Modelling of air handling unit subsystem in a commercial building

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Abstract

A real-time energy management system was developed to improve the energy efficiency of an Air Handling Unit (AHU). The system consists of models to analyse the performance of subsystems in an AHU, which was tested using actual data collected from AHU operation via wireless monitoring. The system detects control-related malfunctions such as simultaneously turning on the cooling coil and the pre-heating coil. The system estimated that this type of control malfunction wastes 63,455 kWh within the cooling coil and the pre-heating coil. Furthermore, the system helped identify other energy saving opportunities through set point changes. For the tested case, the opportunities identified had the potential of 77,141 kWh of energy saving during the same study period.

Keywords: energy saving; real time parameter monitoring; mechanical modelling; Air handling unit (AHU)

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NOMENCLATURE

C_{fan}	Fan speed, m/sec
$C_{p,a}$	Air specific heat, kJ/kg.k
$C_{p,w}$	Water specific heat, kJ/kg.k
h_{fg}	Enthalpy of vaporization, kJ/kg
I	RMS Current, Amp
$\dot{M}$	Total mass flow rate capacity of the coil, kg/sec
$\dot{m}$	Current mass flow rate through the coil, kg/sec
$\dot{m}_a$	Mass flow rate of air, kg/sec
$\dot{m}_w$	Mass flow rate of water, kg/sec
$\dot{Q}_a$	Air energy rate, kW
$\dot{Q}_L$	Latent energy rate, kW
$\dot{Q}_s$	Sensible energy rate, kW
$\dot{Q}_T$	Total heating rate, kW
$\dot{Q}_w$	Water energy rate, kW
P	Power, kW
PF	Power factor, %
V	RMS Voltage, V
$\dot{q}$	Volumetric flow rate, m^3/sec
α	Water valve position, %
β	Fan % speed, %
ρ_a	Air density, kg/m^3
ρ_w	Water density, kg/m^3
ΔT_a	Amount of air temperature change, ℃
ΔT_w	Amount of water temperature change, ℃
ΔW	Change in humidity ratio, dimensionless

1. Introduction

The building sector has a higher percentage of energy consumption than either transportation or industrial operations, using about 74% of the total electricity used in the U.S.A. [1]. Air handling unit (AHU) systems accounted for more than 50% of the total energy cost of commercial building in 2013 [2,3]. Thus, improvement of the AHU system's performance can significantly reduce energy consumption in the building sector.

In the past, much research has been done to improve the overall performance of AHU systems using various control strategies. Various control algorithms have been studied such as Model Predictive Control (MPC) [3], Evolutionary Algorithm (EA)[4], Evolutionary Programming (EP) [5], Proportional-Integral-Derivative (PID) Controllers [6,7], supply air temperature optimization in various climates [8], Proportional-Integral (PI) Controllers for Single Zone AHU [9,10], and Dynamic Model of a Heating, Ventilation, and Air Conditioning (HVAC) System [11,12,13]. However, these control systems were designed to regulate the building temperature, improve system operation, or for troubleshooting. They were not used for the energy performance analysis of an AHU system. Furthermore, none of these algorithms completely covered all climate conditions nor provided general solutions for larger buildings since the models were developed for specific systems. Furthermore, these control systems needed to consider more parameters, such as climate conditions, internal loads, and building shape, which require close monitoring.

White-box, black box and grey-box are three approaches that have been used for AHU systems modelling. The black-box model is a statistical and data-driven approach that is mainly used for fault detection [14,15]; whereas the white-box model is a physics-based approach that is primarily adopted for an optimal design. A few researchers have used a data-driven method for modelling using Genetic Algorithm (GA) [16]. The grey-box approach is a combination of physical and non-physical approaches involving a physical model that is developed to illustrate the process characteristics. It was presented by Haghigat et al. [17] as a software framework in predictive control since it combined physically based models with a generic algorithm. Such control tools are used for new AHU systems to ensure both the ultimate efficiency of the unit and the comfort of the occupants, which is the purpose of energy management.

The goal of this research was to increase the energy efficiency of an AHU in a commercial building. The objective was to develop an energy management system with inputs from real-time sensor data to evaluate system performance, estimate the energy consumption and associated cost of the AHU's subsystems, including the heating and cooling coils, at a certain set temperature. This tool will help energy facility managers make evidence-based decisions regarding AHU control to increase energy efficiency.

2. Methods

2.1 Overview

The energy management system is capable of evaluating the AHU's efficiency and unit performance. Performance evaluation of the AHU was accomplished by monitoring control parameters derived from the data of the sensors in the AHU. The monitored parameters were collected and outliers were filtered. Models were then used to analyse the performance of the AHU. A baseline of the energy consumption can be established which was compared to the actual operation of the unit. Energy consumption and potential energy savings were then estimated. The system was implemented in a building with multiple AHUs.

2.2 AHU System

The AHU system is vital to a building's ability to maintain a comfortable space for occupants, thus, it is tailored to meet various needs for thermal control. Fig. 1 is a schematic of an AHU system. In addition, there is a chiller/cooling tower for removing energy from the return air and then dispensing it into the environment and a boiler for adding heat/energy to the supply air going into the building. The fans are essential for moving air through the ducts and transferring it into the office spaces. Inside the building, various air handling systems can be used to deliver air as needed to each room in the building. The energy consumption consists of electricity used to power the fans and the control system and energy from heat exchangers including the heating coils and the cooling coils.

3. Experimental setup

3.1 Building

A building consisting of three floors and a basement was used to demonstrate the functionality of the tool. Each floor has two AHUs to maintain adequate temperatures and air quality. The AHU provides air to a total of 33 offices and 7 labs. Total office square footage is 7,657 ft^2 (711.4 m^2) and total lab area is 6,236ft^2 (579.3 m^2). The labs require outside exhaust air at all times to make sure that none of the chemicals used in the labs are mixed with the return air to the unit. Exhaust fans are also used to maintain a negative pressure in the lab area and a positive pressure in the plenum with respect to the lab space in order to limit the leak of lab fumes into the plenum. Variable Air Volume (VAV) boxes are used to distribute and reheat air before it reaches the offices/labs. Each VAV box controls one or more rooms depending on the size and location. There is one thermostat in every set of offices, which sends a signal to control the VAV box dampers and reheat coils to supply more air at a higher or lower temperature in the room to maintain the desired room temperature.

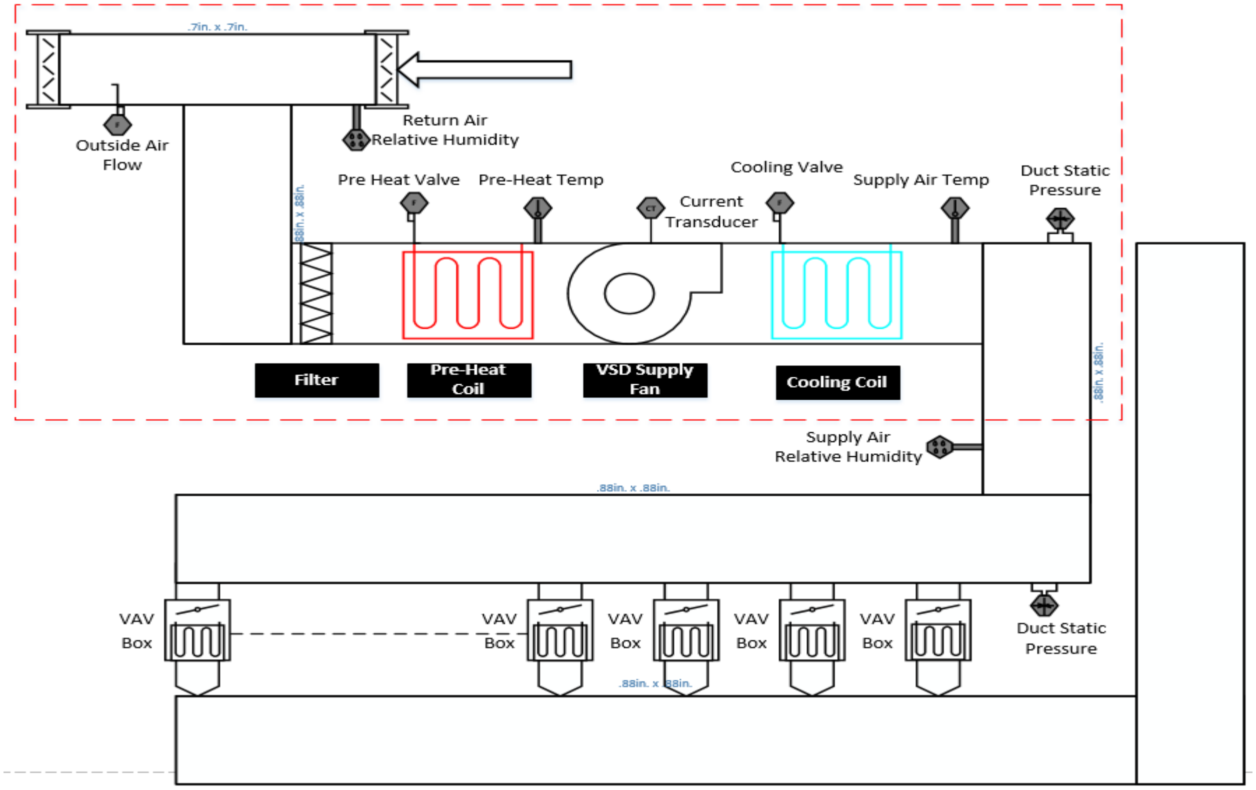

Fig. 1 diagram of the energy users of an AHU

3.2 AHU Operation

The AHU has airflow measuring stations for both outside air (OA) and return air (RA), actuators for RA dampers, preheat coil valves, and cooling coil valves, OA and RA relative humidity sensors, and supply fan drive controllers with current sensors. The AHU operates continuously throughout the day, regardless of occupancy, based on control commands from a central operator workstation. The supply fan runs continuously. The duct static pressure is maintained by modulating the supply fan speed through the Variable Frequency Drive (VFD). The VFD is controlled to maintain a duct static set point of +2" WC (Water Column) which is the AHU's set point and is adjustable at two locations in the duct system. The duct static pressure transmitter controls the VFD through the AHU Controller. An electric static pressure high limit safety device shall stop the supply fan(s) whenever fan discharge static pressure rises above the 5" WC (12.7

cm) (adjustable) high limit. An AHU fan's power, which is a function of RMS Voltage (V), RMS Current (I), and Power Factor (PF), is calculated using equation (1).

$$P = \frac{V \times I \times PF \times \sqrt{3}}{1000} \tag{1}$$

The preheat coil discharge air temperature set point is 53°F (11.7℃), which is adjustable, and the cooling coil temperature set point is 55°F (12.8℃), which is also adjustable. They are maintained by the modulating control valve(s). The cooling is required when the outdoor air temperature and relative humidity (RH) are above 75℉ (23.9℃) db (Dry Bulb) and 50% RH, respectively. The return air relative humidity sensor high limit set point is at 57% RH and discharge air temperature reset point is at 50°F (10.0℃). Furthermore, the humidifier control valve is modulated to maintain a return air relative humidity set point of 35%RH. The supply air has a humidity sensor, which prevents humidity levels from rising above 80% RH. When the unit is stopped, the outdoor air dampers close, the return air dampers open, the chilled water valve closes, the humidifier control valve closes, the preheat coil valve remains in control, and the variable frequency drives ramp down. After identifying all parameters monitored in the AHU for control and troubleshooting purposes, a relationship between the needed parameters and monitored parameters was established as given in table (1).

3.3 Heat Transfer Formulation

Heating and cooling represent a change of sensible heat whereas humidification and dehumidification represent a change of latent heat. The amount of moisture liberated or absorbed by air was obtained using its initial and final absolute humidity [2]. Latent energy flow was calculated using equation (2).

Table 1 Relationship between monitored parameters and mechanical model

Parameter	Action	Equation
Current	Measured	-
Air Mass Flow rate	Calculated through the Fan Speed	$\dot{m}_a = \rho_a \beta C_{Fan}$
Water Mass Flow rate	Estimated by monitoring the Valve position on the coils	$\dot{m}_w = \alpha \dot{M}$
Inlet coil Temp.	Estimated from spec. sheet	$T_c = 7.22$℃ $T_h = 93.33$℃
Outlet Coil Temp.	Estimated from spec. sheet	$T_c = 12.77$℃ $T_h = 77.22$℃
Inlet Air Temp.	Measured	-

$$\dot{Q}_L = \frac{h_{fg}\rho_a \dot{q}\Delta W}{3600} \tag{2}$$

Based on equation (2), energy created by removing latent heat from the supply air can be calculated using enthalpy of evaporation $h_{fg} = 2465.56\frac{kJ}{kg}$, obtained from the saturated steam tables at 55°F (12.78℃) and 1 kPa (absolute). Engineering Equation Solver (EES) was used to convert the measured relative humidity into humidity ratio in order to be used in equation (2). Equation (3) was obtained using constant air density of $1.25\frac{kg}{m^3}$, from equation (2).

$$\dot{Q}_L = 0.856\dot{q}\Delta W \tag{3}$$

Equation (4) was used to calculate sensitive heat during an air handling process. Air mass flow rate was obtained using fan speed: $\dot{m}_a = \rho_a \beta C_{fan}$.

$$\dot{Q}_S = \dot{m}_a C_{p,a} \Delta T_a$$

$$\dot{Q}_S = \rho_a \beta C_{fan} C_{p,a} \Delta T_a \tag{4}$$

For a cooling coil; total energy removed due to passing through the cooling coil was then calculated by combining the sensible heat and latent heat using equation (5).

$$\dot{Q}_T = \dot{Q}_S + \dot{Q}_L$$

$$\dot{Q}_T = \rho_a \beta C_{Fan} C_{p,a} \Delta T_a + 0.856 \dot{q} \Delta W \tag{5}$$

To estimate the required water flow rate for desired set point temperature, sensible energy added to or removed from the supplied air is equivalent to energy of water and the water mass flow rate was obtained using equation (6).

$$\dot{Q}_T = \dot{Q}_W$$

$$\rho_a \beta C_{Fan} C_{p,a} \Delta T_a + 0.856 \dot{q} \Delta W = \dot{m}_w C_{p,w} \Delta T_w \tag{6}$$

Water mass flow rate and volumetric flowrate were calculated as shown in equations (7 & 8).

$$\dot{m}_w = \frac{\rho_a \beta C_{Fan} C_{p,a} \Delta T_a + 0.856 \dot{q} \Delta W}{C_{p,w} \Delta T_w} \tag{7}$$

$$\dot{q} = \frac{\dot{m}_w}{\rho_w} \tag{8}$$

The volumetric flow rate $\dot{q}$ was calculated based on the monitored airflow rate and temperature. To compare this value with the monitored water valve position, an additional equation (equation 9) needed to be added in order to obtain a valve position estimate.

$$\% \, Valve = \frac{\dot{q}}{\alpha} \tag{9}$$

3.4 Monitoring System

A wireless system was used for the AHU data collection. A Fully Functioning Device (FFD) was installed to transmit data from the AHU to the server using ZigBee. ZigBee is a specification for a suite of high-level communication protocols used to create Personal Area Networks (PAN) for small, low-power digital radios. Two ECOMM WC21-1048-ENC4X FFD's were used as a communication link between the sensors and the PAN coordinator. The ECOMM WC21-1048-ENC4X is capable of reading analog signals in addition to having four analog outputs and eight digital outputs. The built-in software package allows connection and communication through the static IP address. The mixed air damper signal was used for controlling the opening of return air and outside air dampers. When the signal is 100%, the unit is not using any return air. Thus, the return air dampers are shut and the unit is economizing and using 100% outside air. The pre-heat valve opening is pneumatically controlled and is linear as a function of input voltage. MatLab was used for data analysis and the flowchart of the code, which consisted of three parts, shown in Fig. 2.

The wireless system uploaded information to a server every hour for 2 minutes with a sampling rate of 20Hz. The information was saved in a separate file and stored in a directory. MatLab software then scanned the directory every hour to check for any new files. The new file was then opened, read, filtered, and converted into appropriate units. A sample of monitored parameters is given in Fig. 3. Fifteen sets of data were collected and processed using the algorithms described above.

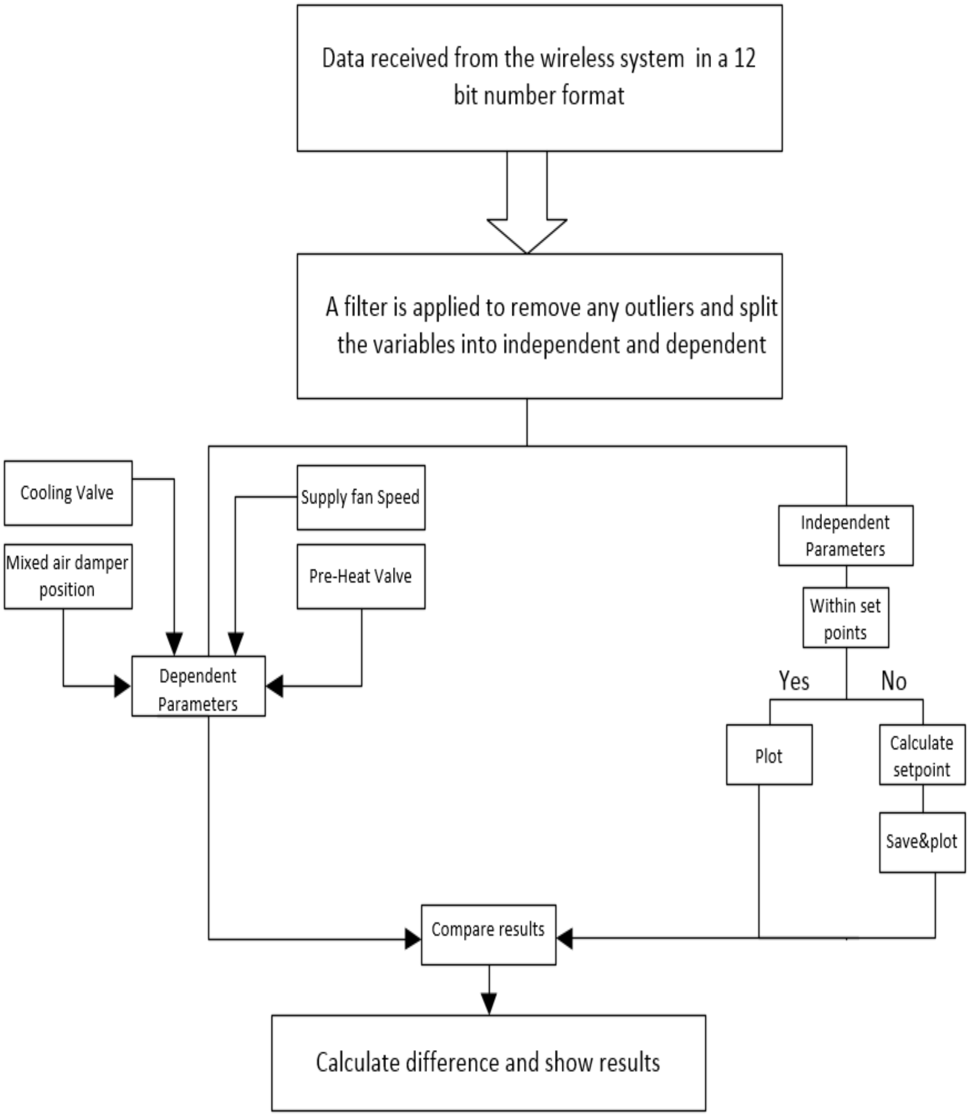

Fig. 2 Matlab Code block diagram

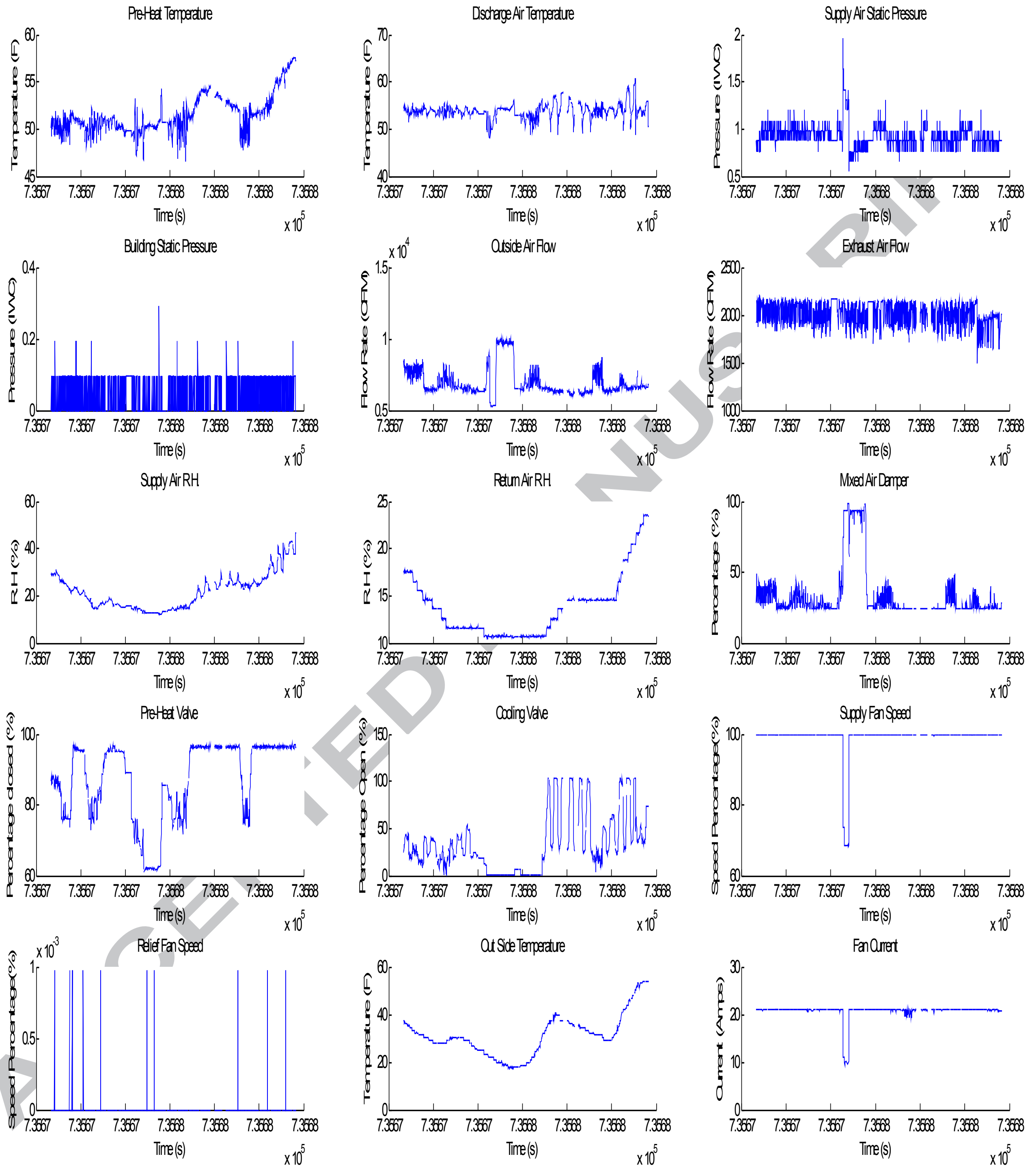

Fig. 3 All monitored parameters data

4. Mathematical Model Validation and Results

One of the mechanical model's aims was to predict the operation of the pre-heating and cooling coils using the physical equations. The data was filtered to remove any signals that are under 5% of the pre-heat and cooling valves opening percentage since the initial pneumatic pressure had to be applied to the valves before water started flowing. To make sure the results obtained from the mechanical model accurately predicted the performance of the unit, a validation system was put in place that allowed for comparing theoretical results with actual operating conditions. An error report was obtained and will be discussed below.

4.1 Mechanical Model Results and Waste Calculation

Fig. 4 shows the profiles of the temperature and status of the cooling and heating valves for the last week of January. The data shows that both cooling and heating valves were open even when outside (or supply) air temperature was below 60°F (15.6℃). Theoretically, the cooling valve is on to cool the supply air, and the heating valve is on to pre-heat the supply air to the air's set point temperature. By comparing actual valve positions with the supplier air temperature in Fig. 4, the cooling valve was trying to reduce the supply air temperature to a cooling valve's set point temperature of 55°F (12.8℃). At the same time, the heating valve was negating this call and applying heat to the supply air, raising it to the set point at 60°F (15.6℃).

To analyse the expected performance, the theoretical position of the cooling valve was evaluated as shown in Fig.5 with a new set point of 60°F (15.6℃) for the cooling valve. It is clear that the subsystems in the unit were contradicting each other, and the unit was confused about the set point temperatures.

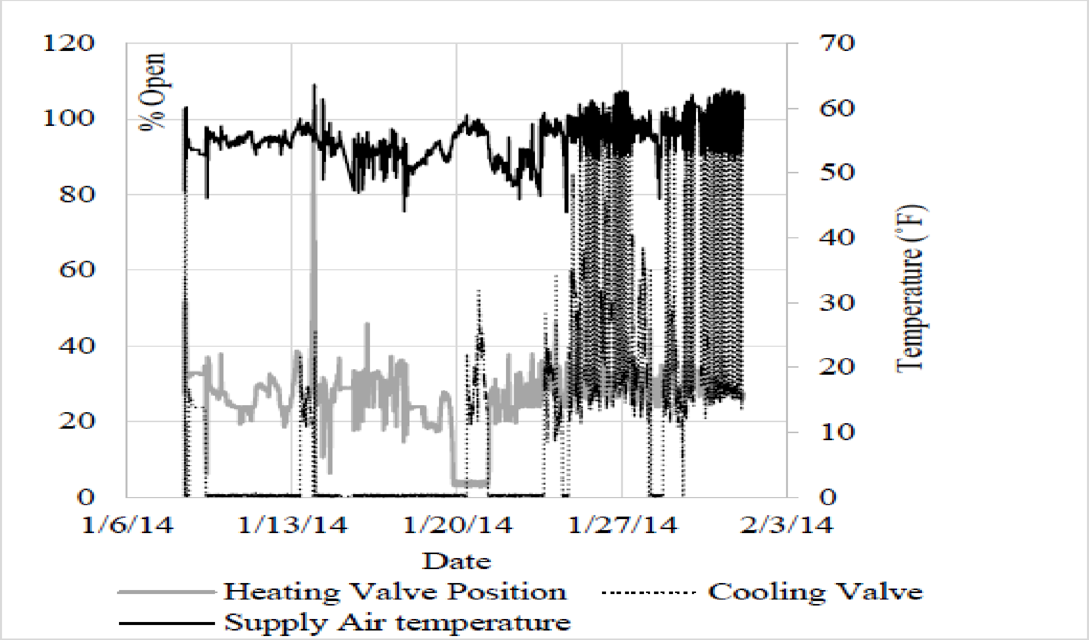

Fig.4 Cooling valve and heating valve position for actual system in comparison with supply air temperature.

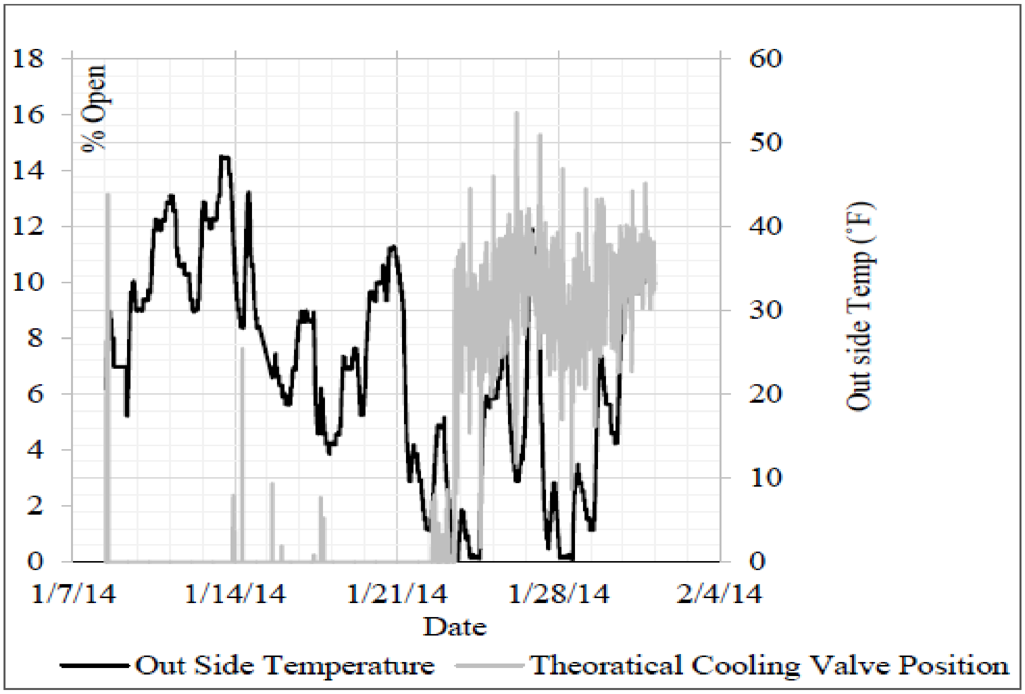

Fig.5 Theoretical cooling valve position compared to low outside temperature

A spike in pre-heat temperature happened at the X as shown in Fig. 6. This was due to the increase in the supply air set point and the VAV air set point. However, the increase was not conveyed to the cooling coil controller, and the cooling coil was still struggling to bring supply air temperature to 55°F (12.8°C). This operation resulted in wasted resources. The effects were estimated using the theoretical model.

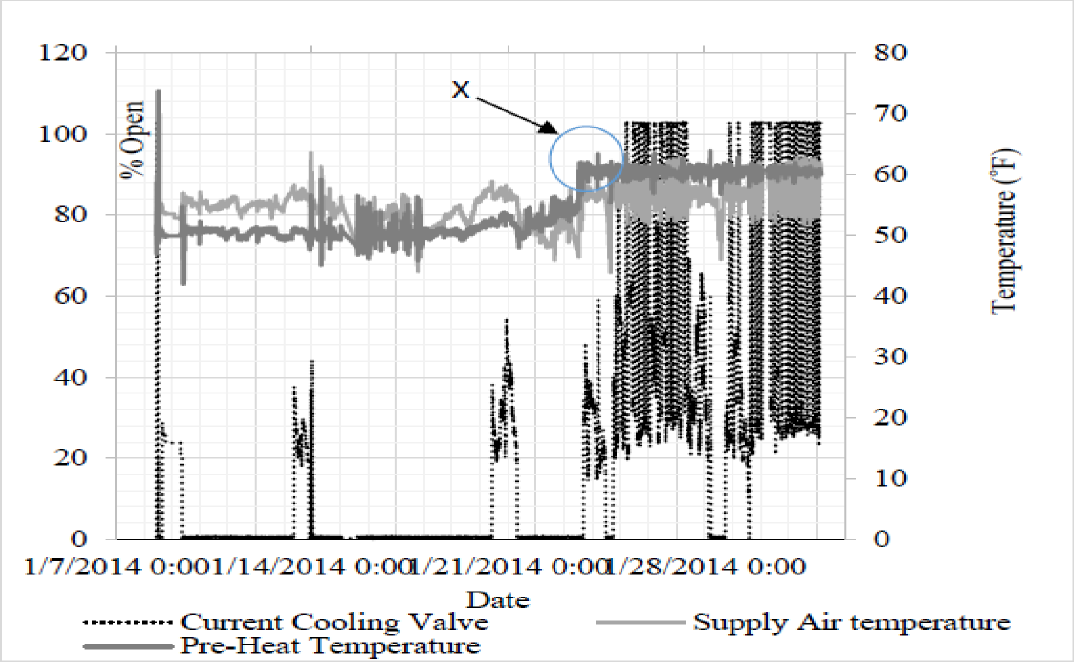

Fig.6 Current cooling valve position in comparison with supply air temperature and pre-heat temperature

The expected AHU behaviour, in terms of theoretical valve position in comparison with supply air temperature and pre-heat temperature, based on mechanical modelling is given in Fig. 7. These were calculated considering a supply air temperature at 65°F (18.3°C), higher than the set point temperatures for cooling and heating coils, to analyse the energy consumption. Comparison of expected performance and actual values of the pre-heat valve position with pre-heat temperature is given in Fig. 8. As seen in the theoretical model, the heating valve was not in operation whenever pre-heat temperature was above 55°F (12.8°C). The theoretical and actual position of the cooling valve in comparison with the pre-heat temperature is given in Fig. 9. As noted before, the cooling valve was fully operational where theoretically it should not exceed 10% open position. From Figs. 8 & 9, the wasted energy was calculated through a comparison between theoretical and actual valve position.

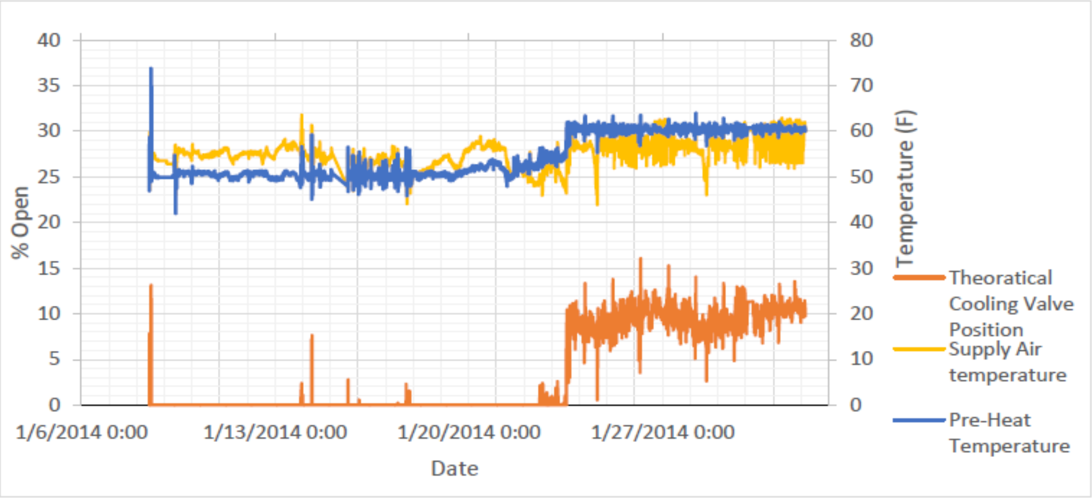

Fig. 7 Theoretical valve position in comparison with supply air temperature and pre-heat temperature

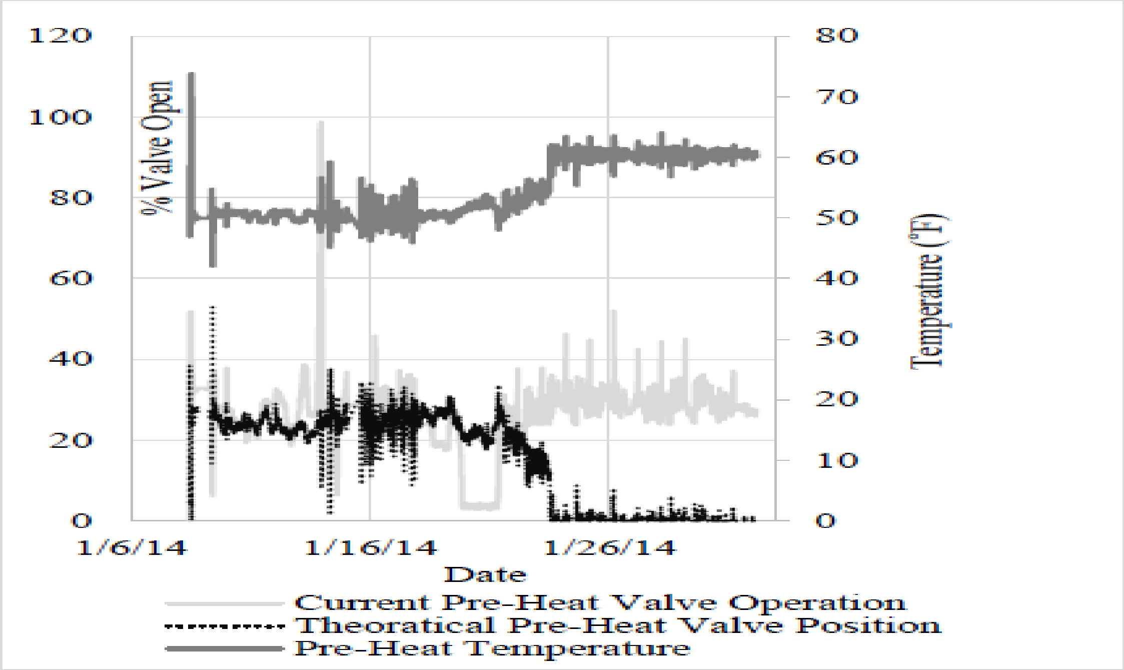

Fig. 8 Theoretical and actual Pre-heat valve position in comparison with Pre-heat temperature

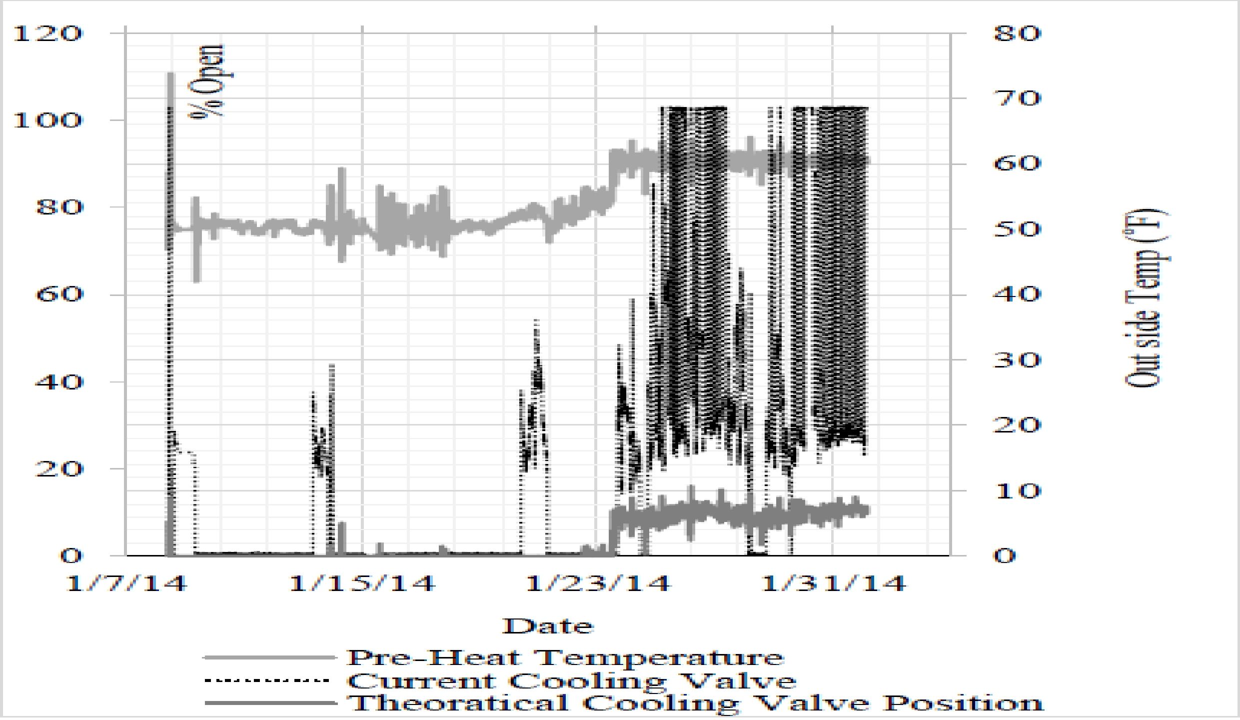

Fig. 9 Theoretical and actual Cooling valve position in comparison with Pre-Heat temperature

4.2 Chilled Water Waste & Heated Water Waste Calculation

4.2.1. Chilled Water Waste

By comparing the operation to the theoretical operation of the valve, the wasted flow in gallons of chilled water was calculated and was converted to energy consumption in kWh. This estimate only considered the amount of energy needed to heat/cool water to reach a temperature difference that was lost through the coils, see in Table 2. Energy Cost was estimated at $0.09/kWh based on the local electric rate. For the low temperature analysis, the results of the theoretical usage of the heating coil was compared to the actual usage. Keeping in mind that the supply air temperature should not exceed 55°F (12.8°C) at any time, thus, the theoretical set point stayed at 55 °F (12.8 °C) rather than 60°F (15.6°C) .

Table 2 Current theoretical and waste gallons used in the cooling coil in low temperatures

Cooling Coil				
Gallons (Liters) used			Energy waste (kWh)	Cost Savings ($)
Current	Theoretical	Waste		
1,887,683.0 (7,145,657.5)	30,337.0 (114,838.0)	1,857,346.0 (7,030,819.4)	45,411	$3,954

4.2.2. Heat Water Waste

From Fig. 9, the heating valve should be engaged even though the pre-heat temperature was above 55°F(12.8°C) . Table 3 shows the water waste during that four-week period in gallons of water at 60°F(15.6°C).

Table 3 Current theoretical and waste gallons used in the Pre-Heat coil

Heating Coil				
Gallons (Liters) used			Energy wasted (kWh)	Cost Savings ($)
Current	Theoretical	Waste		
560,461.0 (2,121,575.7)	306,214 (1,159,146.1)	254,247 (962,429.6)	18,044	$1,571

4.3. Set Point Analysis

After examining the operation of the AHU, a supply air temperature set point analysis was performed. The purpose of this analysis was to study the effects of a set point change on the energy consumption of the unit. The study showed that a single set point cannot be generalized for all operating conditions, because it is a function of outside temperature and number of building occupants. In this case, the building engineer manually changed supply air, which was monitored from Jan. to April. The analysis used a mechanical model to simulate a temperature set point change with increments of 1°F (0.55°C) starting at 45°F (7.2°C) and ending at 65°F (18.3°C). The results are shown in Figs. 10-12.

Based on the Set Point analysis for January 2014, a supply air set point of 61°F (16.1°C) would result in the minimum energy consumption per day compared to other set points. The set point analysis done for March 2014 identified a set point where the minimum energy can be used to maintain comfort levels. According to the analysis, a set point of 58°F (14.4°C) in March would result in the minimum energy consumption per day for that specific month. As shown in Fig. 12, due to the high outside temperature, a clear understanding of the set point effects on the energy usage cannot be established without a clear relationship between the set point and comfort levels in the rooms. For the reasons listed above, more data must be collected in order to optimize the set point.

4.4. Discussion

This research demonstrated that an energy management system with the capability of real-time unit monitoring and performance evaluation can give very important insight on the operation of the AHU and its energy consumption. The example revealed that energy waste existed due to a contradiction in the operation of the cooling coil and pre-heat coil. This was due to a change in the supply air set temperature that resulted in the system calling for both cooling and heating operation. Based on the mechanical model, 63,455 kWh/week was wasted in the case study system due to control malfunction. This system would alert building engineers about such operation error and minimize waste if corrective action is implemented. This case indicated that to increase the efficiency of the AHU, a set point analysis should be done to determine the trade-off between energy consumption and occupant comfort level. A set point should be selected based on weather conditions and occupant comfort level in the building. The system identified additional energy savings opportunities due to set point changes that would result in total energy savings of 77,141 kWh/week.

Due to the limited data for this research, the set point analysis only identified the optimal set points for the months of January 2014 and March 2014. Finally, it is important to emphasize the importance of maintaining historical data that logs the performance of the unit under different circumstances. The data can be used for control optimization, energy usage reduction, and future troubleshooting. Future studies will focus on refining the model and implementation of controls based on the model predictions.

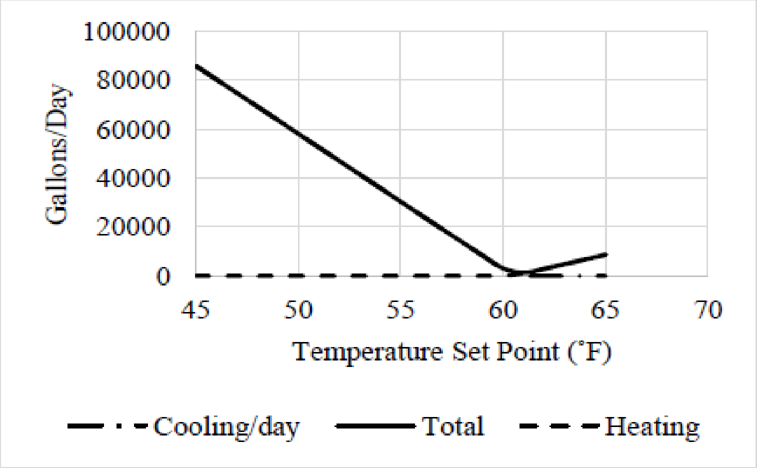

Fig.10 Effect of set point change on the gallons of water use in the cooling and Pre-Heat coils during Jan. 2014

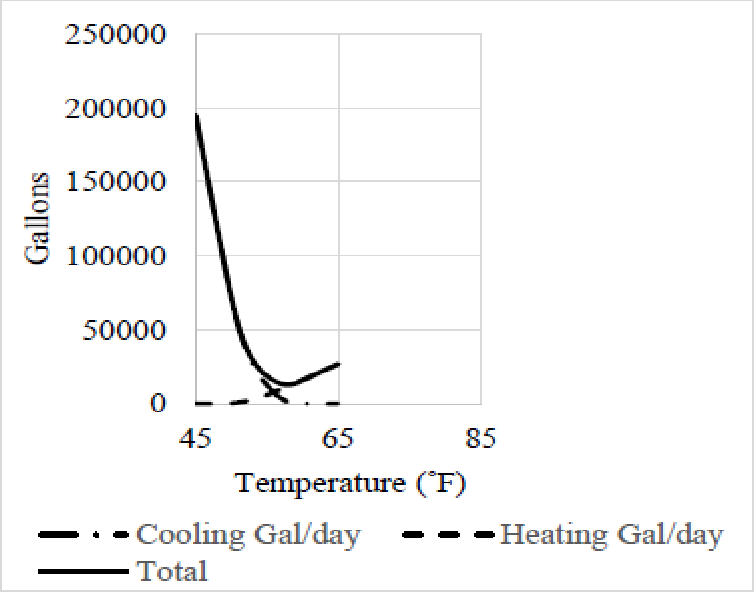

Fig. 11 Effect of set point change on the gallons of water used in both the cooling and Pre-Heat coil during March 2014

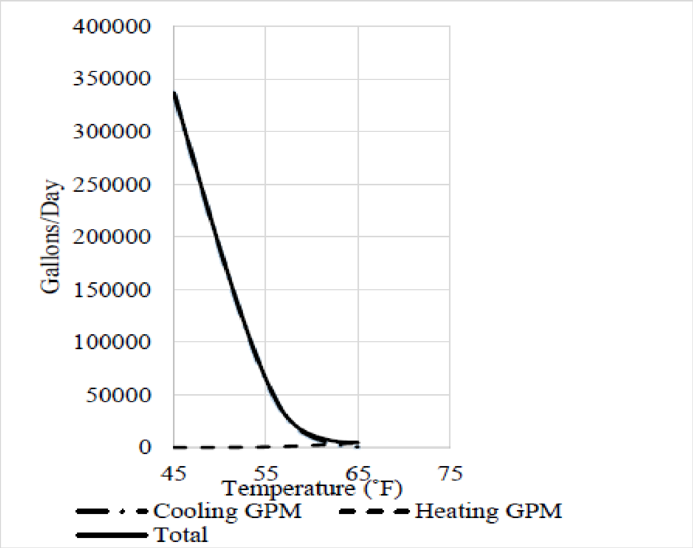

Fig. 12 Effect of set point change on the gallons of water used in both the cooling and Pre-Heat coil during April 2014

5. Conclusion

The AHU energy management system used in this research provides insight into the operation of an AHU and helps to identify various factors that affect the energy consumption in the unit. The system provides the ability to log and analyse historical data that represents the main energy consumers in the unit. The system can be used for control and troubleshooting purposes and can provide options for increasing energy efficiency. The system allows for a clear representation of each component in the AHU, which could not be obtained using the black-box method. Finally, this model along with the historical data allow for energy consumption calculation, controls verification, and overall performance evaluation of an AHU unit, as well as theoretical valve position in comparison with supply air temperature and pre-heat temperature.

6. Acknowledgement

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