Improve Traditional CO_2-DCV with Outdoor Airflow Measurement

David S. Dougan, President
EBTRON, Inc., Loris, SC

ABSTRACT

ASHRAE Standard 90.1-2019, various energy standards and energy codes require demand control ventilation (DCV) of high occupant density spaces. DCV is defined in the Ventilation Rate Procedure (VRP) or ASHRAE Standard 62.1-2019.

DCV adjusts ventilation rates based on the ventilation zone population, however, many industry professionals are convinced that DCV requires that ventilation zone CO_2 levels are maintained.

This paper clarifies industry misconceptions regarding DCV and exposes the significant uncertainties associated with CO_2-DVC. The paper also offers two improved methods for those who want to use CO_2 as a method of demand control ventilation. Both methods use outdoor airflow measurement either at the air handler (recirculating air systems) or ventilation zone (DOAS). Finally, the paper suggest that the industry considers using direct occupancy measurement, rather than CO_2, as a method of DVC when feasible.

Demand Control Ventilation

ASHRAE Standard 90.1-2019 requires demand control ventilation (DCV) for compliance. §6.4.3.8 requires DCV on spaces larger than 500 ft^2 with a design occupancy ≥25 people per 1,000 ft^2 of floor area.

Many HVAC professionals believe that DCV is a method that maintains CO_2 levels, effectively adjusting for changes in the ventilation zone population. Others believe that CO_2 itself is a contaminant of concern and high levels are dangerous and may cause harm to occupants and that is why they maintain CO_2 levels. Regardless of the reason, the method is known to most as CO_2-DCV, and is widely accepted as a ventilation control strategy that saves energy and provides acceptable indoor air quality (IAQ).

What is DCV? Where is it defined?

The Ventilation Rate Procedure (VRP) of ASHRAE Standard 62.1-2019 defines DCV. DCV is a subset of §6.2.6, Dynamic Reset, and is defined under §6.2.6.1, Demand Control Ventilation (DCV). §6.2.6.1.1 states: *For DCV zones in the occupied mode, breathing zone outdoor airflow (V_{bz}) shall be reset in response to the* _current population_*.*

The question we ask of those that use CO_2-DCV as a method of compliance is as follows:

"If you know the indoor CO_2 level and the outdoor air CO_2 level, how many people are in the ventilation zone?"

Nobody answers the question. The reason? CO_2 alone cannot estimate the population. It is not an occupancy counting device.

The follow up question is:

"If you don't know the population, how do you know your CO_2-DCV strategy is in compliance with Standard 62.1-2019?"

The answer we get from most state that "ASHRAE 62 requires CO_2 levels be maintained", which, as we will see, is not true.

To better understand DCV, one must analyze the requirements of the VRP and relationship between CO_2 and ventilation.

ASHRAE 62.1-2019 Compliance

Single zone recirculating and DOAS systems are the simplest to understand and a good starting point for those wishing to understand DCV compliance. Multi-zone recirculating systems are the most complicated and will not be discussed in this paper.

The breathing zone outdoor air, V_{bz}, is determined based on the design, or *typical usage* population in accordance with equation 6-1 of the VRP when the Standard is used for design purposes. However, §6.2.6.1.1 essentially makes 62.1 into an operational standard where V_{bz} must be established in real-time based on the *current population*. V_{bz} is determined in accordance with Equation 6-1 of the Standard based on the *current population*.

$$V_{bz} = R_p \cdot P_z + R_a \cdot A_z \qquad \text{(ASHRAE 62.1-2019 Equation 6-1)}$$

where

R_p = outdoor airflow rate required per person from ASHRAE 62.1-2019 Table 6-1
P_z = the <u>CURRENT</u> population of the ventilation zone (as per §6.2.6.1.1)
R_a = outdoor airflow rate required per floor area from ASHRAE 62.1-2019 Table 6-1
A_z = zone floor area

As a result, any strategy claiming compliance must demonstrate that at least the breathing zone outdoor air, V_{bz}, required by §6.2.6.1.1 is provided for the actual, real-time, population during operation.

CO_2-DCV is only mentioned in an exception of §6.2.6.1 that disallows CO_2-DCV in spaces where CO_2 is either removed or introduced by non-human sources. It is not a required or even a specified method of the Standard.

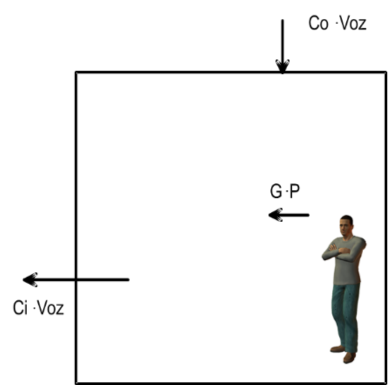
<u>Why are we measuring and controlling CO_2 levels?</u>

Recent studies suggest that CO_2 is a contaminant of concern at lower concentrations (concentrations less than 1,500 ppm). However, conflicting reports do not support that hypothesis. At this time, CO_2 is considered a harmful contaminant at or above 5,000 ppm (OSHA, NIOSH, ACGIH). The 5,000 ppm threshold is unlikely in today's buildings that have significant natural infiltration of outdoor air (not necessarily a bad thing). So, why do we measure and control CO_2 levels (typically at 1,000 ppm)? To understand, one must recognize the relationship between CO_2 and [outdoor air] ventilation.

<u>CO_2 and Ventilation</u>

Spaces unoccupied overnight typically have CO_2 levels similar to that of the ambient, outdoor air (≈ 400 ppm). When the HVAC system enters occupied mode, outdoor air containing CO_2 enters the space. As people enter a space, the CO_2 produced as a biproduct of respiration is also added to the space. The outdoor air that enters the space is either force exfiltrated or relieved/exhausted by the mechanical system. If the outdoor airflow rate to the space is constant and the population is constant, the indoor CO_2 level eventually plateaus at a steady-state level and the volume of the space and rate of change of the indoor CO_2 level can be ignored. The non-reactive, steady state equation is shown in Figure 1.

Figure 1 – Steady-state analysis



Co = Outdoor CO_2 concentration (ft^3 CO_2/ft^3 air)
Ci = Indoor CO_2 concentration (ft^3 CO_2/ft^3 air)
Voz = Outside Airflow Rate (ft^3/min)
Vo=Outside Airflow Rate/Person ((ft^3/min)/person
G = CO_2 generation rate of the occupant (ft^3 CO_2/min)
P = Number of occupants

Steady-state Mass Balance: In = Out
$Co \cdot Voz + G \cdot P = Ci \cdot Voz$

Can be rearranged as:
$G / (Ci - Co) = Voz/P = Vo$

The steady-state equation of Figure 1 can be algebraically rearranged to solve for Voz/P, or Vo, which in I-P units is outdoor air CFM/person. This relationship was described in Appendix D (now removed) of ASHRAE Standard 62.1 prior to 2019 and is the bases for today's CO_2-DCV strategies, even though a DCV system is rarely at steady-state. Fixed setpoint CO_2-DCV (ex. 1,000 ppm) systems use CO_2 as a surrogate to estimate the outdoor airflow rate entering a building. CO_2 levels are not maintained because it is a contaminant of concern.

<u>The CO_2-DCV Dilemma</u>

Engineers, building owners and code writers do not always recognize the codependent relationship between CO_2 and ventilation. Many of today's systems that mandate CO_2-DCV are undersized, do not perform at high population densities, and have higher than expected energy consumption.

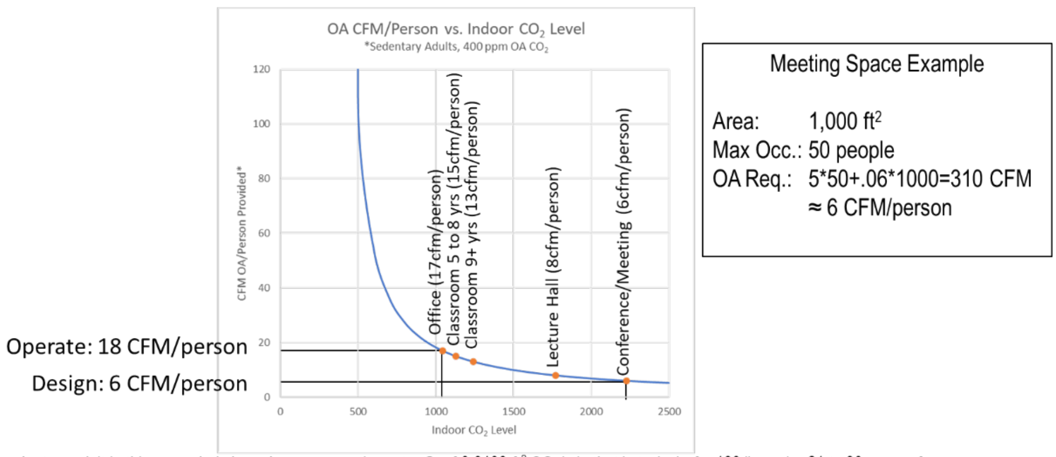
Why?

Most jurisdictions follow the International Mechanical Code (IMC) to size ventilation systems. The IMC is a strict interpretation of the VRP of ASHRAE 62.1. ASHRAE 90.1-2019 requires DCV but does not mandate that CO_2 based DCV is used. Other energy codes and other design guides, however, do require CO_2 ventilation control - often at a defined setpoint near or at 1,000 ppm.

Figure 2 illustrates the problem using default occupancy densities from 62.1. The conference/meeting space was designed to provide the outdoor airflow rate required to satisfy the Standard. The control strategy was operated to maintain 1,000 ppm in the space. As a result, the system was designed to provide 6 CFM/person and forced to operate at 18 CFM/person or be in CO_2 alarm.

Clearly, the system would not provide temperature or humidity control at high population densities and in no way would it save energy. Unfortunately, this design approach is typical, since most do not recognize that CO_2 levels and ventilation are codependent.

Figure 2 - Ventilation/CO_2 codependence



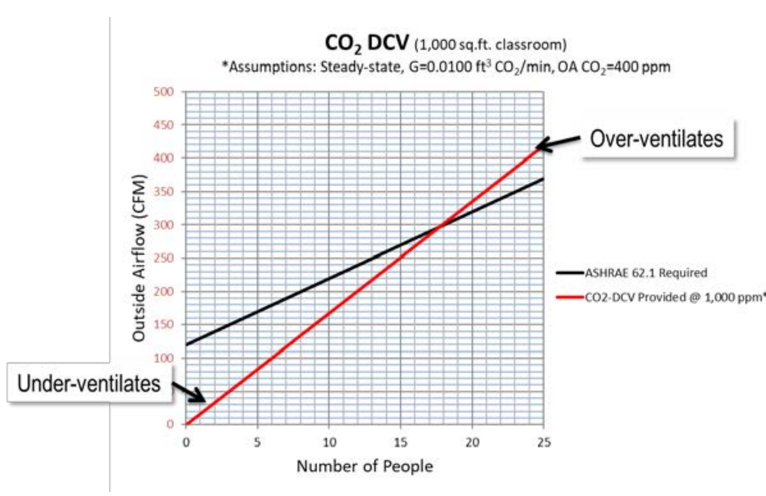
Note: A sedentary adult in this example is based on a generation rate, G, of 0.0108 ft^3 CO_2/min that is typical of a 180 lb. male, 21 to 30 years of age.

ASHRAE 62.1-2019 Compliance

Fixed setpoint CO_2-DCV is widely used and, at best, results in a single rate of outdoor air per person. An argument could be made prior to *addendum n* (adopted permanently in the ASHRAE 62.1-2004 parent document) when 62.1 specified the breathing zone outdoor airflow rate, V_{bz}, as a single ventilation rate per person (ex. Schools - 15 CFM/person ≈ 700 ppm rise ≈ 1,100 ppm setpoint), however, *addendum n*, modified the ventilation requirements so that V_{bz} is now based on occupancy and floor area so that the required ventilation rate per person is no longer a constant. As a result, fixed setpoint CO_2-DCV cannot meet the requirements of 62.1-2019 with varying populations if all assumptions regarding CO_2 measurement accuracy and occupant production rates are accurate (see Figure 3). Nonetheless, it is still widely used, promoted and often mandated.

Figure 3 – Ventilation Provided with a 600 ppm rise (Ci-Co) compared to ASHRAE 62.1-2019 requirements

(1000 ppm nominal setpoint assuming all assumptions* are valid. CO_2 measurement uncertainty: None)



Ventilation Uncertainty: CO_2 Measurement Error

The objective of Standard 62.1-2019 is to provide at least the required minimum outdoor air, V_{bz}, to the breathing zone. When DCV is used, the breathing zone outdoor air must be provided for the *current population*. A reasonable question would be as follows:

"How does CO_2 measurement uncertainty affect the ventilation rate provide to the space?"

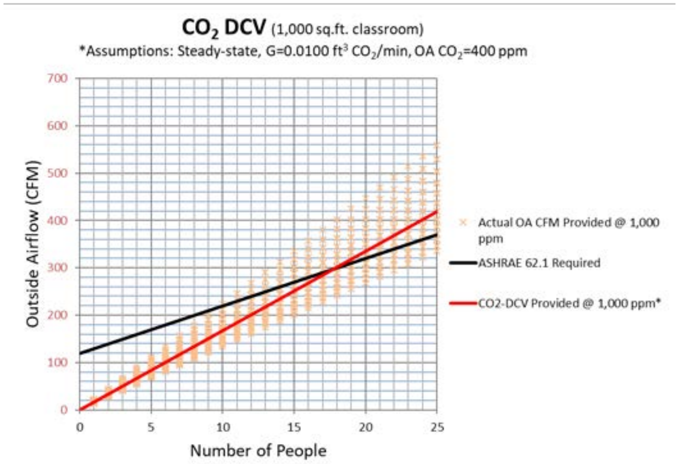
CO_2-DCV system uncertainty was discussed in detail by Dougan and Damiano, (ASHRAE Journal, 1994 and HPAC, 1997). The papers analyzed CO_2 measurement uncertainty and the effect of occupant activity level on CO_2-DCV ventilation rates prior to and after the *addendum n* modification.

CO_2 sensor measurement uncertainty at 1,000 ppm is at best ±75 ppm. Additional uncertainty results from placement and drift of the CO_2 sensor. Therefore, a reasonable indoor uncertainty (good case) is ±100 ppm. Outdoor CO_2 levels vary as a result of season, time of day and climatic conditions (temperature inversions, for example). Outdoor CO_2 levels have been measured as low as 350 ppm and as high as 600 ppm. CO_2 is generally assumed to be 400 ppm. Therefore, an uncertainty of ±50 ppm is not unreasonable. One should note that CO_2 levels of the outdoor air are generally assumed since the measurement of outdoor CO_2 concentrations is not feasible with most commercial CO_2 sensors that are significantly affected by changes in ambient temperature.

Figure 4 shows the ventilation uncertainty associated with an indoor CO_2 uncertainty of ±100 ppm and an outdoor CO_2 uncertainty of ±50 ppm. In this example, the corresponding ventilation uncertainty at the design population is nearly 50% greater than required for the maximum expected population.

Figure 4 – Ventilation Provided with a 600 ppm rise (Ci-Co) compared to ASHRAE 62.1-2019 requirements

(1000 ppm nominal setpoint assuming all assumptions* are valid. CO_2 measurement uncertainty: ±100 ppm indoor and ±50 ppm outdoor.)



Ventilation Uncertainty: Occupant Sex, Age and Weight

The previous examples were based on assumptions that the CO_2 levels and the CO_2 production rates of individuals were accurate (not to mention the assumption of steady-state). Unfortunately, the CO_2 production rate of the occupants vary with age, weight, gender, activity level and even diet. These uncertainties have a dramatic effect on ventilation provided.

Addendum ab, not approved and now in rewrite, provides valuable information regarding the CO_2 production rate of individuals of varying age, sex, weight and activity.

The rightmost column of Table 1 shows the ventilation rate provided for males of average weight between 5 and 60 years old when a 600 ppm rise, or 1,000 ppm nominal indoor CO_2 setpoint is maintained. Figure 5 shows the ventilation provided. The required ventilation to satisfy an adult classroom is shown for comparison. Young adults and children are under-ventilated when traditional fixed setpoint CO_2-DCV is implemented, yet this method is required by more and more school districts each year. Data for females (not shown) generally results in lower ventilation rates for a given CO_2 setpoint.

Adjustments for the nominal age of the occupants can be compensated for and is part of the *addendum ab* normative appendix language that will hopefully be adopted.

Table 1 – Ventilation provided for a 600 ppm rise (Ci-Co) in CO_2

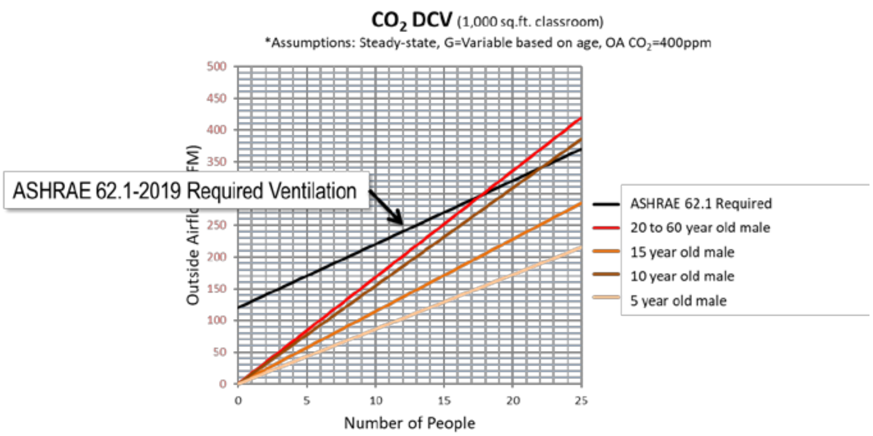
(1000 ppm nominal setpoint assuming all assumptions* are valid. CO_2 measurement uncertainty: None)

Normative Appendix D Calculations (Addendum ab)

Age	Sex	RQ Assumed	BMR Calc. Coef. Table D1.2.2.		Mass (kg) Table D1.2.3.	BMR eq. D1.2.6.1.	M Table 1.2.4.1.	G= RQ·BMR·M·*k*		OA CFM @Ci-Co=600
								L/S	CFM	
5	M	0.85	0.095	2.110	18.6	3.877	1.3	0.002438	0.005165	8.6
10	M	0.85	0.095	2.110	31.8	5.131	1.3	0.003226	0.006836	11.4
15	M	0.85	0.074	2.754	56.8	6.957	1.3	0.004374	0.009269	15.4
20	M	0.85	0.063	2.896	71.6	7.407	1.3	0.004657	0.009868	16.4
30	M	0.85	0.048	3.653	78.4	7.416	1.3	0.004663	0.009880	16.5
40	M	0.85	0.048	3.653	83.6	7.666	1.3	0.004820	0.010213	17.0
50	M	0.85	0.048	3.653	83.4	7.656	1.3	0.004814	0.010200	17.0
60	M	0.85	0.048	3.653	82.6	7.618	1.3	0.004790	0.010149	16.9
Average 20 to 60 years	**M**							**0.004749**	**0.010062**	**16.8**

Figure 5 – Ventilation provided with a 600 ppm rise (Ci-Co) in CO_2 for various male age groups

(1000 ppm nominal setpoint assuming all assumptions* are valid. CO_2 measurement uncertainty: None)

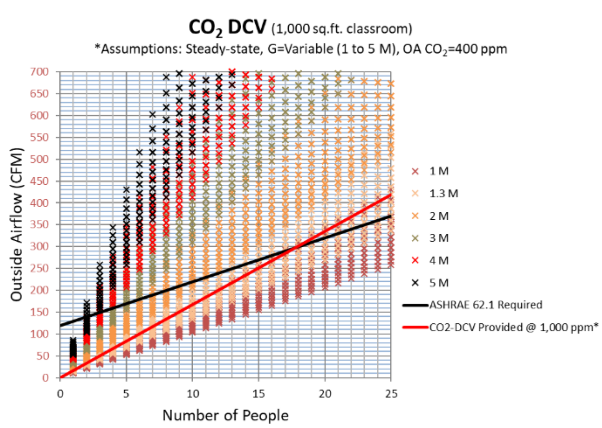


Ventilation Uncertainty: Occupant Activity

The 600 ppm rise, or 1,000 ppm nominal setpoint used today is based on sedentary, or seated, adults with an occupant activity level equal to approximately 1.3 MET. However, CO_2-DCV is often applied to spaces with more active occupants, such as auditoriums, health clubs, dance studios, etc. In these higher activity spaces, the metabolic output of the individuals can exceed 5 MET. Metabolic output is directly proportional to the CO_2 production rate, G, of individuals and G is directly proportional to the ventilation provided for a given rise in CO_2 (refer back to Figure 1). Therefore, a given CO_2 level may result in considerable uncertainty in ventilation unless adjustments are made to the setpoint based on the expected activity level of the individuals in the space. Figure 6 illustrates the massive uncertainty associated when traditional CO_2-DCV is indiscriminately applied to spaces with activity levels greater than those assumed for sedentary adults.

Figure 6 - Ventilation provided for a 600 ppm rise (Ci-Co) in CO_2 at various activity levels

(1000 ppm nominal setpoint assuming all assumptions* are valid. CO_2 measurement uncertainty: ±100 ppm indoor and ±50 ppm outdoor.)



Traditional Fixed Setpoint CO_2-DCV Summary

Traditional fixed setpoint CO_2-DCV is widely used. Unfortunately, most that use it do not understand the ventilation uncertainty and risk associated with the technique.

This author has been attempting to bring some of the issues with CO_2 ventilation control to industry professionals for nearly 20 years. The fact is, CO_2-DCV is not going to disappear overnight and not all the use it will understand the ventilation issues and risk associated with it. Therefore, an improvement to the technique is the first and logical step for this type of ventilation control.

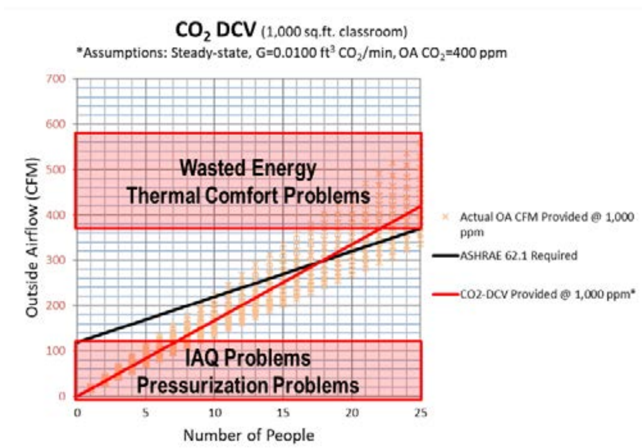
Improving CO_2-DCV

Factors such as age, sex, weight and activity level (occupant attributes) must be considered when establishing the proper setpoint for fixed setpoint CO_2-DCV control. *Addendum ab*, once approved, will hopefully be "normative" and part of required calculations for CO_2-DCV control. However, several factors, including the assumption of steady-state and the measurement uncertainty of indoor and outdoor CO_2 levels cannot be compensated for using the current, fixed setpoint, model.

Assuming that the physical attributes of the occupant and activity level is considered, the uncertainty for fixed setpoint CO_2-DCV is shown in Figure 7. The scatter within the expected population is unavoidable. It is the control outside of the upper and lower limits that must be improved. The upper limit should be set to the ASHRAE 62.1-2019 calculation for V_{ot} based on the maximum expected population. The lower limit should be set to either a.) the ventilation required at the minimum expected population or, b.) the outdoor airflow rate required for pressurization, whichever is greatest.

Figure 7 – Ventilation Provided with a 600 ppm rise (Ci-Co) compared to ASHRAE 62.1-2019 requirements

(1000 ppm nominal setpoint assuming all assumptions* are valid. CO_2 measurement uncertainty: ±100 ppm indoor and ±50 ppm outdoor.)



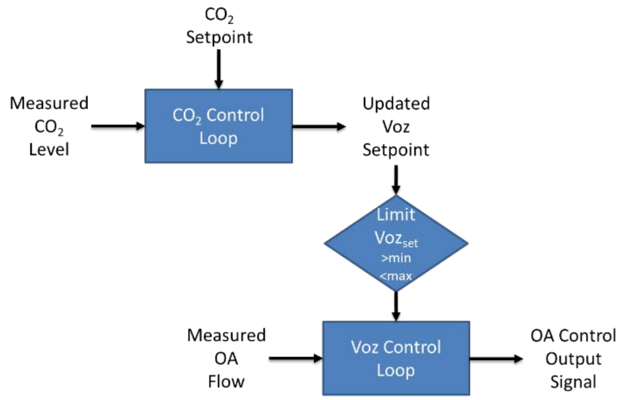
Limiting the upper limit will result in the system going into CO_2 alarm because the system will be limited from reaching the CO_2 setpoint. This has already been addressed in California Title 24 that sates in §120.1(d)4C, "The outdoor air ventilation rate is not required to be larger than the design outdoor air ventilation rate required by Section 120.1(c)3 regardless of CO_2 concentration."

Setting limits may sound easy, but in fact, is very difficult due to fan speed changes, variations in wind and stack pressure, and damper issues such as hysteresis, binding and deterioration.

Systems that rely on one or more fixed damper positions cannot maintain outdoor airflow rates due to changes in fan speed, wind pressure and stack pressure in the return air duct system. The problem is exacerbated on VAV and multi-speed fan systems. This was first demonstrated by in an article published Solberg et al., (ASHRAE Journal, January, 1990). Fixed damper intake systems can vary 50% or more of the desired setpoint and that uncertainty does not include field measurement error that can also be significant due to the intake design of today's air handling systems.

The best way to set limits on a fixed setpoint CO_2-DCV system is to install an airflow measurement device directly in the outdoor air intake of recirculating air systems or at the ventilation zone level of DOAS systems. The control logic required to accomplish this is shown in Figure 8.

Figure 8 – Modified fixed setpoint CO_2-DCV with airflow limits

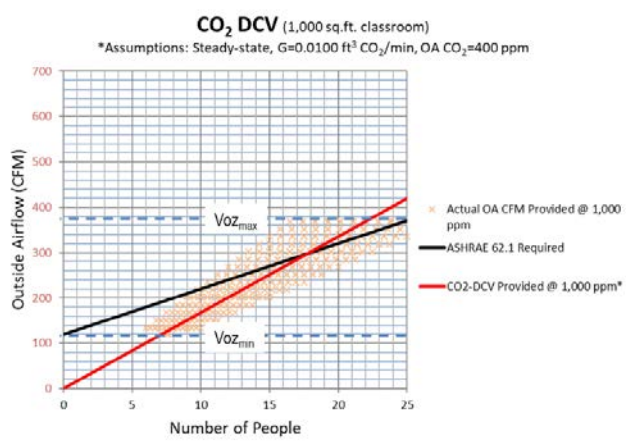


The cascading control logic shown in Figure 8 is analogous that used for space temperature control of a VAV box. The CO_2 setpoint is compared to the measured CO_2 level and the output of the first control loop is an airflow setpoint. The airflow setpoint is compared to the minimum and maximum limits and reset if outside of the desired range. An airflow setpoint between the minimum and maximum limits is then the setpoint for the second control loop and logic that maintains the proper outdoor airflow setpoint.

The improved results are shown in Figure 9. The upper and lower limits are maintained within the measurement uncertainty of the airflow measurement device. Demand control is achieved within the uncertainty (scatter) that results from the CO_2 measurement error and the fact that a single CO_2 setpoint cannot satisfy the requirements of Standard 62.1-2019 at more than one population.

Figure 9 – Ventilation Provided with a 600 ppm rise (Ci-Co) compared to ASHRAE 62.1-2019 requirements using modified fixed CO_2-DCV with airflow limits

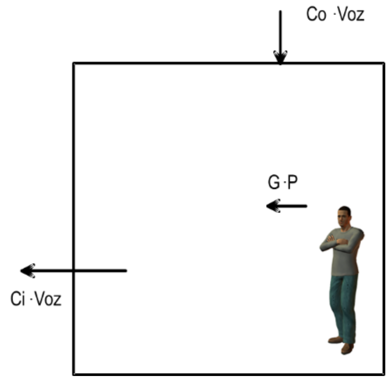
(1000 ppm nominal setpoint assuming all assumptions* are valid. CO_2 measurement uncertainty: ±100 ppm indoor and ±50 ppm outdoor.)



An Even Better Method!

Once the decision has made to use airflow measurement, an even better solution becomes apparent. Since the outdoor airflow rate is known, the only variable that remains is people, P (Figure 10). Therefore, within the limits of uncertainty and the error (lag) resulting from the assumption of steady-state, the required outdoor air to satisfy ASHRAE Standard 62.1-2019 can be provided. The control logic is shown in Figure 11.

Figure 10 – Steady-state analysis

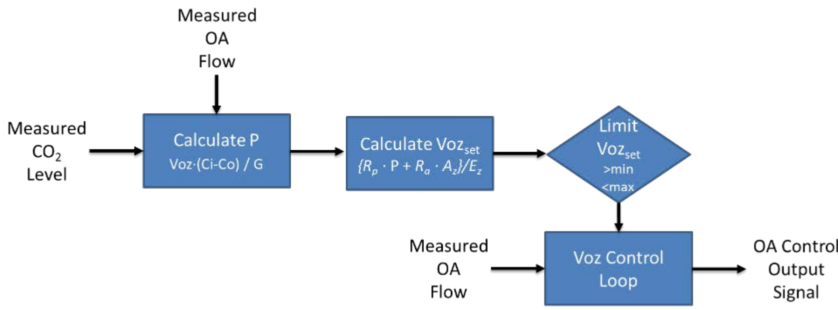


Co = Outdoor CO_2 concentration (ft^3 CO_2/ft^3 air)
Ci = Indoor CO_2 concentration (ft^3 CO_2/ft^3 air)
Voz = Outside Airflow Rate (ft^3/min)
Vo=Outside Airflow Rate/Person ((ft^3/min)/person
G = CO_2 generation rate of the occupant (ft^3 CO_2/min)
P = Number of occupants

Steady-state Mass Balance: In = Out
Co·Voz + G·P = Ci·Voz

Can be rearranged as:
Voz·(Ci-Co) / G = **P = People!**

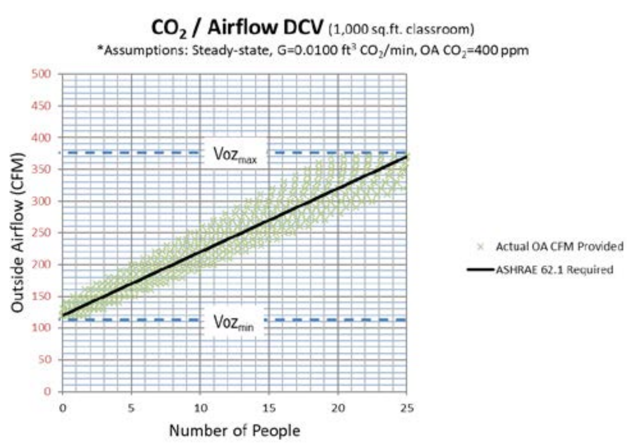
Figure 11 – CO_2/OAF-DCV (population estimating) with airflow limits



The control logic in Figure 11 is easier to implement than the previous fixed setpoint solution. The measured CO_2 and measured outdoor airflow (either at the AHU of single zone recirculating systems or at the ventilation zone of DOAS systems) are used to continuously calculate the population using an assumed CO_2 production rate, G, for the individuals in the ventilation zone based on the attributes of the anticipated population and the expected activity level. The required outdoor air, V_{oz}, is calculated using the VRP for 62.1. Upper and lower limits are set as previously described and the outdoor airflow setpoint is maintained using the control loop and logic that maintains the proper outdoor airflow setpoint.

The results are shown in Figure 12. The upper and lower limits are maintained within the measurement uncertainty of the airflow measurement device. Demand control is achieved within the uncertainty (scatter) that results from the CO_2 measurement. Unlike the fixed setpoint strategy, the uncertainty is centered around the ventilation required for Standard 62.1. The CO_2 levels of the space will vary.

Figure 12 – Ventilation Provided Using CO_2/OAF-DCV compared to ASHRAE 62.1-2019 requirements
(1000 ppm nominal setpoint assuming all assumptions* are valid. CO_2 measurement uncertainty: ±100 ppm indoor and ±50 ppm outdoor.)



Conclusions

Demand control ventilation is a strategy that makes sense on high-occupant density spaces with variable occupancy. Unfortunately, most industry professionals do not understand that a DCV system must respond to the changing population of the ventilation zone. CO_2 is not a contaminant of concern at this point in time (that may change) and CO_2-DCV is simply a method to vary the outdoor airflow rate to a ventilation zone based on changes in the CO_2 level that result from changes in the population and changes in the outdoor airflow rate provided to the ventilation zone.

There are numerous errors associated with CO_2-DCV, that result from assumptions made, or ignored, regarding the population's attributes and the assumption of steady-state. Traditional fixed setpoint CO_2-DCV can severely over-ventilate when the ventilation zone populations are high and under-ventilate when populations are low. In addition, fixed setpoint CO_2-DCV can only satisfy the requirements at a single population level.

Implementing a control strategy that uses airflow measurement in the outdoor air intake of recirculating air handlers or at the ventilation zone of DOAS systems can significantly "improve" traditional fixed setpoint CO_2-DCV.

Using airflow measurement and CO_2 to estimate the population is a better approach and can better satisfy the requirements of ASHRAE Standard 62.1-2019 with no additional cost of equipment compared to the "improved" method.

Both of these methods have been described by this author in presentations and implemented successfully for nearly 15 years.

When one finally recognizes that CO_2-DCV is only one of many methods to maintain ventilation in high-density variable occupancy spaces, other strategies become more evident. Those strategies include methods that count the occupants directly, use a POS system to determine occupancy (ex. theatres), or use some other population estimation strategy. It is time for engineers to "think outside the box" and develop and implement improved DCV systems that not only save energy but provide for our core client, the occupant.