Standard Testing Protocols for HVAC-grade CO_2 Sensors and CO_2-based Demand Control Ventilation Systems

By

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Thesis

Submitted in partial satisfaction of the requirements for the degree of

Master of Science

in

Chemical Engineering

in the

Office of Graduate Studies

of the

University of California

Davis

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2021

To my Grandmother, Mary Elizabeth Williams.

ACKNOWLEDGMENTS

I would like to thank my advisor Dr. Matthew Ellis and the Western Cooling Efficiency Center for being supportive and working with me through this project.

I would also like to thank Dr. Ahmet Palazoglu and Dr. Nael El Farra for taking the time to be on my thesis committee.

Finally, I would like to thank my family and lab members for being supportive and encouraging throughout this journey. A special thanks to my mom for always being there. I could have not done it without you.

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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. Test results are provided and discussed.

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Nomenclature

A	Floor area of chamber	ft^2
$\bar{C}_{\mathrm{CO_2}}$	Time-average CO_2 concentration	ppm
$C_{\mathrm{CO_2}}$	CO_2 concentration	ppm
$C_{\mathrm{CO_2},ea}$	CO_2 concentration of exhaust air	ppm
$C_{\mathrm{CO_2},oa}$	CO_2 concentration of outdoor air	ppm
$C_{\mathrm{CO_2},max}$	Maximum CO_2 concentration in the chamber	ppm
$C_{\mathrm{CO_2},ra}$	CO_2 concentration of return air	ppm
Δt	Time step used in numerical simulation	1 min
$\bar{e}_j$	Average steady state error of the jth sensor	
$\bar{G}_{\mathrm{CO_2}}$	CO_2 generation rate in the chamber	kg/min
$G_{\mathrm{CO_2}}$	CO_2 generation rate	cfm CO_2
$G_{\mathrm{CO_2},max}$	Maximum CO_2 generation rate in the chamber	cfm CO_2
$G_{\mathrm{CO_2},\mathrm{Occ}}$	CO_2 generation per person	cfm CO_2/person
$m_{\mathrm{CO_2}}$	Total mass of CO_2 in the chamber	kg

$\dot{m}_{\mathrm{CO_2},in}$	Mass flow rate of CO_2 into the chamber	kg/min
$\dot{m}_{\mathrm{CO_2},out}$	Mass flow rate of CO_2 out of the chamber	kg/min
Occ	Occupancy	number of people
Occ_{frac}	Occupancy fraction	unitless
Occ_{max}	Maximum occupancy	number of people
$\sigma_{C_{\mathrm{CO_2}}}$	Standard deviation over time of the CO_2 concentration	ppm
$\bar{\sigma}_{C_{\mathrm{CO_2}}}$	Average of the measurement standard deviation of all sensors	ppm
$\sigma^2_{C_{\mathrm{CO_2}}}$	Variance over time of the CO_2 concentration	ppm^2
V	Volume of the chamber	ft^3
$\dot{V}_{in}$	Ventilation rate	cfm
$\dot{V}_{in,min}$	Minimum ventilation rate	cfm

Chapter 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 contaminats at or below their maximum healthy levels. ASHRAE Standard 62.1 specifies the ventilation requirements for acceptable indoor air quality [5]. In commercial buildings, well-ventilated buildings are associated with smaller rates of sick leave compared to poorly ventilated buildings [9]. Under-ventilated buildings have been linked to a condition known as sick building syndrome [9]. 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 [23] and wildfires in California and Oregon [6].

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 [10]. Most of the research and development on single-zone DCV occurred in the 1990s and early 2000s; refer to the review papers [10, 9, 4] and the references therein.

The earlier work on DCV has shown the benefits of using CO_2-based DCV for achieving energy savings and improving air quality. Yet, recent studies on DCV have highlighted several challenges and areas for potential improvement in both residential and public buildings (e.g., [18, 14, 3, 7, 21]). For example, the placement of the CO_2 sensor is an important consideration since spatial variations throughout a building will exist. Elevated CO_2 concentrations have been observed in recent studies in areas of the building if the placement is not chosen carefully [18, 14]. The study [3] uncovered differences in the risk areas in buildings for spreading airborne contaminants in three office buildings located in Denmark, Norway, and Sweden based on variations in the ventilation designs between the three buildings. In California schools, several problems with ventilation have been reported in [7]. In particular, some HVAC equipment was not properly installed or sized, fans were not operating continuously during operation hours, and filters were due for a change, which all contributed to inadequate ventilation in the schools studied. One or more of these problems have been identified in more than half of the classrooms examined. Still, promising results have been shown in a recent study of schools in Sweden [21] where CO_2 concentration levels in 60 of 61 classrooms in four newly constructed schools complied with the Swedish guidelines and regulations.

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 [16, 22]. The work of [11, 8, 15, 2] analyzes 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

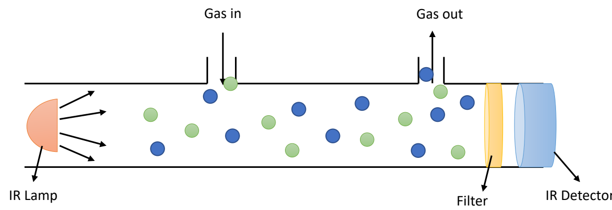


Figure 1.1: Non-dispersive infrared (NDIR) CO_2 sensor.

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 (e.g., [9]) although most of these studies are now over twenty years old.

CO_2-based DCV system controllers require low-cost CO_2 sensors to function properly. A common type of CO_2 sensor used in heating, ventilation, and air conditioning (HVAC) applications is a non-dispersive infrared (NDIR) sensor [19]. 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 (Figure 1.1). As shown in Figure 1.1, a filter allows the spectral range of light that corresponds to the absorption range of CO_2 to pass through it. Since the intensity is proportional to the CO_2 concentration, a correlation is used to relate the measured intensity to the concentration.

The effectiveness of CO_2-based DCV depends on the accuracy of CO_2 sensors. In [12], 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 [12], measurement errors of 100 ppm could result in DCV control action errors as large as 25 percent, compared to that produced with an accurate CO_2 sensor. This result further emphasizes the importance of accurate CO_2 sensors. In [20], 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 a 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. The sensors tested showed some are highly sensitivity to humidity, while others have small effects. The sensors were also sensitive to temperature and pressure, with a greater sensitivity to pressure than to temperature.

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 [5]) 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.

Chapter 2

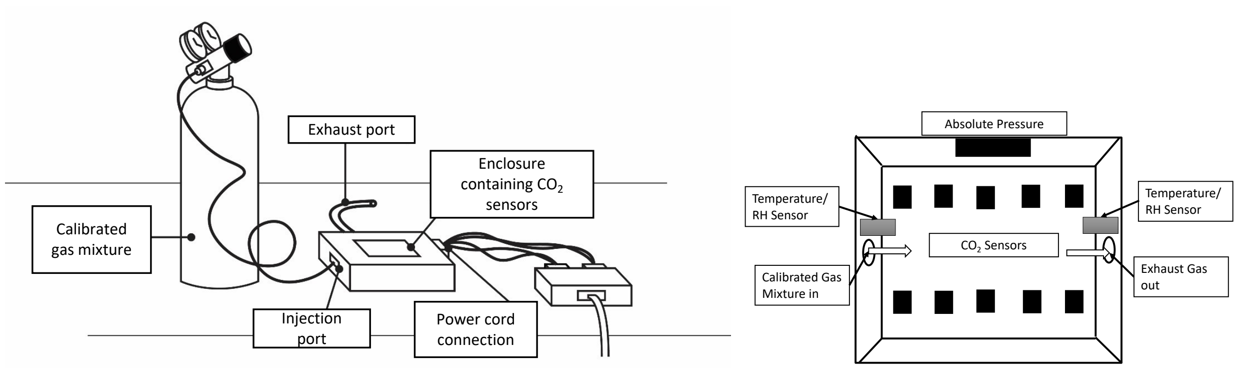
HVAC-Grade CO_2 Sensor Test Protocol

2.1 Objective and Overview

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.

2.2 Test Setup

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. The test enclosure houses ten CO_2 sensors, a pressure gauge, and two temperature and relative humidity sensors and has an injection port and exhaust port. Diagrams of the experimental setup and of the enclosure are shown



(a) (b)

Figure 2.1: (a) An overall diagram of the experimental setup of the CO_2 sensor test protocol and (b) a diagram of the enclosure with ten sensors.

in Figure 2.1a and Figure 2.1b, respectively. 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 a clear plastic so that the readings from the sensor display may be manually recorded. Tubing is used to connect the calibrated gas tank regulator to the injection 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.

2.3 Test Conditions

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. The middle concentration corresponds to a typical target CO_2 concentration of an occupied building. 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

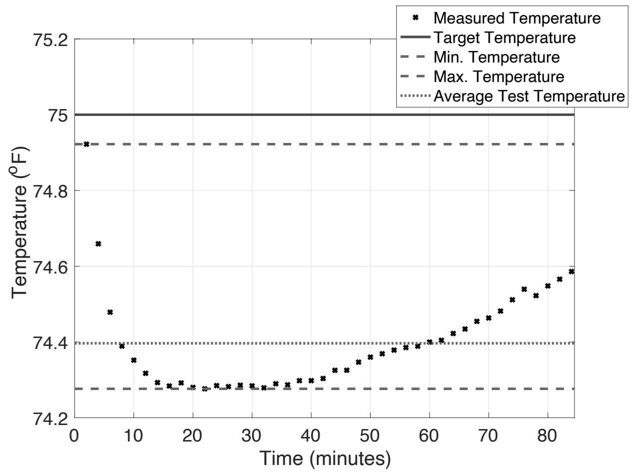


Figure 2.2: Illustration of an example temperature measured during a test with the two tolerances that must be satisfied during the test.

while leaving room in case the sensor bias is substantial (i.e., greater than 100 ppm). Since calibrated gas manufacturers cannot deliver exact concentrations, a range of acceptable concentrations are defined along with an acceptable accuracy of the gas concentration reported by the manufacturer. These calibrated gas conditions are reported in Table 2.1.

During the test, several conditions are imposed to maintain consistency of the environment across all tests. The conditions are summarized in Table 2.2. Specifically, environmental conditions in the enclosure are to be maintained at a temperature of 75°F, an absolute pressure of 101 kPa, and less than 5 percent relative humidity during the test. The conditions are measured every 2 minutes with sensors with the specified sensor accuracy given in Table 2.2. 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. Figure 2.2 illustrates how the two tolerances are defined and verified. The test condition tolerance is defined as the difference between the test condition and the average

Table 2.1: Target calibrated gas concentrations

Target Gas Concentration	Units	Accuracy of Reported Concentration	CO_2 Concentration Minimum	CO_2 Concentration Maximum
Calibrated Gas (425ppm)	ppm	within ± 2%	400	450
Calibrated Gas (1100ppm)	ppm	within ± 2%	1000	1200
Calibrated Gas (1700ppm)	ppm	within ± 2%	1600	1800

Table 2.2: CO_2 sensor test chamber conditions and instrument accuracy.

Measurement	Units	Test Conditions	Instrument Accuracy	Test Operating Tolerance	Test Condition Tolerance
Chamber temperature	°F	75	±1	5	±3
Chamber relative humidity	%RH	<5	±5	-	-
Chamber absolute pressure	kPa	101	±0.5% of reading	3	±1.5
Chamber differential pressure	Pa	> 5	±1	-	-

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. Additional conditions are imposed on the accuracy of the sensors used to monitor the environmental conditions in the chamber. The accuracy of the temperature sensor must be within ±1°F, the relative humidity sensor must be within ±5%, the absolute pressure gauge must be within ±0.5% of the reading, and the differential pressure gauge must be within ±1 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 [19]. 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 measurement 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 [19]. 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.

2.4 Test Protocol

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 first calibrated gas tank (425 ppm gas mixture) is connected. The regulator is adjusted to meet the absolute pressure and differential pressure requirements. When steady state is reached, as defined using the approach described in Section 2.4.1, the measurements specified in Table 2.2 and the CO_2 concentration measurements from all ten sensors are recorded every two minutes until a total of eleven measurements are recorded. This 20-minute period is defined as the recording period. After the recording period, the tank regulator is turned off to stop flow of gas (1100 ppm or 1700 ppm) is connected to the tubing. The test is repeated for both 1100 ppm and 1700 ppm gases.

The average steady state measurement for each sensor is determined based on measurements collected during the recording period. The sensor error, which is 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.

2.4.1 Steady State Detection

To determine when steady state has been reached, indicating the beginning of the recording period start, a moving window average steady state detection approach [13] is used. At the kth time step, the moving average of the past n measurements of the jth sensor is given by:

$$\bar{C}_{\mathrm{CO_2},j,k} = \frac{1}{n} \sum_{i=k-n+1}^{k} C_{\mathrm{CO_2},j,i} \tag{2.1}$$

for $k = n-1, n, \ldots$ where $\bar{C}_{\text{CO}_2,j,k}$ is the moving average measurement of the jth CO_2 sensor at the time step k, n is the number of data points sampled in the window, $C_{\text{CO}_2,j,i}$ is the measured CO_2 concentration for the jth sensor at time step i, and k is the current time with $k = 0$ being the initial time step. Since the steady state detection approach is used in a real-time test setting, the moving averages are defined using past measurements only, as future measurements from $k+1$ and beyond are unavailable at time step k. Additionally, the moving averages are only computed for time steps containing n past measurements, meaning that the first time step that the moving average is computed is for time step $n-1$. In this case, $n = 11$ since the window size is 20 minutes and the sample period is 2 minutes. The moving window variance is given by:

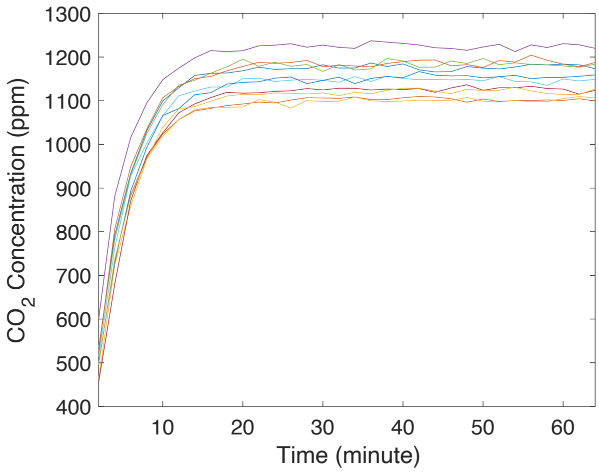
$$\sigma^2_{C_{\text{CO}_2},j,k} = \frac{1}{n-1} \sum_{i=k-n+1}^{k} (C_{\text{CO}_2,j,i} - \bar{C}_{\text{CO}_2,j,k})^2 \tag{2.2}$$

where $\sigma^2_{C_{\text{CO}_2},j,k}$ is the moving average variance. The moving average standard deviation at any time instant k is given by:

$$\sigma_{C_{\text{CO}_2},j,k} = \sqrt{\sigma^2_{C_{\text{CO}_2},j,k}} \tag{2.3}$$

where $\sigma_{C_{\text{CO}_2},j,k}$ is the standard deviation.

The steady state detection approach is defined using the moving average and moving standard deviation. Specifically, at each time step, Eqs. (2.1)-(2.3) are computed for each sensor. Thresholds are determined to be $\bar{C}_{\text{CO}_2,j,k} \pm 4\sigma_{C_{\text{CO}_2},j,k}$. If any of the measurements contained in the window are outside the thresholds, the data is taken to be not at steady state. If all the measurements in the window are within the thresholds, then the data is at steady state. Once the measurements of all sensors are determined to be at steady state,



*Calibrated gas CO_2 concentration in this example is 1111 ppm

Sensor #	Steady State CO_2 (ppm)	Error (ppm)	Standard deviation (ppm)
1	1176	65	6
2	1102	-9	3
3	1102	-9	4
4	1223	112	6
5	1184	73	6
6	1147	36	5
7	1127	16	6
8	1156	45	3
9	1187	76	8
10	1122	11	5
Average error of CO_2 measurement		42	
Standard deviation of error of CO_2 measurement		40	
Noise (Average of standard deviation)			5

Figure 2.3: Illustration of an example test of the steady state average, standard deviation, and noise for each sensor.

the recording period starts, implying that an additional 20 minutes of data is collected. For each test, the average steady state CO_2 concentration measurement and the standard deviation of the steady state measurements of each sensor is defined to be the moving window average ($\bar{C}_{\mathrm{CO}_2,j,N}$) and standard deviation ($\sigma_{C_{\mathrm{CO}_2},j,N}$), respectively, of the last window where N denotes the index of the last time step of the test.

2.4.2 Sensor Performance Assessment

To assess sensor performance, three statistics are computed to quantify the sensor accuracy, variation of the steady state sensor measurements, and measurement variation (i.e., noise) of the sensors. The first statistic, capturing the sensor accuracy, is the average steady state sensor error. For a test with a calibrated gas concentration denoted by $C_{\mathrm{CO}_2,calibrated}$, the average sensor error is given by:

$$\bar{e}_j(C_{CO_2,calibrated}) = \bar{C}_{CO_2,j,N} - C_{CO_2,calibrated}$$

where $\bar{e}_j(C_{\mathrm{CO}_2,calibrated})$ denotes the error of the jth sensor. To quantify the sensor-to-sensor variation of the errors of the ten sensors tested, the standard deviation of steady state errors is computed. This statistic is referred to as the standard deviation of the error. The variation of the steady state jth sensor measurements is quantified by the steady state standard deviation ($\sigma_{C_{\mathrm{CO}_2},j,N}$), computed by Eq. (2.3). Finally, the third statistic considered is the average of all ten steady state standard deviations, given by:

$$\bar{\sigma}_{C_{\mathrm{CO}_2}}(C_{\mathrm{CO}_2,calibrated}) = \frac{1}{10}\sum_{j=1}^{10} \sigma_{C_{\mathrm{CO}_2},j,N}(C_{\mathrm{CO}_2,calibrated})$$

where $\bar{\sigma}_{C_{\mathrm{CO}_2}}(C_{\mathrm{CO}_2,calibrated})$ is the average standard deviation over all ten sensors for the test with a calibrated gas concentration of $C_{\mathrm{CO}_2,calibrated}$. The third statistic quantifies the average steady state measurement noise. Figure 2.3 gives an example of how the three statistics are computed.

2.5 Results and Discussion

In total, ten sensor models were tested using the test protocol described in Section 2.4. For each sensor model, ten sensors were tested (i.e., a total of 100 sensors were tested using the test protocol). Each of the ten sensor models were from a different manufacturer. For simplicity of discussion, the ten sensor models are referred to as Manufacturer 1-10. The numbering is arbitrary, and does not represent any ordering of the sensor models. The known important differences between the sensors, including the type of sensor, the OEM

Table 2.3: Attributes of the CO_2 sensors tested.

Manufacturer	Sensor Type	OEM sensor manufacturer	Auto-calibration	Auto-calibration period
1	NDIR	Manufacturer A	No	-
2	NDIR	Manufacturer B	Yes	4 hour or more
3	NDIR	Unknown	Yes	-
4	NDIR	Unknown	No	-
5	NDIR	Manufacturer A	No	-
6	NDIR	Manufacturer C	Yes	-
7	NDIR	Manufacturer D	Yes	4 hours or more
8	NDIR	Manufacturer E	Yes	1 week
9	NDIR	Manufacturer D	Yes	1 week
10	NDIR	Manufacturer D	Yes	1 week

sensor manufacturer (labeled with arbitrary letters), and the period needed for the auto-calibration function (if any) are summarized in Table 2.3. All the sensors utilized an NDIR sensor. Manufacturers 1 and 5 sensors and Manufacturers 7, 9, and 10 sensors each shared the same OEM sensor manufacturer. Seven out of the ten sensor models tested used an auto-calibration function.

The tests were completed with the three calibrated gases on each of the ten sensor models. Table 2.4 gives the average steady state error, the minimum error, the maximum error, the standard deviation of the error, and the noise for each sensor model and calibrated gas tested. To visualize the results, Figure 2.4 shows a box-and-whisker plot that represents the median, minimum, and maximum error and any outliers across all tests. Figure 2.5 shows the average noise (i.e., the average standard deviation of the sensor measurements) and the minimum and maximum steady state standard deviations of the sensors for all the tests. Each of the tests were successful as determined by the test conditions discussed in Section 2.3, and a summary of the environmental variables monitored during each test is provided in Appendix A.1. Additionally, the linear regression results are given in Appendix A.2. One exception case was encountered, which is denoted by with an asterisk in the results.

Table 2.4: CO_2 sensor test results. All units are ppm.

Value	Manufacturer 1			2			3			4			5		
Target C_{CO_2}	425	1100	1700	425	1100	1700	425	1100	1700	425	1100	1700	425	1100	1700
Actual C_{CO_2}	426	1108	1716	426	111	1716	428	1111	1716	425	1101	1706	425	1101	1706
Error	-3	7	-37	-18	2	-61	27	42	2	44	28	48	35	34	76
Min. Error	-8	1	-43	-30	-34	-124	-13	-9	-58	-46	-91	-91	29	21	55
Max. Error	2	15	-28	-4	22	-30	82	112	72	179	215	277	40	51	101
Std. Dev.	4	4	5	7	18	30	31	40	44	77	105	130	4	9	14
Noise of measurement	3	4	6	2	4	5	5	5	6	11	15	15	3	4	7

Value	Manufacturer 6			7			8			9			10		
Target C_{CO_2}	425	1100	1700	425	1100	1700	425*	1100	1700	425	1100	1700	425	1100	1700
Actual C_{CO_2}	422	1098	1710	422	1098	1710	426*	1108	1706	426	1105	1707	426	1105	1707
Error	-12	-34	-6	-36	-79	-70	-26*	-238	-262	-53	-93	-108	-12	-30	-30
Min. Error	-86	-121	-102	-38	-82	-81	-26*	-310	-186	-57	-109	-141	-16	-36	-36
Max. Error	47	50	99	-34	-72	-51	-26*	-186	-159	-51	-71	-65	-7	-21	-22
Std. Dev.	39	50	61	1	3	9	0*	43	90	2	13	26	3	5	5
Noise of measurement	6	8	12	1	1	2	0*	6	5	1	1	1	1	1	1

*The CO_2 concentration of all sensors saturated at 400 ppm.

In particular, the sensor readings of all ten Manufacturer 8 sensors saturated at 400 ppm for the 425 ppm test.

Based on the three statistics, Manufacturer 1 and 10 sensors gave the best performance, while Manufacturer 4 and 8 sensors gave the worst performance, with absolute errors greater than 250 ppm possible with these two sensor models. Manufacturer 1 sensors do not have an auto-calibration function, while Manufacturer 10 sensors do. Manufacturer 4 sensors do not have an auto-calibration function, while Manufacturer 8 sensors do. Based on these results and the fact that the implementation of the auto-calibration function may vary across sensors, no conclusions on the usefulness of the auto-calibration can be drawn.

On average, Manufacturer 2 and 3 sensors were amongst the better performing sensors in terms of the average steady state error. However, the standard deviation of the errors across all ten sensors was large relative to the other best performing sensors. Thus, while based on the average error Manufacturer 2 and 3 sensors were amongst the better performing sensors, these sensors had larger sensor-to-sensor variability relative to the other best performing sensors.

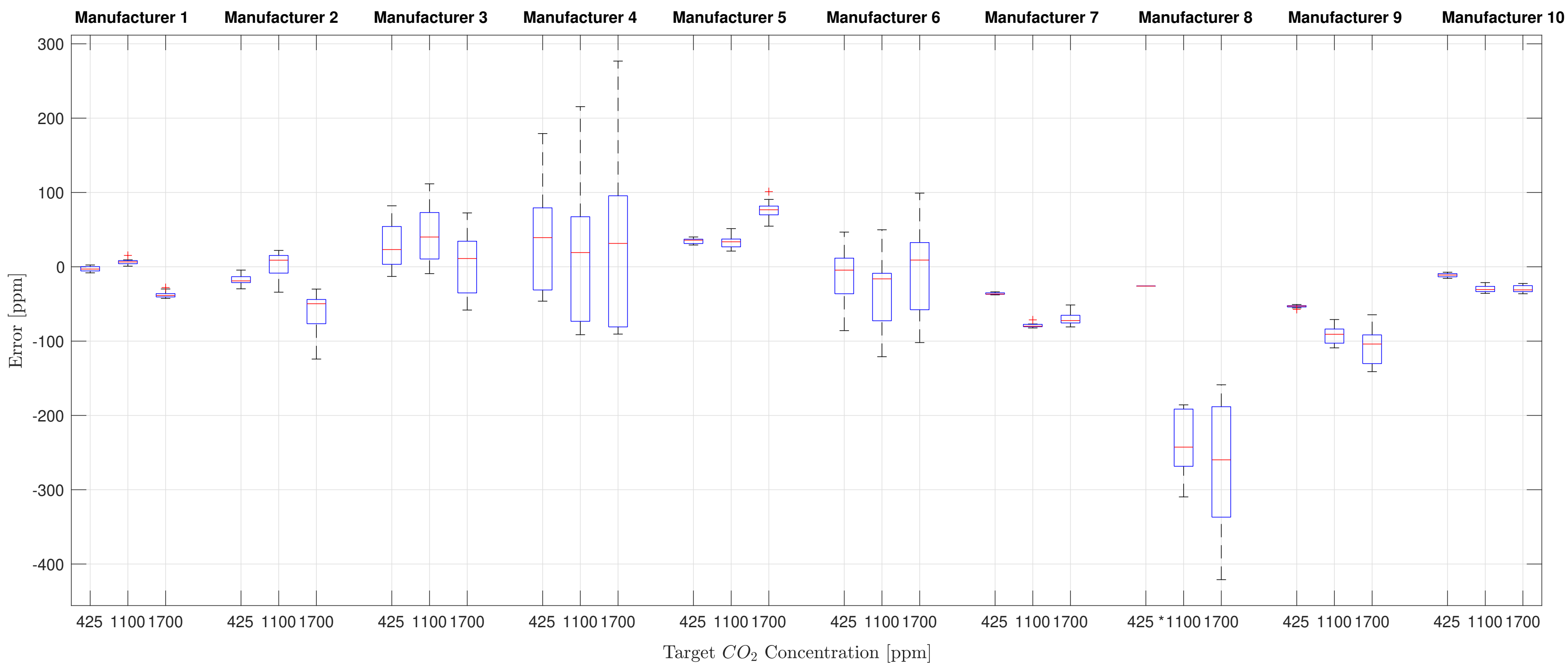
The performance of Manufacturers 1 and 5 sensors were compared since they both have the same OEM sensor manufacturer (albeit the sensors themselves may be a different model). Neither sensor utilized an auto-calibration function (Table 2.3). From Table 2.4, the average error of Manufacturer 1 sensors was -3 ppm for the 425 ppm test, -7 ppm for the 1100 ppm test, and -37 ppm for the 1700 ppm test. The average error of Manufacturer 5 sensors was 35 ppm for the 425 ppm test, 34 ppm for the 1100 ppm test, and 76 ppm for the 1700 ppm test. Although Manufacturer 1 consistently had a smaller error for the three tests compared to the error of Manufacturer 5, both sensors gave good results relative to the other sensors tested based on the three statistics described in Section 2.4.2. In contrast, the third sensor that did not have an auto-calibration function, Manufacturer 4 sensor, was amongst the worse performing sensors.

Manufacturer 7, 9, and 10 sensors all have the same OEM sensor manufacturer. All three sensor models require auto-calibration. The auto-calibration period of the Manufacturer 9 and 10 sensors is one week, while it is 4 hours (or more) for Manufacturer 7 (Table 2.3). The noise of the three sensor models was the lowest amongst all sensors tested. A range of sensor errors were observed across the three sensor models. Manufacturer 10 sensors yielded the smallest maximum absolute error of 30 ppm for the 1700 ppm test, Manufacturer 7 sensors gave the next smallest maximum absolute error of 70 ppm for the 1700 ppm test, and Manufacturer 9 resulted in the largest maximum absolute error of 108 ppm for the 1700 ppm test. Additionally, the standard deviation of the steady state errors over the ten sensors was higher than that of Manufacturers 7 and 10.

Given the range of results observed in Figures 2.4-2.5, a natural question arising is: what are the attributes or features leading to better performance? Unfortunately, given the range of results observed for sensors with similar attributes (described above) as well as the unknown proprietary information about the sensors, this question cannot be addressed from the results obtained using this test protocol. Additional investigation into the technical design of the sensors and their functions would be needed to address this question.

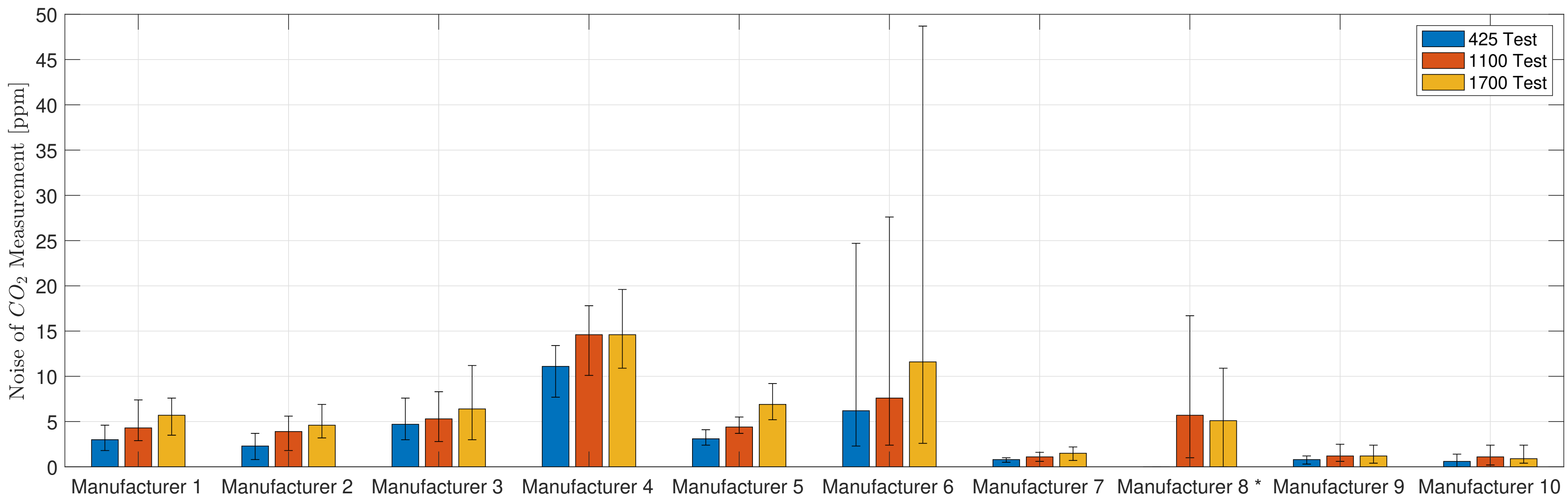
2.6 Conclusions

A testing protocol for evaluating the accuracy of HVAC-grade CO_2 sensors used in CO_2-based DCV system controllers was presented. The test protocols were performed on commercially available sensors. Of the ten sensor models tested, a range of sensor performances was observed as measured by three statistics: (1) steady state sensor error, (2) standard deviation of the steady state error across the ten sensors tested for each sensor model, and (3) steady state noise levels. Four of the ten sensor models performed quite well based on the fact that all ten sensors tested for each of these four models achieved absolute errors of less than 100 ppm with all three calibrated gas concentrations tested. Two sensor models had absolute sensor errors exceeding 250 ppm. Thus, sensor errors of 100 ppm are still possible in widely used HVAC-grade CO_2 sensors. Based on previous studies [12], errors of 100 ppm could result in DCV control action errors as large as 25 percent compared to accurate measurements. Moreover, if the absolute sensor error is greater than 75 ppm (at 600 ppm and 1000 ppm), then the sensor does not meet the Title 24 accuracy requirement [1].



*The CO_2 concentration of all sensors saturated at 400 ppm.

Figure 2.4: The sensor errors for each model tested and each calibrated gas. 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 over all ten sensors. Outliers appear as red crosses.



*The CO_2 concentration of all sensors saturated at 400 ppm.

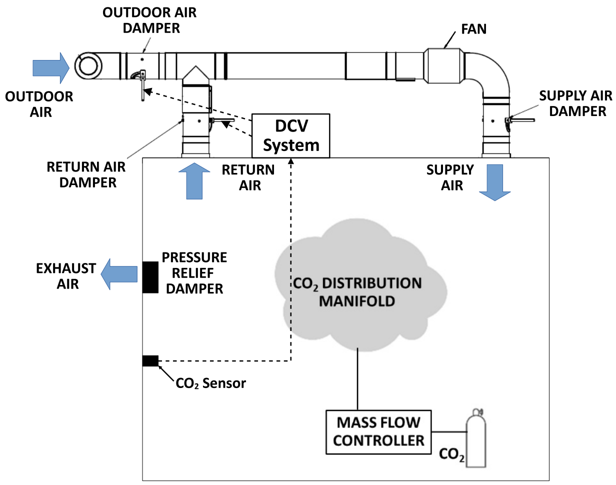
Figure 2.5: The average noise (i.e., average standard deviation over all ten sensors) for each sensor model and calibrated gas tested. The error bars represent the full range (minimum to maximum) of the standard deviations observed across the ten sensors tested.

Chapter 3

CO_2-Based Demand Control Ventilation Test Protocol

3.1 Objective and Overview

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 system performance is compared to the performance of an ideal controller. 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. The ventilation rates and the range of occupancy densities are determined based on the 2019 California Building Energy Efficiency Standards [1] and ASHRAE Standard 62.1 [5], respectively, so the tests reflect realistic conditions.



(a)

(b)

Figure 3.1: (a) A schematic of the test chamber and AHU and (b) a photo showing the CO_2 distribution system.

3.2 Test Setup

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 3.1a, and a picture of the inside of the chamber is given in Figure 3.1b. 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). As a result, the exhaust airflow rate is 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 concentration and to report the value to the DCV system controllers. When compatible, the same (high accuracy HVAC-grade) sensor, which is 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. A calibrated CO_2 sensor is used to monitor the outdoor air CO_2 concentration. To ensure that the chamber contents are well-mixed, additional calibrated CO_2 sensors are placed next to the relief damper and in the return air duct. All CO_2 sensors used have been calibrated using the procedure described in Chapter 2. The conditions imposed on the chamber mixing are discussed in the Section 3.3.

3.3 Test Conditions and Initial Setup

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

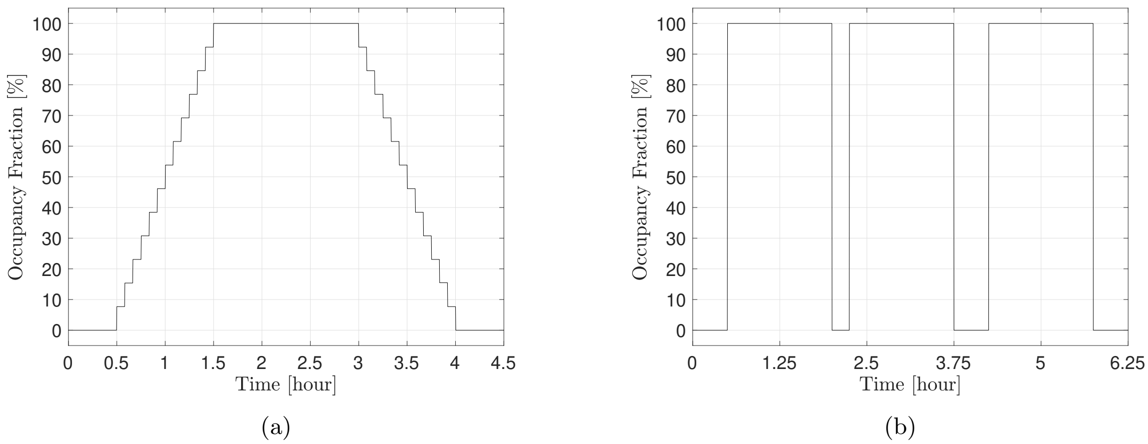


Figure 3.2: Occupancy fraction ($\mathrm{Occ}_{frac}(t)$) for (a) a gradually changing occupancy and (b) a series of step changes in the occupancy.

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

$$\mathrm{Occ}(t) = \mathrm{Occ}_{frac}(t) \times \mathrm{Occ}_{max}$$

where $\mathrm{Occ}(t)$ is the number of occupants at time t, $\mathrm{Occ}_{frac}(t)$ is the specified occupancy fraction at time t, and Occ_{max} is the maximum expected occupancy for each occupant density category. Two different types of occupancy fraction profiles are considered. The profiles are shown in Figure 3.2. These profiles are selected to demonstrate two extreme cases: a gradual change over time and several sudden changes over time. For the remainder, the profile shown in Figure 3.2a is referred to as the gradual profile, while the profile shown in Figure 3.2b is

Table 3.1: 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)	$G_{\mathrm{CO}_2,max}$ ($\times 10^{-2}$ 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

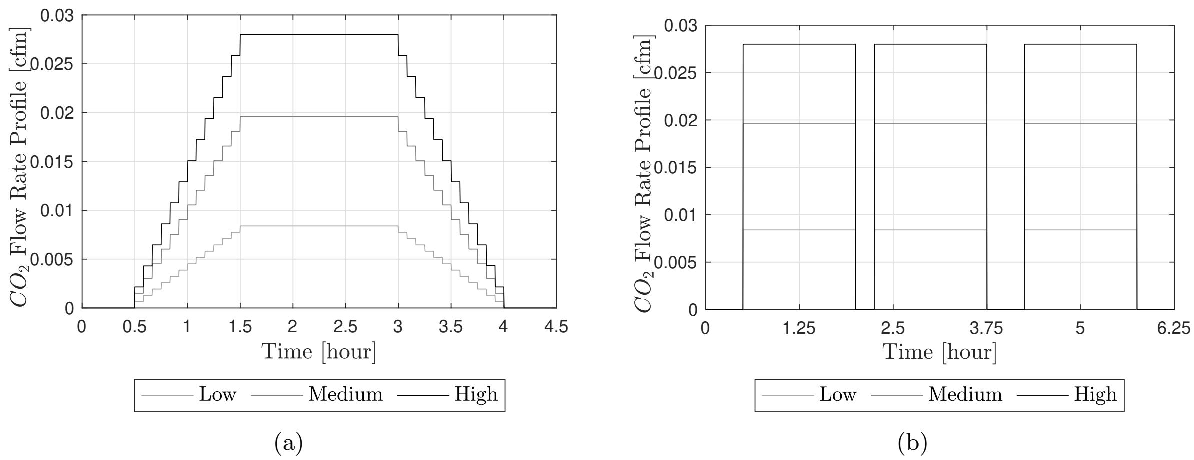


Figure 3.3: CO_2 generation rate for (a) a gradually changing occupancy profile and (b) a series of step changes in the occupancy for three occupancy densities.

referred to as the step profile.

The generation rate is obtained from the occupancy profile and is given by

$$G_{\mathrm{CO}_2}(t) = \mathrm{Occ}(t) \times G_{\mathrm{CO}_2,\mathrm{Occ}}$$

where $G_{\mathrm{CO}_2,\mathrm{Occ}}$ is the generation per occupant taken to be 0.01 cfm CO_2 per occupant and $G_{\mathrm{CO}_2}(t)$ is the generation rate in the chamber as a function of time, which has units of cfm CO_2. Similarly, the maximum CO_2 generation rate may be computed from Occ_{max} and is denoted by $G_{\mathrm{CO}_2,max}$. For each of the occupancy profiles, three occupancy densities are considered to represent a low, medium, and high occupancy density. The occupancy density for each of these categories are provided in Table 3.1 along with the maximum occupancy and maximum CO_2 generation rate. Six CO_2 generation rate profiles result from the two occupancy profiles and three occupancy densities, which are shown in Figure 3.2 implying that a total of six tests are performed for each DCV controller.

The minimum ventilation rate $\dot{V}_{in,min}$ is based on the 2019 California Building Energy Efficiency Standards Table 120.1-A [1], which requires 0.15 cfm of outdoor air per square foot of floor area A. Using this, the minimum ventilation rate is given by:

$$\dot{V}_{in,min} = (0.15\text{cfm}/\text{ft}^2)A \tag{3.1}$$

The supply airflow rate is based on a rule of thumb of 1 cfm per square foot of floor area. The minimum ventilation rate and the supply rates are given in Table 3.1.

Prior to running any tests, a few one-time setup tasks must be performed. The supply air fan speed is set to provide the required supply airflow rate for the test (see Table 3.1), 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. Tracer gas for single zone spaces has proven to be useful for ventilation [17]. 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.

To ensure that ambient and chamber conditions mimic typical operating conditions of

Table 3.2: Test conditions and test tolerances of the DCV system controller test.

Chamber property	Units	Test Condition	Instrument Accuracy	Test Operating Tolerance	Test Condition Tolerance
Absolute pressure	kPa	101	$\pm$2.5% of reading	3	± 5
Chamber dry-bulb temperature	°F	75	± 1	5	± 3
Chamber relative humidity	%RH	40	± 5	20	± 10
CO_2 generation rate	SLPM	Figure 3.3	$\pm$2% of reading	5% of test condition	$\pm$3% of test condition
Outdoor air CO_2 concentration	ppm CO_2	≤ 425	$\pm$2% of reading	$\leq 450^*$	$+10^*$
Other CO_2 sensors	ppm		$\pm$2% of reading		

*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.

a building, test conditions with test operating tolerances and test condition tolerances are defined for several variables (refer to Section 2.3 for definitions of the test operating and test condition tolerances). The variables with test conditions include the absolute pressure, chamber temperature, chamber relative humidity, CO_2 generation rate, and outdoor air CO_2 concentration. The test conditions and tolerances are defined in Table 3.2. Similar conditions on the sensor accuracy as that imposed on the CO_2 sensor tests (refer to Section 2.3) are used with additional accuracy conditions imposed on the CO_2 sensors monitoring the CO_2 concentrations. These accuracy requirements are also given in Table 3.2.

The return and exhaust CO_2 concentrations are monitored to ensure that the chamber is well-mixed during the test. Under perfect mixing, the chamber, exhaust air, and return air concentrations would be identical. However, since perfect mixing is not achievable in practice, test conditions are imposed on the differences between the exhaust and chamber concentration and between the return and chamber concentrations. To filter out high frequency variation (i.e., noise), a moving average filter is applied to these differences using a five-minute moving average window and data sampled every ten seconds. The filtered difference between exhaust CO_2 concentration and the chamber concentration must be maintained within ±50 ppm, while the filtered difference between return air and chamber concentration must be within ±100 ppm of the filtered chamber concentration. A tighter bound on the difference between the exhaust air concentration and chamber concentration compared to the bound on the difference between the return air concentration and chamber concentration is used because the amount of CO_2 in the exhaust air directly impacts the overall CO_2 mass balance around the chamber and air handling unit.

3.4 Test Protocol

The first step in the protocol is to install and configure the DCV system controller. The DCV controller is configured so that the command signal ranges between the minimum ventilation rate to 100 percent outdoor air, and the 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.

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 six profiles shown in Figure 3.3 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 (1) test is set up properly (Section 3.2), (2) the environmental variables are within the test tolerance (defined in Table 3.2), (3) the CO_2 generation rate follows one of the desired profiles (Figure 3.2), and (4) the mixing conditions, defined in Section 3.3, are satisfied. 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.

3.4.1 Ideal Controller

To 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 inputs are 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 using a dynamic model of the chamber CO_2 concentration. 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

$$\frac{dm_{\mathrm{CO}_2}(t)}{dt} = \dot{m}_{\mathrm{CO}_2,in}(t) - \dot{m}_{\mathrm{CO}_2,out}(t) + \bar{G}_{\mathrm{CO}_2}(t) \tag{3.2}$$

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, Eq. (3.2) simplifies to

$$V\frac{dC_{\mathrm{CO}_2}(t)}{dt} = \dot{V}_{in}(t)(C_{\mathrm{CO}_2,oa}(t) - C_{\mathrm{CO}_2}(t)) + G_{\mathrm{CO}_2}(t) \tag{3.3}$$

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.

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 Eq. (3.3).

A simultaneous solution strategy is employed to determine the ventilation rate from the ideal DCV strategy and the solution of Eq. (3.3). 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, Eq. (3.3) 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 Eq. (3.3) with a sufficiently small integration time step, which gives

$$C_{\mathrm{CO_2}}(t+\Delta t) = C_{\mathrm{CO_2}}(t) + \frac{\Delta t}{V}\left(\dot{V}_{in}(t)(C_{\mathrm{CO_2},oa}(t) - C_{\mathrm{CO_2}}(t)) + G_{\mathrm{CO_2}}(t)\right) \tag{3.4}$$

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 Eq. (3.4), 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

$$C_{\mathrm{CO_2}}(t+\Delta t) = C_{\mathrm{CO_2}}(t) + \frac{\Delta t}{V}\left(\dot{V}_{in,min}(C_{\mathrm{CO_2},oa}(t) - C_{\mathrm{CO_2}}(t)) + G_{\mathrm{CO_2}}(t)\right) \tag{3.5}$$

If $C_{\mathrm{CO_2}}(t+\Delta t) \leq C_{\mathrm{CO_2},max}$, where $C_{\mathrm{CO_2},max}$ is the CO_2 setpoint (i.e., target concentration to maintain during occupied periods.), $\dot{V}_{in}(t)$ 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

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

Therefore, the ideal DCV strategy is given by

$$\dot{V}_{in}(t) = \max\left\{\frac{V\left(C_{\mathrm{CO_2},max} - C_{\mathrm{CO_2}}(t)\right) - G(t)}{\Delta t(C_{\mathrm{CO_2},oa}(t) - C_{\mathrm{CO_2}}(t))}, \dot{V}_{in,min}\right\} \tag{3.6}$$

The simulated chamber CO_2 concentration generated by numerically solving Eq. (3.3) using Eq. (3.5) under the ideal DCV strategy defined by Eq. (3.6) is referred to as the (expected) ideal controller CO_2 concentration.

3.4.2 Assessment of DCV Performance

To quantify the performance of a DCV controller, the chamber CO_2 concentration measured during a test, referred to as the actual CO_2 concentration, is compared to the ideal controller CO_2 concentration. Specifically, at each 10 second time step (i.e., the sampling rate is 0.1 Hz), the ideal controller CO_2 concentration is subtracted from the actual CO_2 concentration to calculate the difference. The differences indicate under and over ventilation, with the positive differences indicating under ventilation and negative differences indicating over ventilation. Thus, the differences are categorized into one of three categories: (1) within the target ventilation, (2) under ventilation, and (3) over ventilation.

When the difference between the concentrations is greater than 75 ppm, the time step is binned into the under ventilated category. The percent of time that the DCV controller is dictating a ventilation rate that is under ventilating the chamber is calculated by dividing the number of time steps in the under ventilated category by the total number of time steps.

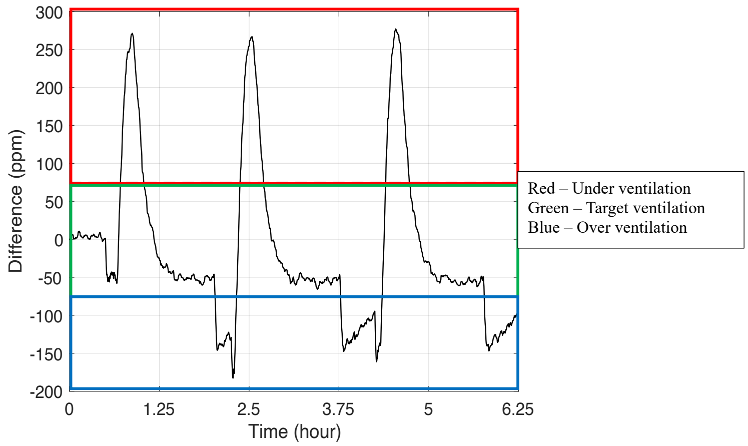


Figure 3.4: An illustration of the categorization that the controller under ventilates, over ventilates, and ventilates within the target is determined. The boxes highlight the times during the test that the controller is under ventilating, over ventilating, or at the target ventilation.

The average elevated CO_2 concentration (in ppm) is calculated as the average chamber CO_2 concentration measurements for all the time steps in the under ventilated category. When the difference between the concentrations is less than -75 ppm, the time step is binned into the over ventilated category. Analogously, the percent of time that the DCV controller is dictating a ventilation rate that resulted in over ventilation and the average lowered CO_2 concentration are calculated. The remainder of the time steps where the difference in concentrations is between -75 ppm and 75 ppm (a 150 ppm range) is considered to be within the target ventilation. Figure 3.4 illustrates how the time steps are categorized into the three categories. To measure the magnitude of under and over ventilation, the average differences in concentration above and below 75 ppm and -75 ppm is calculated. The magnitude of these two averages reflect how extreme the under and over ventilation is.

3.5 Results and Discussion

Four DCV system controllers were tested and the results for all four controllers are provided. The concentration profiles of the six tests performed on each of the DCV system controllers are shown in Figures 3.5-3.8 with the corresponding assessment metrics reported in Tables 3.3-3.6, respectively. In all tests, the test conditions (Section 3.3) were satisfied indicating a successful test. The environmental variables used to verify the test conditions for each test are summarized in Appendix A.3. The DCV system controllers were from different manufacturers and therefore, for simplicity of discussion, the four controllers are referred to as Manufacturer 1-4 DCV system controllers. The numbering is arbitrary.

For measuring the CO_2 concentrations (chamber, outdoor air, return air and exhaust air), high-accuracy HVAC-grade CO_2 sensors were used. The high-accuracy sensor measuring the chamber CO_2 concentration was used as the CO_2 concentration sensor for the Manufacturer 1-3 DCV system controller tests. For the Manufacturer 4 DCV system controller test, the controller requires the manufacturer's sensors. The best performing Manufacturer 8 sensors based on the results of Section 2.5 was selected. The manufacturer also performed a manual calibration on this sensor in an attempt to improve the accuracy of the measurement. The nearest possible setpoint to the outdoor air concentration plus 600 ppm was used in the tests. The setpoints used were 1025 ppm for the Manufacturer 1 controller tests, 1000 ppm for the Manufacturer 2 and 4 controller tests, and 1020 ppm for the Manufacturer 3 controller tests. For performance assessment, the ideal controller calculation was repeated for each test using the initial chamber concentration and outdoor air concentration recorded during the test and setpoint and generation rate used in the test.

In Tables 3.3-3.6, the column "Time fraction > 75 ppm" gives the percentage of the test time that the chamber CO_2 concentration was greater than the ideal controller CO_2 concentration plus 75 ppm (indicating under ventilation). The column "Time fraction < -75 ppm" gives the percentage of the test time that the chamber CO_2 concentration was less than the ideal controller CO_2 concentration minus 75 ppm (indicating over ventilation). The column "Time fraction within ± 75 ppm" gives the percentage of the test time that the chamber CO_2 concentration was within ± 75 ppm of the ideal controller concentration. The columns "Average > 75 ppm" and "Average < -75 ppm" give the average difference between the chamber and ideal controller concentration when the difference was greater than 75 ppm and less than -75 ppm, respectively.

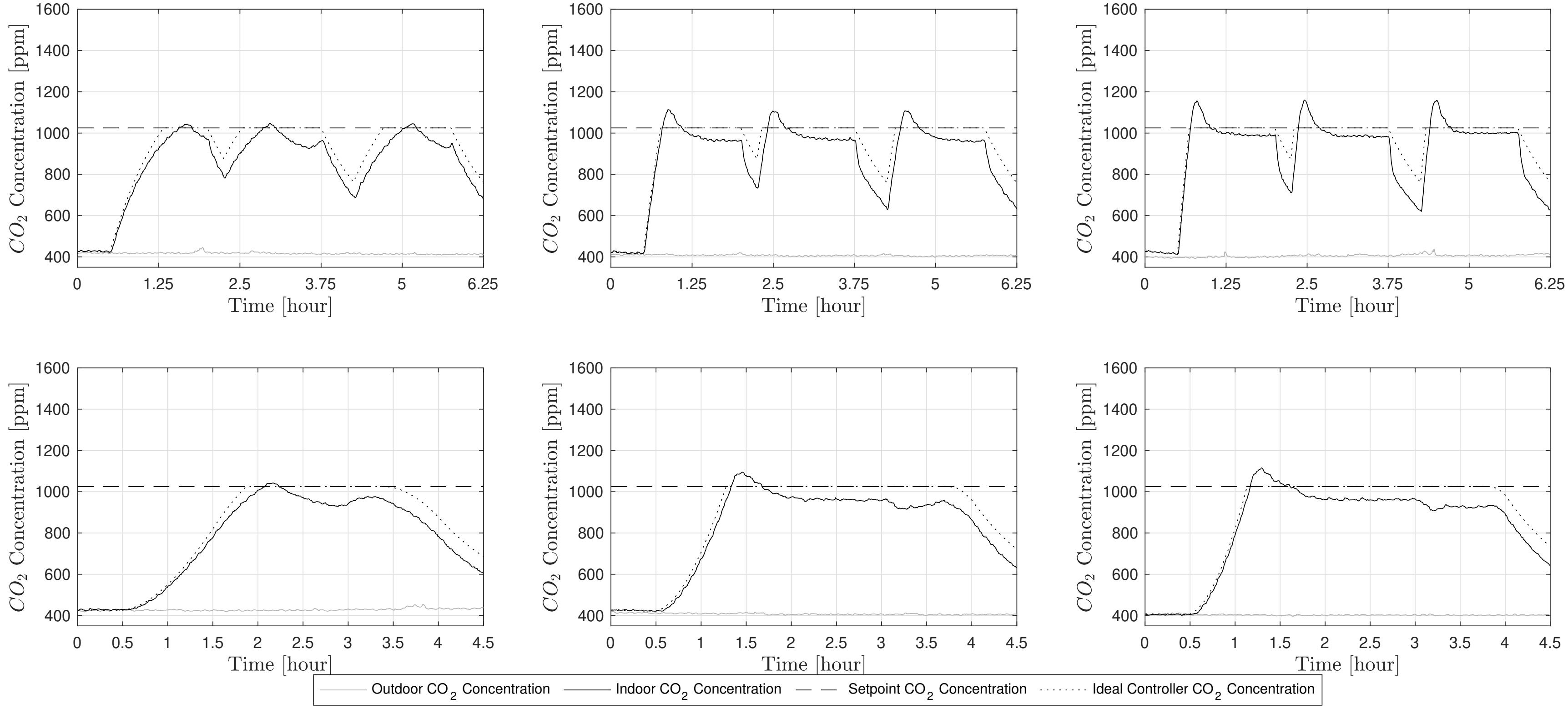


Figure 3.5: The outdoor, indoor (chamber), and ideal controller CO_2 concentrations for the Manufacturer 1 DCV test with the gradual (top) and step (bottom) generation profiles for low, medium, and high occupancy densities (left to right).

Table 3.3: Performance assessment metrics for the Manufacturer 1 DCV system controller.

Test	Time fraction > 75 ppm (%)	Time fraction < −75 ppm (%)	Time fraction within ±75 ppm (%)	Average > 75 ppm (ppm)	Average < −75 ppm (ppm)
Low step	0.0	33.1	66.9	0.0	-90.2
Medium step	3.8	23.4	72.8	80.2	-132.8
High step	7.1	21.9	71.0	109.6	-153.3
Low gradual	0.0	31.2	68.8	0.0	88.3
Medium gradual	0.0	29.7	70.3	0.0	-93.5
High gradual	1.5	31.6	66.9	83.3	-96.5

Figure 3.5 shows the CO_2 concentrations for the six tests preformed with the Manufacturer 1 DCV system controller. Table 3.3 gives the metrics to assess the performance. For the low occupancy density step and gradual profiles, the chamber CO_2 concentration did not exceed 75 ppm above the ideal controller CO_2 concentration, meaning that there were no periods where the chamber concentration was under ventilated. In the other tests, there were a few periods where the chamber concentration exceeded that of the ideal controller by over 75 ppm, but these periods occurred less than 10 percent of the time of the experiment. Over all tests, the concentration was maintained within the target range over the majority of the test.

Over all tests, the Manufacturer 1 DCV system controller behaves similarly across all tests. The initial CO_2 concentration is below the setpoint, so the controller maintains the ventilation rate at the minimum. As the CO_2 generation rate increases, the chamber CO_2 concentration increases until the concentration reaches the setpoint. A delay occurs between when the concentration reaches the setpoint and when the controller commands a large enough ventilation rate, resulting in the concentration exceeding the setpoint (i.e., an overshoot of the setpoint). The controller increases the ventilation rate to reduce the concentration. Another overshoot of setpoint is observed, and the concentration settles at an offsetting steady state concentration. The offset may have resulted from the controller deadband. Once the CO_2 generation rate starts to decline, so does the concentration. In the case of the step change profiles, this behavior is repeated two other times for the next two step changes.

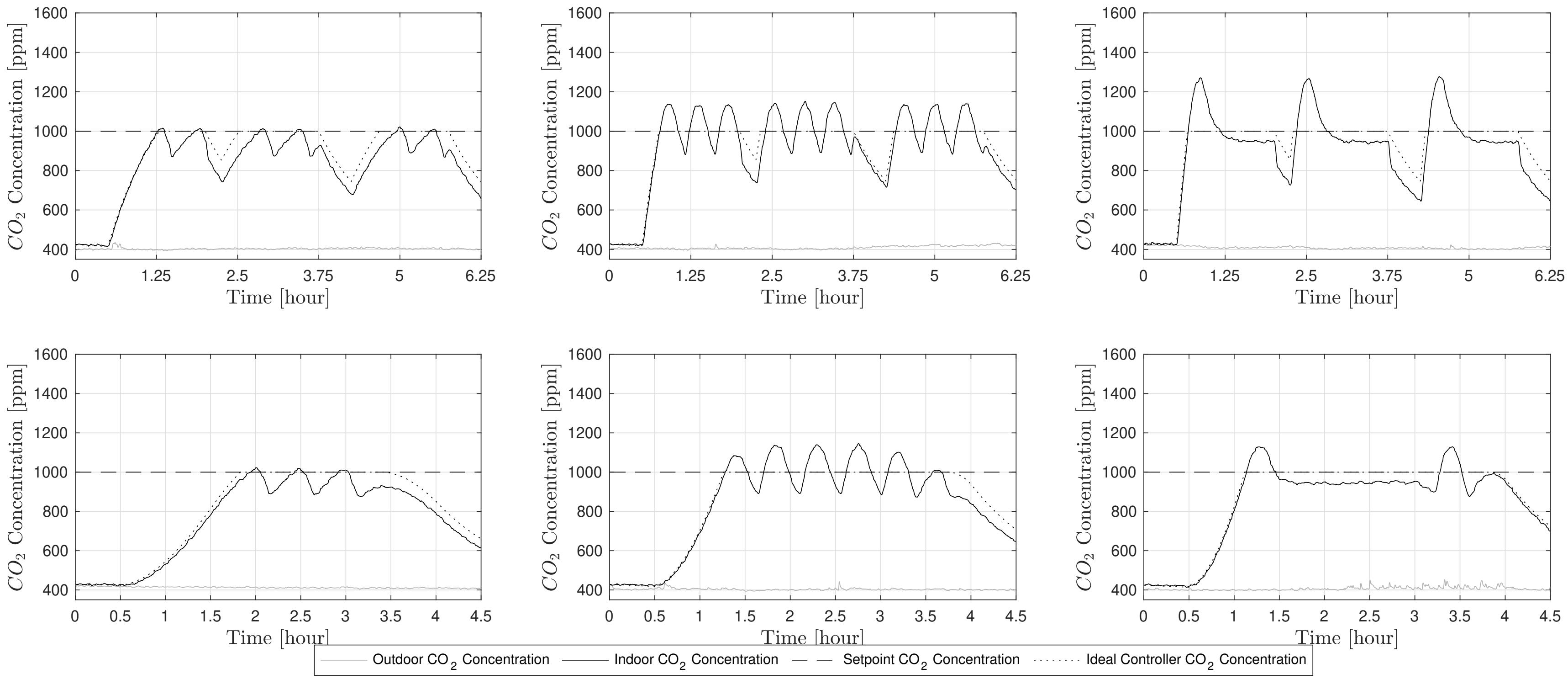


Figure 3.6: The outdoor, indoor (chamber), and ideal controller CO_2 concentrations for the Manufacturer 2 DCV test with the gradual (top) and step (bottom) generation profiles for low, medium, and high occupancy densities (left to right).

Table 3.4: Performance assessment metrics for the Manufacturer 2 DCV system controller.

Test	Time fraction > 75 ppm (%)	Time fraction < -75 ppm (%)	Time fraction within ± 75 ppm (%)	Average > 75 ppm (ppm)	Average < -75 ppm (ppm)
Low step	0.0	36.7	63.3	0.0	-97.5
Medium step	27.2	14.6	58.2	116.7	-109.8
High step	15.7	21.6	62.7	195.7	-125.5
Low gradual	0.0	13.4	86.6	0.0	-96.4
Medium gradual	22.2	16.8	61.0	97.4	-107.9
High gradual	8.2	6.0	85.8	110.3	-94.4

Figure 3.6 shows the CO_2 concentrations for the six tests preformed with the Manufacturer 2 DCV system controller, and Table 3.4 gives the metrics to assess the performance. For the tests with the low and medium occupancy densities and both the gradual and step profiles, noticeable sustained (non-dissipating) oscillations are observed in the chamber CO_2 concentration when the generation rate reaches its maximum. No oscillations are observed in the high occupancy density tests once the generation rate reaches its maximum. However, there appears to be some oscillatory behavior (i.e., one cycle of the oscillation) that begins at 3.25 hours into the high occupancy density gradual profile test. At this point in the test, the generation rate is about equal to the maximum generation rate for the medium occupancy density test (Figure 3.3a). The chamber concentration was maintained below 75 ppm of that for the ideal controller for both low occupancy density tests. Based on the time fraction that the chamber concentration was within 75 ppm of that under the ideal controller, the controller performed better for the gradual profile tests compared to the step profile tests.

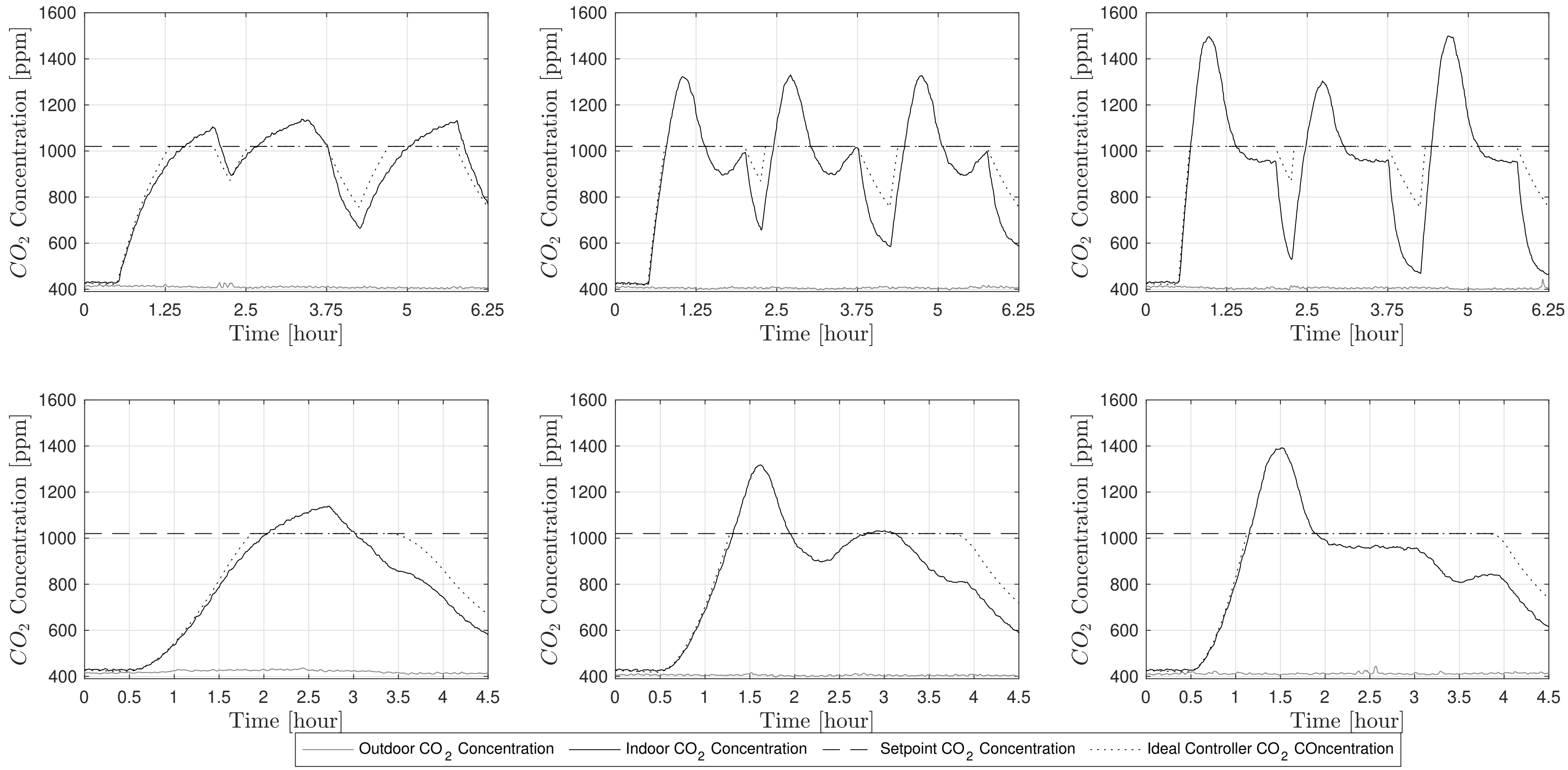


Figure 3.7: The outdoor, indoor (chamber), and ideal controller CO_2 concentrations for the Manufacturer 3 DCV test with the gradual (top) and step (bottom) generation profiles for low, medium, and high occupancy densities (left to right).

Table 3.5: Performance assessment metrics for the Manufacturer 3 DCV system controller.

Test	Time fraction > 75 ppm (%)	Time fraction < -75 ppm (%)	Time fraction within ± 75 ppm (%)	Average > 75 ppm (ppm)	Average < -75 ppm (ppm)
Low step	17.5	13.6	68.9	94.8	-96.7
Medium step	22.8	40.7	36.5	217.8	-146.3
High step	25.7	24.3	50.0	292.2	-280.6
Low gradual	10.1	28.4	61.5	99.3	-123.6
Medium gradual	10.9	35.4	53.7	210.5	-146.8
High gradual	13.0	32.1	54.9	262.6	-160.3

Figure 3.7 shows the CO_2 concentrations for the six tests preformed with the Manufacturer 3 DCV system controller, and Table 3.5 gives the metrics to assess the performance. For this controller, the behavior observed follows a similar trend described above for the Manufacturer 1 DCV system controller tests, although the controller appears to operate sluggishly. For the medium occupancy density step profile test, the concentration was not within ± 75 ppm of the ideal controller concentration for the majority of the test time. For the three other tests, the time within ± 75 of the ideal controller concentration was about 50 percent of the test. For the two high occupancy density tests, the maximum chamber concentration was near or exceeded 1400 ppm (350 ppm above setpoint).

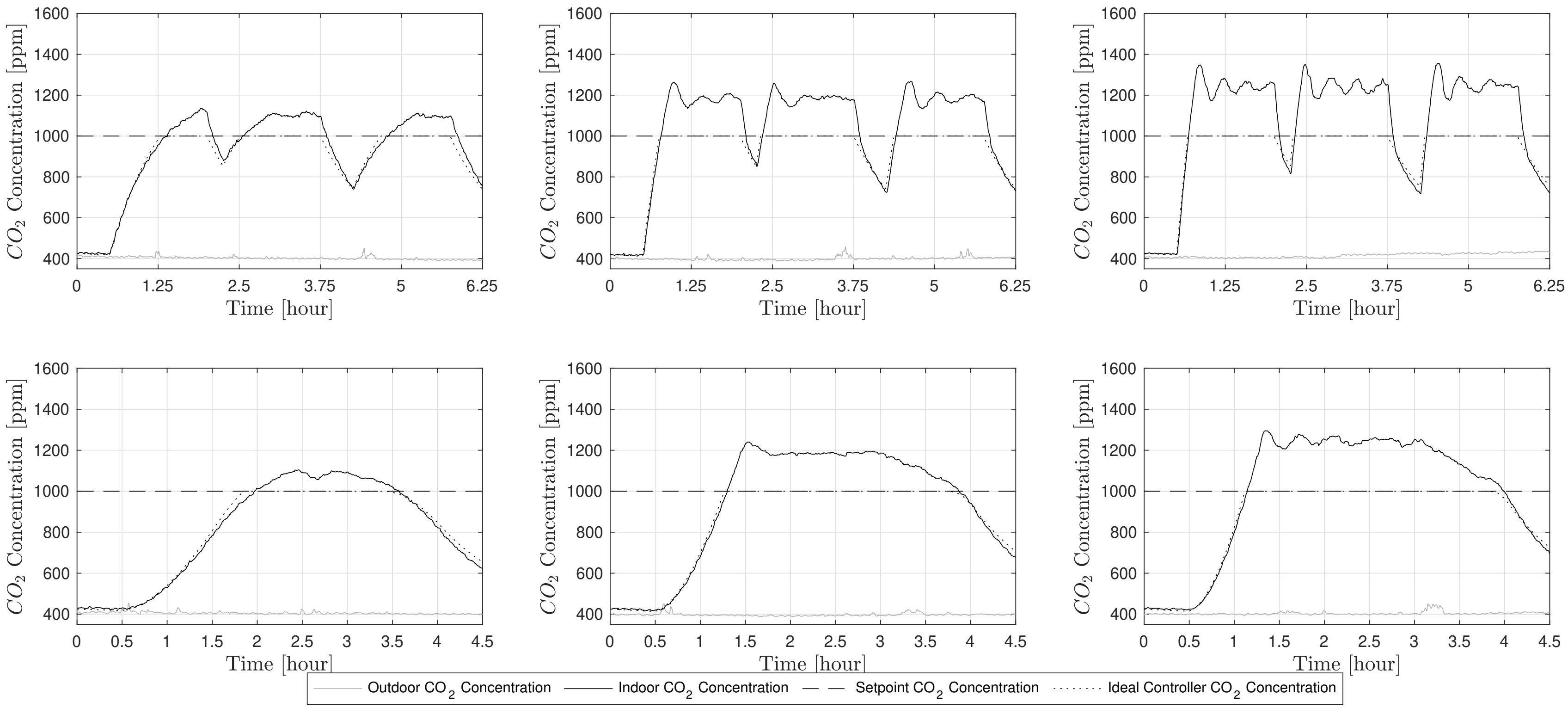


Figure 3.8: The outdoor, indoor (chamber), and ideal controller CO_2 concentrations for the Manufacturer 4 DCV test with the gradual (top) and step (bottom) generation profiles for low, medium, and high occupancy densities (left to right).

Table 3.6: Performance assessment metrics for the Manufacturer 4 DCV system controller.

Test	Time fraction > 75 ppm (%)	Time fraction < -75 ppm (%)	Time fraction within ± 75 ppm (%)	Average > 75 ppm (ppm)	Average < -75 ppm (ppm)
Low step	35.0	0.0	65.0	99.6	0
Medium step	65.0	0.0	35.0	182.7	0
High step	69.0	2.0	29.0	240.9	-82.2
Low gradual	15.0	0.0	85.0	89.6	0
Medium gradual	49.1	0.0	50.9	173.4	0
High gradual	55.2	0.0	44.8	222.4	0

Table 3.7: Performance assessment metrics for the Manufacturer 4 DCV system controller. The ideal controller uses 1200 ppm as the setpoint even though 1000 ppm was used in the DCV system controller during the test.

Test	Time fraction > 75 ppm (%)	Time fraction < -75 ppm (%)	Time fraction within ± 75 ppm (%)	Average > 75 ppm (ppm)	Average < -75 ppm (ppm)
Medium step	0.0	23.0	77.0	0.0	-140.6
High step	13.0	21.0	66.0	104.6	-163.7
Medium gradual	0.0	26.2	73.8	0.0	-127.5
High gradual	2.7	21.5	75.9	86.0	-125.4

Figure 3.8 shows the CO_2 concentrations for the six tests preformed with the Manufacturer 3 DCV system controller, and Table 3.6 gives the metrics to assess the performance. In the medium and high occupancy density tests, a 200 ppm steady state offset between the chamber concentration and the setpoint. Owing to this offset, the difference between the chamber and ideal controller concentration was less than -75 ppm for a small fraction of time across all six tests. Additionally, in the medium density step, high density step, and high density gradual profile tests, the controller yield a damped oscillatory behavior, which is observed in the chamber concentration profiles of these tests.

Based on all the tests, the controller appears to be internally operating with a setpoint of 1200 ppm, even though a setpoint of 1000 ppm was specified. If instead, 1200 ppm was considered to be setpoint for the ideal controller calculations, the performance of the DCV system controller was substantially better (Table 3.7). For this assessment, the low occupancy density tests were not considered since the chamber concentration did not reach 1200 ppm during these tests. From the results using 1200 ppm as the setpoint in the ideal controller, the performance of the Manufacturer 4 DCV controller is comparable to that observed under the Manufacturer 1 DCV system controller.

3.6 Conclusion

A testing protocol for evaluating the performance of CO_2-based DCV system controllers was presented. The performance of four DCV system controllers were evaluated using the test protocol. Noticeable differences in the observed results between all four controllers were observed. The Manufacturer 1 DCV system controller gave reasonable results for a feedback controller. When the generation rate reached the maximum, a steady state offset between the chamber concentration and setpoint of -50 ppm was observed, perhaps, due to the deadband of the controller. The Manufacturer 1 controller appeared to perform equally well for the step and gradual profile tests. Sustained oscillations about the setpoint were observed in the chamber concentration under the Manufacturer 2 DCV system controller. In this case, the controller performed better for the low and high occupancy design gradual tests compared to the corresponding step profile tests. For the medium occupancy design tests, performance was comparable. For the Manufacturer 3 controller, the controller operated sluggishly, resulting in large overshoot of the setpoint for the medium and high occupancy design tests. The Manufacturer 4 DCV system controller yielded a 200 ppm offset between the chamber concentration and the setpoint for the medium and high occupancy tests. Additionally, for these tests, a damped oscillatory response in the chamber concentration was observed. If comparing the chamber concentration for these tests to the ideal controller concentration with a setpoint of 1200 ppm, the performance was comparable to that of the Manufacturer 1 controller.

Chapter 4

Conclusions and Future work

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 ten sensor models and four DCV system controllers tested, a wide range of accuracy and performance was observed with both good and poor performing sensors and DCV system controllers. The test results for the CO_2 sensors and DCV controllers demonstrate the need for continued improvement, technology development, and testing of commercially available sensors and DCV system controllers to improve the performance.

Bibliography

[1] Building energy efficiency standards for residential and nonresidential buildings. Technical Report CEC-400-2018-020-CMF, California Energy Commission, Dec. 2018.

[2] B. Acker and K. Van Den Wymelenberg. Demand control ventilation: Lessons from the field-How to avoid common problems. *ASHRAE Transactions*, 117:502–508, 2011.

[3] A. Afshari, G. Hultmark, P. V. Nielsen, and A. Maccarini. Ventilation system design and the coronavirus (COVID-19). *Frontiers in Built Environment*, 7:54, 2021.

[4] M. G. Apte. A review of demand control ventilation. Technical report, Lawrence Berkely National Laboratory, 2006.

[5] ASHRAE. *ANSI/ASHRAE Standard 62.1-2010. Ventilation for acceptable indoor air quality*. Atlanta, GA, 2010.

[6] California Division of Occupational Safety and Health. Protecting indoor workplaces from wildfire smoke with building ventilation systems and other methods. `https://www.dir.ca.gov/dosh/wildfire/Indoor-Protection-from-Wildfire-Smoke.html`, Sept. 2019. Accessed: Dec. 2020.

[7] W. R. Chan, X. Li, B. C. Singer, T. Pistochini, D. Vernon, S. Outcault, A. Sanguinetti, and M. Modera. Ventilation rates in California classrooms: Why many recent HVAC retrofits are not delivering sufficient ventilation. *Building and Environment*, 2020.

[8] D. S. Dougan and L. Damiano. CO_2-based demand control ventilation: Do risks outweigh potential rewards? *ASHRAE Journal*, 46:47–54, 2004.

[9] S. J. Emmerich and A. K. Persily. State-of-the-art review of CO_2 demand controlled ventilation technology and application. Technical report, National Institute of Standards and Technology, 2001.

[10] W. J. Fisk and A. T. de Almeida. Sensor-based demand-controlled ventilation: A review. *Energy and Buildings*, 29:35–45, 1998.

[11] S. M. Di Giacomo. Differential CO_2 based demand control ventilation (maximum energy savings & optimized IAQ): History, theory, and myths. *Energy Engineering*, 96:58–76, 1999.

[12] J. Jones, D. Meyers, H. Singh, and P. Rojeski. Performance analysis for commercially available CO_2 sensors. *Journal of Architectural Engineering*, 3:25–31, 1997.

[13] M. Kim, S. H. Yoon, P. A. Domanski, and W. V. Payne. Design of a steady-state detector for fault detection and diagnosis of a residential air conditioner. *International Journal of Refrigeration*, 31:790–799, 2008.

[14] B. Merema, M. Delwati, M. Sourbron, and H. Breesch. Demand controlled ventilation (DCV) in school and office buildings: Lessons learnt from case studies. *Energy and Buildings*, 172:349–360, 2018.

[15] M. Mysen, S. Berntsen, P. Nafstad, and P. G. Schild. Occupancy density and benefits of demand-controlled ventilation in Norwegian primary schools. *Energy and Buildings*, 37:1234–1240, 2005.

[16] M. Schell and D. Inthout. Demand control ventilation using CO_2. *ASHRAE Journal*, pages 18–29, 2001.

[17] M. H. Sherman. Tracer-gas techniques for measuring ventilation in a single zone. *Building and Environment*, 25:365–374, 1990.

[18] M.-S. Shin, K.-N. Rhee, E.-T. Lee, and G.-J. Jung. Performance evaluation of CO_2-based ventilation control to reduce CO_2 concentration and condensation risk in residential buildings. *Building and Environment*, 142:451–463, 2018.

[19] S. S. Shrestha. *Performance evaluation of carbon-dioxide sensors used in building HVAC applications*. PhD thesis, Iowa State University, Ames, Iowa, 2009.

[20] S. S. Shrestha and G. M. Maxwell. An experimental evaluation of HVAC-grade carbon dioxide sensors–Part I: Test and evaluation procedure. *ASHRAE Transactions*, 115:471–483, 2009.

[21] B. Simanic, B. Nordquist, H. Bagge, and D. Johansson. Indoor air temperatures, CO_2 concentrations and ventilation rates: Long-term measurements in newly built low-energy schools in Sweden. *Journal of Building Engineering*, 25:100827, 2019.

[22] S. T. Taylor. CO_2-based DCV using 62.1-2004. *ASHRAE Journal*, 48:67–75, 2006.

[23] United States Centers for Disease Control. COVID-19 employer information for office buildings. https://www.cdc.gov/coronavirus/2019-ncov/community/office-buildings.html, Oct. 2020. Accessed: Dec. 2020.

Appendix A

Results of Monitored Variables with Test Tolerances and Sensor Calibration Results

A.1 CO_2 Sensor Test Environmental Conditions

Summary statistics of the environmental chamber conditions monitored during each CO_2 sensor test are given in this section. The summary statistics are provided for Manufacturers 1-10 sensors in Tables A.1-A.10, respectively. All environmental conditions were deemed to be within the test operating tolerance and test condition tolerance, implying that all tests were successful.

Table A.1: A summary of the chamber environmental conditions measured during each test of the Manufacturer 1 sensors.

Target Gas Concentration	Temperature (°F)			Humidity (%)			Absolute Pressure (kPa)			Differential Pressure (Pa)		
	Average	Minimum	Maximum	Average	Minimum	Maximum	Average	Minimum	Maximum	Average	Minimum	Maximum
Calibrated Gas (425ppm)	73.3	73.5	73.6	2.0	2.1	2.3	101.7	101.7	101.8	9.8	9.5	10.1
Calibrated Gas (1100ppm)	74.3	74.3	74.4	1.4	1.5	1.6	101.4	101.4	101.4	9.4	9.2	9.6
Calibrated Gas (1700ppm)	74.8	74.8	74.9	1.3	1.2	1.3	101.5	101.4	101.5	8.2	6.8	8.8

Table A.2: A summary of the chamber environmental conditions measured during each test of the Manufacturer 2 sensors.

Target Gas Concentration	Temperature (°F)			Humidity (%)			Absolute Pressure (kPa)			Differential Pressure (Pa)		
	Average	Minimum	Maximum	Average	Minimum	Maximum	Average	Minimum	Maximum	Average	Minimum	Maximum
Calibrated Gas (425ppm)	73.3	73.3	73.4	3.1	3.4	3.7	102.3	102.3	102.3	6.7	6.6	6.8
Calibrated Gas (1100ppm)	73.7	73.7	73.7	2.1	2.1	2.1	102.3	102.3	102.3	6.8	6.5	7.0
Calibrated Gas (1700ppm)	73.8	73.8	73.8	1.5	1.5	1.6	102.2	102.2	102.2	8.5	8.4	8.5

Table A.3: A summary of the chamber environmental conditions measured during each test of the Manufacturer 3 sensors.

Target Gas Concentration	Temperature (°F)			Humidity (%)			Absolute Pressure (kPa)			Differential Pressure (Pa)		
	Average	Minimum	Maximum	Average	Minimum	Maximum	Average	Minimum	Maximum	Average	Minimum	Maximum
Calibrated Gas (425ppm)	72.3	72.3	72.3	3.6	3.4	3.8	102.1	102.0	102.2	7.5	7.1	7.7
Calibrated Gas (1100ppm)	72.4	72.4	72.4	2.6	2.6	2.7	102.0	102.0	102.0	9.5	9.5	9.5
Calibrated Gas (1700ppm)	72.8	72.8	72.8	2.2	2.1	2.2	102.0	101.9	102.0	8.9	8.8	8.9

Table A.4: A summary of the chamber environmental conditions measured during each test of the Manufacturer 4 sensors.

Target Gas Concentration	Temperature (°F)			Humidity (%)			Absolute Pressure (kPa)			Differential Pressure (Pa)		
	Average	Minimum	Maximum	Average	Minimum	Maximum	Average	Minimum	Maximum	Average	Minimum	Maximum
Calibrated Gas (425ppm)	76.9	76.8	77.0	1.5	1.4	1.7	102.5	102.5	102.5	9.9	9.9	9.9
Calibrated Gas (1100ppm)	77.0	77.1	77.1	1.1	1.0	1.1	102.4	102.4	102.4	8.8	8.8	8.8
Calibrated Gas (1700ppm)	77.1	77.1	77.1	0.8	0.8	0.8	102.3	101.3	102.4	8.5	8.5	8.6

Table A.5: A summary of the chamber environmental conditions measured during each test of the Manufacturer 5 sensors.

Target Gas Concentration	Temperature (°F)			Humidity (%)			Absolute Pressure (kPa)			Differential Pressure (Pa)		
	Average	Minimum	Maximum	Average	Minimum	Maximum	Average	Minimum	Maximum	Average	Minimum	Maximum
Calibrated Gas (425ppm)	75.4	75.4	75.4	2.2	1.9	2.5	102.0	102.0	102.1	10.8	10.7	10.9
Calibrated Gas (1100ppm)	75.6	75.6	75.6	1.5	1.4	1.6	102.0	101.9	102.0	8.3	8.3	8.3
Calibrated Gas (1700ppm)	75.9	75.9	75.9	1.2	1.2	1.2	101.8	101.8	101.8	8.8	8.8	8.8

Table A.6: A summary of the chamber environmental conditions measured during each test of the Manufacturer 6 sensors.

Target Gas Concentration	Temperature (°F)			Humidity (%)			Absolute Pressure (kPa)			Differential Pressure (Pa)		
	Average	Minimum	Maximum	Average	Minimum	Maximum	Average	Minimum	Maximum	Average	Minimum	Maximum
Calibrated Gas (425ppm)	75.6	75.5	75.6	2.2	2.0	2.5	102.2	102.1	102.3	7.4	5.2	8.0
Calibrated Gas (1100ppm)	75.4	75.4	75.4	1.5	1.4	1.6	102.2	102.1	102.3	7.8	5.1	8.4
Calibrated Gas (1700ppm)	75.3	75.2	75.3	1.2	1.1	1.2	102.2	102.1	102.2	8.5	5.1	9.3

Table A.7: A summary of the chamber environmental conditions measured during each test of the Manufacturer 7 sensors.

Target Gas Concentration	Temperature (°F)			Humidity(%)			Absolute Pressure (kPa)			Differential Pressure (Pa)		
	Average	Minimum	Maximum	Average	Minimum	Maximum	Average	Minimum	Maximum	Average	Minimum	Maximum
Calibrated Gas (425ppm)	74.5	74.5	74.7	2.1	1.9	2.2	101.4	101.4	102.0	9.9	9.9	10.0
Calibrated Gas (1100ppm)	75.1	75.0	75.2	1.5	1.5	1.6	101.6	101.6	101.6	8.8	8.4	9.2
Calibrated Gas (1700ppm)	75.7	75.6	75.7	1.2	1.2	1.3	101.6	101.5	101.7	9.9	9.9	9.9

Table A.8: A summary of the chamber environmental conditions measured during each test of the Manufacturer 8 sensors.

Target Gas Concentration	Temperature (°F)			Humidity (%)			Absolute Pressure (kPa)			Differential Pressure (Pa)		
	Average	Minimum	Maximum	Average	Minimum	Maximum	Average	Minimum	Maximum	Average	Minimum	Maximum
Calibrated Gas (425ppm)	72.4	72.3	72.5	3.0	2.8	3.2	101.9	101.8	101.9	8.0	7.5	8.5
Calibrated Gas (1100ppm)	73.2	73.0	73.3	2.2	2.2	2.3	101.9	101.8	101.9	8.9	7.6	9.4
Calibrated Gas (1700ppm)	73.4	73.4	73.4	1.9	1.8	1.9	101.9	101.8	101.9	7.9	7.7	8.2

Table A.9: A summary of the chamber environmental conditions measured during each test of the Manufacturer 9 sensors.

Target Gas Concentration	Temperature (°F)			Humidity (%)			Absolute Pressure (kPa)			Differential Pressure (Pa)		
	Average	Minimum	Maximum	Average	Minimum	Maximum	Average	Minimum	Maximum	Average	Minimum	Maximum
Calibrated Gas (425ppm)	73.1	73.1	73.2	1.8	1.6	2.0	102.0	102.1	102.1	10.5	9.7	11.4
Calibrated Gas (1100ppm)	73.4	73.4	73.4	1.2	1.1	1.3	102.0	102.0	102.0	10.8	9.8	12.0
Calibrated Gas (1700ppm)	73.7	73.6	73.7	1.0	1.0	1.1	102.0	102.0	102.0	10.8	10.0	11.7

Table A.10: A summary of the chamber environmental conditions measured during each test of the Manufacturer 10 sensors.

Target Gas Concentration	Temperature (°F)			Humidity (%)			Absolute Pressure (kPa)			Differential Pressure (Pa)		
	Average	Minimum	Maximum	Average	Minimum	Maximum	Average	Minimum	Maximum	Average	Minimum	Maximum
Calibrated Gas (425ppm)	74.9	74.8	75.1	4.2	4.0	4.5	101.5	101.4	101.5	8.6	8.3	8.8
Calibrated Gas (1100ppm)	75.5	75.4	75.7	3.0	2.9	3.1	101.4	101.4	101.4	9.8	9.7	10.0
Calibrated Gas (1700ppm)	75.8	75.8	75.8	2.4	2.4	2.5	101.2	101.2	101.3	9.8	9.7	9.8

A.2 CO_2 Sensor Linear Regression

The results of the sensor calibrations using linear regression for Manufacturers 1-10 sensors are given in Tables A.11-A.20, respectively.

Table A.11: A summary of the linear regression values for Manufacturer 1 sensors.

Value	Sensor 1	Sensor 2	Sensor 3	Sensor 4	Sensor 5	Sensor 6	Sensor 7	Sensor 8	Sensor 9	Sensor 10
Slope	0.971	0.973	0.978	0.981	0.970	0.971	0.976	0.970	0.975	0.970
Y-Intercept	21.3	15.2	11.5	12.5	17.4	21.4	9.81	21.6	22.1	17.3
R^2	0.999	0.999	0.999	0.999	0.999	0.999	0.999	0.999	0.999	0.999

Table A.12: A summary of the linear regression values for Manufacturer 2 sensors.

Value	Sensor 1	Sensor 2	Sensor 3	Sensor 4	Sensor 5	Sensor 6	Sensor 7	Sensor 8	Sensor 9	Sensor 10
Slope	0.982	0.976	0.984	0.966	0.928	0.958	0.984	0.981	0.938	0.979
Y-Intercept	7.05	3.60	-2.96	23.60	15.1	9.48	11.6	2.67	19.9	2.13
R^2	0.998	0.998	0.998	0.998	0.998	0.998	0.998	0.998	0.998	0.998

Table A.13: A summary of the linear regression values for Manufacturer 3 sensors.

Value	Sensor 1	Sensor 2	Sensor 3	Sensor 4	Sensor 5	Sensor 6	Sensor 7	Sensor 8	Sensor 9	Sensor 10
Slope	0.985	0.964	0.965	0.993	0.984	0.983	0.974	1.00	0.988	0.970
Y-Intercept	60.0	15.0	10.4	95.4	71.0	35.7	25.5	31.3	68.4	24.3
R^2	0.999	0.999	0.999	0.999	0.999	0.999	0.999	0.999	0.999	0.999

Table A.14: A summary of the linear regression values for Manufacturer 4 sensors.

Value	Sensor 1	Sensor 2	Sensor 3	Sensor 4	Sensor 5	Sensor 6	Sensor 7	Sensor 8	Sensor 9	Sensor 10
Slope	1.07	0.954	1.01	0.966	1.00	1.07	0.998	0.988	0.990	0.964
Y-Intercept	142.0	-15.4	67.6	-33.2	43.4	114.6	31.2	42.6	15.1	-38.1
R^2	0.999	0.999	0.999	0.999	0.999	0.999	0.999	0.999	0.999	0.999

Table A.15: A summary of the linear regression values for Manufacturer 5 sensors.

Value	Sensor 1	Sensor 2	Sensor 3	Sensor 4	Sensor 5	Sensor 6	Sensor 7	Sensor 8	Sensor 9	Sensor 10
Slope	1.01	1.03	1.03	1.03	1.02	1.02	1.01	1.03	1.03	1.05
Y-Intercept	21.6	15.1	12.1	16.4	16.0	15.8	14.3	6.60	15.7	8.33
R^2	0.999	0.999	0.999	0.999	0.999	0.999	0.999	0.999	0.999	0.999

Table A.16: A summary of the linear regression values for Manufacturer 6 sensors.

Value	Sensor 1	Sensor 2	Sensor 3	Sensor 4	Sensor 5	Sensor 6	Sensor 7	Sensor 8	Sensor 9	Sensor 10
Slope	0.989	0.973	1.01	1.00	0.986	1.02	1.01	1.04	1.00	0.990
Y-Intercept	-35.4	-34.0	-1.84	14.1	-88.7	-23.1	-17.7	22.0	-7.93	-48.6
R^2	0.999	0.999	0.999	0.999	0.999	0.999	0.999	0.999	0.999	0.999

Table A.17: A summary of the linear regression values for Manufacturer 7 sensors.

Value	Sensor 1	Sensor 2	Sensor 3	Sensor 4	Sensor 5	Sensor 6	Sensor 7	Sensor 8	Sensor 9	Sensor 10
Slope	0.977	0.973	0.969	0.969	0.965	0.980	0.963	0.977	0.987	0.969
Y-Intercept	-36.8	-33.9	-31.2	-30.1	-26.9	-36.9	-26.4	-35.6	-39.0	-31.7
R^2	0.999	0.999	0.999	0.999	0.999	0.999	0.999	0.999	0.999	0.999

Table A.18: A summary of the linear regression values for Manufacturer 8 sensors.

Value	Sensor 1	Sensor 2	Sensor 3	Sensor 4	Sensor 5	Sensor 6	Sensor 7	Sensor 8	Sensor 9	Sensor 10
Slope	0.785	0.688	0.893	0.754	0.745	0.869	0.842	0.868	0.891	0.783
Y-Intercept	39.1	83.7	-8.19	54.6	56.5	-2.52	9.23	7.27	-8.64	40.9
R^2	0.990	0.990	0.991	0.991	0.990	0.988	0.988	0.994	0.991	0.991

Table A.19: A summary of the linear regression values for Manufacturer 9 sensors.

Value	Sensor 1	Sensor 2	Sensor 3	Sensor 4	Sensor 5	Sensor 6	Sensor 7	Sensor 8	Sensor 9	Sensor 10
Slope	0.937	0.932	0.943	0.930	0.957	0.975	0.965	0.991	0.967	0.967
Y-Intercept	-27.2	-27.4	-34.2	-25.6	-42.6	-45.7	-40.4	-53.9	-42.2	-41.1
R^2	0.999	0.999	0.999	0.999	0.999	0.999	0.999	0.999	0.999	0.999

Table A.20: A summary of the linear regression values for Manufacturer 10 sensors.

Value	Sensor 1	Sensor 2	Sensor 3	Sensor 4	Sensor 5	Sensor 6	Sensor 7	Sensor 8	Sensor 9	Sensor 10
Slope	0.994	0.994	0.987	0.991	0.992	0.989	0.992	0.993	0.999	0.987
Y-Intercept	-14.1	-20.1	-7.40	-11.2	-15.0	-13.5	-14.3	-13.9	-19.5	-13.9
R^2	0.999	0.999	0.999	0.999	0.999	0.999	0.999	0.999	0.999	0.999

A.3 CO_2-Based Demand Control Ventilation Test Conditions

Summary statistics of the monitored environmental chamber conditions are given for each DCV system controller test executed. The summary statistics are provided for Manufacturers 1-4 DCV system controllers in Tables A.21-A.24, respectively. All environmental conditions were deemed to be within the test operating tolerance and test condition tolerance, implying that all tests were successful.

Table A.21: A summary of the measured chamber environmental conditions during each test with the Manufacturer 1 controller.

Value		Low step	Medium step	High step	Low gradual	Medium gradual	High gradual
Temperature (°F)	Avg.	74.1	73.9	74.1	74.2	74.6	74.0
	Min.	73.2	72.0	72.1	73.5	73.6	72.7
	Max.	74.9	75.0	75.0	74.9	75.2	75.0
Humidity	Avg.	45.6	45.2	45.2	45.6	45.4	41.9
	Min.	41.6	40.0	41.3	41.8	41.7	35.2
	Max.	49.4	49.3	49.9	49.6	49.6	49.5
Absolute Pressure (kPa)	Avg.	102.4	102.2	102.0	102.4	101.9	101.6
	Min.	102.3	102.1	101.7	102.4	101.7	101.4
	Max.	102.5	102.3	102.1	102.5	102.1	101.6
Outdoor CO_2 Concentration (ppm)	Avg.	417.0	407.5	405.5	428.1	408.0	402.8
	Min.	408.9	397.8	392.6	416.7	400.0	396.3
	Max.	445.2	420.6	437.5	453.7	420.6	413.0
Moving Average $C_{\mathrm{CO_2},oa}$ (ppm)	Avg.	417.0	407.4	405.6	428.3	407.9	402.8
	Min.	411.0	401.1	395.1	421.0	407.9	398.9
	Max.	438.9	417.7	422.5	446.6	415.5	408.4
Moving Average $C_{\mathrm{CO_2},ra} - C_{\mathrm{CO_2}}$ (ppm)	Avg.	20.4	23.3	23.3	24.0	23.5	-1.0
	Min.	-6.5	0.9	5.7	-19.4	-7.8	19.4
	Max.	46.4	59.7	57.3	47.9	50.7	58.2
Moving Average $C_{\mathrm{CO_2},ea} - C_{\mathrm{CO_2}}$ (ppm)	Avg.	8.3	10.1	13.8	12.3	8.4	10.7
	Min.	-1.8	-7.4	-11.3	0.4	-9.1	-10.7
	Max.	24.4	27.0	27.8	26.6	25.6	23.6

Table A.22: A summary of the measured chamber environmental conditions during each test with the Manufacturer 2 controller.

Value		Low step	Medium step	High step	Low gradual	Medium gradual	High gradual
Temperature (°F)	Avg.	73.9	74.3	74.1	74.6	74.7	74.6
	Min.	72.6	73.0	72.8	73.7	73.5	73.8
	Max.	75.0	75.0	75.0	75.1	75.4	75.2
Humidity	Avg.	45.7	45.5	45.2	45.7	45.6	45.6
	Min.	40.8	41.2	40.6	41.8	41.5	42.9
	Max.	49.8	49.0	49.9	49.8	49.7	49.9
Absolute Pressure (kPa)	Avg.	100.7	101.4	102.0	101.8	101.7	101.4
	Min.	100.6	101.2	102.0	102.0	101.7	101.4
	Max.	100.7	101.6	102.2	101.7	101.8	101.5
Outdoor CO_2 Concentration (ppm)	Avg.	403.3	409.5	408.7	412.9	403.4	406.8
	Min.	394.2	395.3	397.9	403.7	393.4	395.8
	Max.	434.7	430.8	427.9	424.2	442.3	452.5
Moving Average $C_{\mathrm{CO_2},oa}$ (ppm)	Avg.	403.3	409.6	408.6	412.8	403.3	406.8
	Min.	395.3	398.7	400.4	406.9	396.1	398.5
	Max.	426.4	429.8	424.0	421.4	422.6	425.0
Moving Average $C_{\mathrm{CO_2},ra} - C_{\mathrm{CO_2}}$ (ppm)	Avg.	19.8	12.2	10.5	25.5	20.8	15.8
	Min.	-18.2	-13.8	-13.6	-3.0	-9.9	-6.9
	Max.	45.8	51.5	57.4	52.2	44.4	55.2
Moving Average $C_{\mathrm{CO_2},ea} - C_{\mathrm{CO_2}}$ (ppm)	Avg.	7.3	-1.2	6.8	11.1	7.8	10.5
	Min.	-5.5	-16.2	-19.9	-2.6	-11.4	-6.6
	Max.	27.3	19.8	25.1	27.9	25.9	26.2

Table A.23: A summary of the measured chamber environmental conditions during each test with the Manufacturer 3 controller.

Value		Low step	Medium step	High step	Low gradual	Medium gradual	High gradual
Temperature (°F)	Avg.	74.5	74.2	74.2	74.0	74.6	74.2
	Min.	73.7	73.2	73.0	73.1	73.6	72.8
	Max.	75.1	75.0	75.0	75.1	75.3	75.0
Humidity	Avg.	45.4	45.5	45.1	45.4	43.9	45.2
	Min.	42.1	40.1	40.3	41.7	38.3	41.2
	Max.	49.3	49.4	49.2	49.3	49.2	49.1
Absolute Pressure (kPa)	Avg.	102.2	101.8	101.8	101.9	101.8	102.2
	Min.	102.1	101.6	101.6	101.7	101.8	102.1
	Max.	102.3	101.8	101.8	102.0	101.9	102.2
Outdoor CO_2 Concentration (ppm)	Avg.	409.6	405.7	406.3	420.7	405.1	412.5
	Min.	400.9	396.1	397.3	408.6	397.1	405.0
	Max.	428.4	416.6	416.2	436.5	416.7	444.1
Moving Average $C_{\mathrm{CO_2},oa}$ (ppm)	Avg.	409.5	405.7	406.2	420.7	405.1	412.5
	Min.	403.9	399.3	400.8	411.5	400.7	408.0
	Max.	421.2	412.2	413.0	436.5	412.0	425.3
Moving Average $C_{\mathrm{CO_2},ra} - C_{\mathrm{CO_2}}$ (ppm)	Avg.	-7.8	-5.5	-3.8	-2.8	-3.9	-3.0
	Min.	-36.4	-40.0	-34.9	-35.2	-28.1	-28.2
	Max.	25.9	-28.8	31.6	32.0	26.4	29.7
Moving Average $C_{\mathrm{CO_2},ea} - C_{\mathrm{CO_2}}$ (ppm)	Avg.	-8.8	-9.8	-7.3	-3.7	-4.9	-3.6
	Min.	-25.4	-39.7	-48.4	-24.1	-32.3	-38.9
	Max.	19.4	15.4	17.5	17.7	16.6	19.1

Table A.24: A summary of the measured chamber environmental conditions during each test with the Manufacturer 4 controller.

Value		Low step	Medium step	High step	Low gradual	Medium gradual	High gradual
Temperature (°F)	Avg.	75.5	75.8	75.2	75.6	75.7	75.3
	Min.	74.6	74.4	73.7	74.7	74.8	74.1
	Max.	76.1	77.3	76.6	77.1	77.3	76.7
Humidity	Avg.	45.6	45.7	45.4	45.5	45.6	45.6
	Min.	42.2	41.2	40.7	42.3	41.0	41.1
	Max.	49.7	49.7	50.1	49.9	49.8	49.8
Absolute Pressure (kPa)	Avg.	100.8	100.6	100.8	101.1	100.8	101.0
	Min.	100.5	100.5	100.7	100.9	100.7	100.9
	Max.	101.0	100.7	101.0	101.1	100.9	101.1
Outdoor CO_2 Concentration (ppm)	Avg.	404.0	399.9	415.6	405.5	397.4	403.9
	Min.	389.3	387.1	399.3	397.0	387.1	394.9
	Max.	451.3	457.3	436.9	454.1	450.8	450.0
Moving Average $C_{\mathrm{CO_2},oa}$ (ppm)	Avg.	402.9	400.0	415.8	405.5	397.4	404.0
	Min.	392.0	390.5	402.1	398.8	389.9	397.5
	Max.	424.0	434.9	434.9	424.8	423.1	440.5
Moving Average $C_{\mathrm{CO_2},ra} - C_{\mathrm{CO_2}}$ (ppm)	Avg.	-19.6	-18.3	-17.7	-7.7	-13.4	-14.8
	Min.	-52.7	-42.3	-42.6	-35.3	-39.8	-40.4
	Max.	15.4	15.5	25.5	25.8	23.8	28.6
Moving Average $C_{\mathrm{CO_2},ea} - C_{\mathrm{CO_2}}$ (ppm)	Avg.	-27.2	-20.0	16.6	-6.6	-16.4	-14.9
	Min.	-49.5	-41.6	-45.3	-28.5	-38.8	-39.9
	Max.	16.5	15.4	17.1	18.3	15.1	15.4