CO_2-Based Demand-Controlled Ventilation With ASHRAE Standard 62.1

Though not as straightforward as it once was, CO_2-based DCV remains a practical way to reduce costs

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Demand-controlled ventilation (DCV) can reduce the cost of operating an HVAC system. But implementing DCV based on indoor levels of carbon dioxide (CO_2) is not as straightforward under the 2007 version of ANSI (American National Standards Institute)/ASHRAE (American Society of Heating, Refrigerating and Air-Conditioning Engineers) Standard 62.1, *Ventilation for Acceptable Indoor Air Quality*, as it was under previous versions. The good news is that DCV remains do-able and practical, especially for spaces such as gymnasiums and meeting rooms, where people and their activities are the main sources of contaminants.

This article reviews Standard 62.1's requirements for dynamic reset and outlines several methods of implementing DCV using CO_2 sensors.

DYNAMIC RESET

In Section 6.2.7, "Dynamic Reset," Standard 62.1 permits an HVAC system to "reset the design outdoor-air intake flow (V_{ot}) and/or space or zone airflow as operating conditions change." Although the standard does not provide details for implementation, any system-control approach that responds to varying conditions must be capable of providing at least the required minimum breathing-zone outdoor airflow whenever the zones served by a system are occupied. The standard lists three types of

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dynamic reset:

- Reset based on occupancy.
- Reset based on ventilation efficiency.
- Reset based on economizer operation.

Reset based on occupancy. Standard 62.1 allows the resetting of intake airflow in response to changes in zone population. This control strategy—DCV—responds to the actual need, or "demand," for ventilation by regulating the rate at which an HVAC system brings outdoor air into a building. Ventilation demand can be assessed one of three ways:

- Occupancy schedules, by which a building-automation system (BAS) predicts population based on time of day.
- Occupancy sensors, which detect the presence or number of people in a zone.
- CO_2 sensors, which monitor the amount of CO_2 produced by occupants and diluted by outdoor air.

Reset based on ventilation efficiency. Standard 62.1 also allows intake airflow to be reset in response to changes in ventilation efficiency. In a multiple-zone variable-air-volume (VAV) system, ventilation efficiency depends on zone- and system-level primary airflows and is higher at part load than it is at design (worst-case) conditions. This control strategy is known as ventilation reset.

Reset based on economizer operation. Lastly, Standard 62.1 allows the resetting of minimum primary airflow at VAV boxes in response to changes in intake airflow. For example, when a system is in economizer (free-cooling) mode, the amount of outdoor air in the primary air is greater than is necessary to meet minimum ventilation requirements, so the minimum primary-airflow settings on VAV boxes can be reduced. If a zone requires reheat during economizer operation, this strategy can reduce both fan and reheat energy.

Let's take a closer look at what may be the most common application of dynamic ventilation reset—DCV based on CO_2 readings—to understand how it works and how Standard 62.1 affects its implementation.

APPLYING CO_2-BASED DCV

In CO_2-based DCV, CO_2 is monitored as a byproduct of respiration, rather than as an indoor contaminant. The rate at which individuals produce CO_2 varies with their diet and health, as well as the duration and intensity of their physical activity. The more exertion an activity entails, the more CO_2 that is produced.

Appendix C of Standard 62.1 provides the following mass-balance equation to predict the difference between indoor and outdoor concentrations of CO_2 at steady-state conditions, given a constant per-person ventilation rate and a constant CO_2-generation rate:

$$V_o = N \div (C_s - C_o)$$

where:

V_o = outdoor-airflow rate, cubic feet per minute (cfm) per person

N = CO_2-generation rate, cfm per person

C_s = indoor CO_2 concentration, parts per million (ppm)

C_o = outdoor CO_2 concentration, ppm

Implementing CO_2-based DCV, then, is a matter of estimating the CO_2-generation rate of occupants (N), measuring the difference between indoor and outdoor CO_2 concentration ($C_s - C_o$), and using that to determine the rate at which ventilation air (V_o) is delivered to a space on a per-person basis.

In most locations, the outdoor concentration of CO_2 seldom varies from the nominal value by more than 100 ppm.[1] Because of this and in lieu of installing an outdoor CO_2 sensor, most designers use either a one-time reading of outdoor CO_2 concentration or a conservative value from historical readings. This simplifies control, lowers installed cost, and usually increases accuracy by avoiding the potential inaccuracy of an outdoor sensor.

IMPACT OF STANDARD

1989 until 2004. The 1989 through 2001 versions of what then was known as Standard 62 based required ventilation rates on either the number of occupants in a zone (cfm per person) or the floor area of a zone (cfm per square foot).

For example, consider a lecture classroom with a design population of 65. To comply with the standard's requirement of 15 cfm of outdoor air per person, the classroom would need to receive 975 cfm of outdoor air (15 cfm per person × 65 people). If the population dropped to 20, the required amount of outdoor air would drop as well, to 300 cfm (15 cfm per person × 20 people).

Assuming a constant CO_2-generation rate of 0.0105 cfm per person, a 700-ppm difference between indoor and outdoor CO_2 concentrations would correspond to 15 cfm of outdoor air per person delivered under steady-state conditions (Figure 1).

Standard 62 required that a breath-

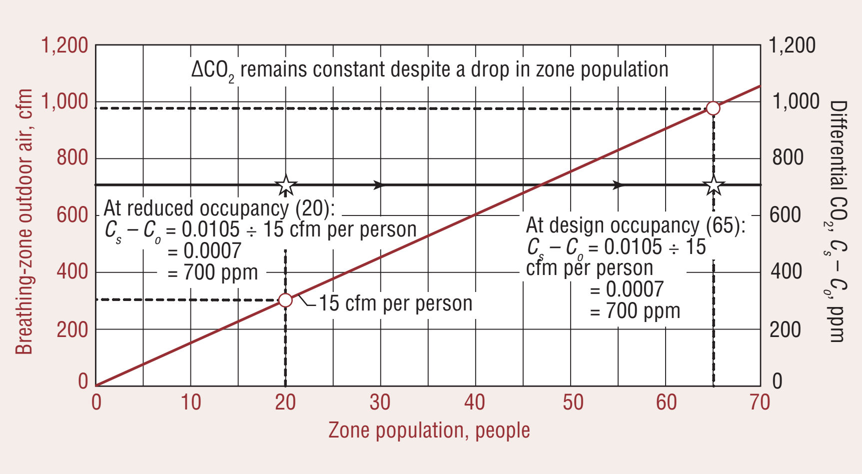


FIGURE 1. CO_2-based DCV under the 1989 through 2001 versions of ASHRAE Standard 62.

ing zone receive a constant rate of outdoor airflow per person—15 cfm in our classroom example—regardless of the number of people actually in the space. Therefore, the desired differential between indoor and outdoor CO_2 concentrations would remain constant, regardless of the number of people actually in the space, as well (Figure 1). By controlling to that constant differential, CO_2-based DCV maintained a constant per-person ventilation rate to a space during periods of reduced occupancy (Figure 2).

(Note: Assumptions simplify DCV, but also introduce inaccuracy. Remember that CO_2-generation rate varies with occupant activity level, diet, and health; required ventilation rate varies by space type under the standard; and outdoor CO_2 concentration can vary by location.[2])

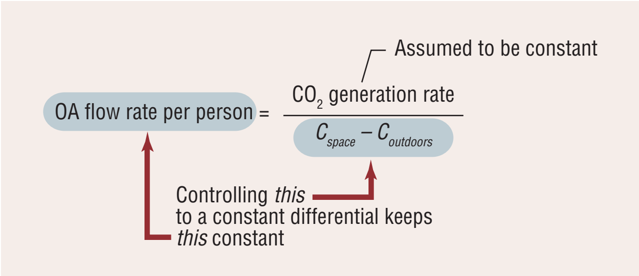


FIGURE 2. CO_2-based DCV under the 1989 through 2001 versions of ASHRAE Standard 62.

2004 to present. In 2004, the method of determining breathing-zone ventilation rate (V_{bz}) was changed. Now, required rates are based on the number of occupants in a zone (cfm per person) and a zone's floor area (cfm per square foot). Therefore, two ventilation rates are prescribed: one for people-related sources (R_p) and one for building-related sources (R_a).

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

where:

R_p = required outdoor-airflow rate, cfm per person

P_z = zone population, number of people

R_a = required outdoor-airflow rate per unit area, cfm per square foot

A_z = zone floor area, square feet

For our example lecture classroom, Standard 62.1 requires 7.5 cfm of outdoor air per person plus 0.06 cfm of outdoor air per square foot of floor area. With a design population of 65 and a floor area of 1,000 sq ft, the delivery of 550 cfm of outdoor air [(7.5 cfm per person × 65 people) +

(0.06 cfm per square foot × 1,000 sq ft)] is required. With 20 people in the classroom, the delivery of 210 cfm of outdoor air [(7.5 cfm per person × 20 people) + (0.06 cfm per square foot × 1,000 sq ft)] is required.

Figure 3 reveals two important effects of changes implemented with the 2004 version of the standard:

• By accounting for people- and building-related sources separately, the standard now results in lower breathing-zone ventilation rates for most occupancy categories (550 cfm vs. 975 cfm for our example lecture classroom). For densely occupied spaces—those that historically benefited most from CO_2-based DCV, such as auditoriums, gymnasiums, conference rooms, lecture classrooms, and cafeterias—the rates are dramatically lower (Table 1).

• As zone population decreases, the required breathing-zone ventilation rate drops less rapidly. In our example lecture classroom, it drops by 7.5 cfm for every person who leaves the zone under Standard 62.1, as opposed to 15 cfm per person under Standard 62.

Those two effects point to less potential for energy savings for most space types with CO_2-based DCV under Standard 62.1.

Assuming a CO_2-generation rate of 0.0105 cfm per person, the difference between indoor and outdoor CO_2 concentrations for our example lecture classroom is 1,250 ppm at design occupancy. As the number of people in the space decreases, the desired difference between indoor and outdoor CO_2 concentrations changes because the effective outdoor-airflow rate—on a cfm-per-person basis—no longer is constant. With 20 occupants, Standard 62.1 requires 210 cfm of outdoor air, which equates to 10.5 cfm per person, compared with 8.5 cfm per person at design occupancy. At 10.5 cfm per person, the desired difference between indoor and outdoor CO_2 concentrations drops to 1,000 ppm with

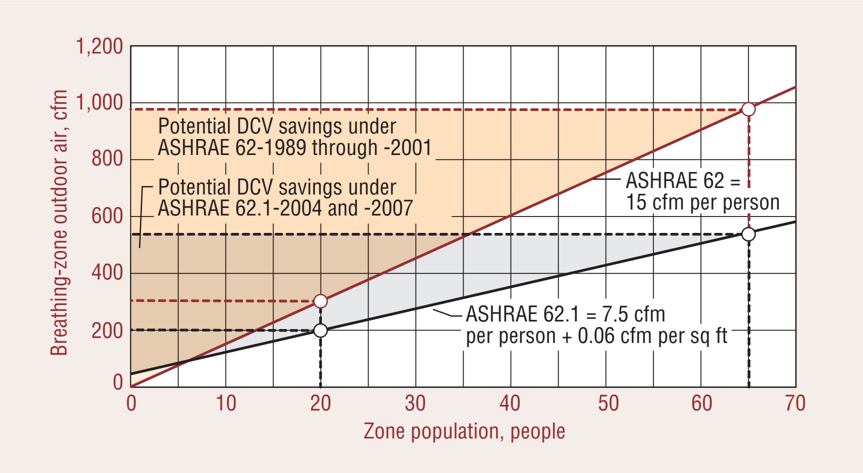


FIGURE 3. Potential DCV savings, Standard 62.1 vs. Standard 62.

Occupancy category		Required ventilation, cfm per 1,000 sq ft		Change[1]
		ASHRAE 62	ASHRAE 62.1	
Education	Art classroom	300	380	+27%
	Classroom, ages 5 to 8	375	370	-1%
	Classroom, ages 9 and up	525	470	-10%
	Lecture classroom	975	550	-44%
	Multiuse assembly	1,500	810	-46%
	Science laboratory	500	430	-14%
Food/beverage service	Bar, cocktail lounge	3,000	930	-69%
	Cafeteria/fast-food dining	2,000	930	-54%
	Restaurant dining room	1,400	705	-50%
General	Conference/meeting	1,000	310	-69%
	Corridor	50	60	+20%
Lodging	Barracks/sleeping area	300	160	-47%
Office	Office space	100	85	-15%
	Reception area	450	210	-53%
Public assembly	Auditorium seating area	2,250	810	-64%
Retail	Sales	300	230	-23%
	Supermarket	120	120	0%
Sports and amusement	Gymnasium, stadium (play area)	600	300	-50%
	Disco/dance floor	2,500	2,060	-18%
	Gambling casino	3,600	1,080	-70%

Note:
[1]"Change" compares ASHRAE Standard 62.1-2004 and -2007 with ASHRAE Standard 62-1989 through -2001 using the default occupant densities in the 2007 version.

TABLE 1. Minimum ventilation rates, Standard 62 vs. Standard 62.1.

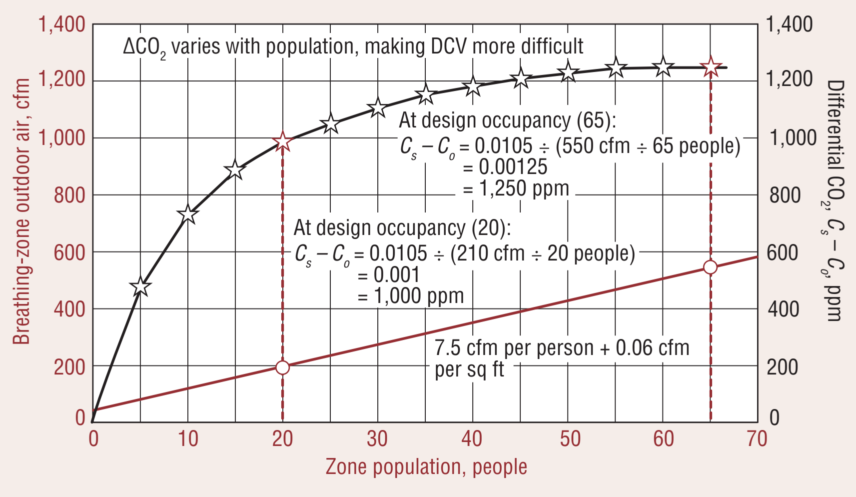


FIGURE 4. CO_2-based DCV under Standard 62.1.

20 occupants (Figure 4).

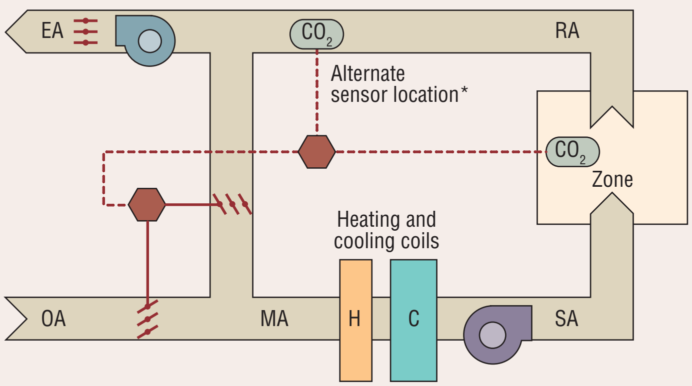
Under Standard 62.1, effective cfm-per-person ventilation rate varies with population. Therefore, the desired difference between indoor and outdoor CO_2 concentrations also varies. Controlling to a constant differential based on design occupancy will under-ventilate a zone at partial occupancy.

The bottom line is that CO_2-based DCV is more difficult to implement under Standard 62.1. More difficult, but not impossible.

CO_2-BASED DCV IN A SINGLE-ZONE SYSTEM

In a single-zone HVAC system utilizing CO_2-based DCV, the CO_2 sensor typically is installed on a wall in the breathing zone (Figure 5). For expedience, the outdoor CO_2 concentration usually is assumed to be constant, which allows the indoor concentration, rather than the difference between the indoor and outdoor concentrations, to be measured and used to modulate the position of the outdoor-air (OA) damper and provide the space with the proper amount of ventilation air on a per-person basis.

Standard 62.1's control strategy for CO_2-based DCV is more complex than Standard 62's. Following is an explanation of two possible approaches:



*Because recirculated air returns from only one zone, some designers prefer to place the CO_2 sensor in the return-air (RA) duct. However, if supply air (SA) bypasses the breathing zone, the sensor in the RA duct may register a less-than-actual indoor CO_2 concentration.

FIGURE 5. CO_2-based DCV in a single-zone HVAC system.

proportional control and single-set-point control.

Proportional control. Appendix A of "Standard 62.1-2007 User's Manual"[3] discusses a method of implementing CO_2-based DCV in a single-zone system. Essentially:

1) Find the required intake flow of outdoor air for the design zone population.

$$V_{ot\text{-}design} = V_{oz} = [(R_p \times P_z) + (R_a \times A_z)] \div E_z = [(7.5 \times 65) + (0.06 \times 1{,}000)] \div 1.0 = 550 \text{ cfm}$$

2) Find the required intake flow of outdoor air when the zone is unoccupied.

$$V_{ot\text{-}min} = [(7.5 \times 0) + (0.06 \times 1{,}000)] \div 1.0 = 60 \text{ cfm}$$

3) Find the target indoor CO_2 concentration at design outdoor-air intake flow.

$$C_{s\text{-}design} = C_o + [N \div (V_{ot\text{-}design} \div P_{z\text{-}design})] = 350 \text{ ppm} + [0.0105 \div (550 \text{ cfm} \div 65 \text{ people})] = 1{,}600 \text{ ppm}$$

4) Set the target indoor CO_2 concentration at minimum outdoor-air intake flow equal to the outdoor CO_2 concentration.

$$C_{s\text{-}min} = 350 \text{ ppm}$$

When actual indoor CO_2 concentration equals design indoor CO_2 concentration (1,600 ppm for our example lecture classroom), actual outdoor-air intake flow should equal design outdoor-air intake flow (550 cfm). When actual indoor CO_2 concentration equals minimum indoor CO_2 concentration (350 ppm), actual outdoor-air intake flow should equal minimum outdoor-air intake flow (60 cfm). When actual indoor CO_2 concentration is between its minimum and design values, a controller should adjust outdoor-air intake flow proportionally between its minimum and design values:

$$V_{ot} = [(C_{s\text{-}actual} - C_{s\text{-}min}) \div (C_{s\text{-}design} - C_{s\text{-}min})] \times (V_{ot\text{-}design} - V_{ot\text{-}min}) + V_{ot\text{-}min}$$

As Figure 6 shows, the proportional-control approach yields an outdoor-air intake flow that equals or exceeds the requirement of Standard 62.1. This strategy is easy to implement, but overventilates zones at partial occupancy. A modulating OA damper, as well as a controller with two CO_2 limits ($C_{s\text{-}design}$ and $C_{s\text{-}min}$) and two OA-damper limits corresponding to intake airflows ($V_{ot\text{-}design}$ and $V_{ot\text{-}min}$), are required.

(Note: A simple improvement to this approach is to use a value other than zero for minimum population. In most cases, this will result in actual intake values closer to the minimum values required by the standard (less overventilation) than the values achieved with the approach described in "Standard 62.1-2007 User's Manual."[3])

Single-set-point control. Following is an alternative control strategy that may result in less overventilation for some occupancy categories:

1) Pick a reasonable value (other than zero) to represent minimum occupancy ($P_{z\text{-}min}$), and find the required intake flow of outdoor air for that population.

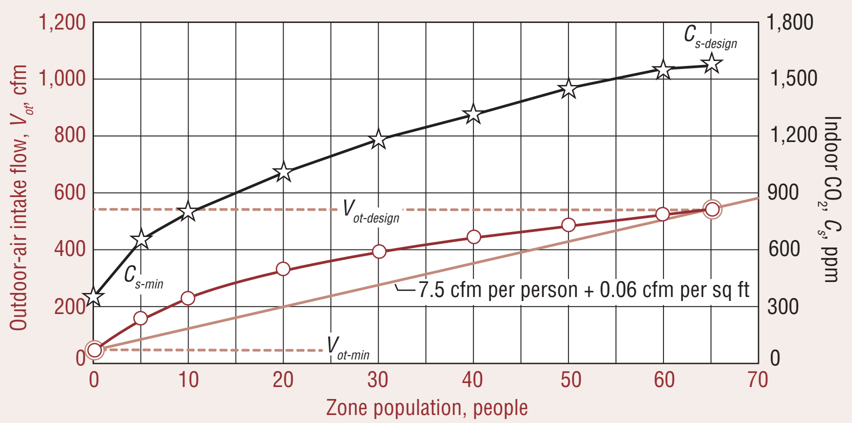
$$P_{z\text{-}min} = 25 \text{ people}$$

$$V_{ot\text{-}min} = [(7.5 \times 25) + (0.06 \times 1{,}000)] \div 1.0 = 250 \text{ cfm}$$

2) Find the target indoor CO_2 concentration at minimum outdoor-air intake flow.

$$C_{s\text{-}min} = C_o + [N \div (V_{ot\text{-}min} \div P_{z\text{-}min})] = 350 \text{ ppm} + [0.0105 \div (250 \text{ cfm} \div 25 \text{ people})] = 1{,}400 \text{ ppm}$$

Intake flow is adjusted to maintain indoor CO_2 concentration at the minimum value (1,400 ppm). If the OA damper reaches minimum outdoor-air intake flow (250 cfm), and zone population drops, the OA damper will maintain minimum outdoor-air intake flow. This will overventilate the zone, causing indoor CO_2 concentration to drift downward. Conversely, as current population nears design, the zone will be overventilated.



V_{ot} and CO_2 are proportional (or linear) with respect to each other, but neither is linear with respect to zone population. The controller adjusts V_{ot} in proportion to the percentage of the CO_2 signal range, but when the controller changes outdoor airflow, the indoor CO_2 concentration changes as well. The controller, then, must adjust V_{ot} in small increments until the indoor CO_2 reaches a stable value. When plotted in relation to zone population, the results of these control actions are curves for both V_{ot} and indoor CO_2.

FIGURE 6. Proportional-control strategy for CO_2-based DCV per Standard 62.1.

As Figure 7 shows, the single-set-point approach results in an outdoor-air intake flow that equals or exceeds the ventilation rate required by Standard 62.1. The approach is simple to implement and, depending on the characteristics of the zone, may result in less overventilation at partial occupancy than the proportional-control method. Like the proportional-control method, it requires a modulating OA damper; however, the controller needs only one OA-damper set point ($V_{ot\text{-}min}$) and one CO_2 set point ($C_{s\text{-}min}$).

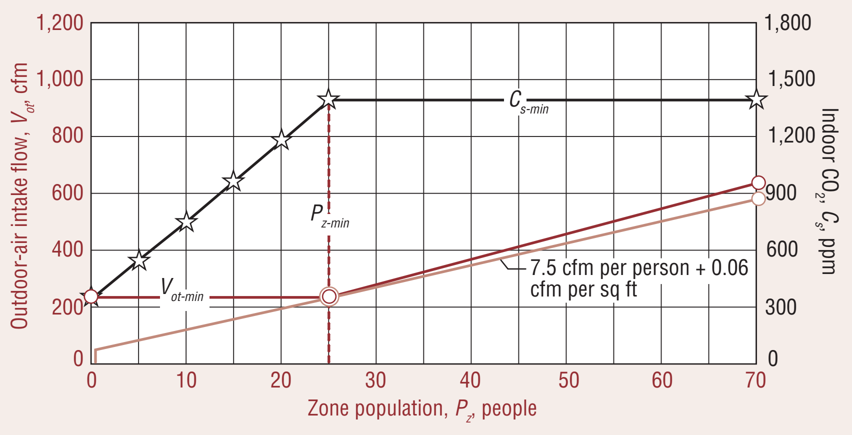


FIGURE 7. Single-set-point-control strategy for CO_2-based DCV per Standard 62.1.

CO_2-BASED DCV IN A MULTIPLE-ZONE VAV SYSTEM

CO_2-based DCV alone. One approach to implementing CO_2-based DCV in a multiple-zone VAV system is to install a CO_2 sensor in every zone. A BAS monitors all of the sensors, determines how much outdoor air must be brought in at the air handler to satisfy the critical zone (and, thus, overventilate all other zones), and repositions the OA damper accordingly.

Installing a CO_2 sensor in every zone is costly, especially considering that most of the zones always will be overventilated, regardless of operating conditions. Installing a sensor in "non-critical" zones offers no added value.

Alternatively, some designers install a single CO_2 sensor in the return-air duct of a multiple-zone system and use that sensor to vary the amount of outdoor air brought in at the air handler. This sensor measures average CO_2 concentration, so some spaces may be underventilated while others are overventilated. Whether this approach provides adequate ventilation is a subject of debate among designers.

Ventilation reset alone. Another control strategy for multiple-zone VAV systems—ventilation reset—resets intake airflow in response to changes in system ventilation efficiency.

Each VAV-box controller senses primary airflow and calculates its outdoor-air fraction. The BAS totals primary airflows and required outdoor airflows from all boxes and determines the highest outdoor-air fraction reported. Then, it solves the equations in Appendix A of Standard 62.1, calculating system ventilation efficiency and the required system-level intake flow of outdoor air. The new intake-flow set point is communicated to the air-handler controller, which adjusts the OA damper to bring in the required amount of outdoor air (Figure 8).

In direct-digital-control VAV systems, this strategy is fairly easy to implement because all of the necessary real-time information already is available digitally (so no new sensors are required). All of the equations are defined in Appendix A of the standard and can be solved dynamically to find the required outdoor-air intake flow.

CO_2-based DCV combined with ventilation reset.[4] For most multiple-zone VAV systems, the best approach often is CO_2-based DCV combined with ventilation reset. Using this strategy, CO_2 sensors are installed only in zones that are densely populated with widely varying patterns of occupancy (e.g., conference rooms).

The sensors are used to reset the ventilation requirements for their

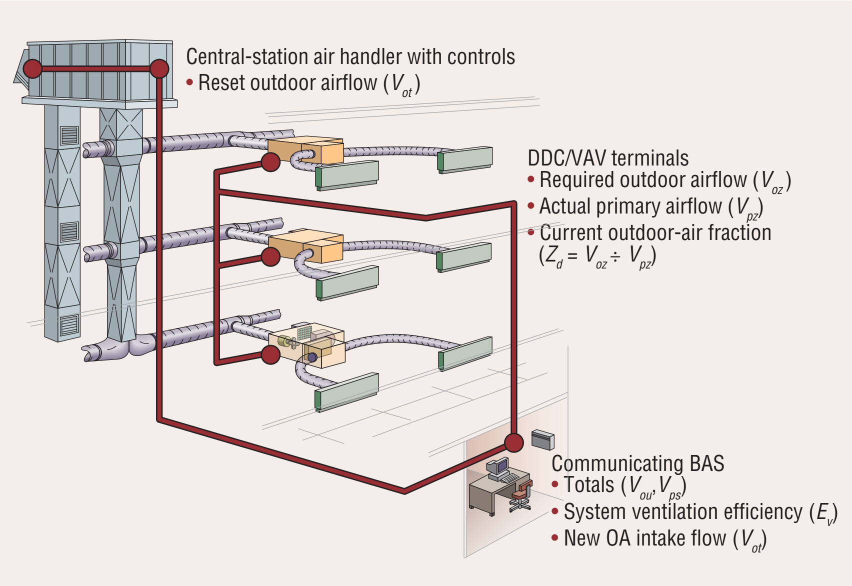


FIGURE 8. Control points for ventilation reset in a multiple-zone VAV system.

respective zones. The other zones—which are not densely populated and/or do not experience significant variations in occupancy—are assumed to require their design ventilation rates whenever they are occupied. The BAS uses ventilation-reset equations to determine how much outdoor air must be brought in at the air handler to satisfy all of the zones served.

		Zone 1	Zone 2	Zone 3		Total OA intake flow, V_{ot}
Ventilation reset only						
Primary airflow, cfm	V_{pz}	1,000	3,000	3,000	= 7,000 cfm	2,370 cfm
Zone outdoor airflow, cfm	V_{oz}	500	600	700	= 1,800 cfm	
OA fraction	Z_d	0.50	0.20	0.23		
Zone ventilation efficiency	E_{vz}	0.76	1.06	1.03		
	$X_s = 1{,}800 \div 7{,}000 = 0.26$, $E_v = 0.76$, $V = 1{,}800 \div 0.76 = 2{,}370$					
Ventilation reset plus CO_2-based DCV in Zone 1						
Primary airflow, cfm	V_{pz}	1,000	3,000	3,000	= 7,000 cfm	1,530 cfm
Zone outdoor airflow, cfm	V_{oz}	**200**	600	700	= 1,500 cfm	
OA fraction	Z_d	0.20	0.20	0.23		
Zone ventilation efficiency	E_{vz}	1.01	1.01	0.98		
	$X_s = 1{,}500 \div 7{,}000 = 0.21$, $E_v = 0.98$, $V_{ot} = 1{,}500 \div 0.98 = 1{,}530$					

TABLE 2. Effect of ventilation-control strategies in a single-duct VAV system at part load.

In the VAV system in Table 2, Zone 1 is a conference room that is densely populated, with widely varying patterns of occupancy, while zones 2 and 3 are general office spaces that are more sparsely and more consistently occupied. The data in the top section of the table concern the use of ventilation reset only. Each zone is assumed to require its design outdoor airflow, regardless of actual population.

The data in the lower section of Table 2 concern the use of a CO_2 sensor in Zone 1 for the reduction of required outdoor airflow from the design value of 500 cfm to 200 cfm when the actual population is less than design. Zones 2 and 3 still require their design outdoor airflows. While sensing CO_2 and finding the current value of Zone 1 outdoor airflow lowers the average outdoor-air fraction (X_s), it increases system ventilation efficiency (E_v) and lowers the required intake airflow from 2,370 cfm to 1,530 cfm.

Combining CO_2-based DCV with ventilation reset:

- Can ensure that each zone receives the proper amount of ventilation without a CO_2 sensor being installed in every zone. CO_2 sensors are used only where they are most beneficial. When other zones are unoccupied, time-of-day schedules or occupancy sensors are used to reduce ventilation.
- Enables documentation of actual ventilation-system performance by communicating ventilation airflows for every zone to the BAS.

SUMMARY

DCV can reduce the cost of operating an HVAC system—especially where contaminants result primarily from people (or their activities) and occupancy varies greatly.

Although it explicitly allows DCV based on CO_2, Standard 62.1 diminishes the value of CO_2-based DCV's implementation for most space types by reducing required design ventilation rates.

Standard 62.1 complicates implementation of CO_2-based DCV because effective cfm per person and, therefore, desired indoor/outdoor CO_2-concentration differential vary as zone population changes.

CO_2-based DCV most commonly is used in single-zone systems serving densely occupied spaces with varying populations. In multiple-zone VAV systems, combining CO_2-based DCV with ventilation reset—using CO_2 sensors only in densely occupied zones with widely varying populations—provides a cost-effective, reliable, and energy-efficient system.

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