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) for 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 of dedicated outdoor air systems (DOAS). Finally, the paper suggests that the industry considers using direct occupancy counting techniques, rather than CO_2, as the preferred method of DCV 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 for ventilation ≥25 people per 1,000 ft^2 of floor area.

Many 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 that causes harm to occupants. 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).

<u>Demand Control Ventilation: Definition</u>

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 <u>current population</u>.*

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. A CO_2 sensor is not an occupancy counting device.

The obvious 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?"

Most state that "ASHRAE 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 DCV systems are the simple and a good starting point for those wishing to understand ventilation 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 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*.

$V_{bz} = R_p \cdot P_z + R_a \cdot A_z$ (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 CURRENT 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.

As for CO_2-DCV and ASHRAE 62.1-2019, 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.

CO_2 and VENTILATION

Recent studies suggest that CO_2 is a contaminant of concern at lower concentrations (concentrations less than 1,500 ppm). However, not all studies support that claim. 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.

If CO_2 is not a contaminant of concern, why are we measuring and controlling it?

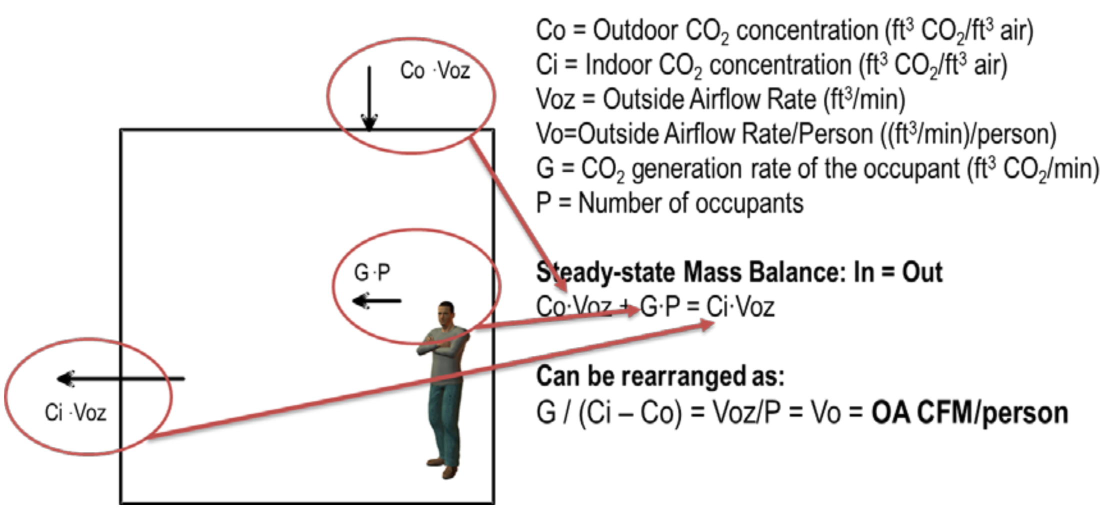
To understand, one must recognize the relationship between CO_2 and [outdoor air] ventilation.

The ventilation zone of spaces that are unoccupied overnight typically have a starting CO_2 level similar to that of the ambient, outdoor air, or approximately 400 ppm.

When the system enters occupied mode, outdoor air containing CO_2 enters the space. As people enter the space, the CO_2 produced as a biproduct of respiration is added to the space. The outdoor air that enters the space is either force exfiltrated or removed by the ventilation 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 steady-state equation is shown in Figure 1.

Figure 1 – Steady-state analysis



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.

VENTILATION and CO_2 CODEPENDENCE

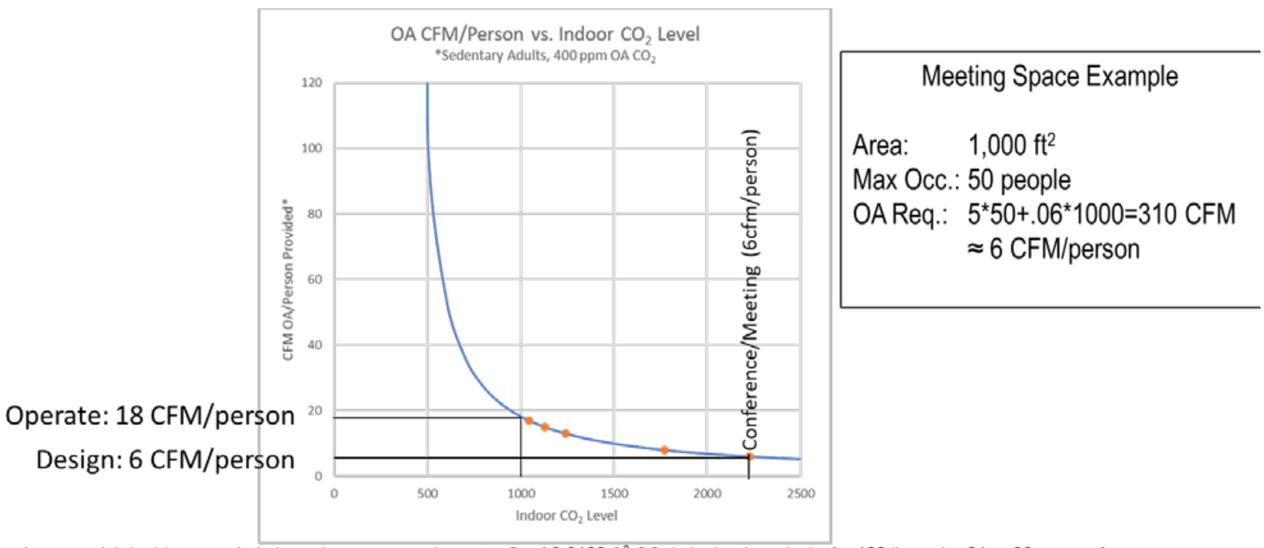
Most engineers, building owners and code writers do not recognize the codependent relationship between CO_2 and ventilation. Many of today's systems that mandate CO_2-DCV are undersized, do not perform at high population densities, and have higher than expected energy consumption. Why?

Most jurisdictions follow the International Mechanical Code (IMC) to determine ventilation requirements. 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.

CO_2-DCV AND 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. The argument was often 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. Schools, for example, required 15 CFM/person that roughly calculated out to a 700 ppm rise or a 1,100 ppm setpoint if a 400 ppm outdoor air CO_2 level was assumed. However, *addendum n*, modified the ventilation requirements so that V_{bz} was based on both occupancy and floor area. As a result, the required ventilation rate per person was, and is, no longer a constant. The method under-ventilates at low populations and over-ventilates at high populations (Figure 3 – next page). Nonetheless, it is still widely used, promoted and often mandated.

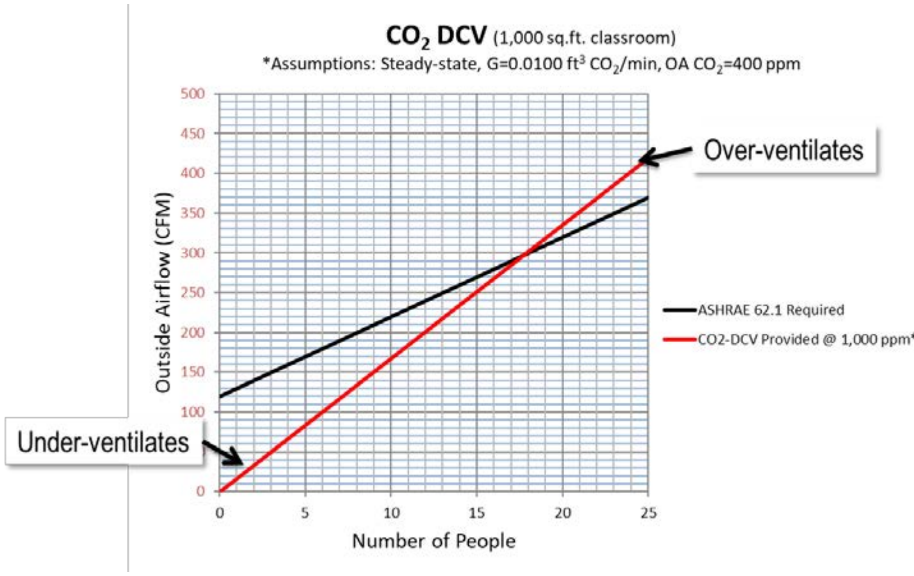
<u>Ventilation Uncertainty: CO_2 Measurement Error</u>

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 is, how does CO_2 measurement uncertainty affect the ventilation rate provided to the space?

CO_2-DCV system uncertainty was discussed in detail by Dougan and Damiano, (ASHRAE Journal, 2004 and HPAC, 2012). 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.

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)

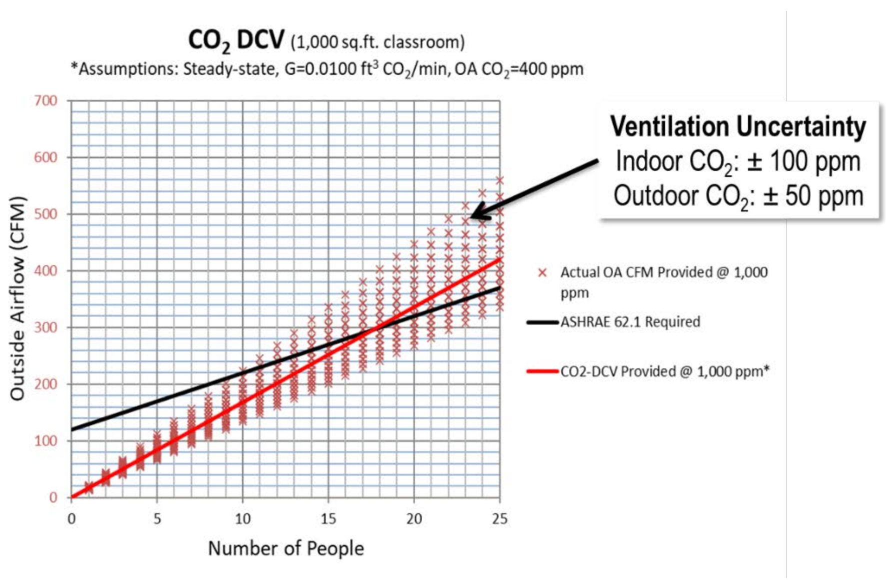


CO_2 sensor measurement uncertainty at 1,000 ppm is at best ±75 ppm (as required by Standard 62.1). Additional uncertainty results from placement and drift of the CO_2 sensor. Therefore, a reasonable indoor uncertainty is ±100 ppm.

Outdoor CO_2 levels vary as a result of season, time of day and climatic conditions. Outdoor CO_2 levels have been measured as low as 350 ppm and as high as 600 ppm. CO_2 levels of the outdoor air are generally assumed to be 400 ppm since the measurement of outdoor CO_2 concentrations are not feasible with commercial CO_2 sensors that are significantly affected by changes in ambient temperature. Therefore, an uncertainty of ±50 ppm is reasonable.

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, now in public review, 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 <u>average</u> 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.

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

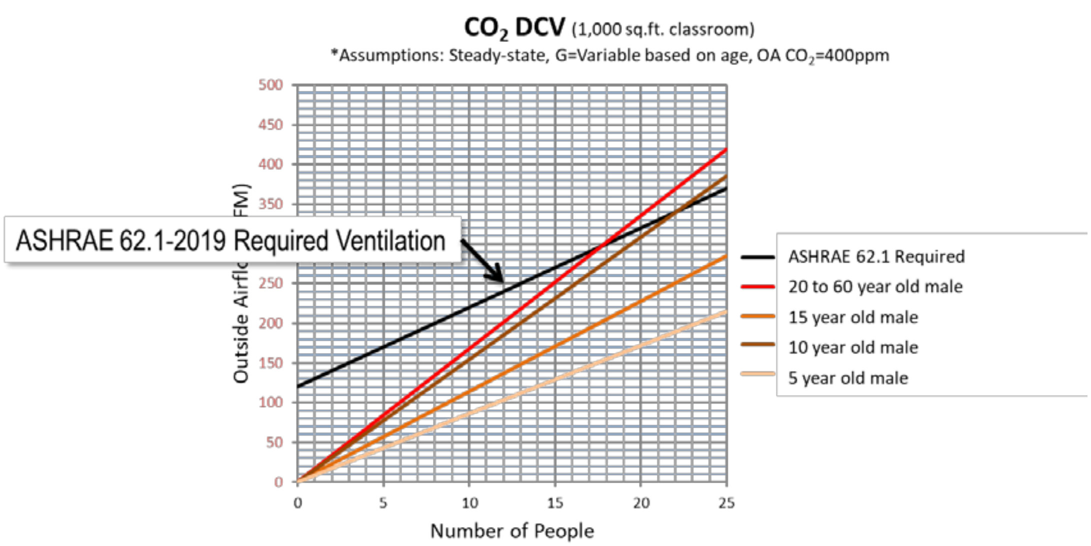
(1000 ppm nominal setpoint assuming all assumptions* are valid. CO_2 measurement uncertainty: None)

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* L/S	CFM	OA CFM @Ci-Co=600
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

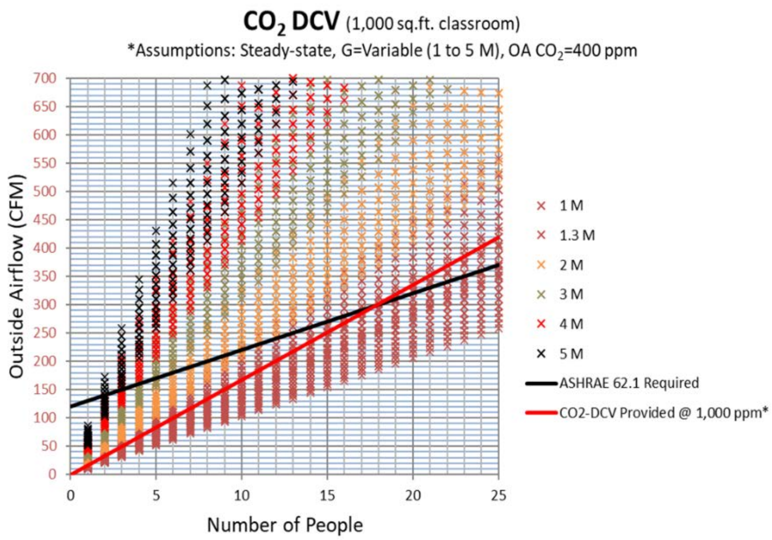
(1000 ppm nominal setpoint assuming all assumptions* are valid. CO_2 measurement uncertainty: None)



<u>Ventilation Uncertainty: Occupant Activity</u>

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, arenas, health clubs and dance studios. 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/±50 ppm outdoor.)



Traditional Fixed Setpoint CO_2-DCV

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 25 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.

IMPROVED FIXED SETPOINT 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 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.

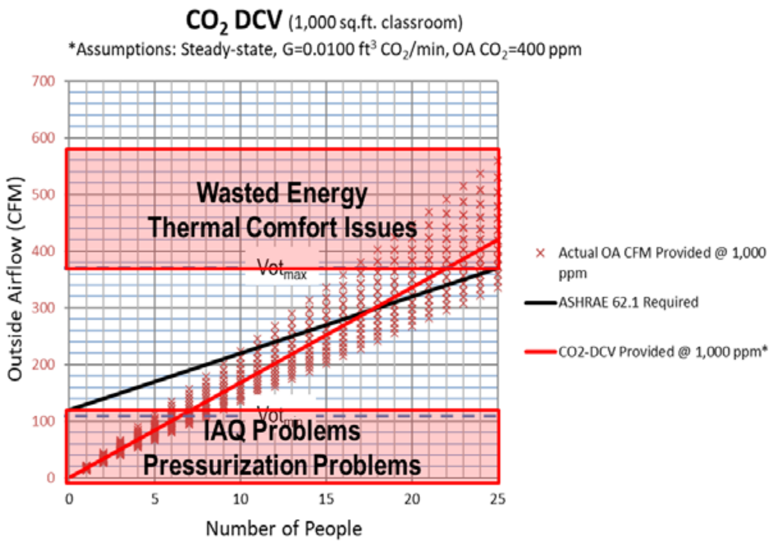
Assuming that the physical attributes of the occupant and activity level is considered, the uncertainty for fixed setpoint CO_2-DCV is shown in Figure 7. The scatter within the expected population is unavoidable. It is the control outside of the upper and lower limits that must be improved. The upper 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.

An upper airflow limit could result in a CO_2 level greater than setpoint and put the system into CO_2 alarm. That may be problematic for those that do not understand that CO_2 is not a contaminant. California Title 24-2019 has already addressed the problem and states in §120.1(d)4C, "The outdoor air ventilation rate is not required to be larger than the design outdoor air ventilation rate required 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.

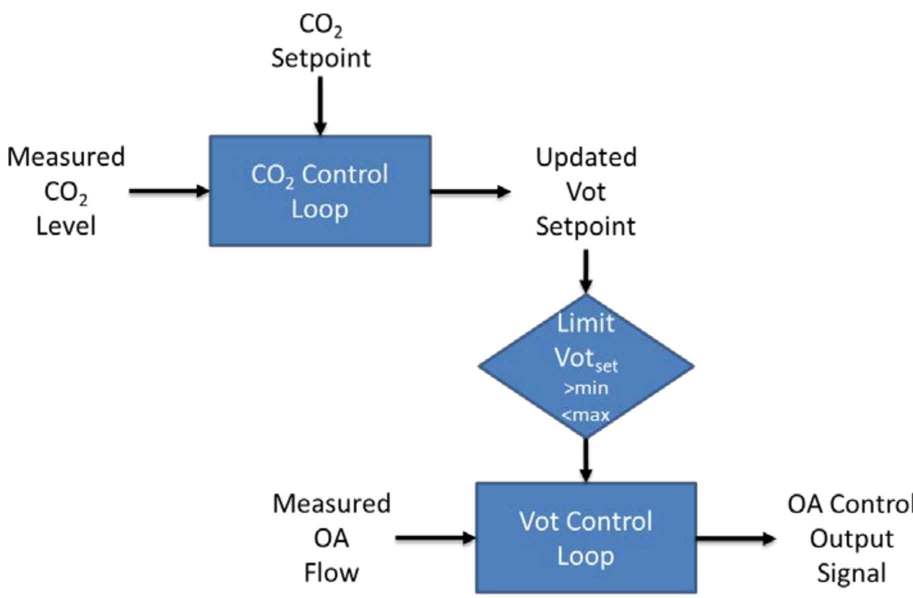
Systems that rely on one or more fixed damper positions cannot maintain outdoor airflow rates due to changes in fan speed, wind pressure and stack pressure in the return air duct system. The problem is exacerbated on VAV and multi-speed fan systems. This was first demonstrated by in an article published Solberg, Dougan and Damiano, (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.

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.)



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

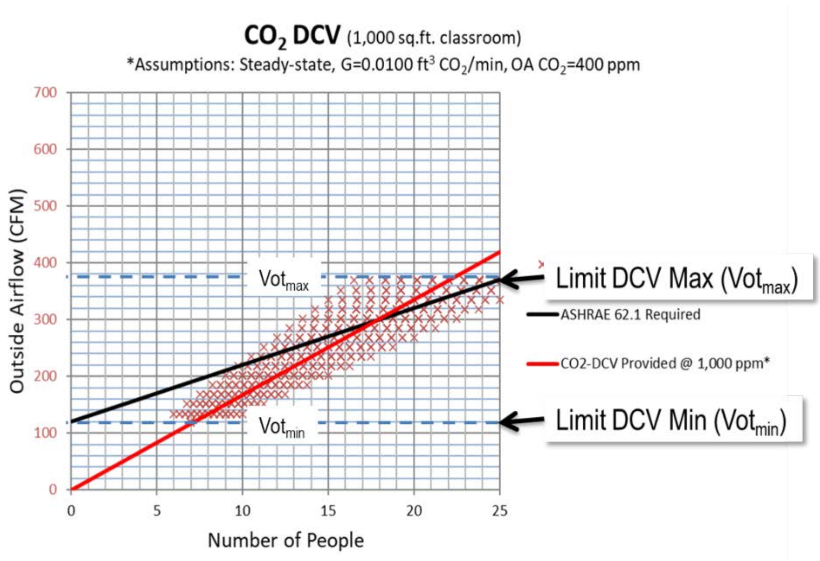


The cascading control logic shown in Figure 8 is analogous that used for space temperature control of a VAV box. The CO_2 setpoint is compared to the measured CO_2 level and the output of the first control loop is an airflow setpoint. The airflow setpoint is compared to the minimum and maximum limits 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 rate.

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, or 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

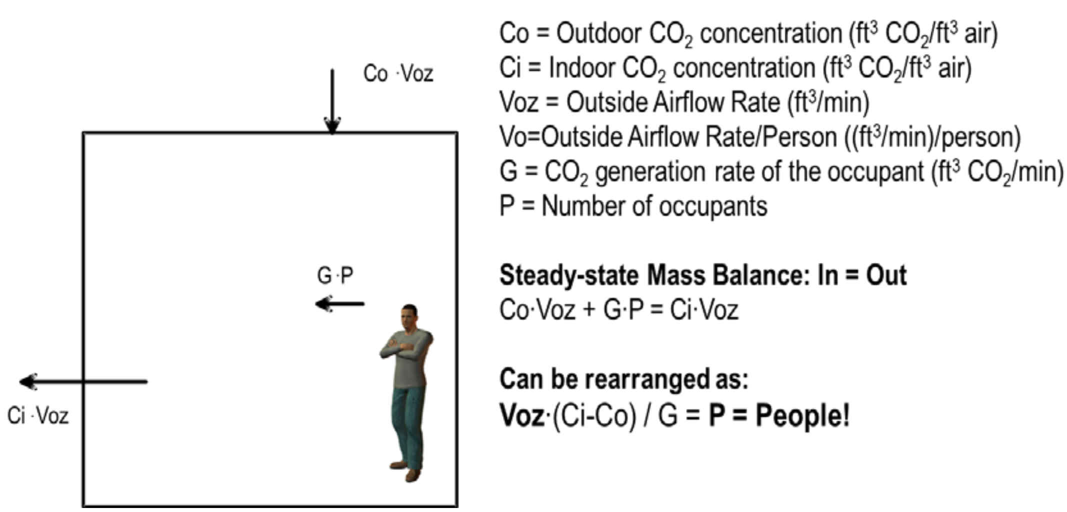
(1000 ppm nominal setpoint assuming all assumptions* are valid. CO_2 measurement uncertainty: ±100 ppm indoor and ±50 ppm outdoor.)



CO_2/AIRFLOW POPULATION ESTIMATION

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.

Figure 10 – Steady-state analysis



The control logic required is shown in Figure 11. 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. The outdoor air CO_2 level is typically assumed unless a high-accuracy industrial CO_2 sensor is provided. The required outdoor air, V_{ot}, is determined using the VRP for 62.1 for the calculated population. 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 rate.

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. Note that the CO_2 levels of the space will vary.

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

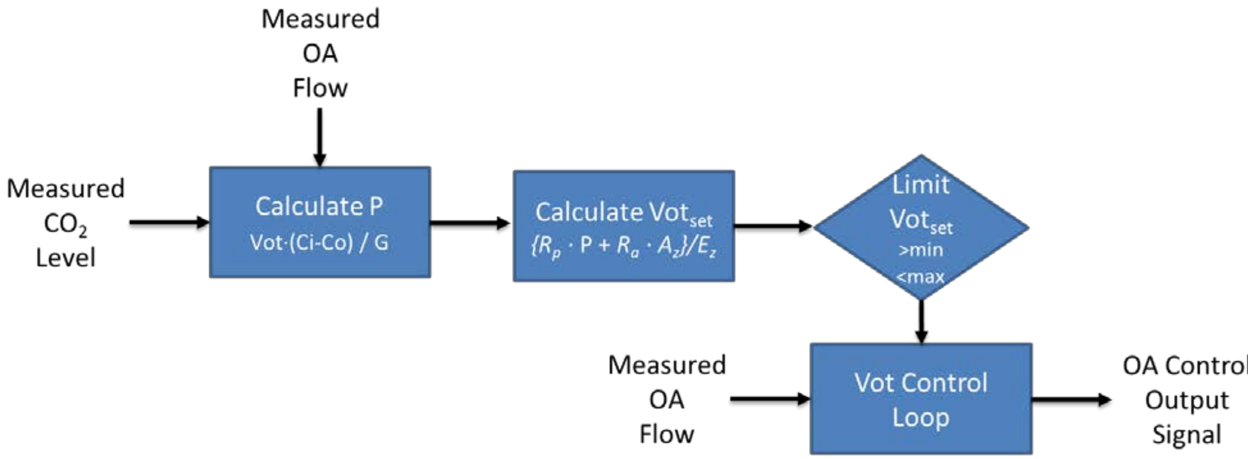
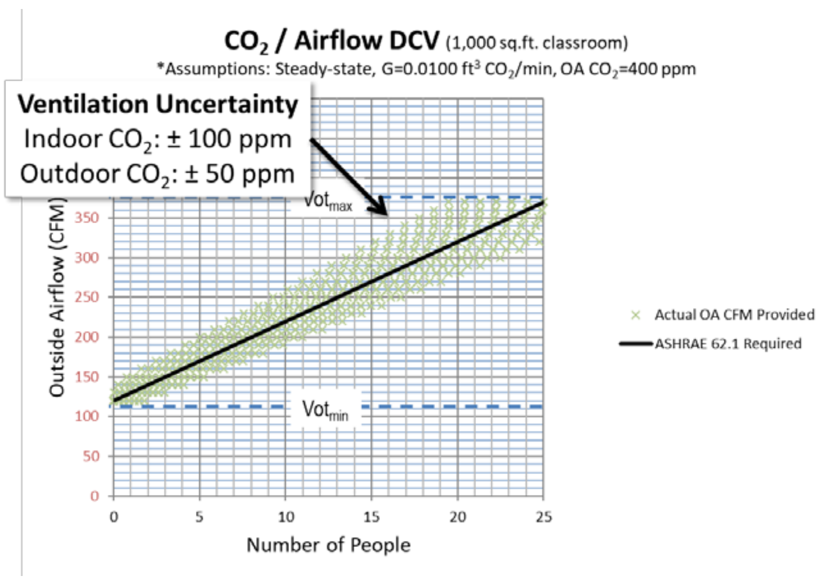


Figure 12 – Ventilation Provided Using CO_2/OAF-DCV compared to ASHRAE 62.1-2019 requirements
(1000 ppm nominal setpoint assuming all assumptions* are valid. CO_2 measurement uncertainty: ±100 ppm indoor and ±50 ppm outdoor.)



CONCLUSIONS

Demand control ventilation is a strategy that makes sense on high-occupant density spaces with variable occupancy. Unfortunately, most 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 under 5,000 ppm (that may change) and CO_2-DCV is simply a method to vary the outdoor airflow rate to a ventilation zone based on the population and outdoor airflow rate provided.

There are numerous uncertainties associated with the ventilation provided from CO_2 based ventilation control strategies. Those uncertainties are a result of variations in the population's attributes, measurement error of indoor and outdoor CO_2 levels and the assumption of steady-state.

Traditional fixed setpoint CO_2-DCV typically over-ventilates when the ventilation zone population is high and under-ventilates when the population is low. In addition, fixed setpoint CO_2-DCV only satisfies the requirements at a single population.

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 aforementioned 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 provide proper ventilation in high-density variable occupancy spaces, other strategies become apparent. Those strategies include methods that count the occupants directly.

Turnstiles and electronic ticket counters can be used in large gathering facilities such as arenas and domed stadiums. Various manufacturers offer occupancy counters that are ideal for smaller spaces such as classrooms, lecture halls and conference rooms. RFID counting systems can be used as can advanced video imaging counting systems. Theaters can use their point of sale (POS) system.

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.