Standard Testing Protocols for CO2 Sensors and CO2-based Demand Control Ventilation Systems

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ABSTRACT

Carbon dioxide (CO_2)-based demand control ventilation (DCV) automatically adjusts building ventilation rates based on indoor CO_2 concentration. Since the indoor CO_2 concentration is directly related to the occupancy, the purpose of CO_2-based DCV is to conserve energy by reducing the ventilation rates during periods of low occupancy. In this work, two standard testing protocols for CO_2 sensors and CO_2-based DCV system controllers are developed and performed on several currently available CO_2 sensors and DCV system controllers. A few sample test results are provided.

1. INTRODUCTION

Proper building ventilation is crucial for achieving healthy indoor air quality since it maintains the concentrations of carbon dioxide (CO_2), volatile organic compounds (VOCs), and other indoor containments at or below their maximum healthy levels. ASHRAE Standard 62.1 specifies the ventilation requirements for acceptable indoor air quality (ASHRAE, 2010). Well-ventilated commercial buildings are associated with lower sick leave rates than poorly ventilated buildings (Emmerich & Persily, 2001). Under-ventilated buildings have been linked to a condition known as sick building syndrome (Emmerich & Persily, 2001). However, over ventilation increases energy consumption because fresh outdoor air must be conditioned. Recently, the focus on ventilation has been magnified by the SARS-CoV-2 pandemic (United States Centers for Disease Control, 2020) and wildfires in California and Oregon (California Division of Occupational Safety and Health, 2019).

Demand control ventilation (DCV) is an approach to building ventilation that automatically adjusts the building ventilation rate (i.e., the flow rate of outdoor air supplied to the building) in response to a sensor signal (Fisk & de Almeida, 1998). Most of the research and development on single-zone DCV occurred in the 1990s and early 2000s; refer to the review papers (Fisk & de Almeida, 1998; Emmerich & Persily, 2001; Apte, 2006) and the references therein. The more recent work on DCV has focused on DCV strategies for multi-zone configurations (Nassif, 2012; Lin & Lau, 2014; Liu et al., 2012; O'Neill et al., 2020). CO_2-based DCV system controllers manipulate the ventilation rate based on the indoor CO_2 concentration. Since CO_2 concentration is correlated with the occupancy amount, CO_2-based DCV system controllers have been demonstrated to conserve energy by reducing the outdoor airflow rate when spaces are not fully occupied (Schell & Inthout, 2001; Taylor, 2006). Giacomo (1999); Dougan and Damiano (2004); Mysen et al. (2005); Acker and Wymelenberg (2011) analyze the benefits and risks of DCV. While there has been some debate on the overall benefit of DCV, CO_2-based DCV for single-zone applications is now a well-established technology, and standard products exist from vendors (e.g., Honeywell Jade, Belimo Zip, and Johnson Controls Peak). Several simulations and field tests have been performed on DCV strategies (Emmerich & Persily, 2001) although most of these studies are now over twenty years old.

CO_2-based DCV system controllers require CO_2 sensors to function properly. A common type of low-cost CO_2 sensor used in heating, ventilation, and air conditioning (HVAC) applications is a non-dispersive infrared (NDIR) sensor (Shrestha, 2009). NDIR CO_2 sensors utilize an infrared radiation (IR) source. The IR passes through an air sample, and a detector (located on the opposite end from the IR source) measures the resulting intensity. A correlation is used to relate the measured intensity to the concentration as the intensity is proportional to the CO_2 concentration.

The effectiveness of CO_2-based DCV depends on the accuracy of CO_2 sensors. In (Jones et al., 1997), a study of 29 sensors was conducted. The testing procedure and setup were described where pure CO_2 was added over a period to obtain a certain concentration in a chamber housing the sensors. From the test results, absolute sensor errors of 100 ppm or more were possible. As pointed out in (Jones et al., 1997), measurement errors of 100 ppm could result in DCV control action errors up to 25 percent, compared to that produced with an accurate CO_2 sensor. This result further emphasizes the importance of accurate CO_2 sensors. In (Shrestha & Maxwell, 2009), a testing procedure was designed to test HVAC-grade CO_2 sensors to evaluate many factors including sensitivity to humidity, temperature, and pressure. The study used dry calibrated N_2/CO_2 gas mixtures. Water vapor was added to the dry gas mixture to achieve the desired humidity level. From the test results, the absolute error in sensor measurement was shown to generally increase with CO_2 concentration. Moreover, for several sensors considered in the study, absolute errors of over 100 ppm were identified.

Quantifying the overall performance of currently available DCV system controllers (i.e., the ability to maintain the CO_2 concentration at or below the standard limit defined in ASHRAE Standard 62.1 (ASHRAE, 2010)) is important given the renewed attention in building ventilation. As illustrated by previous studies, the accuracy of CO_2 sensors and the control performance of DCV system controllers should be evaluated. While previous work has tested various CO_2 sensors and DCV strategies under various conditions, the test results are now out-of-date, and may not reflect the performance of currently available products. Thus, evaluating the current products based on a standardized testing protocol will help inform building operators and managers.

In this work, two testing protocols for CO_2 sensors and CO_2-based DCV system controllers are developed and performed on several available sensors and DCV system controllers. The objective of the first protocol is to quantify the accuracy of CO_2 sensors. The objective of the second protocol is to assess the performance of CO_2-based DCV system controllers. To establish a performance baseline, the test results are compared to the expected results under an ideal DCV strategy. The protocols are described and results after executing each of the protocols are presented.

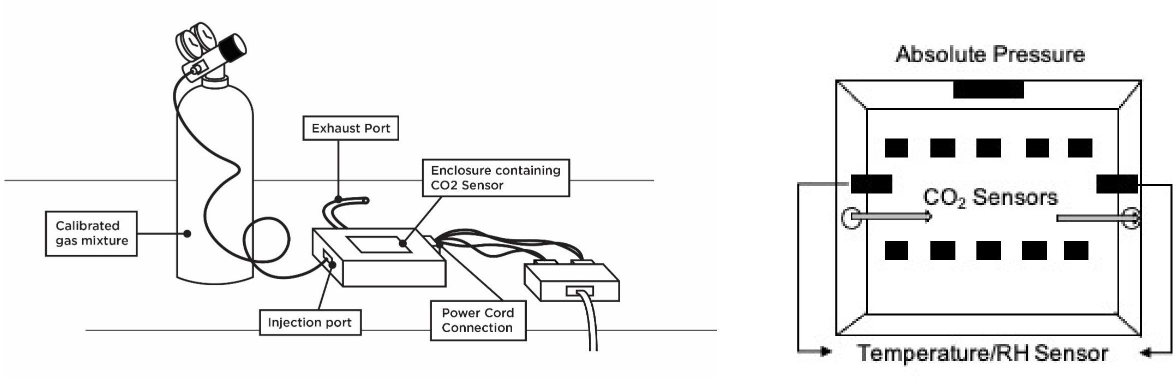
2. CO_2 SENSOR AND CO_2-BASED DCV SYSTEM CONTROLLER TESTING PROTOCOLS

In this section, the CO_2 sensor and CO_2-based DCV system controller testing protocols are described. To assess the performance of the DCV system controller, a baseline control strategy assuming ideal conditions is developed, and the performance under the ideal baseline control strategy is compared to the performance of the DCV system controller under test. The baseline control strategy, referred to as the ideal DCV strategy for the remainder, is also described in this section.

2.1 CO_2 Sensor Test Protocol

The objective of the CO_2 sensor test protocol is to quantify the accuracy of HVAC-grade wall-mount CO_2 sensors used for DCV system controllers under typical building environmental conditions. To evaluate sensor accuracy, sensors are placed in an enclosure that is tightly sealed and is continuously flushed with a calibrated CO_2/N_2 gas mixture. The steady-state sensor measurements obtained from the sensors are compared to the known concentration of the calibrated gas mixture reported by the manufacturer. During the test, environmental conditions in the enclosure are maintained at a temperature of 75°F, an absolute pressure of 101 kPa, and less than 5 percent relative humidity. The conditions are measured every 30 seconds. To define a successful test, the temperature and pressure must satisfy two tolerance types: a test operation tolerance and a test condition tolerance. The test operating tolerance is defined as the difference between the maximum and minimum measurement over the test duration for any operating condition and is 5°F and 3 kPa for the temperature and pressure, respectively. The test condition tolerance is defined as the difference between the test condition and the average value over the test duration for any operating condition and is ±3°F and ±1.5 kPa for the temperature and pressure, respectively. To prevent infiltration, positive differential pressure between the enclosure and surrounding of at least 5 Pa is maintained. The differential pressure must not exceed 100 Pa.

The temperature and pressure conditions are selected to mimic standard building conditions. Previous research has demonstrated that CO_2 sensor response is reasonably consistent over the temperature range allowed by the test (Shrestha, 2009). The absolute pressure condition is selected to be representative of the absolute pressure at sea level. Regarding the relative humidity condition, water vapor could be added to the dry gas mixture so that the relative humidity of the resulting CO_2, N_2 , and water vapor mixture reflects standard building relative humidity. However, lab-grade measure-



(a) **(b)**

Figure 1: (a) A diagram of the experimental setup and (b) a diagram of the enclosure with ten sensors.

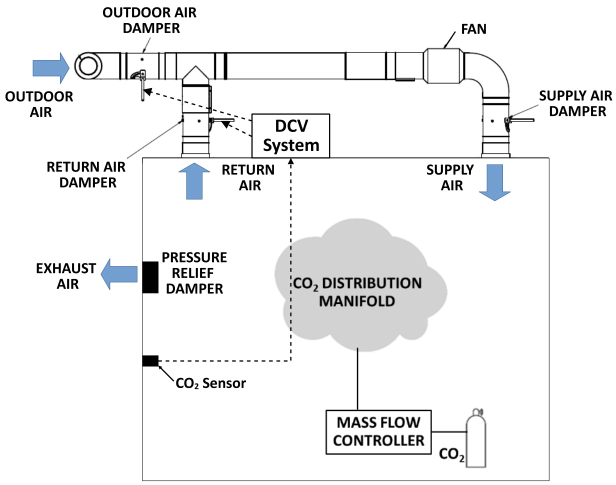
ment equipment would be needed to measure the resulting CO_2 concentration, which is beyond the scope of the present study. Alternatively, when mixing the CO_2/N_2 with water vapor, the flow rates of the two streams could be tightly controlled so that the resulting concentration could be calculated, which was the approach employed in (Shrestha, 2009). Additional error from the flow controls and measurements would be introduced in the calculated concentration. Thus, dry gas mixtures are used in this study to leverage the fact that calibrated CO_2/N_2 gas mixtures are commercially available, which simplifies the test protocol.

The experimental setup includes a tank of calibrated CO_2/N_2 gas, a tightly sealed enclosure, a power supply, and a data acquisition system (Figure 1a). The test enclosure houses ten CO_2 sensors, a pressure gauge, and two temperature and relative humidity sensors (Figure 1b). The relative humidity and temperature sensor devices are located next to the injection and exhaust ports. Since some CO_2 sensors do not interface with the data acquisition system, the front of the enclosure is clear plastic so that the readings from the sensor display may be manually recorded. The enclosure has an injection port and exhaust port. Tubing is used to connect the tank regulator to the inlet port of the enclosure. Initially, the enclosure is filled with ambient air. During the test, the exhaust port allows for the calibrated gas mixture to displace the ambient air. The surrounding laboratory environment where the test is performed is temperature-controlled to satisfy the temperature test condition.

Three calibrated gas mixtures are used in the test: 425 ppm, 1100 ppm, and 1700 ppm. The lowest concentration is selected since it is approximately the concentration of ambient air. Many HVAC-grade CO_2 sensors are rated up to 2000 ppm, and saturate their reading at 2000 ppm if the measured concentration is greater than 2000 ppm. Therefore, the highest concentration is selected to be lower than 2000 ppm to test the full range of sensors while leaving room in case the sensor bias is substantial (i.e., greater than 100 ppm). Regarding the tolerance on the acceptable calibrated gas mixture, the actual concentration of the calibrated gas must be within 2 percent of the reported concentration (this is reported by the gas manufacturer), and the minimum and maximum concentration of the three gases are 400 and 450 ppm, 1000 and 1200 ppm and 1600 and 1800 ppm, respectively.

The test protocol is as follows. Ten CO_2 sensors are placed in an enclosure and powered with the manufacturer specified power requirements. The sensors are allowed to warm-up for at least the manufacturer-specified warm-up period (minimum on-time before obtaining data) in an environment where the absolute pressure requirement is met during the warm-up period. If no manufacturer-specified warm-up period is reported, then the warm-up period will be twenty-four hours. If the sensor utilizes an automatic background calibration (ABC) procedure, the CO_2 concentration of sensor environment must be maintained below 425 ppm for at least one hour during the warm-up period (the concentration during this period is determined by a CO_2 sensor without the ABC procedure calibrated using this procedure). After the warm-up period (if applicable), the test proceeds in order of increasing CO_2 concentration. The tubing between the enclosure and calibrated gas tank (425 ppm gas mixture) is connected. The regulator is adjusted to meet the absolute pressure and differential pressure requirements. Measurements from the CO_2 sensors and temperature, humidity, and pressure sensors are taken every 30 seconds.

When the CO_2 sensor measurements reach steady-state, 41 measurements are recorded in 30-second intervals over a total of 20 minutes. Steady-state is determined by fitting a time-constant for a first-order response to the data. The



(a)

(b)

Figure 2: (a) A schematic of the test chamber and AHU and (b) a photo showing the CO_2 distribution system.

steady-state sensor data collection begins after waiting at least four time constants after the start of the test. The 20 minute period where measurements are collected is referred to as the recording period. After the recording period, the gas supply is turned off, and the next calibrated gas tank is connected to the injection tubing, and the procedure is repeated for the remaining two calibrated gas mixtures.

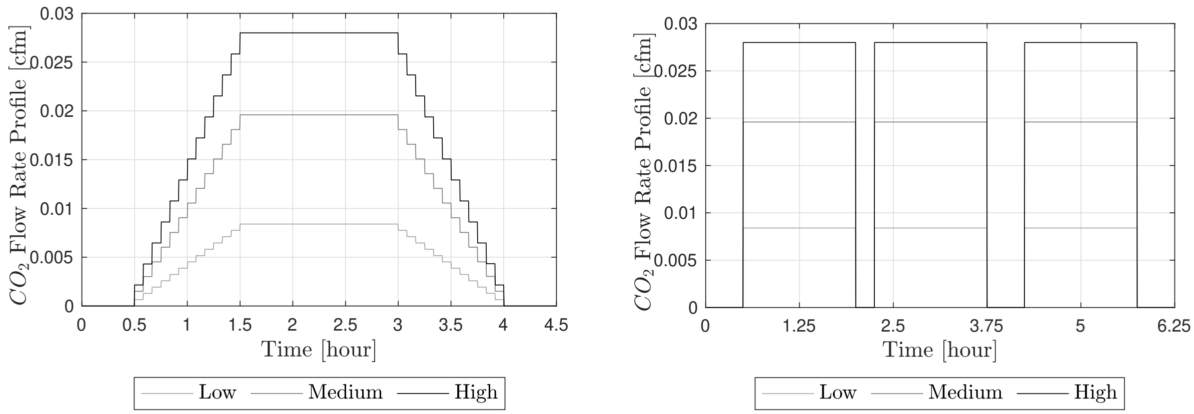
The average steady-state measurement for each sensor is determined based on measurements collected during the recording period. The sensor error, defined as the difference between the average steady-state measurement and the actual calibrated gas CO_2 concentration, is determined for all sensors and tests. The average and standard deviation of the sensor errors over all sensors is calculated. The minimum and maximum instantaneous measurement of any sensor over the recording period is determined. Finally, linear regression is used to calibrate the average sensor measurements to the actual concentrations for all sensors. The results are tabulated.

2.2 CO_2-based DCV System Controller Test Protocol

The objective of the CO_2-based DCV system controller test protocol is to assess the performance of DCV system controllers. The protocol features a laboratory procedure that tests the ability of the controller to maintain the indoor CO_2 concentration at a setpoint. The performance of the system is compared to the performance of an ideal controller, which will be discussed in detail in the next section. The protocol applies to DCV system controllers that receive a single CO_2 sensor input and modulate the outdoor and return air dampers for an HVAC system to maintain an indoor CO_2 setpoint. Parameters such as the ventilation rates, occupancy densities, and CO_2 generation rates are determined based on the 2019 California Building Energy Efficiency Standards (*Building energy efficiency standards for residential and nonresidential buildings*, 2018) and ASHRAE Standard 62.1 (ASHRAE, 2010) so the tests reflect realistic conditions.

To mimic an occupied building space where occupants exhale CO_2, a chamber equipped with a constant air volume air handling unit (AHU) and a CO_2 distribution system located inside the chamber is used to test the DCV system controllers. A schematic of the chamber and AHU are shown in Figure 2a, and a picture of the inside of the chamber is given in Figure 2b. The chamber has an interior height of 8 feet and a floor area of 56 square feet. The AHU is responsible for mixing the return air from the chamber with outdoor air and supplying the mixed air to the chamber. The fraction of outdoor air to return air is controlled by the DCV system controller, which modulates the outdoor air and return air dampers. The mixed air is supplied to the chamber at a constant flow rate using a constant speed supply fan. Additionally, a supply air damper controlled by a proportional-integral controller is used to tightly control the supply airflow rate. A relief damper is used to maintain a positive differential pressure in the chamber relative to the surrounding environment (1-10 Pa). The exhaust airflow rate is approximately equal to the outdoor airflow rate.

Within the chamber, a wall-mounted CO_2 sensor is placed four feet from the floor to measure the chamber CO_2 concen-



(a) **(b)**

Figure 3: CO_2 generation rate for (a) a gradually changing occupancy profile and (b) a series of step changes in the occupancy for three occupancy densities.

Table 1: Test chamber CO_2 generation, ventilation, and supply airflow rates for the 56 sq. ft. test chamber.

Occupant Density Category	Occupant Density (# people/1000 sq. ft.)	Occ_{max} (# people)	$G_{\text{CO}_2,max}$ ($\times 10^{-2}$ cfm)	$\dot{V}_{in,min}$ (cfm)	Supply Airflow Rate (cfm)
Low	15	0.84	0.84	8.4	56.0
Medium	35	1.96	1.96	8.4	56.0
High	50	2.80	2.80	8.4	56.0

tration and to report the value to the DCV system controllers. When compatible, the same (high accuracy HVAC-grade) sensor calibrated with the CO_2 sensor calibration procedure described in Section 2.1, referred to as the chamber CO_2 sensor, is used in all tests to send the CO_2 signal to the controller under test. The goal of using a calibrated CO_2 sensor is to isolate testing of the DCV system controller response characteristics. If the DCV manufacturer's CO_2 sensor must be used with the controller under test due to compatibility requirements, then all manufacturer recommendations for the operation of the CO_2 sensor are followed. In this case, the chamber CO_2 sensor is still used to record the CO_2 concentration during the tests for consistency. Additional calibrated CO_2 sensors are placed in the outdoor air duct and next to the relief damper to measure the exhaust air CO_2 concentration.

Pure CO_2 is released into the chamber at a controlled rate with a mass flow controller to simulate different occupant time profiles and densities. The CO_2 is dispersed through a tubing manifold with nine distribution locations at a height of four feet above the floor. Each tube has an identical length to ensure that the flow resistance of each tube is identical. In the chamber, a ceiling fan is used to promote the mixing of the supply air and the chamber air. A mini-split system and humidifier are used to regulate the chamber temperature and humidity to maintain the test conditions and tolerances specified below. Since the laboratory is located in a dry climate, dehumidification is not required.

A pre-specified CO_2 generation rate is used to mimic expected CO_2 generation rates of two occupant types: a profile with gradual changing occupancy and a profile with a series of step changes in the occupancy. For each profile, three maximum CO_2 generation rates are considered for a total of six tests. The generation rate as a function of time is computed based on each occupancy profile. Specifically, the occupancy profile (i.e., number of occupants) is computed by $\text{Occ}(t) = \text{Occ}_{frac}(t) \times \text{Occ}_{max}$ where $\text{Occ}(t)$ is the number of occupants at time t, $\text{Occ}_{frac}(t)$ is the specified occupancy fraction at time t, and Occ_{max} is the maximum expected occupancy for each occupant density category. The generation rate is obtained from the occupancy profile and is given by $G_{\text{CO}_2}(t) = \text{Occ}(t) \times G_{\text{CO}_2,\text{Occ}}$ where $G_{\text{CO}_2,\text{Occ}}$ is the generation per occupant taken to be 0.01 cfm CO_2 per occupant and $G_{\text{CO}_2}(t)$ is the generation rate in the chamber at time t, which has units of cfm CO_2. Similarly, the maximum CO_2 generation rate may be computed from Occ_{max} and is denoted by $G_{\text{CO}_2,max}$. The resulting generation rate profiles are shown in Figure 3 with parameters given in Table 1. For the remainder, the profiles shown in Figure 3a are referred to as the gradual profiles while the profiles shown

Table 2: Test conditions and test tolerances of the DCV system controller test.

Chamber property	Units	Test Condition	Test Operating Tolerance	Test Condition Tolerance
Absolute pressure	kPa	101	3	±5
Dry-bulb temperature	°F	75	5	±3
Relative humidity	%RH	40	20	±10
CO_2 generation rate	SLPM	Figure 3	5% of test condition	±3% of test condition
Outdoor air CO_2 concentration	ppm CO_2	≤ 425	≤ 450*	+10*

*Over the test, the average outdoor air CO_2 concentration must be maintained below 435 ppm. Additionally, the maximum outdoor air concentration over the test must be below 450 ppm.

in Figure 3b are referred to as the step profiles. The three occupancy densities are referred to as the low, medium, and high occupancy densities.

The minimum ventilation rate $\dot{V}_{in,min}$ is based on the 2019 California Building Energy Efficiency Standards Table 120.1-A (*Building energy efficiency standards for residential and nonresidential buildings*, 2018), which requires 0.15 cfm of outdoor air per square foot of floor area A, is

$$\dot{V}_{in,min} = (0.15\text{cfm}/\text{ft}^2)A \tag{1}$$

The minimum ventilation rate and the supply rates are given in Table 1. The supply airflow rate is based on a rule of thumb of 1 cfm per square foot of floor area.

The test protocol requires some preliminary setup tasks. The supply air fan speed is set to provide the required supply airflow rate for the test (see Table 1), which requires a one-time measurement of the supply airflow to ensure that it is within ±10 percent of the desired flow rate. The minimum damper position is fixed to ensure that the minimum ventilation airflow rate is achieved for all tests (within ±10 percent). The minimum damper position is determined using a tracer gas flow calibration. In the configuration of the DCV system controller for all tests, the maximum outdoor air damper position is set to its fully open position, which corresponds to a fully closed return damper position, so the AHU draws 100 percent outdoor air to supply the chamber when the DCV system controller commands the maximum ventilation rate. For consistency between all tests, the settings for the supply air fan, minimum damper position, and maximum damper position are recorded and used in all tests.

The first step in the protocol is to install and configure the DCV system controller with the manufacturer's CO_2 sensor (if required). The DCV controller is configured so that the command signal ranges between the minimum ventilation rate to 100 percent outdoor air, and the DCV system controller CO_2 concentration setpoint is set to 600 ppm above the outdoor air concentration. At the beginning of each test, the test chamber is flushed with outdoor air until the chamber CO_2 concentration is within the outdoor air concentration plus 30 ppm. The test chamber temperature, humidity, pressure, CO_2 generation rate, and outdoor air CO_2 concentration must be within the tolerances specified in Table 2. Once the preliminary setup tasks are completed, the main test protocol may be executed. CO_2 is added to the chamber through the CO_2 distribution system following one of the profiles shown in Figure 3 to simulate an occupancy pattern. As the chamber CO_2 concentration increases, the DCV system controller will start modulating the damper system to increase the ventilation rate. For all time-series data, measurements are sampled at 0.1 Hz. Throughout the test, the chamber temperature, humidity, pressure, supply airflow rate, and outdoor air CO_2 concentration are monitored. A successful test is one where the test is set up properly, the environmental variables are within the test tolerance (defined in Table 2), and the CO_2 generation rate follows one of the desired profiles (Figure 3). Upon completion of a test, the chamber is flushed with outdoor air to return the CO_2 concentration to within 30 ppm of the outdoor air concentration to begin the next test. The process is repeated until the tests for all six profiles are completed.

2.3 Ideal Baseline DCV Strategy

To help quantify the performance of each DCV system controller, the chamber CO_2 concentration obtained from the tests under each DCV system controller is compared to the expected concentration under an ideal DCV strategy. The ideal DCV strategy is a theoretical controller whose input is the outdoor CO_2 concentration, the generation rate, and the initial chamber CO_2 concentration recorded during the test and whose output is the optimal ventilation rate. The optimal ventilation rate maintains the minimum ventilation rate when the chamber CO_2 concentration is below the setpoint. For all other times, the optimal ventilation rate is the one that maintains the chamber CO_2 concentration at the setpoint. To generate the expected chamber CO_2 concentration, a closed-loop simulation is performed of the chamber under the ideal DCV strategy. Comparing the results obtained from the DCV system controller test protocol with that obtained from the closed-loop simulation under the ideal DCV strategy gives a measure of how close the DCV system controller performance is relative to the optimal performance.

The ideal DCV strategy is a model-based strategy, which uses a dynamic model to describe the chamber CO_2 concentration over time. Assuming that the chamber is well-mixed so that the contents are spatially uniform, an overall mass balance of CO_2 over the chamber and duct yields

$$\frac{dm_{\mathrm{CO_2}}(t)}{dt} = \dot{m}_{\mathrm{CO_2},in}(t) - \dot{m}_{\mathrm{CO_2},out}(t) + \bar{G}_{\mathrm{CO_2}}(t) \tag{2}$$

where $m_{\mathrm{CO_2}}(t)$ is the total mass of CO_2 in the chamber, $\dot{m}_{\mathrm{CO_2},in}(t)$ is the mass flow rate of CO_2 in the outdoor air stream, $\dot{m}_{\mathrm{CO_2},out}(t)$ is the mass flow rate of CO_2 in the chamber exhaust air stream, and $\bar{G}_{\mathrm{CO_2}}(t)$ is the mass generation rate of CO_2. Under the assumptions that the air density is constant and the outdoor airflow rate into the chamber is equal to the airflow rate leaving the chamber through the exhaust relief damper, (2) simplifies to

$$V\frac{dC_{\mathrm{CO_2}}(t)}{dt} = \dot{V}_{in}(t)(C_{\mathrm{CO_2},oa}(t) - C_{\mathrm{CO_2}}(t)) + G_{\mathrm{CO_2}}(t) \tag{3}$$

where $C_{\mathrm{CO_2}}(t)$ is the CO_2 concentration in the chamber, $\dot{V}_{in}(t)$ is the outdoor airflow rate (ventilation rate) that will be determined by the ideal DCV strategy, and $G_{\mathrm{CO_2}}(t)$ is the generation rate of the CO_2 in the chamber.

As described above, the ideal DCV strategy may be considered to be a feedforward controller, which utilizes perfect information of the CO_2 generation rate in the chamber to compute a ventilation rate that exactly rejects the effect of the disturbance. The CO_2 generation rate, which imitates occupancy in the chamber, is considered to be the disturbance. On the contrary, DCV system controllers are feedback controllers (i.e., reactive instead of proactive) since measuring the generation rate is not practical. The ideal DCV strategy is to maintain the minimum ventilation rate if the expected CO_2 concentration is at or below the maximum CO_2 concentration. Otherwise, the strategy selects the ventilation rate that exactly maintains the CO_2 concentration at its setpoint. Determining the ventilation rate that maintains the chamber concentration at exactly its setpoint, requires the solution of (3).

A simultaneous solution strategy is employed to determine the ventilation rate from the ideal DCV strategy and the solution of (3). Provided the input data including the chamber air volume, the outdoor air CO_2 concentration profile, the CO_2 generation rate profile, and an initial chamber CO_2 concentration, (3) may be numerically solved. For a fair comparison between the ideal DCV strategy and each DCV system controller test, the outdoor air CO_2 concentration profile and initial concentration are taken to be equal to the recorded data from each DCV system controller test. The explicit Euler method is employed to solve (3) with a sufficiently small integration time step, which gives

$$C_{\mathrm{CO_2}}(t+\Delta t) = C_{\mathrm{CO_2}}(t) + \frac{\Delta t}{V}\left(\dot{V}_{in}(t)(C_{\mathrm{CO_2},oa}(t) - C_{\mathrm{CO_2}}(t)) + G_{\mathrm{CO_2}}(t)\right) \tag{4}$$

where Δt is the integration time step, $C_{\mathrm{CO_2},oa}(t)$ is the CO_2 concentration recorded during the DCV system controller test and $C_{\mathrm{CO_2}}(0)$ is set to be equal to the initial chamber concentration at the beginning of the DCV system controller test. In (4), there is an implicit conversion of $G(t)$, which has units of cfm CO_2, to the units of (cfm air)/(ppm CO_2). The conversion has been omitted in the equation for simplicity of the presentation, but must be accounted for in the calculation. To determine $\dot{V}_{in}(t)$ under the ideal DCV strategy, first consider that $\dot{V}_{in}(t) = \dot{V}_{in,min}$. The expected CO_2 concentration at the next integration time is

$$C_{\mathrm{CO_2}}(t+\Delta t) = C_{\mathrm{CO_2}}(t) + \frac{\Delta t}{V}\left(\dot{V}_{in,min}(C_{\mathrm{CO_2},oa}(t) - C_{\mathrm{CO_2}}(t)) + G_{\mathrm{CO_2}}(t)\right)$$

If $C_{\mathrm{CO_2}}(t+\Delta t) \leq C_{\mathrm{CO_2},max}$, $\dot{V}_{in}(t)$ is set to $\dot{V}_{in,min}$ under the ideal DCV strategy. Else, the ventilation rate that keeps $C_{\mathrm{CO_2}}(t+\Delta t) = C_{\mathrm{CO_2},max}$ is computed by

$$\dot{V}_{in}(t) = \frac{V(C_{\mathrm{CO_2},max} - C_{\mathrm{CO_2}}(t)) - G(t)}{\Delta t(C_{\mathrm{CO_2},oa}(t) - C_{\mathrm{CO_2}}(t))}$$

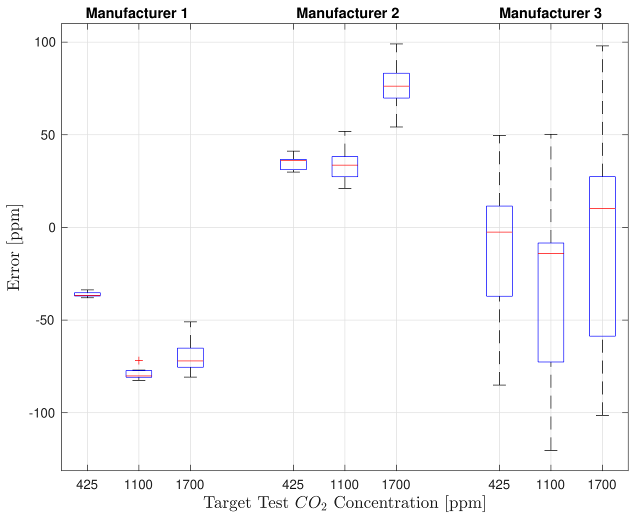


Figure 4: A box-and-whisker plot of the errors of each calibrated gas mixture. The box represents the second and third quartile, the line represents the full range (minimum to maximum), and the red line is the median error.

Table 3: CO_2 sensor test results. All units are ppm.

Manufacturer	Value	425 ppm	1100 ppm	1700 ppm
1	Actual CO_2 Conc.	422	1098	1710
	Average	386	1019	1640
	Minimum	382	1013	1627
	Maximum	391	1028	1661
	Std. Dev.	1.6	3.2	8.6
	Error	-36.2	-79.2	-69.7
2	Actual CO_2 Conc.	425	1101	1706
	Average	460	1135	1782
	Minimum	447	1114	1750
	Maximum	474	1165	1823
	Std. Dev.	4.8	10.1	14.4
	Error	35.1	34.3	76.3
3	Actual CO_2 Conc.	422	1098	1710
	Average	410	1064	1702
	Minimum	289	942	1515
	Maximum	527	1215	1929
	Std. Dev.	38.4	49.6	59.2
	Error	-11.3	-33.7	-7.0

Therefore, the ideal DCV strategy is given by

$$\dot{V}_{in}(t) = \max\left\{\frac{V(C_{\mathrm{CO_2},max} - C_{\mathrm{CO_2}}(t)) - G(t)}{\Delta t(C_{\mathrm{CO_2},oa}(t) - C_{\mathrm{CO_2}}(t))}, \dot{V}_{in,min}\right\} \tag{5}$$

3. RESULTS AND DISCUSSION

Due to space limitations, only a few example results are given here. The complete results will be presented at the conference and will also be posted to `https://empowerprocurement.com` after the conference.

3.1 CO_2 Sensor Tests

The CO_2 sensor test protocol was executed on three sensor model types from three different manufacturers (labeled as Manufacturer 1, Manufacturer 2, and Manufacturer 3). Each test considered ten sensors of the same model. Figure 4 presents a box-and-whisker plot of the error for each sensor model and each calibrated gas test. The x-axis of Figure 4 is the target concentration of the test calibrated gas. Table 3 presents a summary of the key statistics collected from the test and includes the actual CO_2 concentration of the gas used in each test. In Table 3, the average, standard deviation, and error are taken over all average steady-state sensor measurements while the minimum and maximum are the minimum and maximum instantaneous measurement of any sensor over the recording period.

From Figure 4 and Table 3, the steady-state average measurements of the ten sensors of Manufacturer 1 and 2 were consistently less than and greater than, respectively, the actual concentration. Manufacturer 1 sensors had the smallest standard deviation compared to that of the other sensors. However, Manufacturer 2 sensors had a comparable standard deviation as that of Manufacturer 1 sensors. Manufacturer 3 sensors had a substantially larger standard deviation compared to that of the other two sensor types. Interestingly, the average error across all ten sensors was the smallest for Manufacturer 3 sensors. While the standard deviation increased with CO_2 concentration for all sensors, the sensor error did not monotonically increase or decrease with the CO_2 concentration.

3.2 DCV System Tests

The DCV system controller test protocol was executed on an example DCV system controller. Since the local outdoor air that supplies the chamber air handling unit was generally above 400 ppm and reached levels above 425 ppm at times, the CO_2 setpoint was set to 1025 ppm (425 ppm plus 600 ppm). The resulting chamber CO_2 concentration is

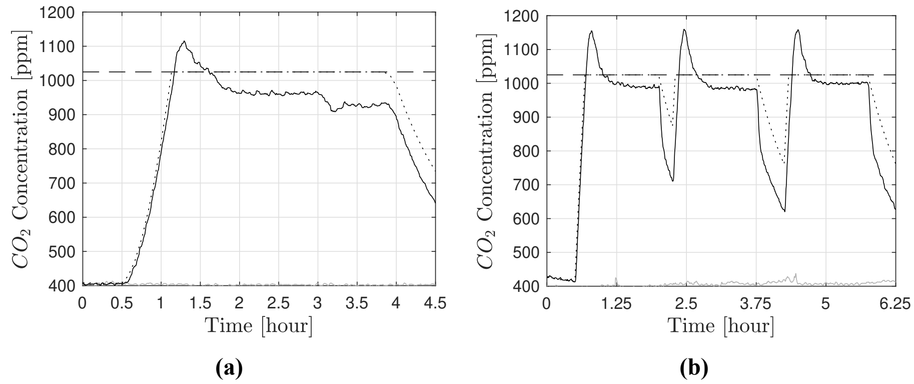


Figure 5: The chamber CO_2 concentration (solid), expected concentration under the ideal strategy (dotted), outdoor concentration (grey), and setpoint (dashed) for the high density (a) gradual profile and (b) step change profile tests.

Table 4: Time fraction within and outside the ideal ventilation target.

Test	Time Fraction Above 75 ppm Ideal Ventilation Target (%)	Time Fraction Below 75 ppm Ideal Ventilation Target (%)	Time Fraction within Ideal Ventilation Target (%)
Low step	0.0	33.1	66.9
Medium step	3.8	23.4	72.8
High step	7.1	21.9	71.0
Low gradual	0.0	31.2	68.8
Medium gradual	0.0	29.7	70.3
High gradual	1.5	31.6	66.9

shown in Figure 5. For performance comparison, the chamber was simulated with the ideal DCV strategy (5) with the initial chamber and the outdoor CO_2 concentrations recorded during the DCV test as inputs to the simulation. The expected chamber concentrations under the ideal DCV strategy are shown in Figure 5 (dotted black trajectory).

For the gradual profile tests (Figure 5a), the behavior under the DCV system controller is similar. Initially, the chamber CO_2 concentration is maintained at its ambient levels. After 30 minutes when CO_2 is introduced into the chamber through the CO_2 distribution system, the chamber CO_2 concentration starts to increase until the CO_2 concentration exceeds the setpoint. The DCV system controller responds by increasing the outdoor airflow rate. The chamber CO_2 concentration decreases below the setpoint where it is maintained at a constant level for a period. Finally, as the CO_2 generation rate decreases, the chamber CO_2 concentration decreases. For the step profile tests (Figure 5b), similar behaviors are observed as that of the gradual profile tests. The DCV system controller reactively increases the ventilation rate after the concentration exceeds the setpoint.

Comparing the responses under the DCV system controller with the expected responses under the ideal DCV strategy, there is general agreement between the two responses initially for all cases. The ideal DCV strategy can prevent the chamber CO_2 concentration from exceeding the setpoint owing to the feedforward nature of the ideal DCV strategy. Once the expected CO_2 concentration under the ideal DCV strategy reaches the setpoint, it is maintained there for a period. Once the generation rate decreases, the expected CO_2 concentration decreases at a comparable rate to that under the DCV system controller. The main differences between responses under the DCV system controller and the ideal DCV strategy occur when the concentration increases to the setpoint. The DCV system controller takes time to respond so the concentration increases past the setpoint (i.e., overshoots the setpoint). Eventually, the DCV system controller responds to decrease the concentration until the concentration decreases past the setpoint (over-ventilation). On the other hand, the ideal DCV strategy can anticipate the concentration reaching the setpoint and then, adjusts the ventilation rate to maintain the concentration at setpoint (i.e., prevents overshoot and then, over-ventilation).

To quantify the difference between the performance under the DCV system and that expected under the ideal DCV strategy, the difference between the measured CO_2 concentration under the DCV system and the expected CO_2 concentration under the ideal DCV stategy was computed. Table 4 tabulates the time fraction within and outside the ideal ventilation rate, which are defined as the time fraction that the difference between the two concentrations are within 75 ppm and the time fraction that the absolute value of the difference are greater than 75 ppm, respectively. Differences greater than 75 ppm represents under-ventilation while differences less than -75 ppm represents over-ventilation. From

Table 4, the chamber CO_2 concentration was within the target concentration for the majority of the time.

4. CONCLUSIONS

Two test protocols were presented: one for evaluating the accuracy of HVAC-grade CO_2 sensors used in CO_2-based DCV system controllers and the other for assessing the performance of CO_2-based DCV system controllers. The test protocols were performed on commercially available sensors and DCV system controllers. Of the three sensor models tested, one sensor model consistently measured the concentration less than the actual, one consistently measured the concentration greater than the actual, and the third was able to measure the CO_2 concentration with less than a 35 ppm absolute error on average, but had a large variance between the measurements of each sensors. From the DCV system controller test results, the main differences in the closed-loop performance of the DCV system controller test compared to that under an ideal DCV strategy is that the chamber CO_2 concentration under the DCV system showed considerable overshoot and over-ventilation not present in the expected CO_2 concentration under the ideal DCV strategy.

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