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Demand-Controlled Ventilation Energy Savings for Air Handling Unit

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Abstract— Heat, cooling, and ventilation units are major energy consumers for commercial buildings, consuming as much as 50% of a building's total annual power usage [1]. Management of an air handling system's energy is a key factor of reducing the energy costs and carbon dioxide (CO_2) emissions that are associated with the demand when ventilating and conditioning the air in a building. One issue is that buildings are frequently over-ventilated as a full assessment of the air handling unit (AHU) data is not evaluated by building operators. There are multiple variables that account for energy consumption of the AHU which need to be monitored by building operators. In order to assess the demand, it is required that the CO_2 levels of the occupied zones be measured, and the outdoor air ventilation rate be adjusted based on real-time CO_2. The concept of an energy management system and its characteristics are defined in respect to use with an AHU system. The prototype system used for the research is demonstrated and key data analyzed using real-time data collection. The goal of the research is to assess the number of CO_2 sensors needed to accurately measure the demand-based needs for ventilation and provide review of the data required to monitor the AHU energy. Findings indicate that no more than one CO_2 sensor would be required for a large lecture hall.

Keywords—air handling unit, ventilation, CO_2, occupancy data, energy management, demand-controlled ventilation, energy management system

I. INTRODUCTION

Demand controlled ventilation (DCV) is a strategy employed to control ventilation systems based on real-time occupancy conditions. Previous research indicates that up to 75% energy savings for fan motors can be achieved by implementing DCV strategies while still maintaining standards for acceptable indoor air quality (IAQ) [2]. Growth in demand for heating, ventilation, and air conditioning (HVAC) systems is significant and accounts for 50% of building consumption and 20% of the total energy consumption in the United States [3]. The need for energy saving strategies is further emphasized by the energy information administration's (EIA's) predictions of a 65% increase in energy consumption in the commercial buildings sector between 2018 and 2050 [1]. It is certain that research regarding energy savings for HVAC systems has the capacity to impact the reduction in commercial building energy consumption.

Energy management systems (EMSs) are a promising method of managing a complex system's energy consumption, while giving building operators the ability to implement intricate strategies which can minimize a systems energy usage. Building and plant operators often control a system based on a narrow set of parameters which have defined set-points that meet a process or production requirement. At the same time, many systems have multiple parameters which are disregarded by operators. However, these variables may have an identifiable relationship to the system's energy utilization. Air handling units (AHUs) are a model example of a system which is often controlled this way. For instance, the parameters which building operators use for control are the temperature set point and, in some cases, the relative humidity set point. An effective EMS will give building operators access to and deeper understanding of the data which can be used to optimize the control systems and further strategize operations.

The following research seeks to identify major parameters which impact the operation and energy consumption of the AHU while determining the sensors and models which are necessary to employ an effective EMS. After identification of the minimum requirements for the data regarding accurate management of the AHU the appropriate models must be outlined and relationships between the data verified. In order to discuss the capabilities, features, and benefits of an EMS we clearly define the system based on three characteristic abilities: the sensors, the models, and the control strategies. An effective EMS for an AHU will have the following capabilities:

1. Grant access to real-time reliable data that characterizes energy consumption.
2. Assist building operators with decision making.
3. Provide a warning system for operators.
4. The ability to provide energy saving control strategy implementation.
5. Analyze the savings and computationally assess the impact of decisions made and actions implemented.

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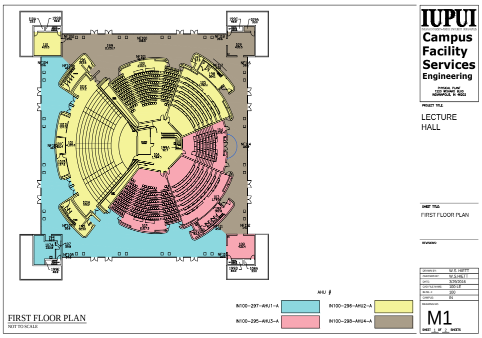

Fig. 1. AHU zones specified by campus facility services

Using DCV methods coupled with an EMS has the capability of providing building operators an effective way to assess AHU performance while making decisions about how to manage the energy consumption.

II. Case Study and System Description

The Lecture Hall (LE) building located on the Indiana University—Purdue University, Indianapolis campus served as a testbed for the experimental setup and assessment of DCV energy saving strategies. LE is a large building which hosts six auditorium-style lecture spaces, ranging in occupant capacity from 54 to 425 people, which makes them ideal for DCV research. These six lecture halls are split into two zones which determine the AHU that ventilates and conditions the occupied space. There are two additional zones which account for lounging and commuting space. For the case study, one of the four zones was selected and determined to be the space that would be explored in regard to DCV strategies. Shown in Fig. 1 is the floor plan for LE where the portion of the plan highlighted yellow is the zone selected for the case study. It is controlled by AHU-2 which ventilates three lecture halls LE 100, LE 101, and LE 105. These three lecture halls have a total floor area of 734 m^2 and a combined occupancy of 734 people. These three lecture halls have a temperature setpoint of 21.1 ˚C with no fixed relative humidity setpoint.

A. *AHU System*

The system that conditions and ventilates the three lecture halls is a constant air volume (CAV) system, which is fitted with a supply fan and a return fan, both of which are equipped with a variable frequency drive (VFD). The system maintains the temperature set-point using chill water coils (i.e., cooling coils) and hot water coils (i.e., heating coils or preheat coils), where the cooling and heating coils are operated independently. Additionally, each lecture hall has its own independent heating coil (i.e., reheat) that provides supplementary heating as well as dehumidification capacity. Both the cooling coil and preheat coil have a total face area of 4.6 m^2 with a standard face velocity of 2.6 m/s. Given the air flow is at standard face velocity, the cooling coil has 86.5 tons of cooling capacity and the preheat coil has 260-kW of heating capacity. The coiling coil conditions the air using chill water that is purchased from a local chill water plant, while the heating coil conditions the air using hot water which is produced by using a heat exchanger operated by steam purchased from a local plant. The campus facility service (CFS) has a building automation system (BAS) which operates the AHU. The BAS has valves which are capable of being controlled remotely, changing the mass flow rate of the coil fluid and controllable dampers. These are regulated to maintain the temperature setpoint and dehumidify the lecture halls. This is done by measuring the discharge air temperature (DAT), after which the automated system opens and closes the chill water or hot water valves to maintain the DAT setpoint.

B. *Data*

To accurately calculate and regulate the energy consumption of an AHU, relevant data needs to be collected to measure the system’s energy. AHUs have multiple variables which affect their operation; therefore, it is a significant objective to define variables that are both essential to the AHU operation and significant to energy consumption. The variables related to the occupied space are temperature, humidity, and CO_2 of the lecture halls. The variables related to the AHU system are return air temperature (RAT), outside air temperature (OAT), mixed air temperature (MAT), supply air temperature (SAT) coil fluid inlet and outlet temperatures, damper positions, relative humidity, and fan speeds. The data is collected using various types of sensors that are compatible with the EMS. This data can be used to both control and model the system. Based on this data, the outcome of different decisions can be determined and changes can be executed to improve AHU performance while ensuring that indoor air quality (IAQ) requirements remain satisfied.

III. Methodology

A. *Overview*

Energy is a quantitative physical property that can be defined by energy-flow equations. Many of the physical characteristics of AHU systems can be modeled with these equations which provide the ability to understand the systems in the terms of energy. However, AHU control procedures are often not based on a comprehensive assessment of data. Instead, a measurement of a single variable will often determine the control sequence.

As previously defined, the EMS is a compound system that is made up of sensors, models, and control strategies. Using an EMS would give building operators the ability to implement control algorithms that are multivariate and based on the comprehensive evaluation of the data related to AHU subsystems energy performance. The ultimate goal of employing EMS is to improve energy management through data-based decision making. The question arises, what data is relevant to the AHUs energy consumption? Fig. 2 depicts the variety of data that is related to the system energy of the AHU and its relationship to occupancy which is then used to identify the impact DCV has on energy.

B. *Energy Management System*

The physical hardware of the EMS consists of sensors, data collection processors, and communication hardware. The sensors are selected based on what data is needed for the system or process that is being monitored, whereas the data collection processors and communication hardware

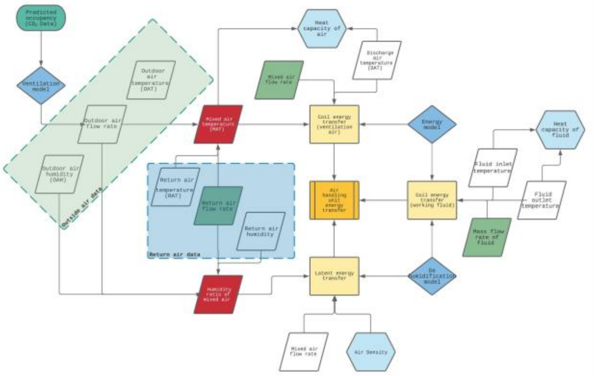

Fig. 2. Data/model flow chart

are generically assembled based on the needs of the EMS. Based on the list of data defined in TABLE I, the types of sensors needed for the EMS related to an AHU are CO_2, temperature, humidity, mass flow, air velocity, and valve/damper actuator position sensors. The automation system managed by CFS presently employs some of the necessary sensors to collect important data, which is shown in TABLE II.

Data collection is required to be as noninvasive as possible and, therefore, data that could be collected by the BAS was accessed through communication with CFS. Additional data of interest, such as $CO_{2,}$ was collected by installing sensors compatible with the energy management system's data collection processor.

TABLE I. VARIBALES NOTED FOR DATA COLLECTION

Data Collected	*Purpose*	*S.I. Units*	*Imperial Units*
CO_2 concenrtration	Predict occupancy, DCV strategies	ppm	ppm
Air temperature	Setpoints, coil performance, and energy management	˚C	˚F
Relative humidity	Setpoints, energy management	%	%
Air velocity	Ventilation model, coil performance	m/s	ft/min
Coil fluid mass flowrate	Coil performance, energy management	kg/s	lb/s
Coil fluid temperature	Coil performance, energy management	˚C	˚F

TABLE II. DATA COLLECTED BY BAS

BAS Sensor Data	
Area	*Data collected by sensors*
LE 100, LE 101, LE 105	SAT, room temperature, relative humidity
Cooling coil	Chill water supply temperature, return water temperature, chill water valve position
Preheat coil	Hot water supply temperature, return water temperature, hot water valve position
Reheat coils	Hot water valve position
AHU	RAT, OAT, outdoor air humidity (OAH), MAT, DAT, return air damper position, outside air damper position, exhaust air damper position, OA velocity-pressure, RA-velocity-pressure

C. *Sensitivity Study*

In order to provide a precise assessment of the system's energy performance, it is essential to have both accurate collection and description of the variables from the data. For instance, will one CO_2 sensor per lecture hall provide an accurate description of occupancy in the room? To determine the minimum sensor requirements, multiple CO_2 sensors were distributed throughout the lecture halls. This data was then analyzed by statistical modeling and regression analysis to determine the best fit of the corresponding data.

D. *Ventilation Model*

One of the main goals of energy management is identifying models which provide the means to evaluate energy performance. Based on the data collected by the system, the next step is analyzing the data in an effective way so that relevant information can be understood in the terms of the system's energy. To develop the models, we analyze the system through the scope of thermodynamics by which we can identify the energy transfer of the system. One of the major functions of an AHU is ventilation; the function of ventilation is to return and supply air from the occupied space. The return air (RA) is mixed with fresh outside air (OA) while some is exhausted—this is done to maintain the quality of the air in the building. The air that is returned from the space and mixed with outside air is called mixed air (MA), this air is conditioned and supplied to the space to maintain the setpoint. Strategically located actuated dampers allow building operators to control the flow of the RA, OA, and exhaust air (EA). We can use the steady-state conservation of mass flow, shown in (1), as a method of modeling that mass flow of air in the system [4]. We can substitute the flow rate for the RA and OA as inlet air $\dot{m}_{a,i}$ and the EA and MA as exiting air $\dot{m}_{a,e}$. It is notable that (2) neglects important information about the air's mass and energy properties, such as the temperature and water vapor present in the system. The adiabatic mixing of two streams is a more generalized approached and gives us the ability to account for vapor mass show in (3) and the energy (4) [4, 5].

$$\sum \dot{m}_{a,i} = \sum \dot{m}_{a,e} \tag{1}$$

Mass flow of dry air,

$$\dot{m}_{RA} + \dot{m}_{OA} = \dot{m}_{EA} + \dot{m}_{MA} \tag{2}$$

Mass flow of water vapor,

$$\omega_{RA}\dot{m}_{RA} + \omega_{OA}\dot{m}_{OA} = \omega_{EA}\dot{m}_{EA} + \omega_{MA}\dot{m}_{MA} \tag{3}$$

Energy,

$$\dot{m}_{RA}h_{RA} + \dot{m}_{OA}h_{OA} = \dot{m}_{EA}h_{EA} + \dot{m}_{MA}h_{MA} \tag{4}$$

where
$\dot{m}$ = mass flow rate of air
ω = humidity ratio water vapor to air
h = enthalpy
T = temperature
c_p = specific heat capacity

If we substitute the following (5) in for the enthalpy in (4) and assume specific heat of air is constant, then we arrive at (6). (6) allows us to analyze the temperatures of the RA, OA, EA, and MA as a function of their respective flow rates [5].

$$h(T) = c_p T \tag{5}$$

$$\dot{m}_{RA} T_{RA} + \dot{m}_{OA} T_{OA} = \dot{m}_{EA} T_{EA} + \dot{m}_{MA} T_{MA} \tag{6}$$

When controlling ventilation based on demand it is important to have a threshold by which to monitor and control the AHU system. ASHRAE standard 62.1 provides the criteria for the required outside air flow rate for a lecture hall based on occupancy and floor area. The required air flow rate per person R_p is 7.5 cfm/person (3.8 L/s) and the area air flow rate R_a is 0.6 cfm/ft^2 (L/s-m^2), while the total outdoor air flow rate for the breathing zone is given by V_{bz} shown in (7) [6].

$$V_{bz} = R_p \times P_z + R_a \times A_z \tag{7}$$

P_z = total number of occupants in the zone
A_z = total floor area of the zone

IV. RESULTS AND DISCUSSION

A. *Baseline Oberservations*

In order to understand the energy usage and identify the areas where energy can be saved a baseline assessment, the data is analyzed. Fig. 3 shows data collected by the BAS for AHU-2's operation between February 16, 2021 and February 18, 2021. The average outdoor air temperature is around 15°F for these three days through which the impact that the OAT has on the MAT can be clearly observed. The RAT is between 72°F and 74°F and after return air mixes with the outside air the MAT is between 40°F and 50°F. It is notable that over-ventilation of OA has an impact on the temperature of the air to be conditioned by the heating coils in the winter months. Note that the peaks in the temperatures shown in fig. 3. are assumed to be caused by the AHU system shutting down and the heat energy stored in subsystems, such as the coils, radiating. Additionally, data from the BAS was analyzed for a week in May shown in fig.4. For this data set, the system is in cooling mode, therefore the preheat coil valve is closed. Note that the reheats still operated in order to provide dehumidification for the lecture halls by raising the temperature of the air which decreases the relative humidity of the air [4]. Again, we see a correlation between the OAT and MAT such that as the OAT increases so does the MAT. It is evident that optimized operation for OA flow could prove beneficial to the building operators. Using models such as equation (6) and (7) to determine the effect on the MAT would reduce the amount of heating and/or cooling required of the coils when the OAT is not optimal.

B. *Sensitivity Analysis Results*

In order to determine the optimal number of sensors for DCV strategies, each lecture hall was equipped with two Honeywell C7232A CO$_2$ sensors. The C7232A is a wall mountable CO$_2$ sensor designed for occupancy information and damper control strategies. The individual sensors are denoted by S1 and S2 in the plots so that the data can be distinguished between entities. The data was collected using a FRDM-K64 microcontroller mounted on a printed circuit board shown in fig. 5. Using the microcontrollers built-in 2.4 GHz Wi-Fi communication capabilities, the data was sent to the database 60 times per minute for each sensor connected. The data was then retrieved from the database and organized in Excel tables which were imported into MATLAB for analysis. For each lecture hall, the data for the two CO$_2$ sensors was fitted using linear regressions. The fitted regression was then plotted against a scatter plot of data to analyze the correlation of the sensors' readings.

The data for LE 100 shown in fig. 6-7 has been filtered for a sample interval of 5 minutes over the period of 13

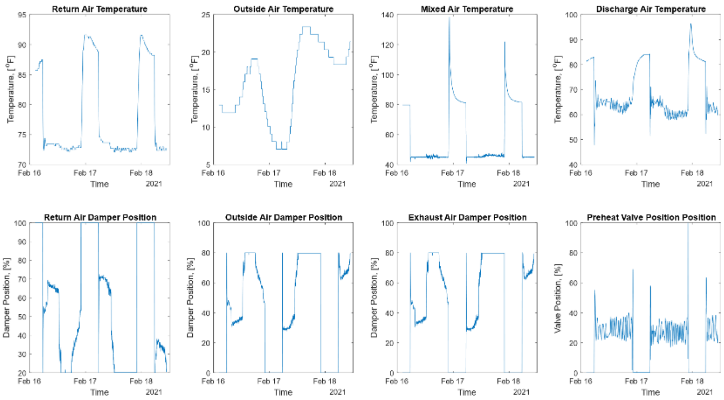

Fig. 3. BAS Data for AHU-2 and LE 100, 101, 105
for 02/16/2021-02/18/2021

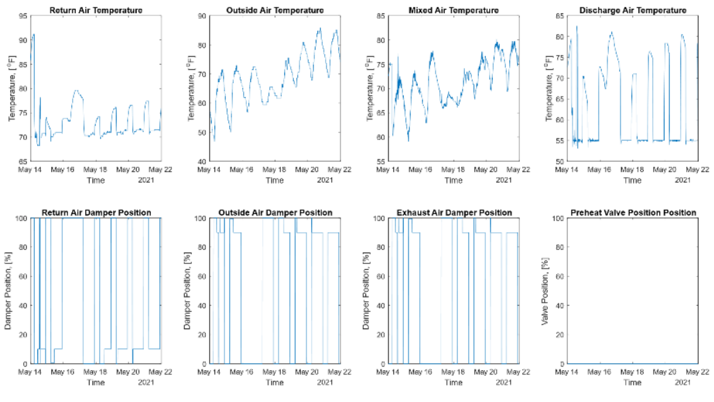

Fig. 4. BAS Data for AHU-2 and LE 100, 101, 105
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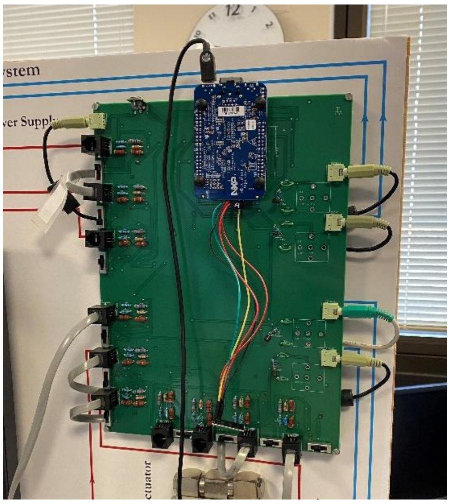

Fig. 5. EMS data collection processing system

days. LE 100 is a medium sized lecture hall in the LE building and has a floor area of 1,017 ft^2 (187.4 m^2) with a maximum occupancy of 214 people. The two CO_2 sensors' proximity to each other is approximately 50 ft (15.24 m). It is notable that the occupancy rate for this sample interval is low as the sample data set was taken during summer sessions when fewer classes are in session.

The correlation analysis shows a strong fit for the sensors' data indicating that there is a correlation of the CO_2 concentration reading among the sensors. However, the changes in the CO_2 readings with respect to time for the two sensors have a weak correlation. This suggests that the concentration change for CO_2 is either varying throughout the space and these changes are sensed differently by the sensors or the sample rate is not sufficient to indicate these changes.

The CO_2 data for LE 105 is shown in fig. 9-11 and has a filtered sample rate of 5 minutes over a period of 6 days. Again, this data set sample was taken during summer sessions. LE 105 is the smallest sized room in the AHU-2 zone with a floor area of 1,078 ft^2 (100.2 m^2) and a maximum occupancy of 95 people. The CO_2 sensors' proximity in LE 105 is 35 ft (10.7 m). The correlation of CO_2 concentration is strong, similar to LE 100. The rate of change in CO_2 concentrations read by the sensors is moderate with an R^2 of 0.6457, which is an improvement compared to the correlation of LE 100.

The results for the largest lecture hall, LE 101, is shown in fig. 12-17. LE 101 has a floor area of 4,105 ft^2 (381 m^2) with a maximum occupancy of 425 people. The sensors' proximity to one another is 35 ft (10.7 m), similar to LE 105. Two different data sets were analyzed for LE 101. The first data set shown in fig. 12-14 is based on a filtered sample interval of 5 minutes over a period of 6 days. The trend data shown in fig. 12 shows a large divergence in the CO_2 concentrations read by the two sensors. Furthermore, the correlation of the sensors' readings is weak for the sample set with an R^2 of 0.3297 as shown in TABLE III. It is interesting to note that the correlation for the rate of change of the CO_2 concentration with respect to time, although weak, is better than the correlation for LE 100. The first assumption for the cause in divergence of the CO_2 concentration was sensor placement. For LE 101 CO_2 sensor S1 was mounted on a riser close to the floor and sensor S2 was wall mounted approximately 3 ft (0.91 m)

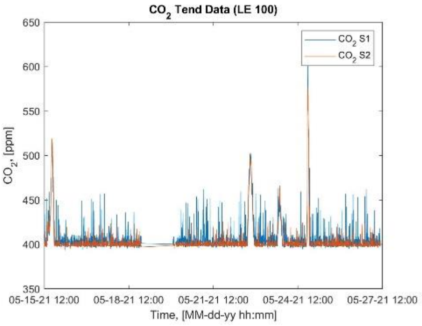

Fig. 6. CO_2 concentration readings for LE 100

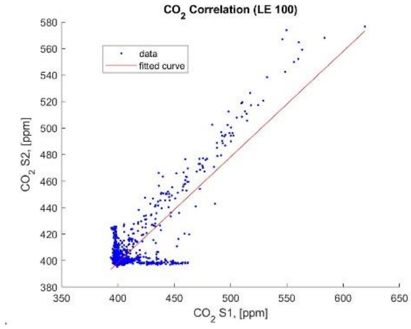

Fig. 7 CO_2 concentration readings for sensor S1 and S2 correlation

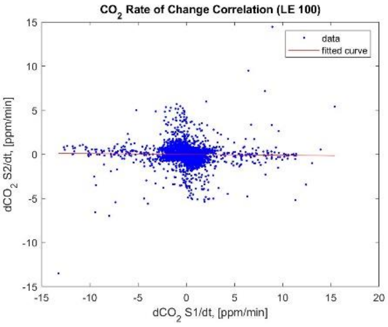

Fig. 8. CO_2 change in concentration correlation for sensor S1 and S2 in LE 100

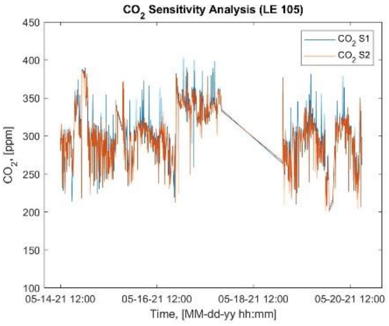

Fig. 9. CO_2 concentration readings for LE 105

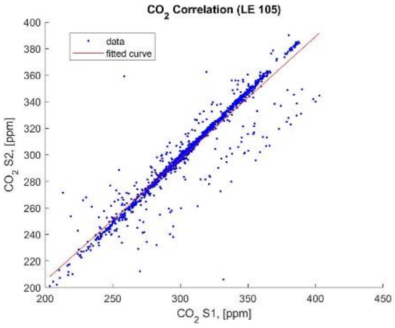

Fig. 10. CO_2 concentration readings for sensor S1 and S2 correlation

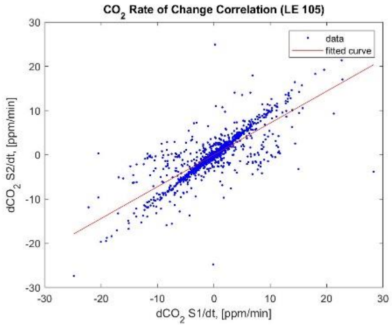

Fig. 11. CO_2 change in concentration correlation for sensor S1 and S2 in LE 105

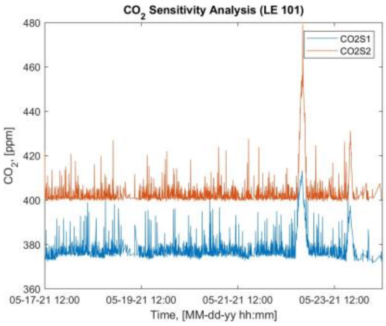

Fig. 12 CO_2 concentration readings for LE 101

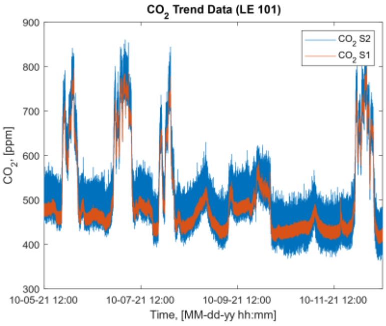

Fig. 13. CO_2 concentration readings for LE 101

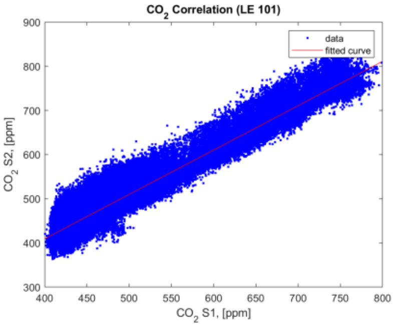

Fig. 14. CO_2 concentration correlation for sensor S1 and S2 (LE 101)

from the floor. Further investigation of the sensor placement and sample readings from a hand-held CO_2 device suggested that the sensors placements should not affect this large of a divergence in the concentration readings. Investigation of the data collection processor and sensor termination indicated that the voltage signal for sensor S1 was not satisfactory. In order to resolve this issue, the sensor S1's port termination at the EMS data processor was changed, and sample data inspected to verify the correction. The second data set shown in fig. 13-14 was collected after the issue was resolved. The CO_2 concentrations for the individual sensors in this data set are concurrent as expected. This data set is analyzed with a sample interval of 1 second. It is observed that the correlation in the concentration readings from the sensors is strong; however, the correlation in the rate change of CO_2 with respect to time is still weak.

TABLE III: CORRELATIONS FOR CO_2 DATA

Lecture Hall CO_2 Sensitivity Study			
Lecture Hall	***Variable***	***Fit***	***Correlation Coefficient R^2***
LE 100 fig. 6-8	CO_2	Linear	0.72
	dCO_2/dt	Linear	3.68e-04
LE 105 fig. 9-11	CO_2	Linear	0.8937
	dCO_2/dt	Linear	0.6457
LE 101 fig. 12	CO_2	Linear	0.3297
	dCO_2/dt	Linear	0.0147
LE 101 fig. 13-14	CO_2	Linear	0.9713
	dCO_2/dt	Linear	3.29e-06

V. CONCLUSIONS

AHUs are a complex system with multiple variables and parameters which influence the energy usage of the system. Using an EMS will provide building operators the capability to effectively manage the AHU subsystems' variables related to energy consumption and identify the areas where the operation of the AHU can be improved. It is important to first identify the data that is needed to proficiently analyze and model the system. Once sample data is collected, a baseline assessment of the data will provide insight to the efficiency of operation and provide operators with a way to assess the energy savings after implementing more effective control strategies. In order to implement DCV strategies, the CO_2 data is a critical parameter. Through the regression analysis we see the effect that sensor placement, room size, sampling rate, and sensor setup have on the concentration readings. The analysis shows that one sensor will accurately read the CO_2 concentration throughout the room. However, the changes in the CO_2 concentration with respect to time are more elusive as the diffusion rate of CO_2 may be too slow to be accurately sensed by multiple sensors simultaneously. This research has demonstrated that EMSs are a promising solution to the complex problem of managing an AHU's energy consumption and should be considered in future research related to AHUs.

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