main communication network. The $CO_2$ sensors were looked within the range of breathing height from the floor about 48-72 inches. Also 24 inches far from the entrance of the rooms to make sure the data collections would be accurate on $CO_2$ levels.

Fig. 3.4. CO2 sensor and FFD in hallway.

Figures 3.4, 3.5 and 3.6 show all locations that $CO_2$ sensors were installed. Locations installed are in hallways in the ET basement, class in ET019 and also in the lab ET010.

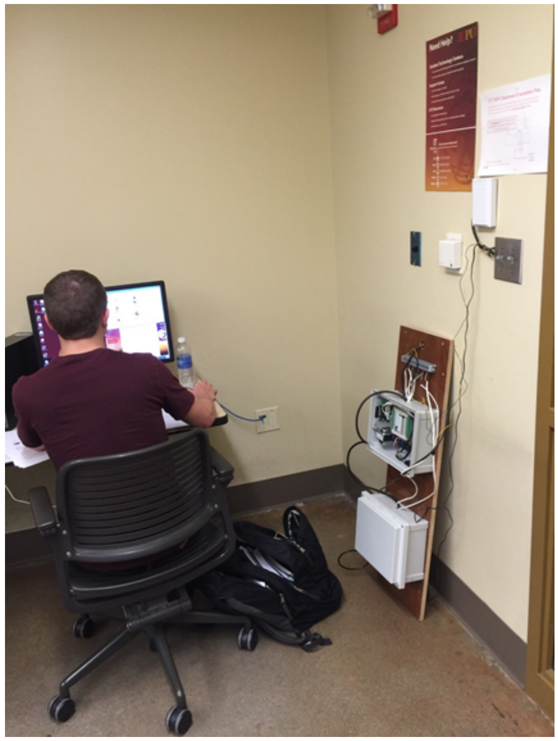


Fig. 3.5. $CO_2$ sensor and FFD in lab ET010.

Three locations were chosen based on most common places that students use during a regular day in the school. Locations of the sensor also were chosen based on manufacturing information listed on sensors manual.

Table 3.3.
AHU I/O List

| Parameter type | Parameter | Description | Unit |
|---|---|---|---|
| Analog inputs | AI1 OA-CFM | Outside air flow | CFM |
| | AI2 MA-T | Mixed Air Temperature | F |
| | AI3 SA-CFM | Supply Air Flow | CFM |
| | AI4 PH-T | Preheat Air Temperature | F |
| | AI5 DA-T | Discharge Air Temperature | F |
| | AI6 DA-STAT | Discharge Air Static Pressure | In. H2O |
| | AI7 SA-STAT | Supply Air Static Pressure | In. H2O |
| | AI8 CHR-T | Chilled Water Return Temp | F |
| Analog outputs | AO1 SF-VFD | Supply Fan VFD | % |
| | AO2 RF-VFD | Return Fan VFD | % |
| | AO9 MA-DMPR | Mixed Air Damper | % |
| | AO10 PHT-VALVE | Preheat Valve | % |
| | AO11HUM-OUTPUT | Humidifier Output | |
| | AO12 CLG-VALVE | Cooling Coil Valve | |
| Digital inputs | DI1 SF-S | Supply Fan Status | NA |
| | DI2 RF-S | Return Fan Status | |
| | DI3 CHWP-S | Chilled Water Pump Status | |
| | DI4 HILO-STA | HI LO Static Status | |
| | DI5 LOWLIMIT | LOWLIMIT Status | |
| | DI6HUMALARM | Humidity Alarm | |
| | DI7DC ALARM | DC Power Supply Alarm | |
| | DI8 TRX-A | Transformer Alarm | |
| Digital inputs | DO3 SF-C | Supply Fan Command | NA |
| | DO4 RF-C | Return Fan Command | |
| | DO5HUMENABLE | Humidity Enable | |
| | DO6CHWP-C | Chilled Water Pump Command | |

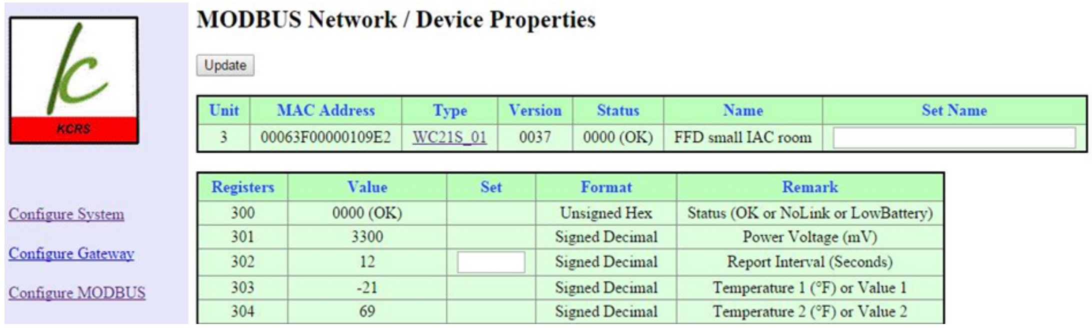
Table 3.4.
Sensor types

| Sensor | Part no | Output signal | Range | Accuracy |
|---|---|---|---|---|
| CHR-T | TE-632AP-1 | 1k ohm | -50 to 220F | 0.73F at 70F |
| RA-T/H | HMD60Y | 4-20mA | 0-100% RH | 2% RH |
| MA-T | TE-6328P-1 | 1k ohm | -50 to 220F | 1.08Fat 70F |
| PH-T | TE-6328P-1 | 1k ohm | -50 to 220F | 1.08Fat 70F |
| DA-T | TE-6328P-1 | 1k ohm | -50 to 220F | 1.08Fat 70F |
| DA-STAT | DPT241 | 4-20mA | 0-10 in WC | 0.5% |

Fig. 3.6. $CO_2$ sensor and FFD in lab ET019.

## 3.8 MODBUS Network Connection

All information through the FFD is being sent to what is called PAN coordinator shown in Figure 3.8. Pan coordinator basically is a wireless router which collects all the information from the sensors.



KCRS

Configure System

Configure Gateway

Configure MODBUS

**MODBUS Network / Device Properties**

Update

| Unit | MAC Address | Type | Version | Status | Name | Set Name |
|---|---|---|---|---|---|---|
| 3 | 00063F00000109E2 | WC21S_01 | 0037 | 0000 (OK) | FFD small IAC room | |

| Registers | Value | Set | Format | Remark |
|---|---|---|---|---|
| 300 | 0000 (OK) | | Unsigned Hex | Status (OK or NoLink or LowBattery) |
| 301 | 3300 | | Signed Decimal | Power Voltage (mV) |
| 302 | 12 | | Signed Decimal | Report Interval (Seconds) |
| 303 | -21 | | Signed Decimal | Temperature 1 (°F) or Value 1 |
| 304 | 69 | | Signed Decimal | Temperature 2 (°F) or Value 2 |

Fig. 3.7. MODBUS network

Figure 3.7 shows the MODBUS network which is built in for PAN coordinator. Multiple different FFD and RFDs can be connected to this MODBUS network. The IP address can only be access via school network.

Fig. 3.8. PAN coordinator

A configuration on the MODBUS network was already done in previous researches. The current work had an extra step to add CO2 sensors to FFD and attached to the system. Configuration of the MODBUS network is also available on Reference [32].

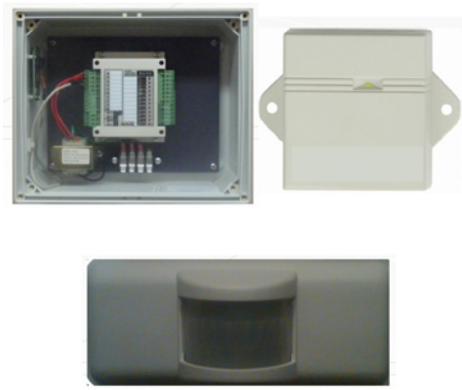


Fig. 3.9. Example of sensors attached to FFD

## 3.9 AHU Sequence of Operation

Sequence of operations is documented by Johsnon Control and is available to the building staff. Paragraphs below are exactly what is/was listed in the air handling unit sequence of operation from AHU-1 (Drawing Number 050061-1.1) on Figure 3.10.

1. Air handling unit start/stop: The air handling unit should work continually and lowest temperature has been set to 60 degrees Fahrenheit.

2. Preheat valve: Once air handling unit stops working all outside dampers should be closed, also all valves would be closed. Pre heat valve stays at 50 degrees Fahrenheit.

3. Duct static pressure control: Duct static pressure is set on 1.75 in WC. Supply fan should also be set for the higher limit on 4.5 in WC and lower limit of 5 in WC.

4. Carbon dioxide control (demand control ventilation/DCV): Current CO2 level for the system has been set to between 600pm and 1100ppm. The outside air damper is set to minimum of 10% all the time for minimum ventilation.

5. Economizer/mixed air damper control: Minimum of 5% the fan delivery flow rate has been set to mix the air between outside and indoor air.

6. Cooling coil control: Cooling coil temperatures are set to 55 till 60 degrees Fahrenheit from average of all highest zone temperatures. Also cooling recirculation

pump will start if the temperatures fall below 40 degrees Fahrenheit to avoid any freezing. Heating and cooling warm-up

7. Outside dampers: When temperature is below 45 degrees Fahrenheit all outside dampers will be closed. The outside only will be used in the building if the outdoor temperature is between 45 and 68 degrees Fahrenheit.

8. Cooling pull-down: In case of emergency, fire, freezing temperature, or smoke detection the air handling unit will be stopped automatically.

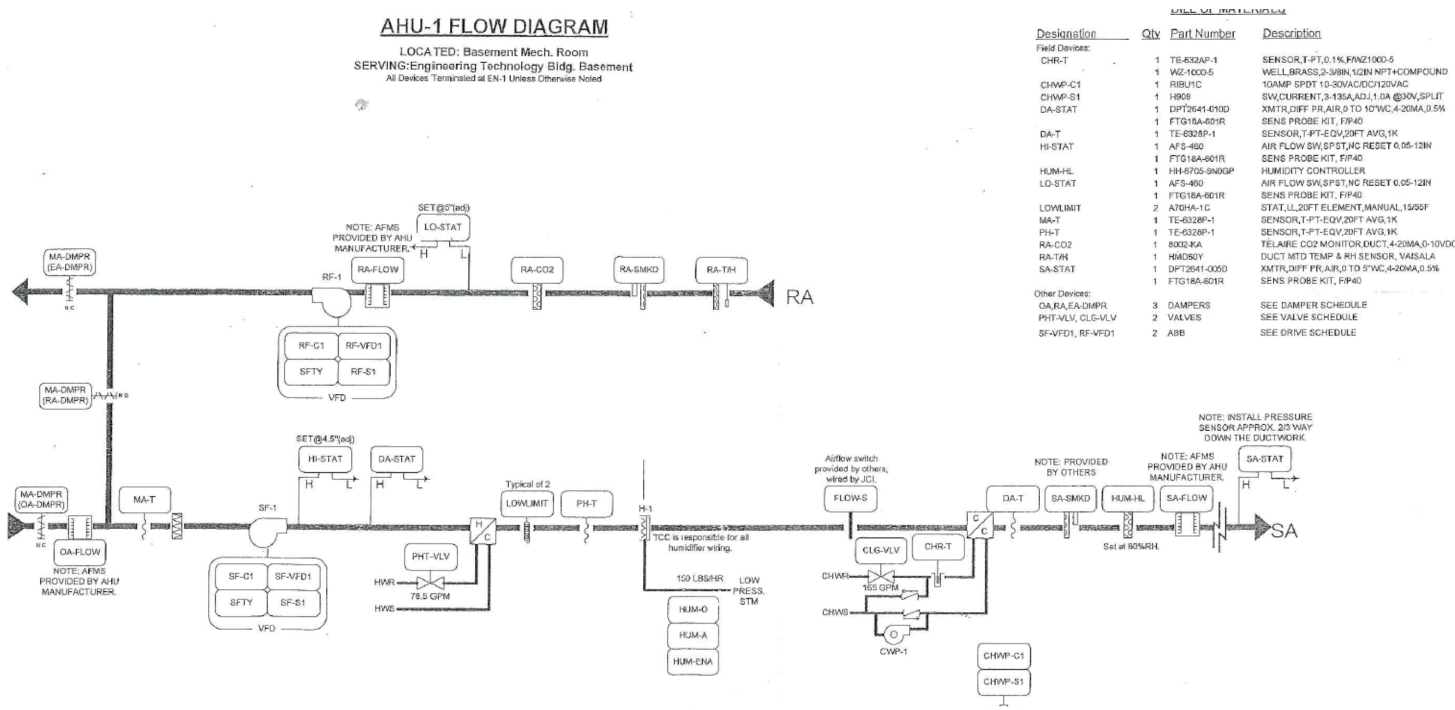



Fig. 3.10. AHU flow diagram (Provided by Johnson Control)

# 4. THERMODYNAMIC AND MATHEMATICAL MODELING

In this section the models and equations are presented. After attaching sensors and getting wireless information we used hourly data to run the model. There are several inputs to this model that are listed later on. Equations are all based on thermodynamic laws. Overall performance for the coils on air handling unit is modeled.

In this thesis the focus of the modeling is on cooling, heating coils, and heat exchanger as well as energy usage for the fans. Individual subsystems were programmed for this model with EES software. Most of the information for EES modeling was imported from the Metasys and air handling unit monitoring software as described in the previous chapter. Also coil information was taken from manufacturing data sheets for this specific air handling unit.

Chilled water and team pump were not included in this model since the building purchases these two for the whole campus so there is no chiller or boiler inside the house to make these two materials. Temperature data was taken from Indianapolis international airport location and website.

There are different scenarios assumed for each coil performance methods that are described in details in Chapter 5. Number of transfer units and log mean temperature difference also were used to tune the model and find the temperature relations for the heat exchangers. There are couple of EES library functions used for certain analysis such as fouling factors, conductance, and heat exchanger correlations that are described in each section, Figure 4.1 shows the main energy consumers in air handling unit.

Currently humidifier for this air-handling unit is not functioning but it is taking to account for the model. Current data sets were mostly for end of summer and beginning of fall where the weather conditions are moderate.

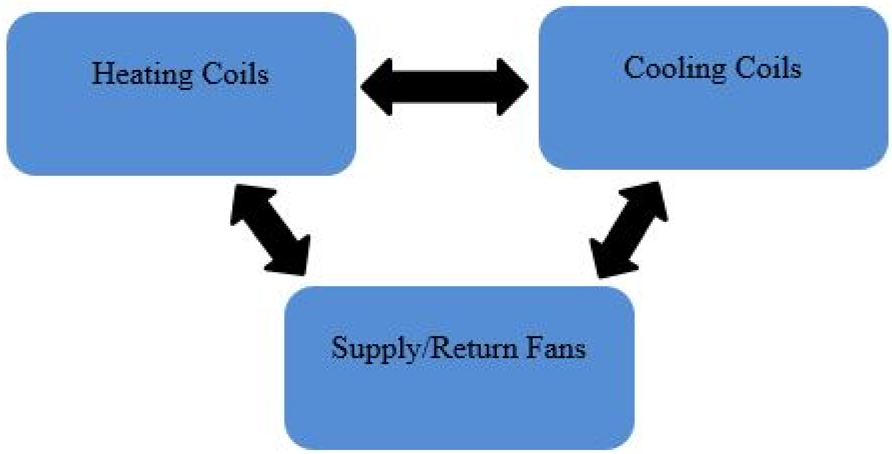



Fig. 4.1. Main energy consumers

Dehumidification occurs in cooling part of the model so the EES model focuses on cooling at the beginning since it has more inputs for the system equations. Later in the next section the model for the heating side also is presented.

## 4.1 Number of Transferred Units

Number of transfer unit method was used to model a counter-flow heat exchanger operation in this modeling. This method is mostly used in heat exchangers and especially in a condition that there is no insufficient information available. In most situations where the temperatures for inlet and outlet of heat exchangers are specified the log mean temperature difference is used. But when any of this information is not available the NTU method can be used. This method works based on the maximum possible heat transfer that can be achieved in heat exchangers, so in this method one fluid will face a maximum heat transfer.

In this case the inlet temperature for the hot and cold stream are compared and used to find the maximum heat transfer.

$$q_{max} = C_{min}(T_{h,i} - T_{c,i}) \tag{4.1}$$

The effectiveness is basically the ration between the actual heat and maximum heat transfer.

$$E = \frac{q}{q_{max}} \tag{4.2}$$

In this case the actual heat transfer equation is presented below

$$q_{max} = C_h(T_{h,i} - T_{c,o}) = C_c(T_{c,o} - T_{c,i}) \tag{4.3}$$

From maximum heat transfer and effectiveness equations, the actual heat transfer equation can be derived as below

$$q_{max} = EC_{min}(T_{h,i} - T_{c,i}) \tag{4.4}$$

$$E = f(NTU, \frac{C_{min}}{C_{max}}) \tag{4.5}$$

So, this general equation can be assigned for any heat exchanger. Calculating heat capacity ratios the Cr can be calculated and later will be used in the main NTU equation.

$$C_r = \frac{C_{min}}{C_{max}} \tag{4.6}$$

$$NTU = \frac{NTU}{C_{min}} \tag{4.7}$$

Theoverall heat transfer for the system can be written in this form, A is also the heat transfer area for the heat exchanger. Based on Cr the equations for parallel flow heat exchanger and counter-current flow heat exchanger can be derived.

$$E = \frac{1 - exp[-NTU(1 - C_r]}{1 - C_r exp[-NTU(1 - C_r]} \tag{4.8}$$

The equation above is calculating effectiveness and number of transfer units for counter current flow. Also when condensation occurs and during the substance phase change the $C_r$ would be zero. So the general equation for number of transfer unit can be written as

$$E = 1 - exp[-NTU] \tag{4.9}$$

Also an important factor for number of transfer units is how many shell and tubes are used in air handling units. [33]

## 4.2 Chilled Water Model

The first portion of chilled water modeling includes inputs of Metasys software from excel file. The inlet humidity ratio and dew point are calculated for the incoming air to unit. In case the entering water temperature would be less than air the water inside air would start to condensate. Humdity Ratio and Dowpoint for Air as :

$$AirH_2O, P = p_a, T = T_{a,in}, R = RH_{a,in} \tag{4.10}$$

$$AirH_2O, P = p_a, \omega = omega_{a,in}, R = 1 \tag{4.11}$$

Equations above show example of different parameters and thermodynamic characteristics for material can be called using built in functions in EES code.

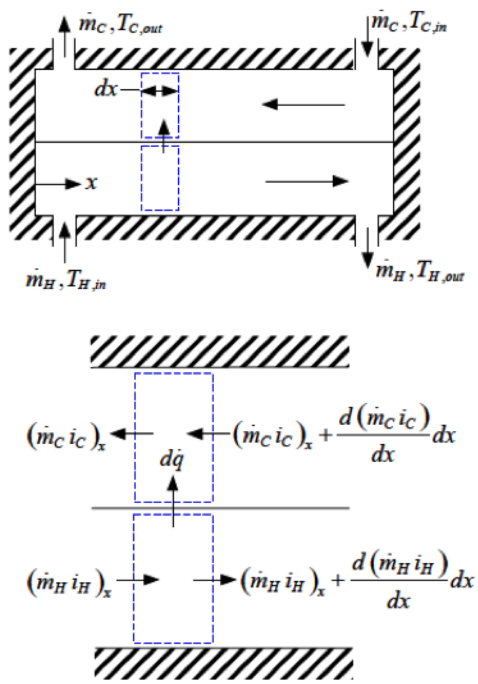



Fig. 4.2. Counter flow heat exchanger example no mass transfer [33]

Figure 4.3 also shows how the generic model in this software works and was set up. The majority of input values was imported from the sensors and building automation system. Then parameters and governing equations were made in the modeling equations. Output for the system was calculated based on the identification model.

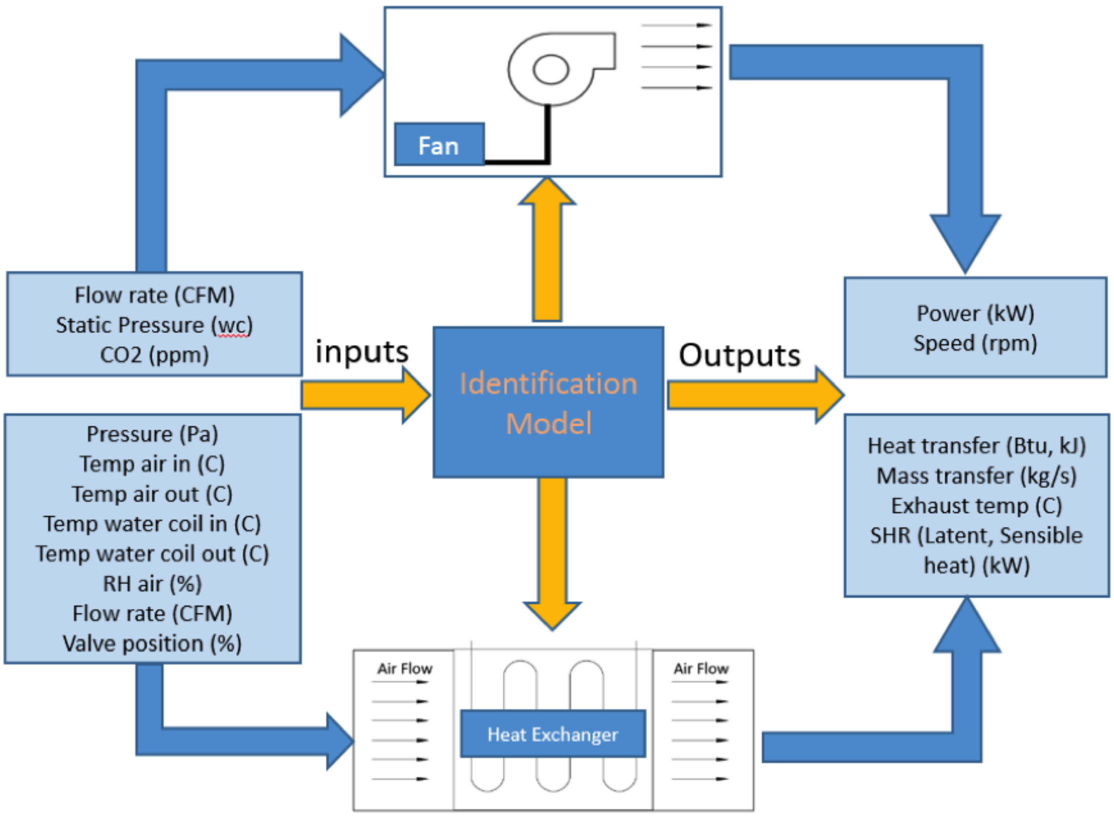



Fig. 4.3. Flow chart for identification model inputs and outputs.

As it was explained earlier the chiller model, it has multiple settings of equations for reading dew point and humidity ratios. Later on these information will be related and used to next sub modules.

Based on the sequence of air handling units there are three different scenarios for when the cooling and heating coils should be enabled. Using the input values if temperature entering the air-handling unit is lower than 45 degrees Fahrenheit, the cooling coil will be locked out and only heating coil will perform. If the inlet temperature would be from 45 to 65 degrees Fahrenheit then economizer would come to work and not all the air-cooling coil would be enabled, instead outside air would be used to cool the air. Currently this damper positions and the amount of mixing air is being imported from the automation system. In case that the air temperature is above 65 degrees the cooling coil and dehumidification process would be fully functional.

In the next section there will be more information about how the internal flow through the tube would be modeled using EES software. The inner diameter of the tube can be calculated as below.

$$D = \frac{D_{out} - D_{in}}{2} \tag{4.12}$$

And also the total length for the tube would be modeled as:

$$L(tube) = N(t, row)N(t, col)Width \tag{4.13}$$

So heat transfer resistance for water and inner surface of tube can be computed using.

$$R_{in} = \frac{1}{\pi - D_{in} L_{tube} h_w} \tag{4.14}$$

## 4.3 Internal Flow Model

Internal flow for pipe models can be used through the built in functions and libraries inside the Engineering Equation Solver. The equation then can come as below:

$$PipeFlow = (Water, T_{avg}, p_w, m_{dot,w}, D_{in}, D_{tube}, D_{in}, h_{bar,w}, Nusselt_{bar,w}) \tag{4.15}$$

So in this line of code we are simply calling Pipe flow function based on the inputs that are given to the system. So the procedure fist calls unit functions and make sure the units are all matching. Then the pipe flow turbulent equations will be executed using below inputs:

$$Re, Pr, \frac{L}{D}, Roughness, Nusselt, friction \tag{4.16}$$

In the built-in functions there are multiple warnings set up in case the flow is not turbulent or the Reynolds value is less than 2300. Also the same applies for Prant, Nusselt number and the roughness values for the fluid. The procedure also takes to account multiple simple factors, such as pipe diameters, heat exchanger surface, number of fins and etc. Figure 4.4 shows the internal flow inputs for pipe flow function.

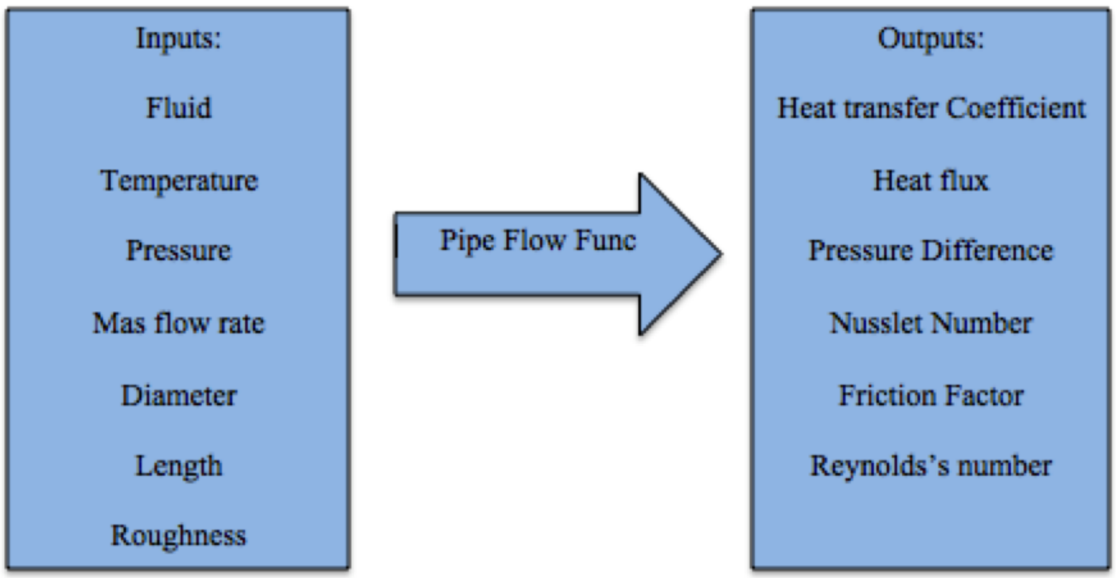



Fig. 4.4. Internal flow model Input/Outputs

## 4.4 Fouling and Conduction Resistance Model

As discussed in previous sections EES has great library of thermodynamics functions. One of the other factors/functions that can be calculated using the built-in function is fouling resistance. Fouling is basically the unwanted material, which covers the inside of the tube and reduces the performance of the system and conductance of the tubes. General equation of the fouling conductance can be written as:

$$R_{f,in} = \frac{R''_{f,in}}{\pi D_{in} L_{tube}} \tag{4.17}$$

$R``_f$ is the fouling factor returned by this function and $R_f$ is the constant fouling factor. Fouling would increase the resistance to the heat transfer between the fluid and surface of the pipe material. Fouling is dependent on different factors such as temperature, fluid type, surface material, and fluid velocity. [34–36] Also the conductivity of the pipe can be modeled as:

$$R_{cond} = \frac{ln\left(\frac{D_{out}}{D_{in}}\right)}{2\pi k_m L_{tube}} \tag{4.18}$$

## 4.5 Heat Exchanger Model

After modeling the chilled water and corresponding resistances, using this information the heat exchanger model can be made. Like it was discussed in previous sections there are built-in functions in Engineering Equation Solver that help to solve complicated thermodynamic equations like these particular heat exchanger correlations:

$$HeatExchanger(TypeHX, m_{dot,a}, \omega \times HT_{avg}, P_a, h_{bar}) \tag{4.19}$$

This function uses the various dimensional parameters, which are applicable for specific finned tube geometry on heat exchangers. Most of the functions in EES at the beginning also they perform unit checks and there will be warnings generated if there are mismatches in the units. The inputs and outputs for these functions are listed in Figure 4.5.

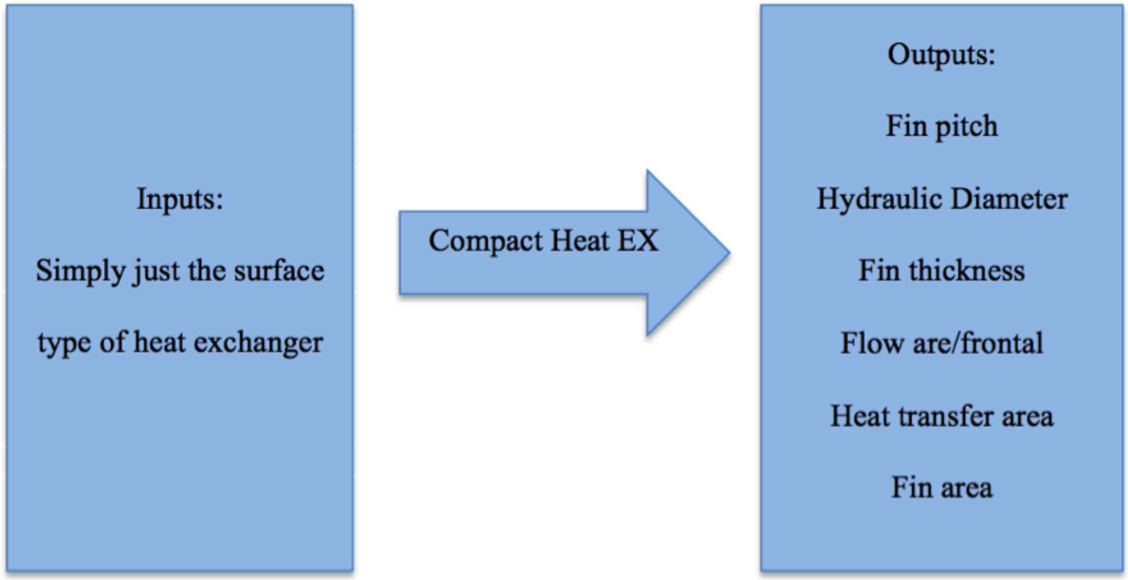



Fig. 4.5. Compact heat exchanger model Input/Outputs

Also the total surfaces for the fins and unfinned tubes can be model using equations below:

$$A_{s,fin,tot} = 2\left(\frac{W}{p_{fin}}\right)\left(HL - N_{t,row}N_{t,col}\frac{\pi D_{out}^2}{4}\right) \tag{4.20}$$

$$A_{s,unfin} = \pi D_{out} L_{tube}\left(1 - \frac{th_{fin}}{p_{fin}}\right) \tag{4.21}$$

## 4.6 Cooling Coil Model

As discussed earlier this modeling approach uses two different methods to come up for the heat transfer values in cooling and heating coil. The details of each wet coil and dry coil will be discussed later in Section 4.8. The general approach for each model is mainly range limit or working condition assumptions on the heat exchanger parts then using thermodynamic energy balance equations to calculate heat transfer based on assumptions. Important factor in cooling coil model, as mentioned earlier, is the dew point temperature values for air when condensation happens. Calculating heat capacity for each section of the coil and also air would complete general equation of heat transfer. Also discussed earlier effectiveness method and number of transfer units would allow us to estimate temperature and models more accurately:

$$\dot{q}_{dc,max} = \dot{C}_{dc,min}\left(T_{a,in} - T_{w,in}\right) \tag{4.22}$$

$$\epsilon_{dc,max} = \frac{q_{dc}}{q_{dc,max}} \tag{4.23}$$

## 4.7 Pre-heat Coil Model

Pre heat coil basically prevents cooling coil from freezing. The valve for pre heat coil opens when the temperature in below 50 degrees Fahrenheit to keep the coil from freezing. The modeling for heating and cooling coil is almost the same except the fact that there will noy be any separation of wet dry coil and, in fact, the entire coil will be considered as dry.

This part of modeling also uses same energy balance and heat transfer equations used in cooling coil model. In the next section there would be detailed information of energy balance and heat transfer equations for each method.

## 4.8 Coil Performance Model

As mentioned earlier this research includes methods of calculating the performance for coils inside the air-handling unit. The advantages of this method is basically based on the mechanical inputs for each system and whats called semi-mechanical modeling. Consider knowing some mechanical information about the coils and using them as the input to the system. Later sensor information will be used to provide rest of thermodynamics characteristics for the equations.

### 4.8.1 Dry Coil Model

Dry wet coil method divides coil into two different regions: dry part and wet part. As it was explained in Figure 2.12 dry part is considered the starting point part until the saturated line or the dew point temperature. So the input temperature to dry coil is normal outside air temperature and also the output temperature of the coil is the dew point temperature.

$$T_{a,dc,out} = T_{dp} \tag{4.24}$$

Using the internal library of the EES we can also calculate the specific heat capacity of the moist air. On the other side we also determine the specific heat capacity for the water.

$$\dot{C}_{a,dc} = \dot{m}_a C''_a \tag{4.25}$$

$$\dot{C}_w = \dot{m}_w C_w \tag{4.26}$$

Assuming that the cooling coil is large enough, so the temperature can reach the dew point. After that we can calculate the amount of heat transfer for dry coil.

$$\dot{q}_{dc} = \dot{C}_{dc}(T_{a,in} - T_{a,dc,out}) \tag{4.27}$$

Calculating minimum heat capacity

$$\dot{q}_{dc,max} = \dot{C}_{min,dc}(T_{a,in} - T_{w,in}) \tag{4.28}$$

At the end using effectiveness of the dry coil we can calculate the heat transfer for dry coil method.

$$\epsilon_{dc} = \frac{q_{dc}}{q_{dc,max}} \tag{4.29}$$

### 4.8.2 Wet Coil Model

In order to go through the analysis for wet coil, first we need to determine how much fraction of the heat exchanger was used as a dry coil so we can the rest of resistance and area as wet coil.

$$UA_{dc} = NTU_a \dot{q}_{min,dc} \tag{4.30}$$

Using number of transfer units method we can determine the conductance required in dry coil. For calculation of conductance we need to use the Heat exchanger function in the EES. As it was discussed in Chapter 2 there are two ways of analysis for Heat Exchangers. One is the number of transfer units and the other is log mean temperature difference. So in this scenario was decided to move on with NTU analysis since we are separating two parts in the heat exchanger and temperature values should be estimated.

There are two general forms that EES uses to calculate the heat exchanger analysis.

$$\epsilon = HX(TypeHX, Ntu, C_1, C_2, Return) \tag{4.31}$$

or

$$Ntu = HX(TypeHX, \epsilon, C_1, C_2, Return) \tag{4.32}$$

First function reruns epsilon value and second option returns number of transfer units. The flow configuration is defined by different types of flows, which are listed:

'parallelflow' 'counterflow' 'crossflow both unmixed' 'crossflow one unmixed' C1 must be the unmixed fluid. 'shell and tube N' 'regenerator'

C1 and C2 are capacitance rate in above equations that in some cases we should be careful choosing them. In the most cases they do not matter which fluid is C1 or C2, but in a cross flow heat exchanger C1 should be the unmixed fluid. Mass flow rate (e.g., kg/s or lbm/hr) and fluid specific heat (e.g., J/kg-K or Btu/lbm-R) have the output of capacitance rate. Calculating conductance we can get the total resistance of the dry coil by the inverse of conductance.

$$R_{dc} = \frac{1}{UA_{dc}} \tag{4.33}$$

So at the end the total resistance of the water side is made up by fouling resistance, resistance to conduction through the tube and convection resistance to air side.

$$R_{dc} = \frac{R_{in} + R_{f,in} + R_{cond}}{F_{dc}} + \frac{1}{h_a A_{tot} F_{dc}} \tag{4.34}$$

F-dc would give us the fraction or percentage of heat exchanger used as the dry coil. So the rest of heat exchanger will be used as the wet coil.

$$F_{wc} = 1 - F_{dc} \tag{4.35}$$

### 4.8.3 Enthalpy Based Effectiveness

Enthalpy based effectiveness basically considers the coil as entirely wet based on the idea that not all the air will get into the same situation of dehumidification and condensation. Air that as passing closer to the fin and towards the center of the coil, will get more energy transfer with result of dehumidification. Also, some air can bypass the coil since they are not in the center of the coil. This method can actually explain that even though the mean air temperature is somewhat greater than dew point temperature but still condensation can occur (Figure 4.6).

In this case the effectiveness is based on the enthalpy and humidity ratio but not the temperature.

$$\epsilon = \frac{\omega_{a,in} - \omega_{a,out}}{\omega_{a,in} - \omega_{a,out,min}} \tag{4.36}$$

$$\epsilon = \frac{i''_{a,in} - i''_{a,out}}{i''_{a,in} - i''_{a,out,min}} \tag{4.37}$$

The enthalpy out and relative humidity can be calculated using these two equations. After using the energy balance equation we can find the heat transfer and mass balance for coil analysis.

Once we assume the entire coil is wet, we can calculate the heat capacity ratio in EES based on the equation below.

$$C''_{sat,a,ebe} = \frac{[i''_a(T_{a,in}, p, RH = 1) - i''_a(T_{a,out,ebe}, p, RH = 1)]}{(T_{a,in} - T_{a,out,ebe})} \tag{4.38}$$

Since it is assumed coils are entirely wet, relative humidity value is set to 1. Therefore, the capacitance rate of air can be modeled as:

$$\dot{C}_{a,ebe} = C''_{a,sat}\dot{m}_a \tag{4.39}$$

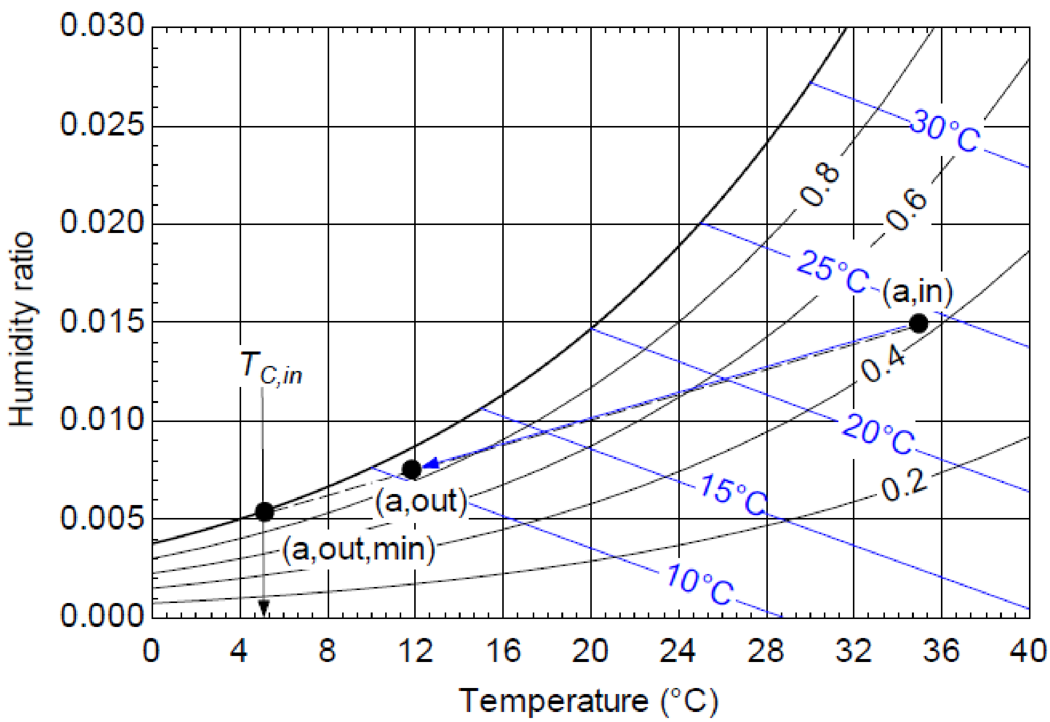



Fig. 4.6. Enthalpy based effectiveness air path assumption [33]

Once the total coil is wet, the thermal resistance can be calculated as.

$$R_{ebe} = R_{in} + R_{f,in} + R_{cond} + \frac{c''_a}{h_a c''_{a,sat,ebe} A_{tot}} \tag{4.40}$$

And therefore the conductance of the wet coil is the inverse of resistance:

$$UA_{ebe} = \frac{1}{R_{ebe}} \tag{4.41}$$

The number of units as it was explained before is calculated using equation below:

$$NTU_{ebe} = \frac{UA_{ebe}}{\dot{C}_{min,ebe}} \tag{4.42}$$

An the end Heat Exchanger function in EES is used model the heat exchanger in enthalpy based effectiveness method. Using also psychometric chart the outlet air enthalpy and relative humidity is calculated. The rate of heat transfer and also rate of condensation is thermodynamically modeled as:

$$\dot{q}_{ebe} = \dot{m}_a (i''_{a,in} - i''_{a,out,ebe}) \tag{4.43}$$

$$\dot{m}_{cond,ebe} = \dot{m}_a(\omega_{a,in} - \omega_{a,out,ebe}) \tag{4.44}$$

Values and results of these equations are discussed in Chapter 6. Both models give us amount of heat transfer and also amount of condensation, but since the origin of the models is different we are expecting close results, but slightly different as it is discussed in Chapter 6.

# 5. POWER OUTPUT CONTROLLER

Ventilation rates in buildings are mostly ruled by the organization standards and regulations. These rates can affect the whole energy usage of the air handling units. Many of current regulations are based on the zone and areas in different countries and continents rather than focusing on the actual healthy factors of the building [37].

After investigating in current test building it was found that the ventilation for the air handling unit is on all the time since there is no good way of measurement for the fresh air needed inside the building. The building will operate more efficient if different classrooms air ventilation can be optimized by implementing a real-time occupancy-based controller.

The idea of using this power output controller is to optimize the fan energy consumption in each room based on $CO_2$ levels and air ventilation needed to lower the $CO_2$ profile in the building. By this method, the waste energy of unnecessary ventilations can be reduced and eliminated. Also this assumption for air ventilation should be always valid since air quality is the main reason of ventilating the air inside the building. This occupancy level is linked to the $CO_2$ level that can be measured. This will be discussed in details later in Chapter 8.

## 5.1 Fuzzy Logic Controller

The term Fuzzy comes from the opposite meaning of true and false. This research has chosen this method to make a continues controller in order to estimate and model the output power for the fan, VAV or etc. This model can be general and be used by many other applications. In this research $CO_2$ values have been chosen to be the input to the system. Fuzzy logic controller consists of three sections: input, output, and membership functions. Figure 5.1 shows the schematic of fuzzy logic controller used in this work.

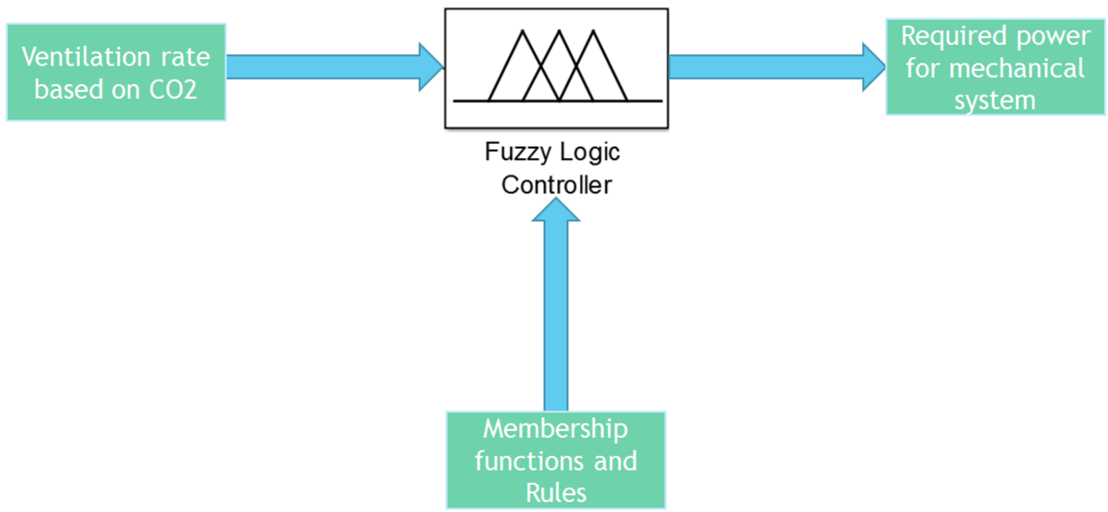



Fig. 5.1. Current fuzzy logic controller

The membership functions have been chosen based on the characteristics of the air handling unit and amount air quality needed in the building.

## 5.2 Membership Functions

Membership functions are set of rules that are determined based on the system characteristics. Figure 5.2 shows how three different regions cold, warm and hot are corresponding with temperature axis to define the rule of functions.

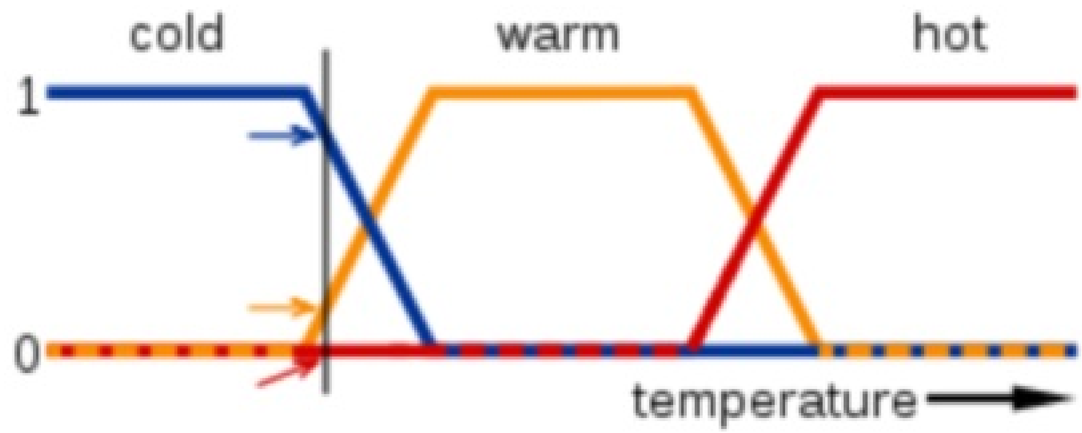



Fig. 5.2. Fuzzy logic membership functions

### 5.3 Simulink Control Blocks

Matlab Simulink software has been used to model the fuzzy logic controller and setting the membership functions rules. There is a Matlab script also has been written to work inside the fuzzy logic block diagram.

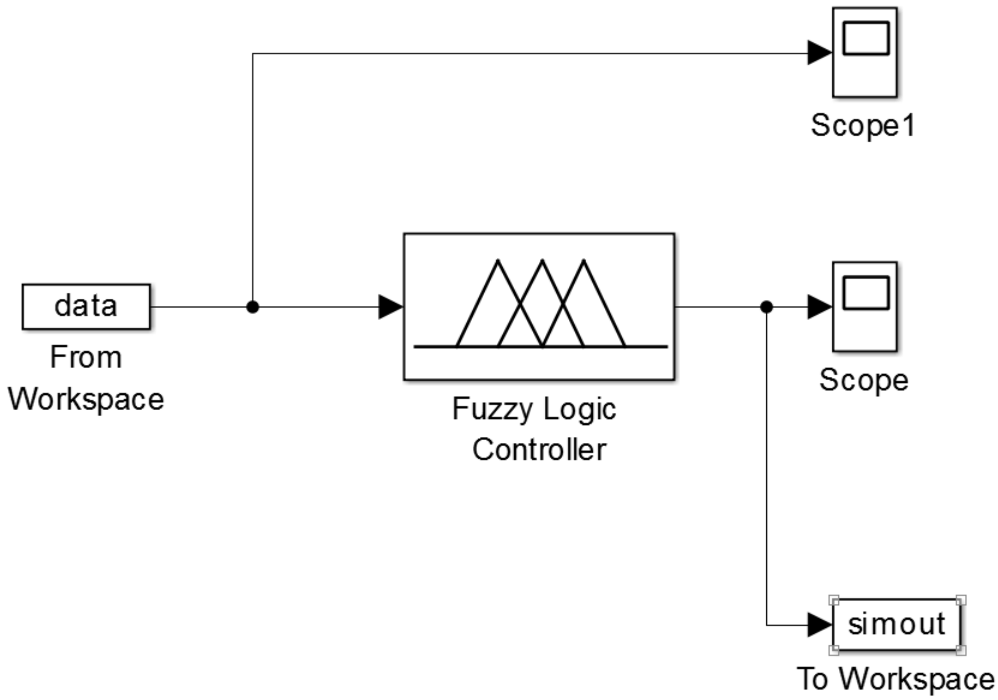



Fig. 5.3. Example of Simulink blocks

Data is generated from the script into the workspace. Multiple functions can be called from fuzzy logic controller as well as membership functions and rules defined for the system. Scopes for the system will allow us to view and plot the results real time. So, as long as the modeling is running we can visualize the output of the controller. More details and results of the controller output as well as energy reduction associated with using this type of controller will be discussed later on in Chapter 8.

# 6. MODELLING RESULTS AND VALIDATIONS

## 6.1 AHU Model Validation

Real-time data were collected during the analysis time as the inputs of the model. Some of these inputs are as follows: physical properties of the coils and air handling unit, volumetric flow rate of air, the static pressure for the duct, inlet air temperature, inlet air relative humidity, and inlet water temperature.

The heat exchange comparison and AHU modeling validations are explained later in this chapter. The validations in heat exchanger modeling parts were based on comparison of two different modeling results with experimental results of heat exchanger. Errors on heat exchanger were mainly compared based on inlet air relative humidity, since it was concluded that has the most effect heat exchange values variations. Also solutions and recommendations are provided when the modeling does not meet the accuracy requirements. $CO_2$ model validations were based on how the models meet the air quality requirements mainly comparing as ppm values (details in Section 6.3). Since the most important factor in ventilations needed in buildings is $CO_2$ ppm.

Pressure for chilled water was used as the average of campus building since there is no specific sensor for this test building. The data is valid since the usage for building is almost the same and chilling water is being purchased for the whole campus. Information for water flow rate also was collected. Table 6.1 shows different data sets were collected during the analysis. Data set number one shows building data collected for heat exchanger modeling as shown the same as model inputs in Figure 4.3. Data set number two shows data collection for $CO_2$ analysis the results of which will be discussed later. $CO_2$ data collections were test with 2 hours of dataset then data was collected for a whole week in order to get persistent weekly results and energy reduction information. In general for heat exchanger modeling was expected to re-

Table 6.1.
Description of data sets

| Data Set | Data Collection Period | Sampling Time | No. of Samples |
|---|---|---|---|
| 1 | 09/17/2015-10/03/2015 Building data for heat exchanger modeling | 16 hours | 2,831 |
| 2 | 09/29/2015 CO2 sets | 2 hours | 200 |

ceive more accurate results on enthalpy-based effectiveness. For $CO_2$ validation also fuzzy logic controller was expected to be more accurate and robust to the ventilation demand.

### 6.1.1 Dry Wet Coil Model Validation

Figure 6.1 shows a comparison between experimental values for the amount heat exchanged and the wet dry coil modeling. As it is shown in the graph there is a good consistency between model and experimental values. The submodel which was test here is the heat exchanger. There is also error associated with specific points and data set in the model that is discussed later in this paper. The main difference of this modeling and experimental values is that the modeling on heat exchanger makes two different scenarios for dry and wet region but experimental values are calculated based on the input and output of the heat exchanger. The model cannot predict overshoot when system starts. When there is an overshoot in experimental values it takes time for the model to pick up with the real values but at the end the trend for both data sets are almost the same.

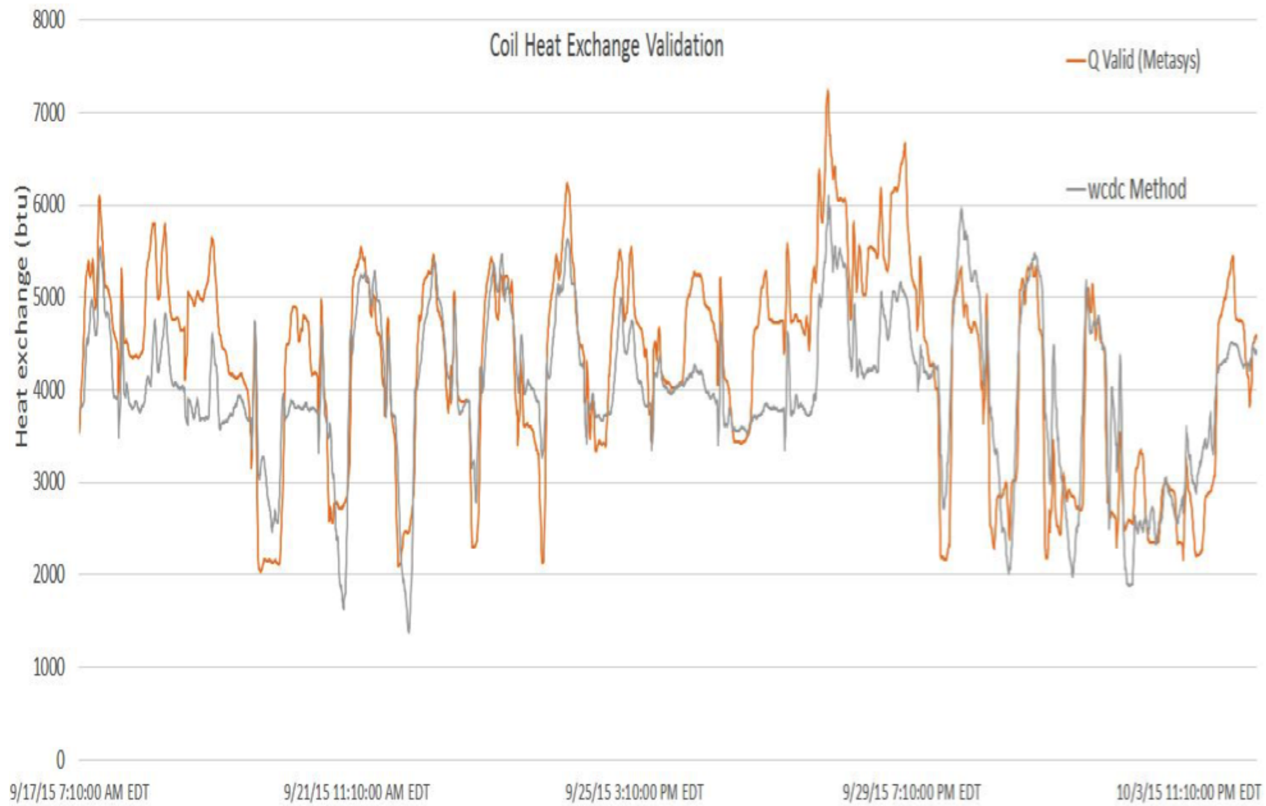



Fig. 6.1. Dry wet coil method heat exchange comparison

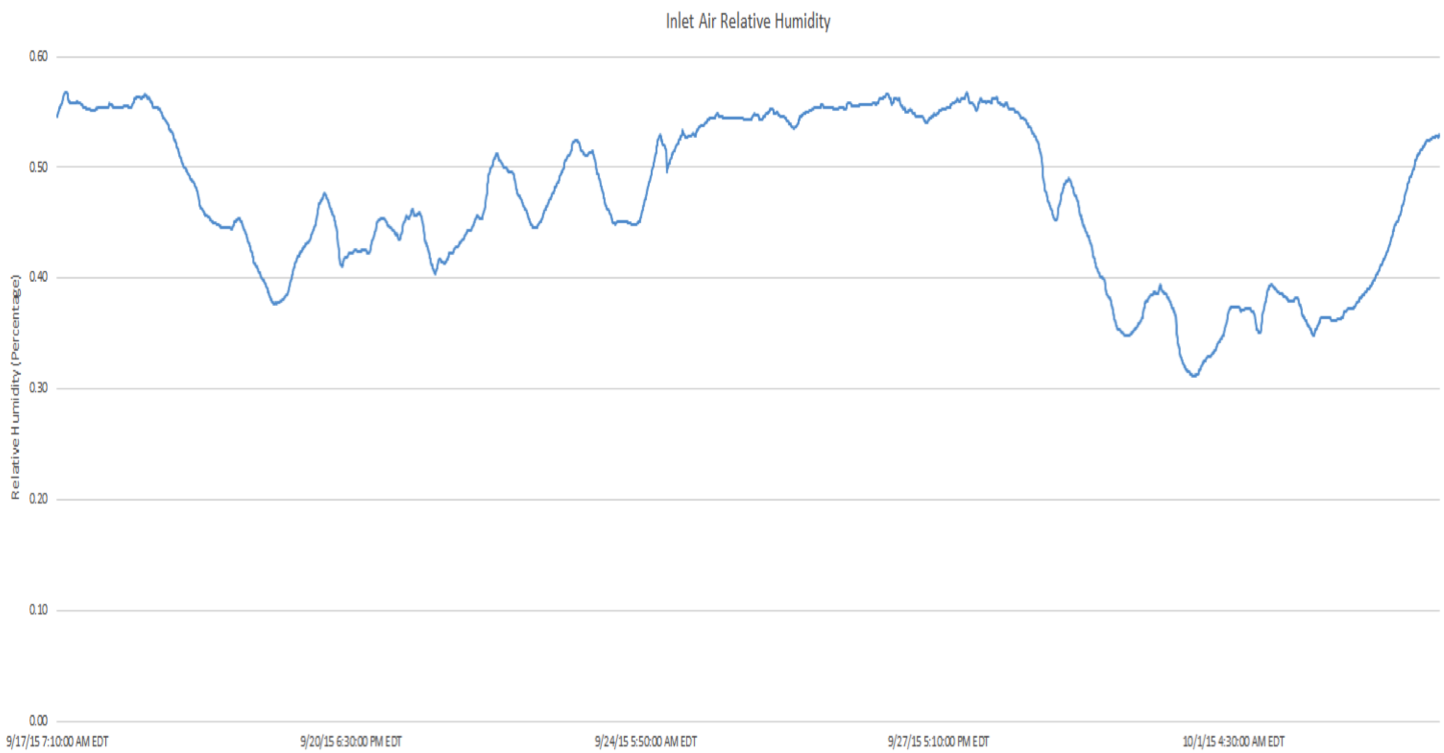



Fig. 6.2. Inlet air relative humidity

Figure 6.1 shows the comparison between wet dry coil model and experimental values in the coil heat exchanger. Figure 6.2 shows the relative air humidity during the analysis period. This figure shows how the wet coil dry coil analysis trend would change during the data analysis. Later this input data is used to explain the accuracy of each model. The modeling error and comparison in Figure 6.6 can be compared with inlet air relative humidity results from this section.

### 6.1.2 Enthalpy Based Effectiveness Model Validation

As it is shown in Figure 6.6 the comparison between enthalpy based effectiveness and also experimental values from Metasys software was calculated. The origin of experimental values equation and enthalpy based effectiveness is slightly closed since the enthalpy based effectiveness looks at the enthalpy values through energy balance. Experimental equations are based on input and output of building automation system but temperature wise.

As it was mentioned the enthalpy based effectiveness method is expected to have less error comparing it to experimental values. This also was discussed in Chapter 4. Generally, when there is a spike in experimental values it is harder for each model to get to spike value quickly but at the end the trends merge to the same values. Figure 6.3 shows less data variation and more actual data trend as it is shown in the most areas the trend matches between models. Later in next section the error between models are calculated and discussed in details, the trend in the model also was calculated using the moving average method calculation to make the data more smooth. Figure 6.3 also will be explained more in details in statistical analysis section.

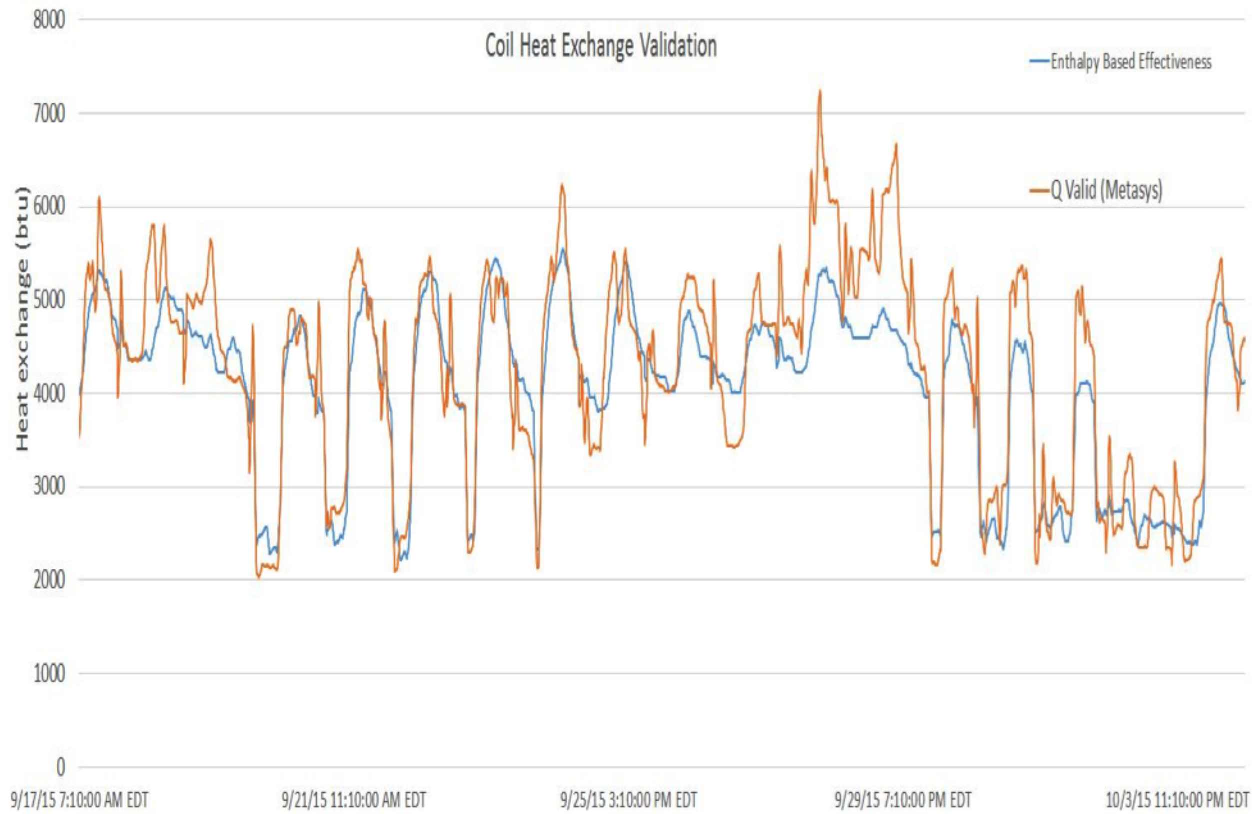



Fig. 6.3. Enthalpy based effectiveness method comparison

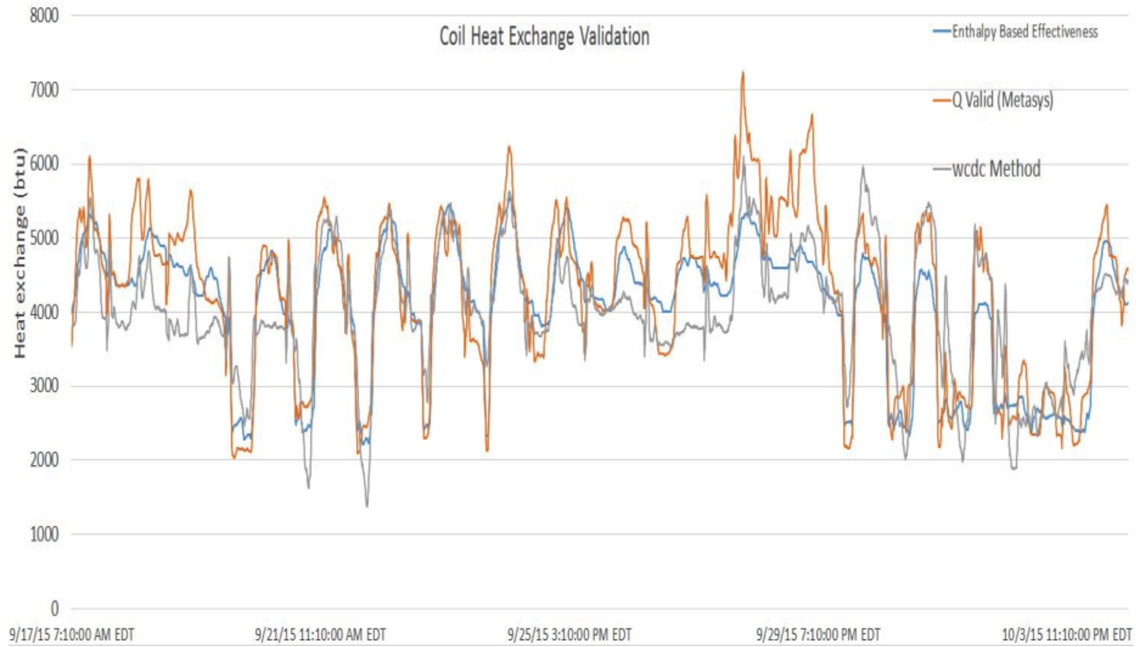



Fig. 6.4. Correlation between the trends for sub models (heat exchanger)

### 6.1.3 Heat Transfer Comparison Validation

Dry wet coil method and enthalpy based effectiveness both give us results that are close to the experimental values, but this section focuses more on the comparison for model results. Also the error for two methods was calculated and is explained in this section.

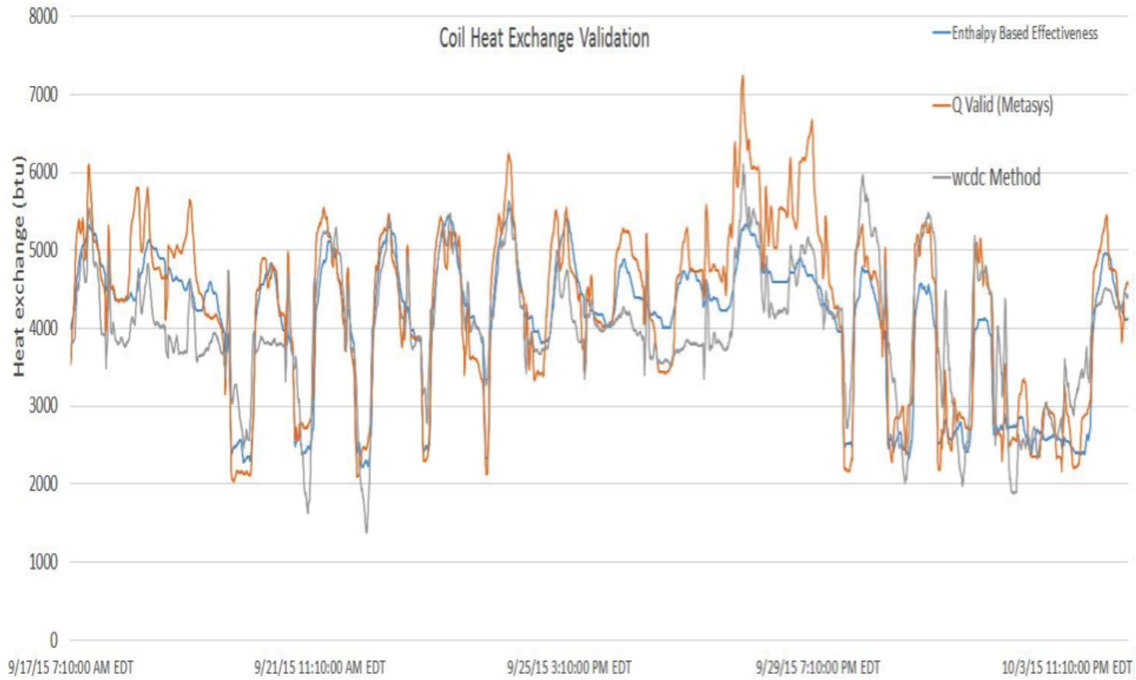



Fig. 6.5. Correlation between heat exchange values and model comparison

From Figure 6.4 its obvious that two models have almost the same results as experimental values which are shown with orange color of called Q valid data. The error between two models also shows the difference of modeling and why there is a change between two models. Figure 6.6 shows the error between two models. Majority of the time this error values remain under 20%, but there are two highlighted areas showing that the consistency between two models is very low and unstable.

Most of the unreliability comes from wet dry coil method as this method is not suitable for the humidity values below fifty percent. In fact, in Figure 6.7 is shown whenever the two regions for relative humidity go below fifty percent. The dry coil method predicts the entire coil is dry. This assumption from wet dry coil method leads to more errors rather than enthalpy based effectiveness method.


Fig. 6.6. Error between two models

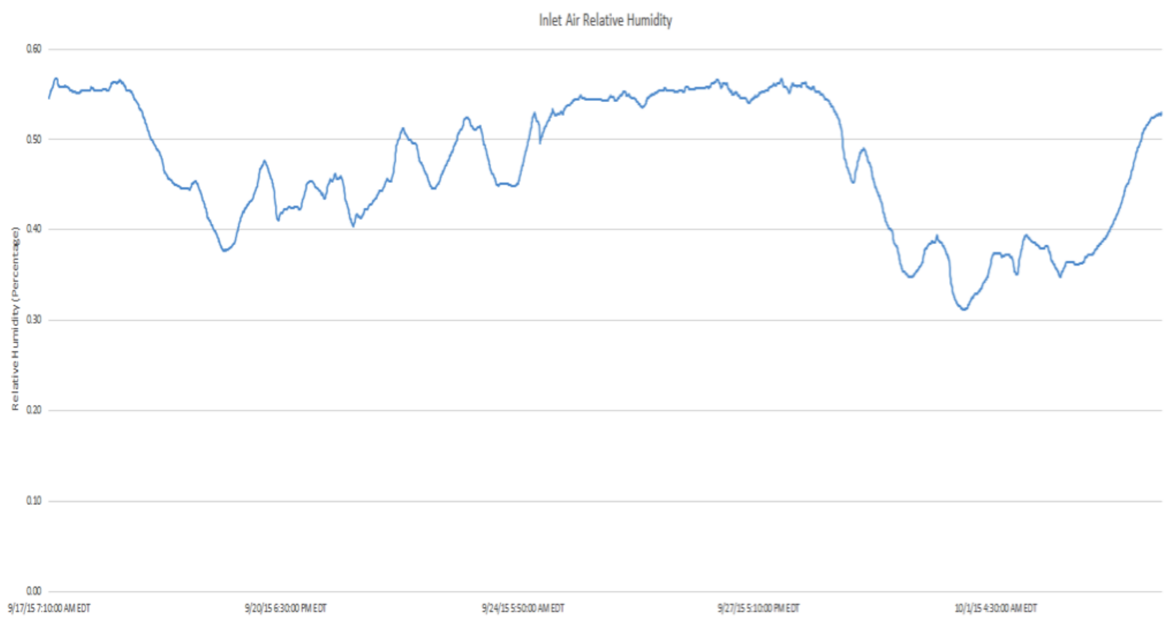



Fig. 6.7. Inlet air humidity

In fact [28] shows whenever we have less relative humidity through the coil there is more error between two models of dry wet coil and enthalpy based effectiveness. Also once we get to higher temperature, since there would be more heat transfer required these errors get to higher values.

Therefore, whenever we have higher values of relative humidity the wet dry coil method could be more valuable and useful since it will give us the details of information on separation dehumidification and reducing temperature. But enthalpy based effectiveness can give us more accurate results if the outside air is pretty dry already once it comes inside the air handling unit box. Table 6.2 includes information on results accuracy corresponding to each modeling. (errors less than 20% in modeling were marked as acceptable results)

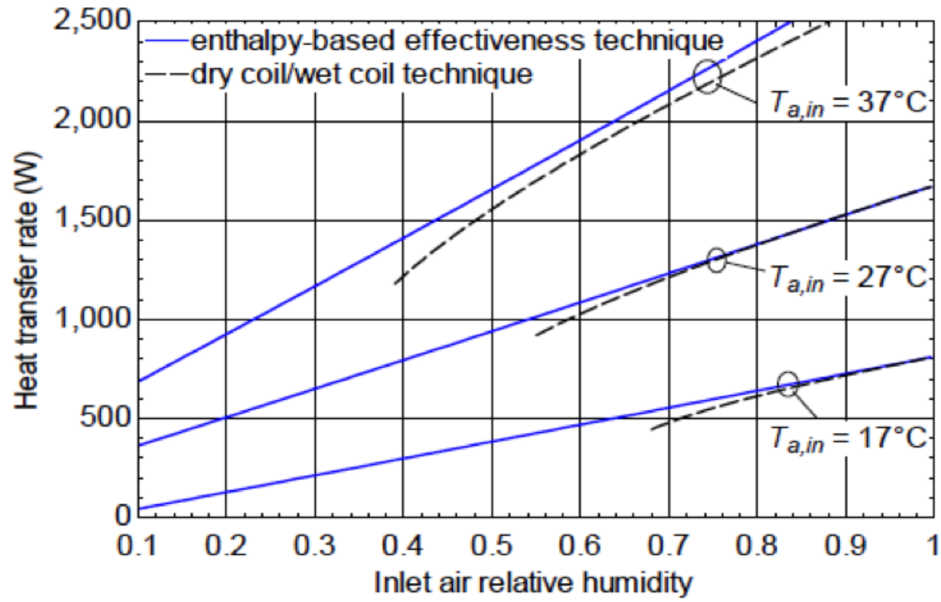



Fig. 6.8. Comparison of two models in various relative humidity and inlet temperature values [33]

Table 6.2.
Error difference between two models

| Model | Humidity above 50% | Humidity below 50% |
|---|---|---|
| Dry Wet Coil Method | Acceptable results with details of dehumidification | Not accurate results for heat exchanger |
| Enthalpy based effectiveness | Acceptable results no details | Accurate results |

## 6.2 Sensor Faults and Accuracy Research

Results and conclusions are made in this chapter based on the integrated model of heat exchanger sub model and also error comparisons discussions. There were different time periods for data collections as there were two different models discussed in this research. Data for the modeling validations was basically from September 17 through October 4, 2015.

Almost a month of data was collected to validate each heat transfer model comparing to experimental values which were calculated through the Metasys software and building automation system. Sensor information also was collected and investigated though this time period to make sure there are valid results available for the models.

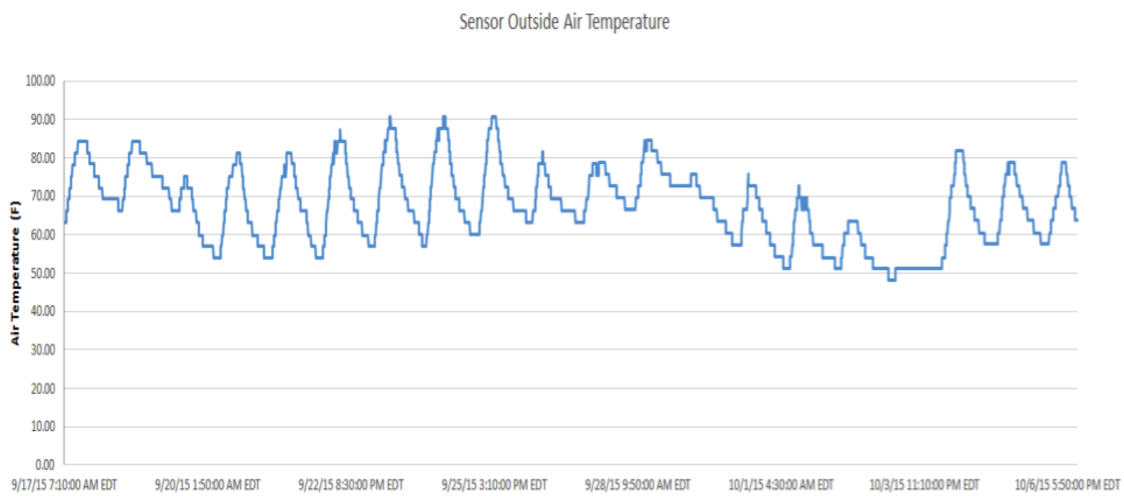



Fig. 6.9. Outside air temperature sensor data

Figure 6.9 shows the data for outside air temperature. Initially this information was gathered through September 17 and October 4, 2015 just to make sure data is valid from the sensors. Later on, as it is shown on the graph one day in October temperature data had a flat line. So the performance of the sensors was under investigation. Figure 6.10 shows investigation to see if the outside air temperature sensor was functioning right. As a matter of fact, the weather data on that day was abnormal from the

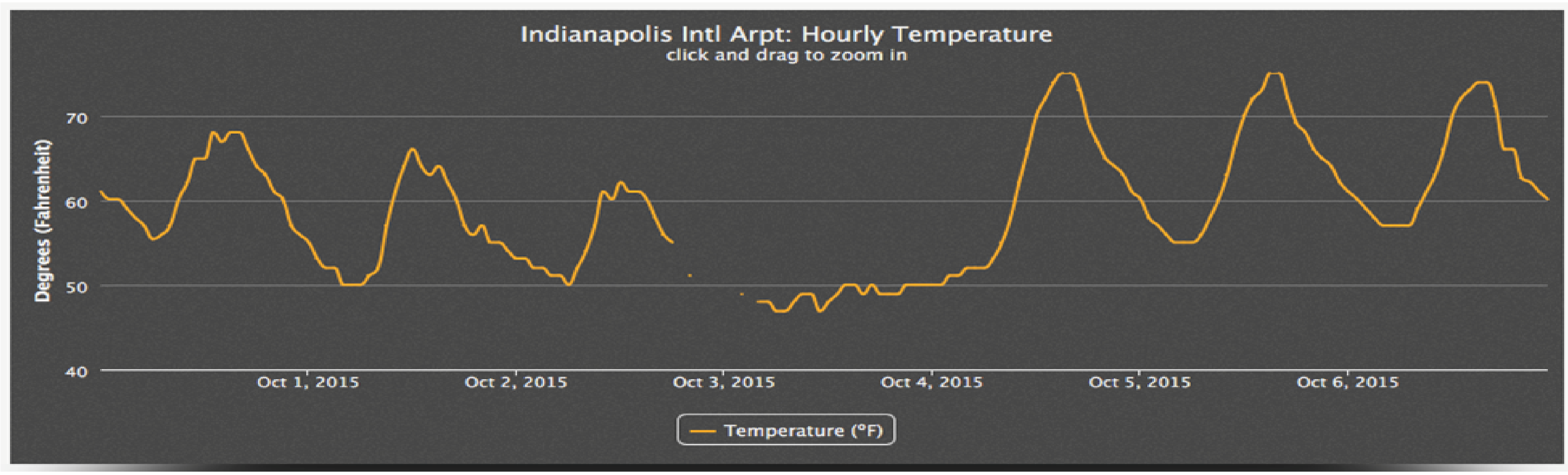



Fig. 6.10. Outside air temperature Indianapolis airport data [38]

reference Figure 6.10 [38]. So the result from out temperature sensors was trusted for the time period of data collection.

Later on, the air flow sensor was investigated to see the right functioning over the same amount of time: September 17 and October 4, 2015. But, as the Figure 6.3 shows there are couple of spikes in the data collection. This was researched and also discussed with building personnel to see why such error occurs for the sensors. In fact, sensors have auto reset and once a day the values from the sensor gets rest so there only one dataset everyday which gives us wrong values. Later on, this data fault was suggested to be removed from input data to the modeling. Moreover, in statistical analysis chapter discusses ways to smooth the data and make it more readable or valuable for model comparison.

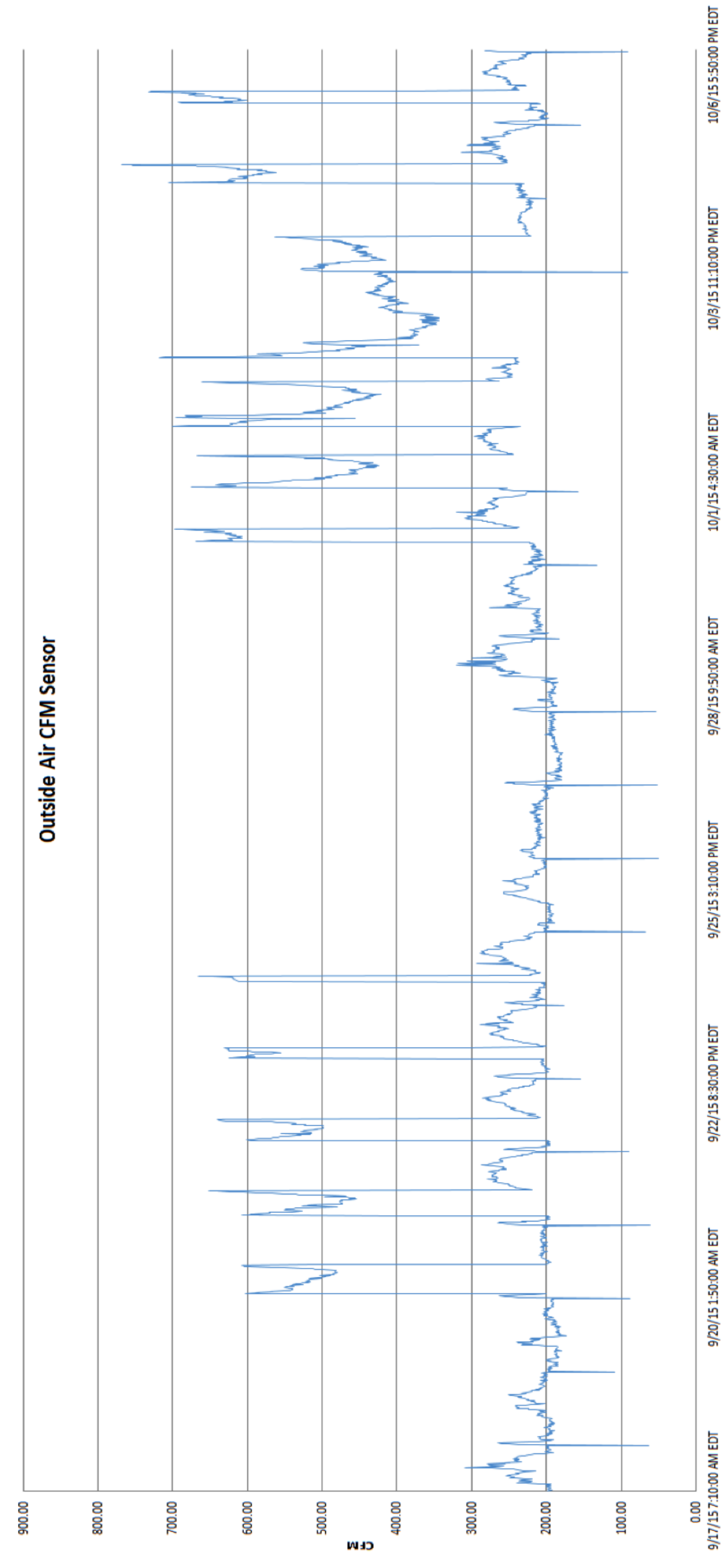



Fig. 6.11. Outside CFM sensor

## 6.3 Ventilation Energy Model Validation

There are many studies focused on air qualities inside buildings. Fresh air allows people to work more efficiently and stay healthy. Regarding the importance of air qualities in schools, studies show students spend on average of 12% of their time in schools more than any other buildings. Also other researches such as [37,39–43] have shown that many buildings have indoor air quality problems.

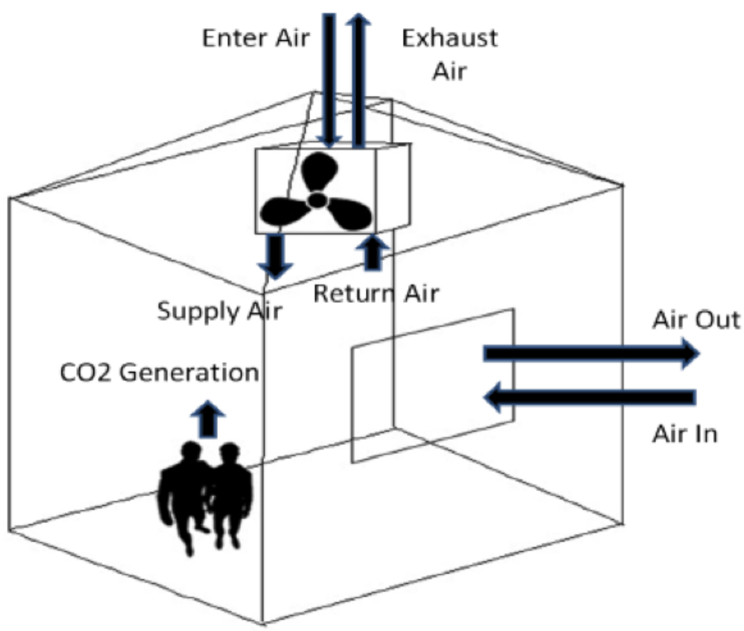



Fig. 6.12. Air ventilation inside building [39]

Such studies show the importance of having a good model for better air quality. Organizations such as American Society of Heating Refrigeration and Air Conditioning (ASHRAE) have defined a rules and limits for the $CO_2$ values inside the buildings. "ASHRAE 62.1" focuses on $CO_2$ levels that mentions typical outside air $CO_2$ level is around 380ppm. ASHRAE maximum target for indoor $CO_2$ value is at 650ppm. So this rule defines above 1,030ppm $CO_2$ is dangerous breathing condition that buildings should avoid to reach to that level. Also other references have set values for $CO_2$ levels what is called as Normal $CO_2$ levels. Table 6.3 has listed $CO_2$ normal operating ranges. This research has used this CO2 settings range in order to find a model for

Table 6.3.
Normal $CO_2$ levels

| Condition | $CO_2$ Values |
|---|---|
| Normal Outdoor Level | 350-450 ppm |
| Acceptable levels | Higher than 600 ppm |
| Complaints of stiffness and odors | 600 to1000 ppm |
| ASHRAE and OSHA standards | 1000 ppm |
| General drowsiness | 1000 to 2500 ppm |
| Adverse health effects expected | 2500 to 5000 ppm |
| Maximum allowed concentration within 8 hours working period | 5000 ppm |

the fan inside current test building. Currently, this fan is running all the time since there is no way of measurement for how much fresh air is needed inside the building. Also the cost calculations have been done at the end of this research and impact of having a good model controller on energy savings. Figure 6.13 also shows the data was collected in the basement area for the whole week in October 2015.

Table 6.4.
$CO_2$ data collection

| Data Set | Time Period | Sampling Time | Number of Samples |
|---|---|---|---|
| $CO_2$ | 10/04/2015 to 10/11/2015 | 7 Days | 1010 |

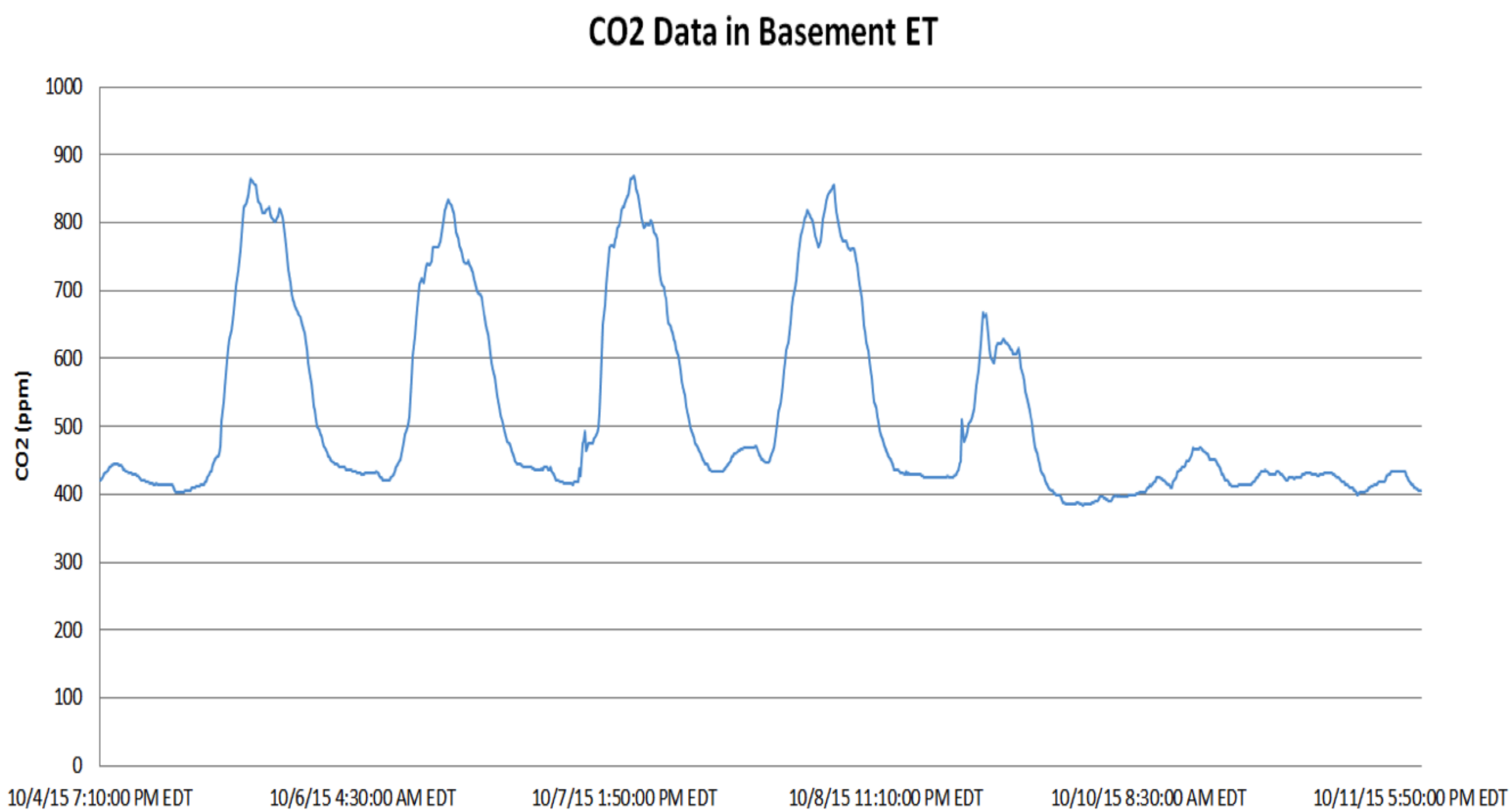



Fig. 6.13. $CO_2$ values for the week of data collection in the test building

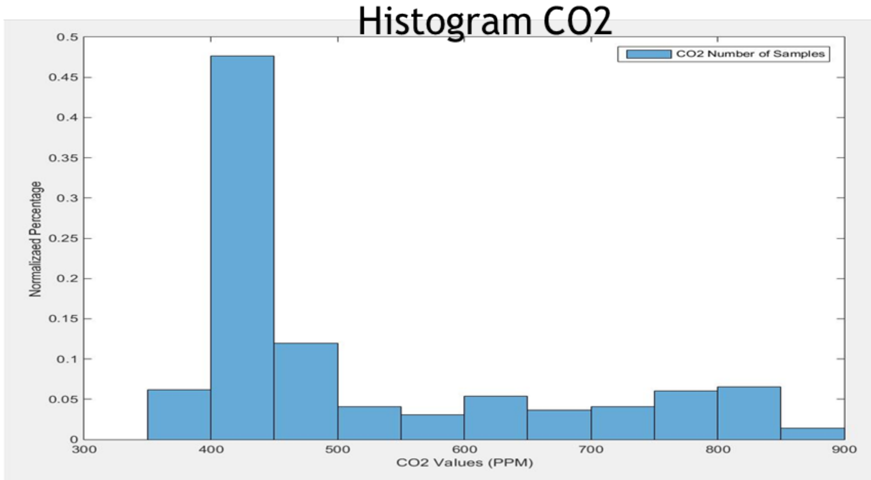



Fig. 6.14. $CO_2$ histogram for ppm values during week of data.

As it is shown in the graph above, the $CO_2$ values go up during weekdays almost for 5 peaks since specially this is the week of classes. As you can see the $CO_2$ values for these days are almost reaching to the limit that was set by ASHRAE standards. This tells us that more ventilation is required during this time of the week. Also, at the end of Figure 6.13 it is clearly seen that $CO_2$ values are pretty low and they are below 500 ppm. That's where no ventilation is required and energy savings can be made by using intelligent model and controller for this kind of building.

### 6.3.1 Fan Discrete ON/OFF Output Method

Closer look at the data in Figure 6.13 shows that most of the time the $CO_2$ values are not higher than limits in fact almost 50 percent of the time these values are below 500ppm. Figure 6.14 shows the histogram of $CO_2$ values , where the x-axis shows the ppm values and y-axis shows the normalized percentage number of samples. Blue bars are percentage values corresponding to $CO_2$ ppm.

A model has been made using Matlab codes to show when the fan should be on to reduce the $CO_2$ values and increase the ventilation. Thus, this model is working on Comfortable Air Level parameter.

$$ComfortAirLevel = 1 - \frac{(CO2 - CO2Desired)}{CO2Desired} \tag{6.1}$$

Comfort air level consists of experimental $CO_2$ values, which is named as $CO_2$ in the model. Also $CO_2$ desired value that is set as a threshold for the air handling unit fans. Using this parameter a Matlab code and a for loop was designed to automatically read the $CO_2$ values from the sensors.

$$CO2Values > CO2Desired \tag{6.2}$$

$$CO2Values < CO2Desired \tag{6.3}$$

In a for Loop

$$ComfortAirLevel = 1 - \frac{(CO2 - CO2Desired)}{CO2Desired} \tag{6.4}$$

For Calculating the fan power, the for loop calculates the comfort air level for each data set and also sets the fan power to the value 0 or 1, meaning that if air level is not 100% the value for fan power should be equal to fan running value. Also, if the comfort air level is at 100% the fan power should be equal to zero, meaning that fan should be off and ventilation is not needed.

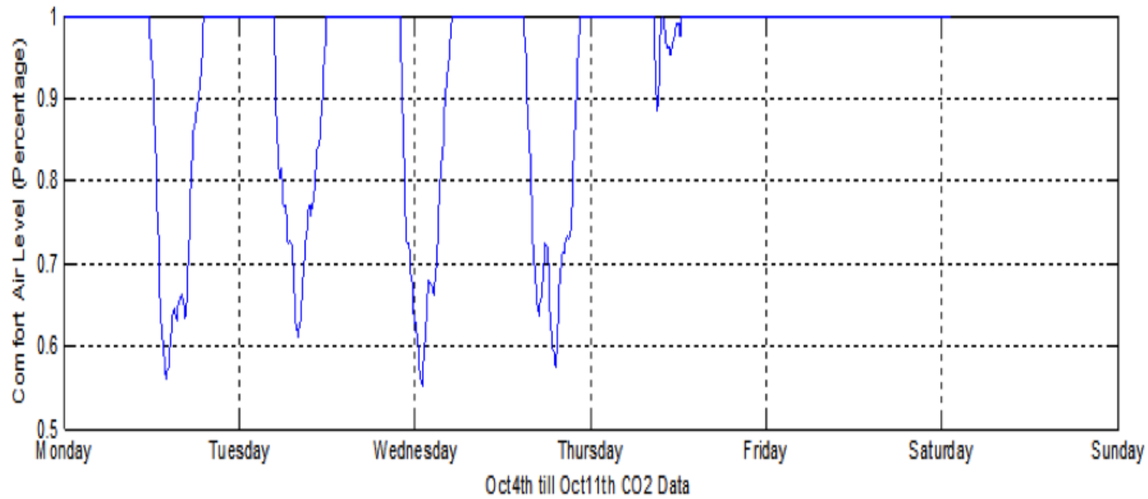



Fig. 6.15. Fan model for corresponding comfort air levels

Example presented in Figure 6.15 shows the percentage of air comfort level data during October 4 until October 11. This figure suggests that most of the time we have 100% comfort air level. Meaning that most of the time the $CO_2$ level inside the building is below our limit and threshold. In this example the $CO_2$ threshold was set at 600ppm.

## 6.4 Fan Continues Output (Controller) Method

Previous method or what is called ON/OFF method is a good modeling strategy that gives us control on the system and eventually energy savings on power outputs. But previous method also had few issues and problems. The ON/OFF method is a discrete controller, so overall ventilation performance and ventilation rate cannot be vary continuously. Also, the other problem is that in order to provide better air comfort level the discrete system will keep the fan most of the time running with higher cost of energy. So, the goal of this section is to control the system, find a balance between air comfort quality and the power consumption. Intelligent controller was introduced in this section of research in order to provide better system performance and control. As it was discussed in Chapter 5, fuzzy logic controller consists of membership functions, which was defined for this specific AHU system and Figures 6.16 and 6.17 show how this membership functions are set for this fuzzy logic controller. Input membership functions are shown in Figure 6.16. There are 5 scenarios in this section explained for the outputs that are driven by inputs.

Moreover, Figure 6.17 shows the controller output actions and corresponding values for power output. This scenario is for the current fan, which has 4kW of power. There is a rule in the power output fan that always keeps the minimum power of 10% running. This action is required to make the flow inside the duct and have the minimum static pressure to keep in air handling unit.

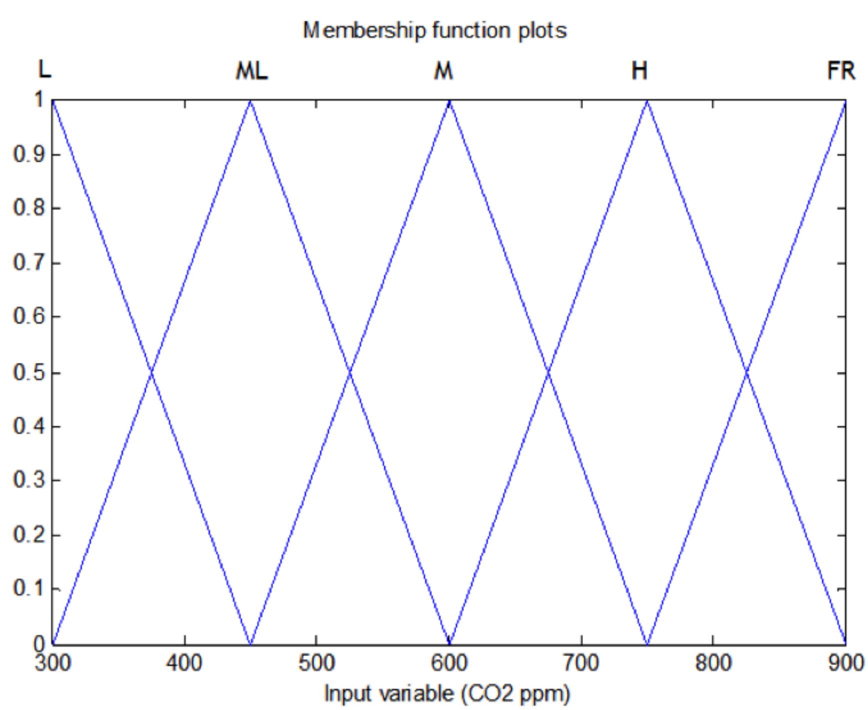



Fig. 6.16. Fuzzy logic controller input membership functions

Table 6.5.
Input membership actions

| $CO_2$ (ppm) | Corresponding Action |
|---|---|
| 300 - 450 | Low |
| 450 - 600 | Medium Low |
| 600 - 750 | Medium |
| 750 - 900 | High |
| Greater or Equal than 900 | Full Run |

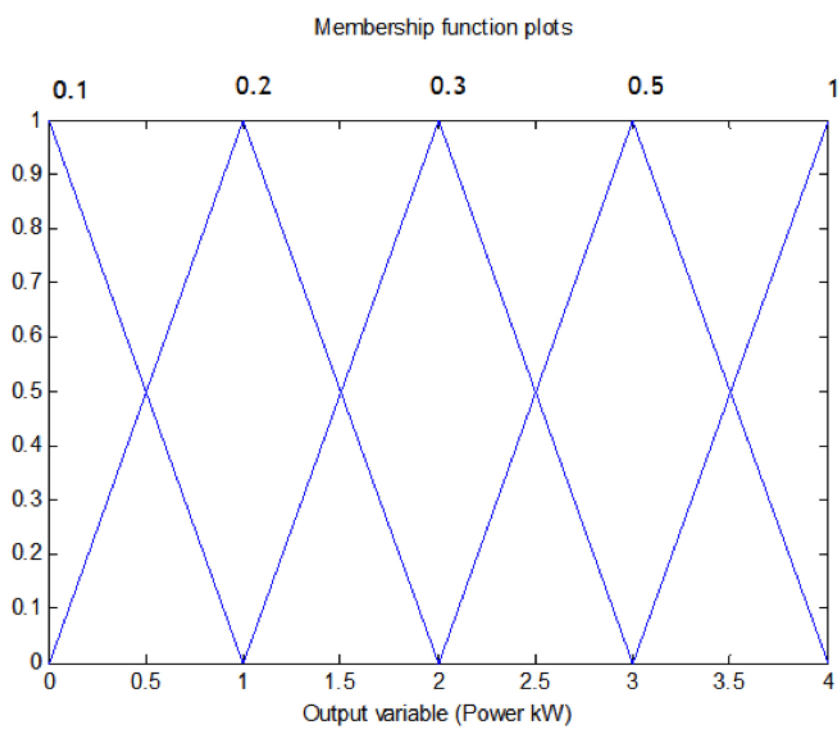



Fig. 6.17. Fuzzy logic controller output membership functions

Also the rule view for the fuzzy interface system is shown through Figures 18 to 22. Figure 6.18 shows how the input of 448 ppm will be translated in fuzzy logic controller

Table 6.6.
Input membership actions

| Fan Output Power (kW) | Corresponding Running Percentage |
|---|---|
| 0 - 1 | %10 |
| 1 - 2 | %20 |
| 2 - 3 | %30 |
| 3 - 4 | %50 |
| Greater or Equal than 4 | %100 |

to the output of 1kW. Figure 6.19 shows how the input of 602 ppm will be translated in fuzzy logic controller to the output of 2.02 kW. Figure 6.20 shows how the input of 843 ppm will be translated in fuzzy logic controller to the output of 3.2kW.

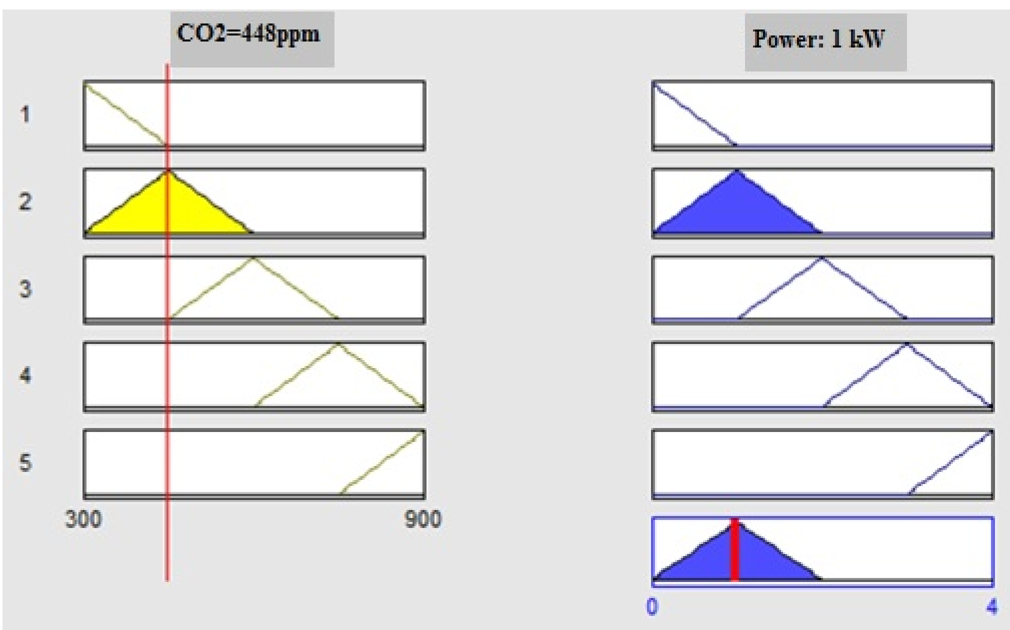



Fig. 6.18. Rule view for fuzzy interface system 448ppm ex (Simulink)

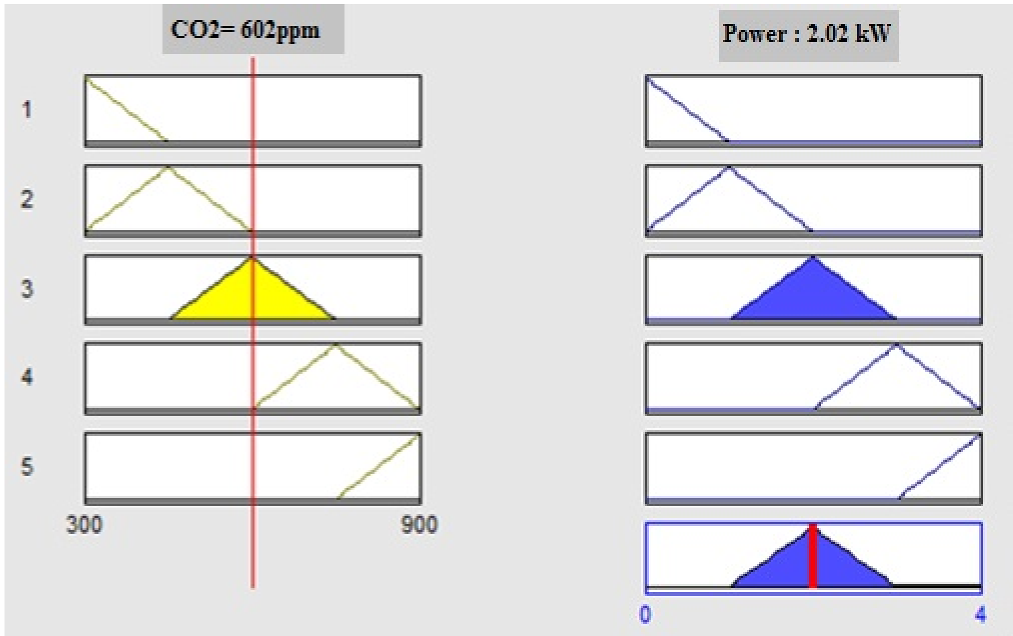



Fig. 6.19. Rule view for fuzzy interface system 602ppm ex (Simulink)

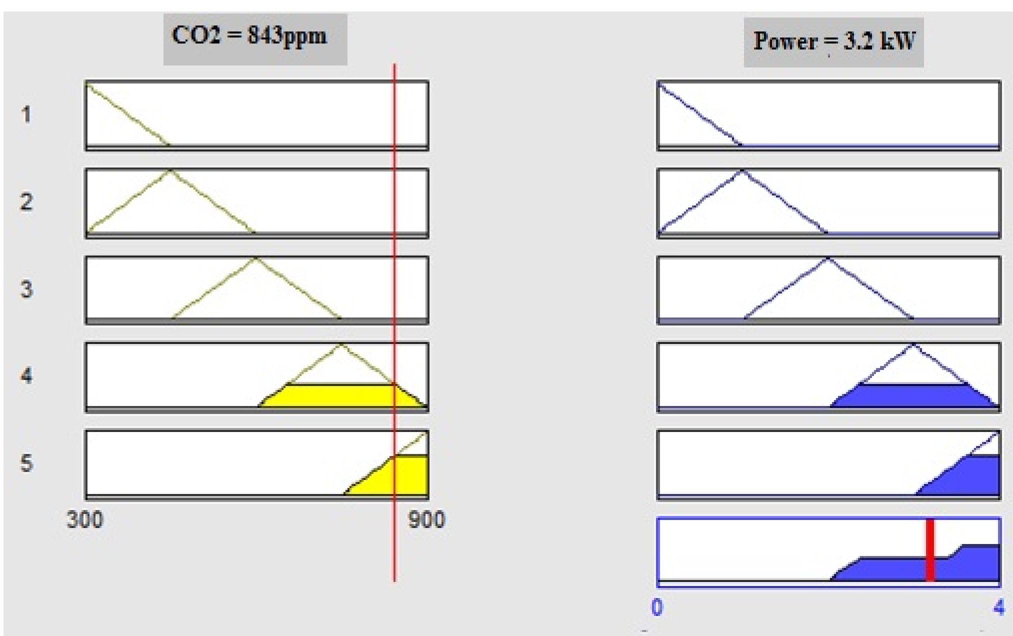



Fig. 6.20. Rule view for fuzzy interface system 843ppm ex (Simulink)

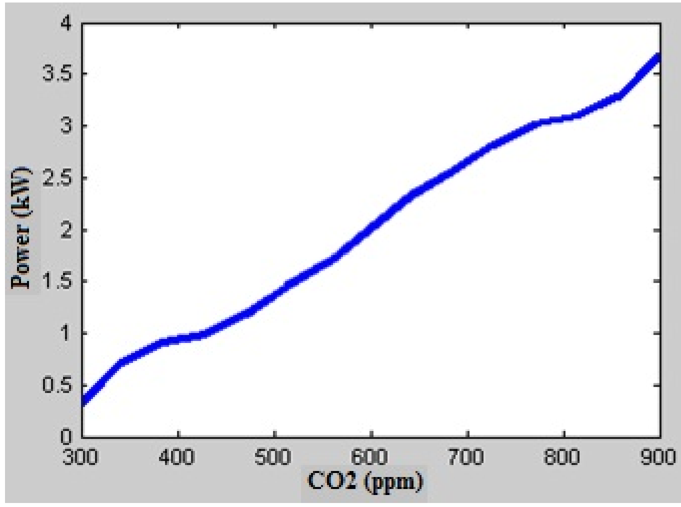



Fig. 6.21. Fuzzy logic controller continuous correlation between Inputs/Outputs

In the end, Figure 6.21 shows how fuzzy logic interface system translates the inputs as CO2 ppm values to the output of air handling unit as a power output (kW) for the system. This method allows us to get better values and optimization on the power output instead of having a discrete ON/OFF values. Also finding the optimal point for the fan running is another advantage of running this type of controller.

# 7. CONTROL STRATEGY OPTIMIZATION RESULTS

In Chapter 6 two different methods were discussed for modelling of air handling unit power outputs. Each method has advantages and disadvantages, so this section is dedicated to show how the controls for the air handling unit were optimized.

## 7.1 Discrete Fan Output Energy Reductions (ON/OFF)

ON/OFF method was used to control the fan output instead of having it run all the time. As it was discussed in Chapter 6, this method is based on comfort air level, which is the top graph in Figure 7.1.

Figure 7.1 also shows the power output required to start the ventilation, when comfort air level is not at a good point. The power output in this section was measured based on the rule that whenever the comfort air level is below 100% the fan should be on and actually equal to 1; as soon as we have 100% comfort air level the fan can go off. This method has some disadvantages as it was discussed in Chapter 6. Better controls were needed to calculate this power, since minimum power required to keep the static pressure inside the duct positive. Also, gradual speed for increasing and decreasing the fan power is more logical, since it will reduce the cost of maintenance on the fan.

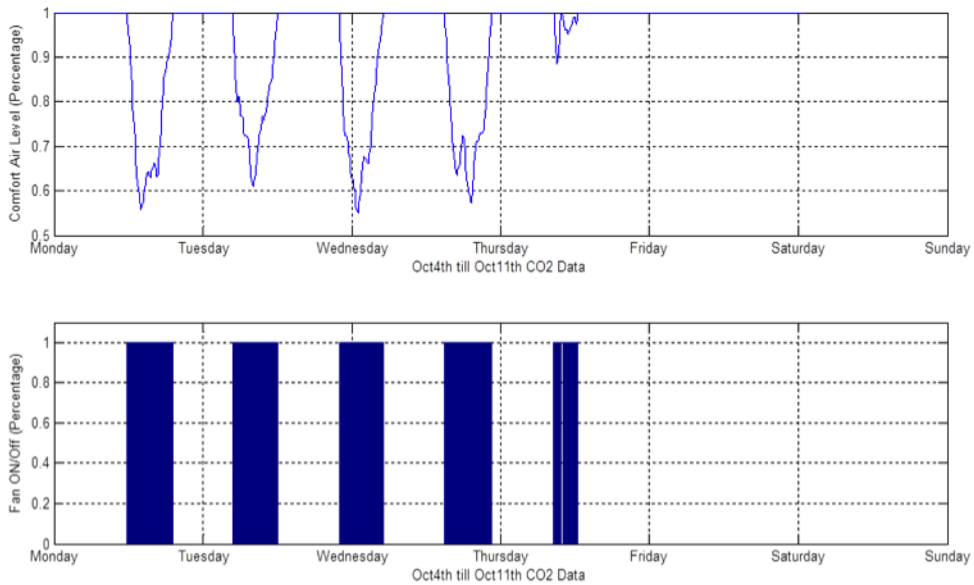



Fig. 7.1. On/Off method modeling

## 7.2 Continuous Fan Output Energy Reductions (Fuzzy Logic)

On the other side the output power was calculated using the continuous calculations and fuzzy logic controller to give the best performance to the system as well as energy reduction on the fan. Figure numbers 7.2 and 7.3 show the system performance using Simulink, Matlab, and fuzzy logic controller method.

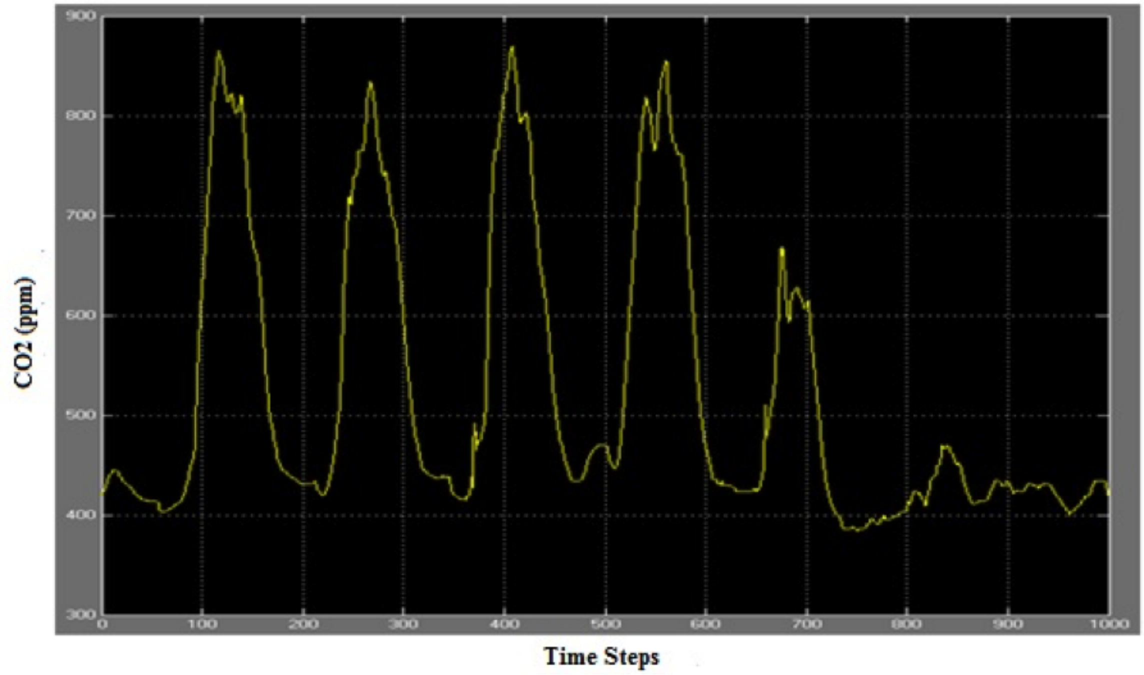



Fig. 7.2. Simulink scope input CO2 data (Simulink)

Figures 7.2 and 7.3 are scopes from Simulink tool. Figure 7.3 shows the power output of the system based on percentage (values from 0 to 1). As its shown, the output of the fuzzy logic controller for the current data set is more robust and optimized. The fan always keeps the minimum power running, so there is always flow in the duct and positive pressure. Also, this method is very responsive and fast to any change in $CO_2$ values. Comparing Figures 7.2 and 7.3 it can be seen that both Simulink scopes have the same trend meaning that controller completely follows the consistency of input data.

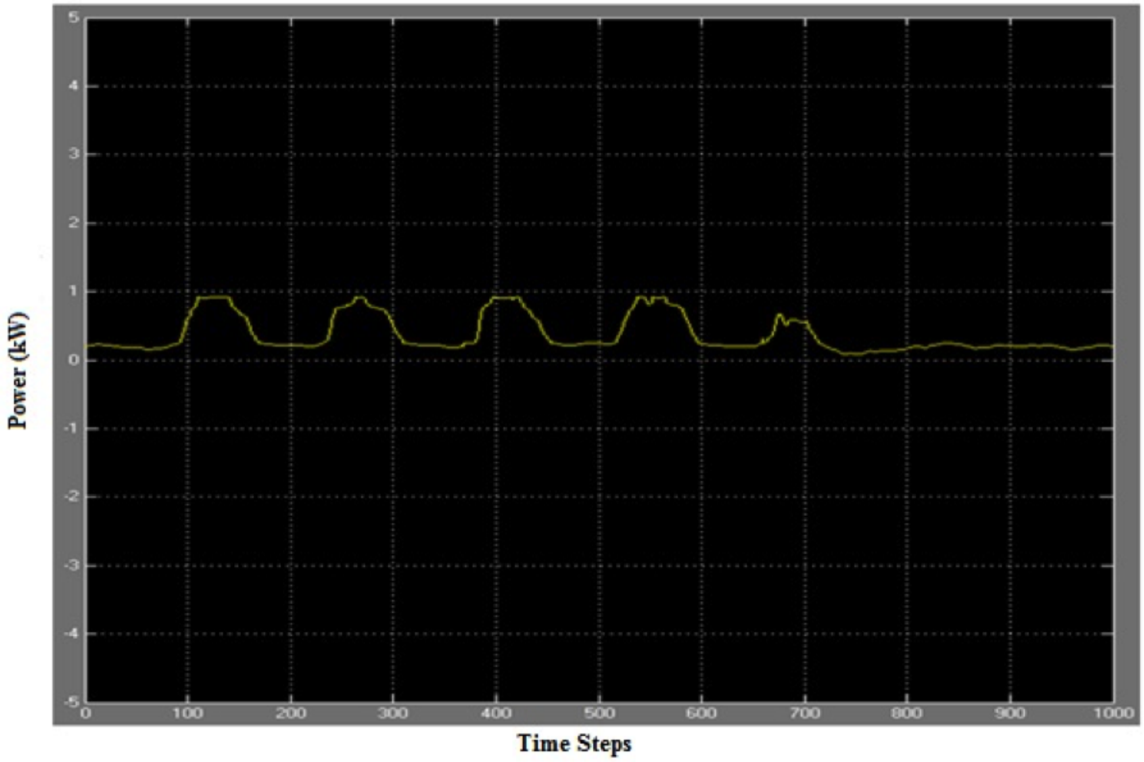



Fig. 7.3. Simulink scope output power (Simulink)

## 7.3 Potential Energy Savings

Energy savings in both methods have been analyzed. Comparisons have been shown in Figure 7.4. ON/OFF method has a blue color and fuzzy logic controller is shown with red. The fact that ON/OFF method will keep the fan off most of the time may be an advantage for the method, but in long term period it will be a problem for most of air handling units, since the pressure inside the duct would decrease significantly.

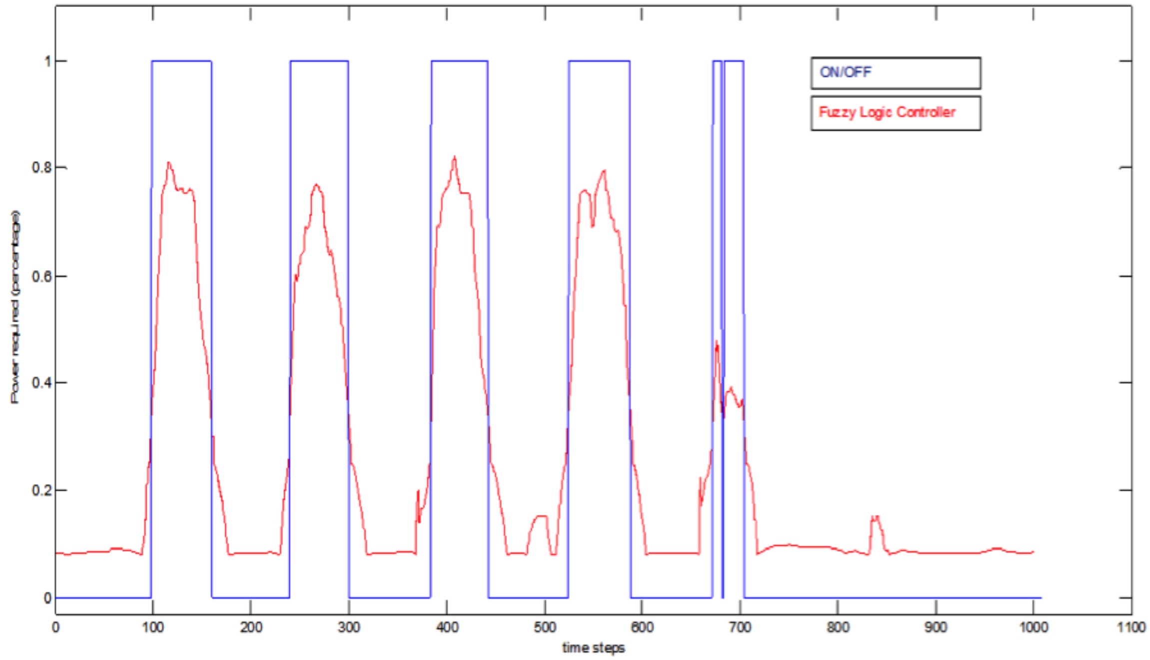



Fig. 7.4. Two controlling methods comparison

The savings were calculated corresponding to each method comparing with the current practice that is having the fan always running, which is the case in this building for ventilation purposes.

Table 7.1.
Energy reduction data collection

| Data Set | Time Period | Sampling Time | Number of Samples |
|---|---|---|---|
| $CO_2$ | 10/04/2015 to 10/11/2015 | 7 Days | 1010 |

Since the data was collected weekly, the baseline for the savings also set on a weekly basis. Table 8.2 demonstrates how much each method can save during week of October. Basically this percentage numbers in Table 8.2 are from comparing the

Table 7.2.
Energy reduction comparison ON/OFF and fuzzy logic controller

| Simulation | ON/OFF method | Fuzzy Logic Controller |
|---|---|---|
| Power Reduction Percentage | 72.94% | 62.79% |
| Weekly Energy Reduction | 490 kWh | 422 kWh |

total fan running time during the whole week. Table 8.2 in second row represents savings calculated by the energy reduction on the Fan. As it was mentioned before, the current power for the fan running in the air handling unit system is 4 kW. ON/OFF method has more savings; however, this method will bring more maintenance cost and reduce the life time of the fans. Also, air handling unit requires positive static pressure inside the duct. This condition can be met with fuzzy logic controller at all times. For other type of air handling units that have only one fan the ON/Off method can be more useful. If fuzzy logic method is used to simulate the power for VAV air boxes then ON/OFF method still has more advantages, but for bigger operations like air handing units based on this research the fuzzy logic method is preferred.

# 8. CONCLUSIONS AND RECOMMENDATIONS

## 8.1 Conclusion for Air Handling Unit Modeling

This thesis is mainly focused on energy efficiency and energy reduction in the buildings. The modeling was done to achieve better monitoring the energy usage and also control the building air handling unit subsystems efficiently. In air handing unit there were two models explained, defined, and modeled using thermodynamic equations and software modeling. Dry wet coil model and enthalpy effectiveness models were also validated comparing to experimental values from the units. Statistical analysis has been done to make the data smoother and more readable. After comparing two models it was concluded, enthalpy based on effectiveness provide less accurate results. Wet dry coil method is more complex analysis considering different regions on the coils but it gives more information on dehumidification and physical system parameters, this would help to estimate the system behavior in more detailed manner.

From the deviation analysis, the reason why two models in some regions have big gaps is mostly because when outside air is already dry, the wet dry coil method does not perform as accurately as enthalpy based effectiveness. So its recommended to use wet dry coil method in humid regions and enthalpy based effectiveness mostly in dry regions. Performance of dry/wet coil in general is higher in our test case. Considering current test case in this research dry wet coil method can be a better fit to show the system performance and more accurate simulations. This accurate modeling helps with energy reduction by estimating the system behavior. Also, fouling and resistance analysis can be an indicator of how our air handling unit performs in general through its lifetime or if any maintenance is needed.

### 8.2 Conclusion for Fan Power Controller

In the conclusion, $CO_2$ analysis and modeling have been done based on wireless data collection. There were two control methods/models described and compared for system power output. The fuzzy logic controller for air handling units has better control performance but less energy reductions. The ON/OFF method has more energy loss but less complicated system as it does not require complex control algorithme comparing to fuzzy logic method. The ON/OFF method would be more suitable for smaller applications, such as single fan HVAC units or VAV boxes inside the building. The fuzzy logic controller would give a better system performance on the whole air handling units. Fuzzy logic controller made energy reduction of 62% for the fan power on the current system, while ON/OFF method made 73% of energy reduction. But its proven for the purpose of this research based on the current condition of air handling unit the fuzzy logic controller is a better fit with better system performance.

### 8.3 Recommendations for Future

#### 8.3.1 Control Implementations

Implementing the current strategy and controls on the air handling unit can be a huge milestone and improvement of current system performance. Based on analysis and theoretical data, the fuzzy logic controller would be a great energy optimization method.

#### 8.3.2 Powerful and Faster Wireless Communication System

As it was discussed, current wireless system has a lot of limitations due to the outdated technology used during the research. There are many other products on the market for wireless communication that can enhance the speed of current project and ease the process of data collection.

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# LIST OF REFERENCES


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