

Demand-Controlled Ventilation

CO₂-Based DCV Using 62.1-2004

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Control of carbon dioxide (CO₂) concentration has been used for many years as an energy conservation measure in buildings to reduce outdoor air rates, and the energy required to condition the outdoor air, when spaces are not fully occupied. In fact, CO₂-based demand-controlled ventilation (CO₂-DCV) is required for most densely occupied spaces by energy conservation standards such as ANSI/ASHRAE/IESNA Standard 90.1-2004, *Energy Standard for Buildings Except Low-Rise Residential Buildings*, and California's Title 24.¹

However, revisions to the way ventilation rates are calculated in ANSI/ASHRAE Standard 62.1-2004, *Ventilation for Acceptable Indoor Air Quality*, necessitate a change to the way CO₂ concentration is used in DCV control systems.

This article summarizes how to use CO₂-DCV with Standard 62.1-2004 from a theoretical standpoint and discusses in detail one CO₂-DCV approach for single zone systems. Additional details on CO₂-DCV, including applying DCV to multiple zone systems, are outlined in Appendix A of the new *Standard 62.1-2004 User's Manual*.

rates are calculated in Standard 62.1 using the prescriptive Ventilation Rate Procedure. In previous versions of the standard, ventilation rates generally were determined by multiplying the number of people in the space times an outdoor airflow rate per person that varied by occupancy type. In the latest version of the standard, rates are calculated by summing two components, one intended to dilute the contaminants generated by occupants (bioeffluents) and their activities, and one intended to dilute contaminants emitted from building

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Standard 62.1 Ventilation Rates

To understand how to use CO₂-DCV, it is first necessary to understand how ventilation

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materials, furnishings, and other non-occupant related sources. Mathematically, this is expressed in Equation 1:

$$V_{bz} = R_p P_z + R_a A_z \quad (1)$$

where V_{bz} is the minimum breathing (occupied) zone outdoor air rate, R_p is the occupant ventilation rate component, P_z is the number of occupants, R_a is the building ventilation rate component, and A_z is the occupiable floor area of the space. R_p and R_a are determined from Table 6-1 in Standard 62.1 based on occupancy type.

The amount of outdoor air required at the supply air diffuser serving the space must be adjusted to account for how effectively outdoor air is delivered from the diffuser into the breathing zone. This is expressed in Equation 2:

$$V_{oz} = \frac{V_{bz}}{E_z} \quad (2)$$

where V_{oz} is the outdoor air rate required to be supplied to the zone and E_z is the zone air distribution effectiveness, which is determined from Table 6-2 in Standard 62.1 showing values of E_z for various supply air configurations.

For single zone systems, the outdoor air rate required at system air intake, V_{ot} , is equal to the zone outdoor air rate, so:

$$V_{ot} = V_{oz} = \frac{V_{bz}}{E_z} \quad (3)$$

For methods to calculate V_{ot} for multiple-zone systems, consult the standard and the *62.1 User's Manual*. This article is limited to single zone systems.

CO₂ DCV Fundamentals

CO₂ is a bioeffluent generated by people at a rate determined by their size, age, fitness, and activity level. At the same time people are generating CO₂, they also are producing odorous bioeffluents. These odorous bioeffluents are generated pro-

portionally to the rate of CO₂ production,² although diet and personal hygiene also play a role. Nevertheless, CO₂ concentration is a fairly dependable indicator of the concentration of the odorous bioeffluents that the occupant component of the ventilation rate in Equation 1 attempts to control. Hence, we can use CO₂ concentration to dynamically adjust the ventilation rate, reducing outdoor air intake rates when zones are not occupied at their design occupancy. This CO₂ based demand-controlled ventilation is specifically allowed by Standard 62.1-2004.

Figure 1 shows airflow rates and CO₂ concentrations for a single-zone ventilation system, where:

- V_{pz} = the primary supply flow rate to the zone
- V'_{ot} = the outdoor air rate at the air handler (V'_{ot} is equal to the design outdoor air rate V_{ot} when the zone is at full occupancy)
- v = the zone volume
- C_s = the concentration of CO₂ in the supply air
- C_R = the concentration of CO₂ in the room at breathing level
- C_{RA} = the concentration of CO₂ in the return air
- \dot{N} = the generation rate of CO₂ in the zone

The zone is assumed to be pressurized and thus exfiltrating the outdoor air supplied. The exfiltrated air is assumed to have CO₂ concentration equal to the room air concentration since space leakage is likely to occur at windows and doors that are located within the breathing zone.

Using a control volume around the room and balancing CO₂:

$$\dot{N} + V_{pz} C_s - (V_{pz} - V'_{ot}) C_{RA} - V'_{ot} C_R = v \frac{\partial C_r}{\partial t} \quad (4)$$

Assuming steady-state (this assumption is justified below), the equation simplifies to:

$$\dot{N} = V_{pz} (C_{RA} - C_s) + V'_{ot} (C_R - C_{RA}) \quad (5)$$

At the air handler, mass balance equations yield:

$$V'_{ot}(C_{RA} - C_{OA}) = V_{pz}(C_{ra} - C_s) \quad (6)$$

Combining these two equations results in:

$$\dot{N} = V'_{ot}(C_R - C_{OA}) \quad (7)$$

From Equation 3 for single zone systems, the system outdoor air rate can be converted to the breathing zone outdoor air rate:

$$V'_{ot} = \frac{V'_{bz}}{E_z} \quad (8)$$

where V'_{bz} is the breathing zone ventilation rate calculated from Equation 1 when the number of occupants is below the design occupancy. V'_{ot} and V'_{bz} in Equation 8 become design values V_{ot} and V_{bz} when the occupancy is at design conditions.

If people are the only sources of CO₂ in the zone, then the source strength of CO₂ is

$$\dot{N} = kmP_z \quad (9)$$

where k is the generation rate of CO₂ and m is the activity level of the people in the zone (in met). Generation rate k

averages about 0.0084 cfm/met/person over the general adult population.³ Table 1 shows typical met levels for a variety of activities.

Combining the last three equations and Equation 1, the outdoor air intake rate can be determined as a function of CO₂ concentration as:

$$V'_{ot} = \frac{R_a A_z}{E_z - \frac{R_p(C_R - C_{OA})}{km}} \quad (10)$$

With typical adult CO₂ generation rates and the units of concentration in parts per million, this equation can be written:

$$V'_{ot} = \frac{R_a A_z}{E_z - \frac{R_p(C_R - C_{OA})}{8400m}} \quad (11)$$

Equation 11 can be combined with Equations 1 through 3 and used to determine the CO₂ concentration that will occur in the breathing zone at design occupancy and minimum outdoor air rate under steady-state conditions:

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$$V_{ot} = \frac{R_p P_z + R_a A_z}{E_z} = \frac{R_a A_z}{E_z - \frac{R_p (C_R - C_{OA})}{8400m}} \quad (12)$$

Solving for room CO₂ concentration we get:

$$C_R = C_{OA} + \frac{8400 E_z m}{R_p + \frac{R_a A_z}{P_z}} \quad (13)$$

Table 2 shows steady-state CO₂ concentrations for several common occupancy types calculated using Equation 13 assuming default occupant density, estimates of activity levels, zone air distribution effectiveness E_z equal to 1.0, and an ambient CO₂ concentration of 400 ppm.

For offices, the steady-state CO₂ concentration (990 ppm) that results from Standard 62.1 ventilation requirements is about the same as the concentration (904 ppm) that results using ventilation requirements from the 1989 to 2001 versions of Standard 62 (20 cfm/person [10 L/s per person]). Concentrations for the other occupancy types listed, which are all densely occupied zones, are significantly higher than those resulting from prior Standard 62 ventilation rates. This is due to the less conservative “code intended” philosophy used to determined ventilation rates in Standard 62.1-2004. (For a more detailed rationale for the revised ventilation rates, see the *62.1 User’s Manual*.)

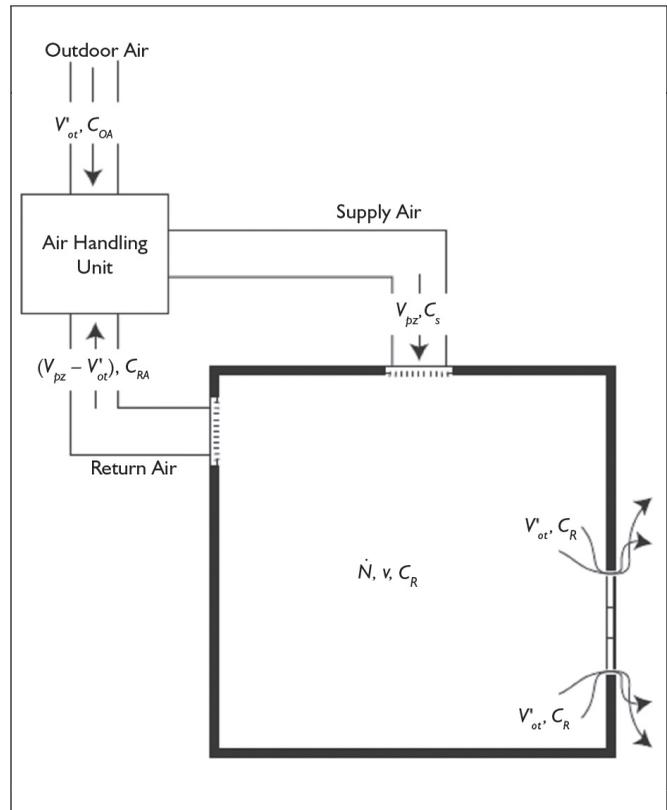


Figure 1: Single zone airflows and CO₂ concentrations.

Assumption of Steady-State Conditions

Both Equation 11 and Equation 1, from which it was derived, are based on an assumption of steady-state conditions. In non-steady-state conditions, typical of most real-world applications, CO₂ concentration will generally lag behind changes in the actual number of occupants in the zone and changes in ventilation airflow rates. However, using Equation 11 to control outdoor air rates is still valid because the rate of generation of CO₂ by occupants should be nearly proportional to the rate of bioeffluent generation; both are generated at a rate proportional to the number of people and their activity level. It is bioeffluent (odor) concentration we are trying to control, and if the source strengths of CO₂ and bioeffluents are proportional, CO₂ concentration may be used as an indicator of bioeffluent concentration. Thus the steady-state assumption in Equation 11 is made not because the actual system is at steady-state but because the ventilation rate equation, Equation 1, is based on steady-state conditions.

This steady-state relationship is simply being used to establish the relationship between CO₂ (odor) concentration and airflow setpoint in Equation 11. Therefore, while the rate of air supplied using Equation 11 will not exactly track the source strength of bioeffluents due to

transient effects, it should maintain an acceptable bioeffluent concentration.

To help understand this argument better, consider a cooling system analogy with variables of cooling load (analogous to bioeffluent source strength), cooling capacity (ventilation rate), thermal mass (space volume), and temperature (CO₂ concentration). A thermal analysis of a space would result in a differential equation analogous to Equation 4. Temperature is used as an indicator of thermal comfort just as CO₂ is used as an indicator of bioeffluent concentration, and we know from chamber studies (and common practice) approximately what temperature setpoint range to maintain to maintain a sense of comfort for most occupants. If we control cooling capacity (ventilation rate) to maintain temperature (CO₂ concentration) at the desired setpoint, then we have achieved our goal without any need to calculate the cooling load (bioeffluent source strength) using differential equations.

This is not to say that the control logic should not look at the time-rate-of-change of the controlled variable (temperature, CO₂ concentration) to improve the control system’s ability to maintain the desired setpoint; just as with temperature controls, CO₂-DCV controls can use proportional or proportional plus integral logic depending on the system design.

Activity	met
Seated, Quiet	1.0
Reading and Writing, Seated	1.0
Typing	1.1
Filing, Seated	1.2
Filing, Standing	1.4
Walking at 0.89 m/s	2.0
House Cleaning	2.0–3.4
Exercise	3.0–4.0

Table 1: Typical met levels for various activities.⁶

Occupancy Category	Activity Level	Steady State CO ₂ Concentration
Classrooms (age 9 plus)	1.0 met	1025 ppm
Restaurant Dining Rooms	1.4 met	1570 ppm
Conference/Meeting	1.0 met	1755 ppm
Lobbies/Prefunction	1.5 met	1725 ppm
Office Space	1.2 met	990 ppm
Sales	1.5 met	1210 ppm

Table 2: Steady-state CO₂ concentrations at 400 ppm ambient.

Dynamic Reset of Outdoor Air Intake—Constant Volume Systems With Airflow Measurement

For single zone systems with outdoor airflow measuring and control devices, Equation 11 can be used to dynamically reset outdoor air intake rate, V'_{ot} . The control system, such as a direct digital control system, would have to be capable of using Equation 11 to dynamically calculate the required outdoor air rate setpoint and then modulate dampers (or provide some other means) to adjust the outdoor air rate to the new setpoint.

The variables in Equation 11 can be determined from Table 3.

Dynamic Reset of Outdoor Air Intake—Constant Volume Systems Without Airflow Measurement

In the previous example, DCV was implemented by solving Equation 11 dynamically for the outdoor air intake airflow setpoint and adjusting dampers to maintain this setpoint. This requires a sophisticated control system (such as a direct digital control system) to make the setpoint calculation and an airflow measuring device (such as a pitot array) to measure outdoor airflow, neither of which are commonly

found on typical single-zone HVAC systems such as packaged air conditioners. DCV could be implemented with prior versions of Standard 62 using only a CO₂ sensor and controller in the zone and a standard outdoor air economizer (mixing damper) assembly. Unfortunately, no precise way exists to do this with the current Standard due to the addition of the occupant and building components in Equation 1, which complicates the mathematics since the effective ventilation rate per person and the CO₂ concentration both vary with population. But a very simple approach to DCV is still possible:

- Calculate the required V_{ot} at design occupancy using Equation 1 to Equation 3.
- Using the same equations, calculate the outdoor air rate with no occupants ($P_z = 0$). Call this value V_{at} (the area building based component adjusted for distribution effectiveness).
- Using Equation 13, determine the steady-state CO₂ concentration when the zone is fully occupied and at its design outdoor airflow rate, V_{ot} . See examples in Table 2. Call this value CO_{2max}.

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Parameter	Determining Parameter Value
Ventilation Parameters (R_p , R_a , and A_z)	These parameters are determined in accordance with Standard 62.1-2004. See the Standard 62.1 or the <i>62.1 User's Manual</i> .
Zone Air Distribution Effectiveness (E_z)	E_z is determined from Table 6-2 in Standard 62.1-2004 and may be adjusted dynamically in some cases. For instance, if the system uses overhead supply and return, E_z could be 0.8 when the unit is heating, and 1.0 when the unit is cooling.
Activity Level	Activity level is estimated from <i>Table 2</i> . The lower the estimate, the more conservative the resulting outdoor airflow rates will be.
Indoor Concentration	Indoor concentrations of CO ₂ are measured with a CO ₂ sensor located within the breathing zone of the zone (usually located adjacent to the zone thermostat). Typical sensors are of the infrared type with accuracies on the order of ± 75 ppm. Many commonly used commercial sensors are factory calibrated and guaranteed not to require recalibration for as long as five years.
Outdoor CO ₂ Concentration	<p>Outdoor CO₂ concentration is commonly determined in one of two ways:</p> <ul style="list-style-type: none"> • Conservatively assumed constant value typical of the area where the intake is located: outdoor air CO₂ concentration remains fairly constant unless the intake is located near roads where vehicle exhaust can raise levels during traffic conditions. But even where such spikes can occur, assuming a typical background (non-traffic affected) concentration (e.g., 400 ppm) will still be effective even if it results in somewhat higher outdoor air rates when spikes occur. Assuming a typical value is of course a very reliable approach since there are no additional sensors to get out of calibration. • Dynamic measurement using a CO₂ sensor located outdoors, typically a duct-mounted type located in the outdoor air intake plenum or duct: although arguably the most accurate approach since it results in actual differential CO₂ concentration measurement, this approach can also be the least accurate and reliable due to sensor inaccuracy. For example, one sensor could read low while the other reads high, creating a doubly inaccurate differential reading. On the other hand, in areas where outdoor CO₂ concentration varies considerably (e.g. from 400 ppm to 600 ppm due to local automobile traffic), using an outdoor CO₂ sensor can improve energy savings even with sensor inaccuracy. The accuracy of differential CO₂ concentration measurement can be improved by using a single CO₂ sensor with a sampling pump, sequenced valves, and tubes piped to the zone and to the outdoors—but first costs will be higher.

Table 3: Determining parameters used in CO₂ DCV equations.

- Provide a CO₂ sensor/controller that is adjusted to send a maximum output signal when the room CO₂ is at the CO_{2max} and a minimum output signal when the room CO₂ is at the ambient conditions (e.g., 400 ppm).
- Adjust the outdoor air damper so that at the maximum controller output signal the system delivers design outdoor air rate V_{ot} . This is generally done by or in conjunction with the test and balance contractor.
- Adjust the outdoor air damper so that at the minimum controller output signal the system delivers the building area outdoor air rate V_{at} . Again, this is generally done by or in conjunction with the test and balance contractor.

In this way, the minimum outdoor air intake rate varies from the building area rate (V_{at}) to the design rate (V_{ot}) as the CO₂ concentration varies from ambient to the steady-state maximum rate

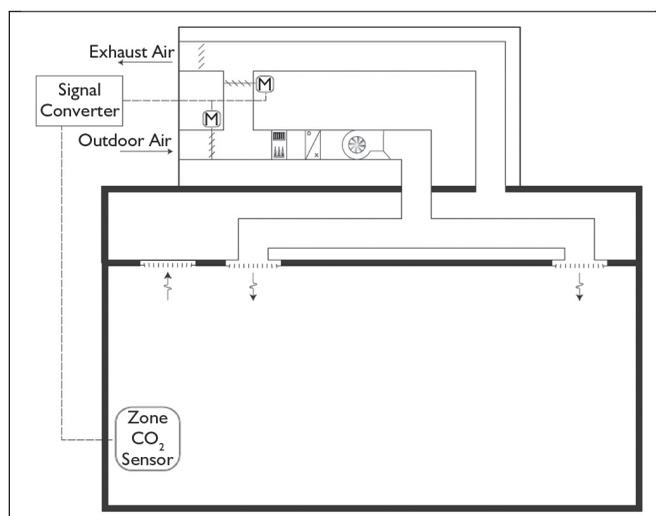


Figure 2: CO₂ DCV for packaged air-conditioning unit.

CO_{2max} . Note that this control varies the *minimum* outdoor air rate; the economizer controller can override this DCV minimum rate to provide additional outdoor air to reduce cooling energy usage when weather and load conditions are favorable.

The design is shown in *Figure 2* for a packaged single zone AC unit. A CO_2 sensor provides an analog signal proportional to CO_2 concentration. It is wired to a signal converter (transducer) that scales the output and converts it to be compatible with the damper actuator. For instance, the damper actuator may operate using a variable resistance signal with a potentiometer to maintain a minimum damper position when the AC unit is on. The signal converter replaces the potentiometer—the CO_2 DCV controls will maintain minimum outdoor air rates instead. The signal converter is adjusted to send a resistance that provides V_{at} (as measured at the AC unit outdoor air intake by the test & balance contractor) when the CO_2 sensor output corresponds to ambient CO_2 concentration and to send a resistance that provides V_{ot} when the CO_2 sensor output corresponds to CO_{2max} .

Implementing CO_2 -DCV under previous versions of Standard 62 would require essentially the same components except that a controller (e.g., proportional, two-position) would also be required to maintain space CO_2 at the desired setpoint. The controller must be tuned in the field to ensure stable control. The cost of the controller and controller tuning is not required with the latest version of Standard 62.1, so in a sense CO_2 -DCV may be simpler and less expensive to implement than in the past.

Conclusions

CO_2 -based demand-controlled ventilation has been a commonly used energy conservation strategy for many years. However, changes to the way outdoor air rates are calculated in the latest version of Standard 62.1 requires that DCV control system designs be modified. This article shows that using CO_2 -DCV in single zone systems based on the latest version of Standard 62.1 is no more complicated, and in fact may be simpler, to implement compared to CO_2 -DCV system designs based on prior versions of the standard.

References

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