

Application of CO₂-Based Demand-Controlled Ventilation Using ASHRAE Standard 62: Optimizing Energy Use and Ventilation

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ABSTRACT

CO₂-based demand-controlled ventilation (DCV), when properly applied in spaces where occupancies vary below design occupancy, can reduce unnecessary overventilation while implementing target per-person ventilation rates. A recent interpretation of ANSI/ASHRAE Standard 62-1989, Interpretation IC 62-1989-27, has affirmed that carbon dioxide (CO₂)-based demand-controlled ventilation (DCV) systems can use CO₂ as an occupancy indicator to modulate ventilation below the maximum total outdoor air intake rate while still maintaining the required ventilation rate per person, provided that certain conditions are met.

This paper, co-written by the author of the interpretation, provides guidelines on the application of CO₂-based DCV. In addition, a method is presented that allows reasonable estimates of the actual ventilation rate per person being effectively delivered to the space, based on comparing predicted CO₂ ventilation levels with CO₂ levels logged in an occupied space. Finally, a model is presented to evaluate various CO₂-based DCV strategies to predict their delivery of target per-person ventilation rates within the lag times required by the standard.

INTRODUCTION

The appropriate role of carbon dioxide (CO₂) in ventilation for acceptable indoor air quality has been clarified in a recent interpretation to ANSI/ASHRAE Standard 62-1989. This interpretation, which is now included with the standard, describes the proper procedure for using CO₂ control to modulate ventilation based on actual occupancy.

For spaces subject to variable or intermittent occupancy, overventilation can be avoided by reducing total ventilation below design ventilation rates (which are based on an assumption of full occupancy). This approach allows target cfm per

person ventilation rates, for example, in a classroom or theater auditorium, 15 cubic feet per minute (cfm) (7.5 liters per second [L/s]) per person, to be maintained based on actual occupancy (ASHRAE 1990). Energy can be conserved and ventilation for acceptable indoor air quality can be maintained in accordance with ANSI/ASHRAE Standard 62-1989. Ideal candidates for this approach include schools, meeting rooms, restaurants, theaters, and office spaces.

There has been much progress in understanding the usefulness of measuring CO₂ in efforts to understand IAQ and ventilation. A recent literature review reported on 50 papers or reports issued since 1983 (Emmerich and Persily 1997). Proper application of CO₂-based demand-controlled ventilation (DCV) requires consideration of both the theoretical approaches in the literature as well as practical insight into the various application methods available and then translating the theoretical methods into functional HVAC systems. This paper begins with a review of three different control approaches and discusses their proper application to suitable spaces.

The use of CO₂ technology to estimate the actual ventilation rate in a design space that utilizes a constant maximum ventilation rate is one of several applications of CO₂ technology under recent investigation. When taken and interpreted with care, CO₂ measurements can be useful in efforts to assess the effective delivery of outdoor ventilation air into the occupied space. Particularly useful are measurements data-logged over time. A method is presented here that allows reasonable estimates of the actual ventilation rate per person being effectively delivered to the space, based on comparing a CO₂ ventilation model with CO₂ levels logged in an occupied space.

In addition to general utility in conducting HVAC system operating assessments and IAQ investigations, accurate assessment of the actual ventilation rate permits more accurate prediction of savings to be realized from implementation of

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demand-controlled ventilation. A model is presented to test various CO₂-based DCV strategies and to predict their delivery of target per-person ventilation rates within the lag times required by the standard. The model facilitates prediction and comparison of daily outdoor air intake volumes for constant ventilation systems versus CO₂-based DCV systems.

BACKGROUND

The ventilation rates tabulated in the ventilation rate procedure of *ANSI/ASHRAE Standard 62-1989* have been utilized in building ventilation system design to dilute constituents of concern, including bioeffluents associated with building occupants. The established rates are tabulated in classifications of occupied space so that a design engineer, noting space classification and use, can select a prescribed rate as the basis for a target design ventilation rate. This rate is expressed as a flow rate per occupant for most occupancies. The total target design ventilation rate then is the product of the maximum space occupancy and the target design ventilation rate per occupant, adjusted as required for ventilation effectiveness or other application considerations.

Buildings utilizing the total target design ventilation rate may provide more ventilation air than is required to meet *ANSI/ASHRAE Standard 62-1989*, particularly during periods when occupancy is far below the maximum space occupancy used in design calculations. The actual ventilation rate delivered by the HVAC system(s) to the space may vary from the target design ventilation rate. Oversupply of outdoor air carries an energy penalty in many systems and, in extreme weather conditions, can impede the ability of some building

systems to maintain the comfort conditions presented in *ANSI/ASHRAE Standard 55-1992* (ASHRAE 1992). Hot, humid air in cooling conditions or cold air in heating conditions can result in indoor humidity values beyond the comfort zone of Standard 55.

Traditional methods to evaluate outdoor air intake, such as traverse velocity readings at the outdoor air intake, do not account for factors associated with underventilation in the occupied space, such as low ventilation effectiveness, or for factors associated with overventilation, such as unaccounted infiltration.

Saving Energy with CO₂-Based Demand-Controlled Ventilation

Typically, when a building is designed according to Standard 62, the amount of outdoor air to be delivered to interior spaces is based on providing enough outdoor air to meet the requirements of the building at full occupancy (e.g., 15 cfm [7.5 L/s], multiplied by the design occupancy of a space for classrooms or theater auditoriums, or 20 cfm (10 L/s), multiplied by the design occupancy of a space for dining rooms or offices). This ventilation rate is typically maintained during all occupied hours, or it may be maintained for longer periods or on a continuous 24-hours-a-day basis. Some means of time control would typically be used to activate outdoor air ventilation at the beginning of the day and turn it off at the end of the day. This constant provision of the target design ventilation rate, regardless of occupancy, is represented by the uppermost line in Figure 1. Using this method, if a space is partially or intermittently occu-

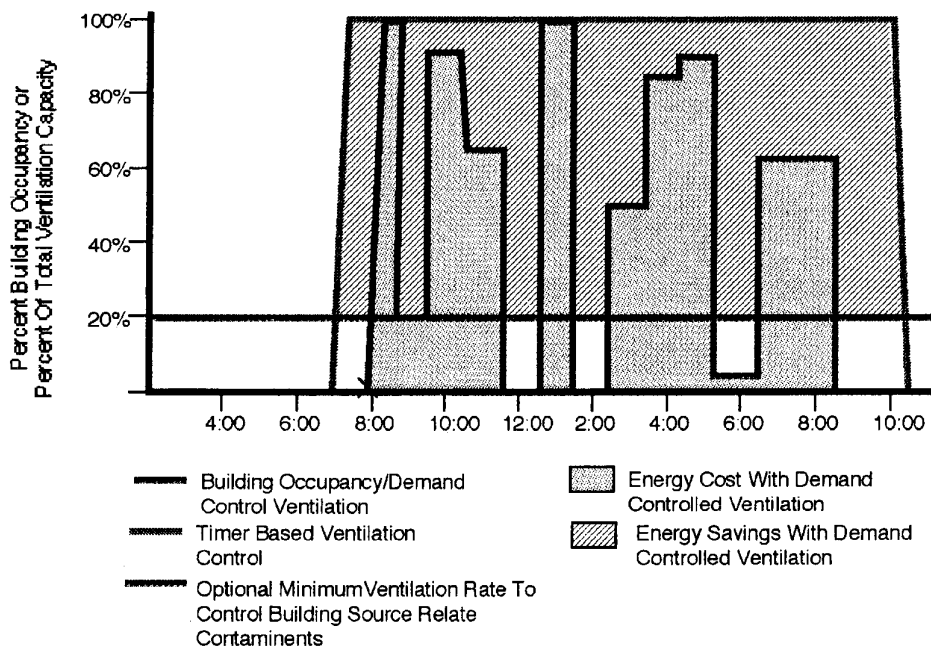


Figure 1 Opportunity for energy savings in a classroom.

ped, such as at the beginning or end of the day, costly and unnecessary over ventilation can occur.

Demand-controlled ventilation using CO₂ can save energy by reducing total ventilation when occupancy is below the full occupancy assumed by designers. A properly implemented CO₂-based DCV strategy will maintain the target cfm per person ventilation rates, with acceptable lag times. Lag time is the delay after occupancy before the system adjusts outdoor air intake to the desired per-person flow rate.

With CO₂-based DCV, ventilation systems can track occupancy and provide ventilation air as required, instead of providing an oversupply of ventilation air during periods of reduced occupancy. The result is energy savings, as represented by the area with diagonal lines in Figure 1. The actual amount of energy savings is dependent on the variability of occupancy in the space. For example, if a classroom is fully occupied all day and the ventilation system is properly sized, potential savings using CO₂ may be negligible. If moderate variation takes place in the space, such as one or two unoccupied periods and two or three periods below full capacity, reductions in the volume of outdoor air intake during the day of 30% to 50% are possible without compromising per-person ventilation requirements for acceptable indoor air quality.

Another factor that can affect potential energy savings is how closely the actual design ventilation rate achieves the ventilation required for the actual occupancy in the space. In an office building, the design ventilation rate may have been based on an assumed density that is very different from the actual occupancy. In other cases, a damper intake position may have been set at an arbitrary position such as 10% open without regard to whether the resulting outdoor air intake rate meets the required design ventilation rate. There are also other instances where outdoor air intake may have been set to zero to maximize energy savings or to address peak load capacity shortfalls. In addition to failing to provide the required design ventilation rate, such approaches can adversely impact indoor air quality through their effect on pressurization of the building envelope.

In many cases, a designer or building operator may wish to maintain a minimum amount of outdoor air ventilation regardless of occupancy to meet exhaust needs or to control pollutants from other sources such as building materials or art supplies. The example shown in Figure 1 assumes that 20% of the design capacity would be provided at all times.

APPLYING CO₂-BASED DCV IN COMPLIANCE WITH STANDARD 62

Interpretation IC 62-1989-27 of *ANSI/ASHRAE Standard 62-1989* regarding CO₂-based demand-controlled ventilation establishes the criteria a control strategy must meet to allow application under the variable and intermittent occupant provisions (Section 6.1.3.4) of the ventilation rate procedure. (ASHRAE interpretations are official clarifications of the provisions of ASHRAE standards and are often useful in obtaining approvals from local code officials for designs

affected by the clarified provisions.) The interpretation confirms that Standard 62 provides for the use of CO₂ as a control parameter to vary outdoor air intake flow rates, based on actual occupancy, while maintaining target per-person ventilation rates under the variable and intermittent occupancy provisions of the standard. For the purposes of this interpretation, CO₂ is considered a predictable indicator of occupancy. When used as an input for a control strategy, CO₂ is not being evaluated as a contaminant that might generate a physiological response at typical concentrations, nor is it being considered a surrogate for body odor or as a pass/fail benchmark for indoor air quality under the ventilation rate procedure.

Two key factors governing the selection of an appropriate CO₂-based DCV strategy are that (1) target per-person ventilation rates can be met and maintained in the space based on actual occupancy and (2) the lag time for the control strategy to work must be within that prescribed by the standard. Additional criteria as provided by the interpretation are summarized below.

General Control Considerations

- Sensor location and control strategy should be selected to achieve the per-person ventilation rates as selected in Table 2 of the standard, which details recommended ventilation rates, typically in cfm (L/s) per person, for various applications.
- A control strategy should be used that ensures the delivery of ventilation is responsive to changes in occupancy within the lead and lag times established by the standard. Simply opening and closing a damper at 1000 parts per million (ppm) is not likely to satisfy this requirement.

Dealing with Non-CO₂-Related Contaminants

- A strategy should be in place to control and reduce any appreciable buildup of contaminants that might occur during unoccupied hours. (This is because CO₂ levels are related to people and will not indicate contaminants that may build up during unoccupied hours.)
- During occupied hours, maintaining a base ventilation rate may be required to ensure that general levels of contaminants are controlled. In the authors' experience, this base ventilation rate could range from 15% to 50% of the design ventilation rate in buildings one year old or older. Ongoing work seeks to provide an appropriate and practical methodology for providing this base ventilation rate. Buildings with activities or sources that may generate constituents of concern may require higher base ventilation rates. In new or extensively renovated buildings, higher levels of ventilation during the first year may be desirable to deal with off-gassing of new building components.

Approaches That Conflict with CO₂-Based Demand-Controlled Ventilation

- Assumptions for diversity or other methods that lower the total design ventilation rate based on average occupancy cannot be used in conjunction with CO₂-based DCV.
- CO₂ removal in the space by means other than dilution ventilation cannot be used in conjunction with CO₂ control. For example, special adsorption air cleaning of CO₂ would not be an appropriate control strategy. Many approaches to gas-phase air cleaning in HVAC applications such as charcoal filters do not remove CO₂.

GUIDELINES FOR CO₂-BASED DEMAND CONTROLLED VENTILATION

A CO₂ sensor can control ventilation in a space much as a thermostat controls heating or cooling. In much the same way that an economizer saves energy when outdoor air can be used for cooling, CO₂-based DCV control saves energy when room occupancies are below full capacity. Some guidelines for implementing a CO₂-based DCV system are provided below.

Determine Location for CO₂ Sensors

A CO₂ sensor for demand-controlled ventilation can be duct mounted or wall mounted. Criteria for selecting sensor location will vary with system type and building specifics. During design, construction, start-up, and continuing operations, the sensor location's role in ventilation control should be evaluated with respect to performance factors, including delivery of design ventilation rate upon controller call for maximum outdoor air intake, base ventilation rate delivered upon full throttling of outdoor air intake, and lag time upon call for increased outdoor air intake.

Duct-Mounted Sensors. Duct-mounted sensors are typically located in the return airstream of an air-handling system. This approach is best applied where the ventilation system operates continuously and where all the zones served by the air handler have similar levels of activity and occupant densities, occurring at the same time. A duct-mounted sensor is not recommended where the system serves a number of areas with diverse occupancy. A duct-mounted sensor in the return air duct of a system that also incorporates a ceiling return plenum may be subject to error because of building infiltration or supply duct leakage. A CO₂-based DCV system incorporating a duct-mounted sensor should be evaluated and corrected, if required, for ventilation effectiveness in the occupied zone.

Wall Mounted Sensors. Wall-mounted sensors can be installed in a location similarly to a thermostat. The location selected should provide input that provides indication of conditions within the occupied zone. Locations that should be avoided are areas close to doorways or air vents and areas that are within one foot of where people would regularly sit or stand. When using one sensor to represent multiple spaces, the location most critical for ventilation rate delivery should be selected.

Determine the CO₂ Control Anchor Point

In using CO₂ to conduct spot measurements of ventilation, it is important to ensure that steady-state conditions have been met (Persily 1997). This is not necessarily so with CO₂-based DCV. The concentrations of CO₂ do not have to reach equilibrium for the approach to work. With demand control, the CO₂ equilibrium level corresponding to the desired ventilation rate is a reference or "anchor point" for a control strategy. The phrase "anchor point" is used in this paper to describe the upper set point of the control range used to adjust the outdoor air intake flow rate. CO₂-based DCV is typically achieved with an outdoor air intake damper fitted with a motorized or pneumatic actuator or, in some cases, with an outdoor air intake fan fitted with speed-controlled drive or controllable inlet vanes.

Appendix D of Standard 62 provides the foundation for a rationale as to how CO₂ concentrations, occupancy, and per-person ventilation rates are related (ASHRAE 1990). The equation below replicates the mass balance equation used in Appendix D of the standard to correlate CO₂ concentrations and ventilation rate. This equation applies only where equilibrium conditions exist, and it ignores dynamic effects. It is not used to infer an absolute ventilation rate per person on an instantaneous basis since, in most DCV applications, equilibrium conditions do not exist and dynamic effects cannot be ignored. The equation can be useful as a reference to predetermine the upper set point in a proportional control band or anchor point. Since it applies only where equilibrium conditions exist and it ignores dynamic effects, it is not appropriate for calculating an instantaneous CO₂ concentration or ventilation rate.

$$V_o = \frac{N}{C_s - C_o} \quad (1)$$

where

V_o = outdoor airflow rate per person;

N = CO₂ generation rate per person, based on age and metabolic rate for an assumed activity level (refer to 1997 *ASHRAE Fundamentals*, Chapter 8, Table 4, for guidance);

C_s = CO₂ concentration in the space;

C_o = outdoor CO₂ concentration.

Restating the equation to express the CO₂ equilibrium concentration that corresponds to a given ventilation level yields Equation 2. Recall that the equation can be useful as a reference to predetermine the upper set point, or anchor point, in a control band, but it is not appropriate for calculating an instantaneous ventilation rate, as discussed above.

$$C_{EQ} = C_s = C_o + \frac{N}{V_o} \quad (2)$$

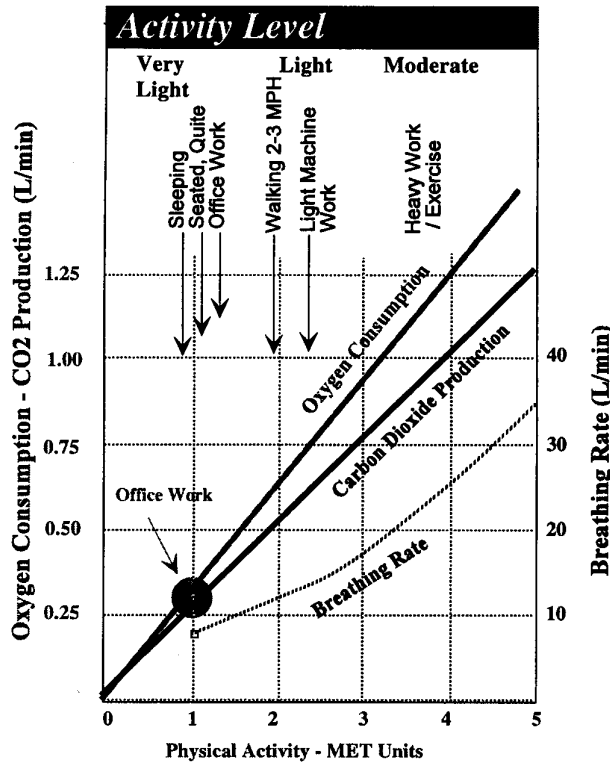
where C_{EQ} = equilibrium level for a given outdoor air ventilation rate expressed in cfm per person.

The differential between indoor and outdoor CO₂ concentrations that corresponds to the target ventilation rate under equilibrium conditions is

$$\Delta C = C_{EQ} - C_o \quad (3)$$

where ΔC = differential between the outdoor CO₂ concentration and the indoor CO₂ concentration that corresponds to the target ventilation rate under equilibrium conditions.

As shown in Figure 2, generation of CO₂ by occupants is predictable based on the activity level for typical adults. Figure 3 shows calculated CO₂ differentials for various ventilation rates assuming an activity level of 1.2 met for adults at



Source: ASHRAE 62-89 "Ventilation for Acceptable Indoor Air Quality"

Figure 2 Building occupant activity level and CO₂ production.

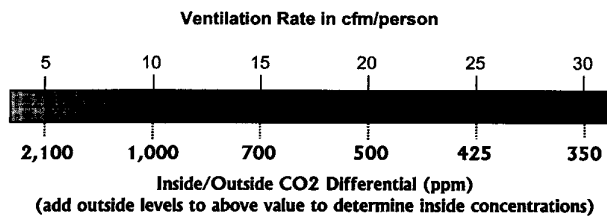


Figure 3 Conversion of inside/outside CO₂ differential to ventilation rate for adults involved in office work.

equilibrium conditions. The differential equilibrium value can be used to predetermine a value for the anchor point, or upper set point, of a CO₂-based DCV control strategy, but it cannot be used as the sole criterion for an approach that will meet the requirements of IC 62-1989-27. The next section discusses how this key anchor point is incorporated into various control methodologies.

Determine Control Approach

This section discusses three possible approaches to CO₂-based DCV that can be used under Interpretation IC 62-1989-27 of ANSI/ASHRAE Standard 62-989. A graphical representation of each of the approaches is provided in Figure 4. Proportional or exponential modulation of ventilation rates based on rising or falling CO₂ concentrations are two typical approaches utilized in successful CO₂-based DCV applications. Another approach with more limited application, referred to here as set point control, implements an on/off, or open/shut, ventilation strategy based on a specific CO₂ set point.

As recommended by Interpretation IC 62-1989-27, an effective CO₂-based DCV control strategy should include the provision of a base ventilation rate that is intended to control nonoccupant sources during occupied hours. Depending on the presence of such sources, this base ventilation rate varies in actual applications. In the authors' experience, the base ventilation rate has ranged from 15% to 50% of the design ventilation rate in buildings one year old or older. Ongoing work seeks to provide an appropriate and practical methodology for determining the base ventilation rate. A minimum base ventilation rate may be required as makeup air to offset exhaust and maintain building pressurization.

Set Point Control. The set-point control approach has limited application, since it will not increase outdoor air intake within acceptable lag times in many cases. Spaces with higher occupant densities, which reach full or nearly full occupancy rapidly once occupancy commences, can be suitable candidates for this approach.

A set-point control system controls outdoor air intake flow rate by opening a damper or activating a fan to bring in the design ventilation rate. This occurs when a sensor indicates CO₂ levels have built up to an upper set point that is typically the equilibrium level for the space (or a somewhat lower level), based on outdoor CO₂ concentration. The damper is held open or the fan is left on until CO₂ concentrations drop a given difference below the upper set point. The difference is called dead-band. When choosing a CO₂ sensor to provide relay control, one that allows for adjustment of set point and dead band is recommended. Proper adjustments of the set point and dead band are required to ensure that the system delivers the required ventilation rate within permissible lag times for the space. The adjustable dead band allows control of the frequency with which the damper actually opens and closes the fan cycles. Depending on the occupancy pattern in the space, the dead band should be adjusted to ensure that periods of lower ventilation do not exceed the lag times prescribed in

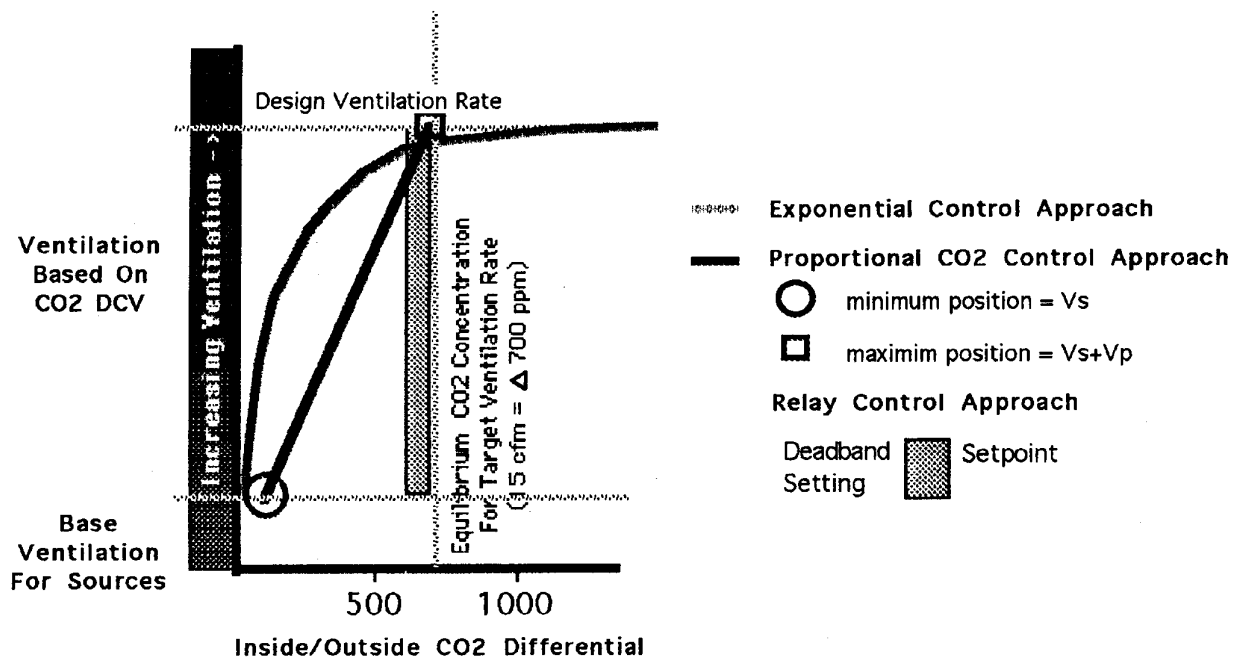


Figure 4 CO₂ control approaches.

Standard 62. Improper adjustment can lead to frequent cycling of the control system, or relay “chatter,” which can cause frequent opening and closing of the outdoor air intake damper.

The set-point approach is not likely to meet the requirements of Standard 62 in many moderate and low-density applications due to the extended lag time that would result as CO₂ levels build to the upper set-point target equilibrium level. For example, in applications with low occupant density, such as office spaces, equilibrium levels may not be reached for a number of hours (Persily 1997; Bearg 1993). However set-point control may be appropriate for some spaces with high occupant density, depending on actual occupancy patterns.

CO₂ set-point control can be used in a limited number of applications to meet the requirements of Interpretation IC 62-1989-27. In the authors’ experience, suitable applications have design density of over 20 people per 1,000 ft² (roughly 20 people per 100 m²), and actual occupancies, when they occur, are always near design density. In these applications, CO₂ levels can build up to the set point quickly enough to avoid excessive lag times. Start-up or commissioning and maintenance of such systems should include procedures to verify compliance with the lag time provisions of Standard 62, set forth in paragraph 6.1.3.4. The values for the actual control range should be adjusted to ensure timely delivery of the full design ventilation rate upon increase in occupancy and CO₂ levels. This control approach is compatible with implementation of a base rate when increased outdoor air is not being called for, which can address possible build-up of non-occu-

nant-related contaminants and may be required to maintain building pressurization.

Proportional Control. A proportional control approach starts to open a damper or increase the introduction of outdoor air when indoor CO₂ levels are a certain amount above outdoor levels. This lower control set point in the control range is often 100 to 200 ppm above outdoor levels. As CO₂ levels in the occupied zone rise, the damper opens wider. Once CO₂ levels reach the anchor point, or upper set point of the control range, the damper position should provide the design ventilation rate for full occupancy. The lower and upper set-point values of the control range described here provide initial values for the control range when using proportional control. As with any control system, these initial values should be adjusted as required upon start-up or commissioning of the CO₂-based DCV system. Start-up or commissioning of such systems should include procedures to verify compliance with the lag time provisions of Standard 62, set forth in paragraph 6.1.3.4. By monitoring the percent of occupancy and the outdoor air intake flow rate, the actual lag time can be observed. The values for the actual control range should be adjusted to ensure timely delivery of the full design ventilation rate upon increase in occupancy and CO₂ levels.

The selection of an equilibrium value for the upper set point of the control range often confuses the principle that underlies the use of CO₂-based demand-controlled ventilation. CO₂ concentration in a space is a dynamic phenomenon that is dependent on many variables including the number of occupants, the rate at which they generate CO₂ by breathing,

and the outdoor air intake flow rate that dilutes the occupant-generated CO₂. With properly selected values for the upper and lower limits of the control range, CO₂-based demand-controlled ventilation provides sufficiently accurate control of the outdoor air intake flow rate to satisfy the ventilation rate procedure of Standard 62, particularly the provisions of paragraph 6.1.3.4, “Intermittent or Variable Occupancy.”

One example of a proportional control CO₂-based DCV approach is provided by Equation 4. This equation describes the ventilation rate called for by the control system, using the indoor CO₂ concentration as input, the anchor point as the upper set point, and a lower set point somewhat higher than the outdoor CO₂ concentration, as described above.

$$V_{DCV} = V_B + (V_{DVR} - V_B) \frac{C_I + C_{LSP}}{C_{USP} + C_{LSP}} \quad (4)$$

where

- V_{DCV} = ventilation rate provided by a proportional DCV strategy,
- V_B = base ventilation rate for non-occupant-related contaminant sources,
- V_{DVR} = design ventilation rate (maximum occupancy multiplied by design per-person ventilation rate),
- C_I = indoor CO₂ concentration expressed in ppm above outdoor level,
- C_{LSP} = lower set point of control strategy expressed in ppm above outdoor level,
- C_{USP} = upper set point (anchor point) of control strategy expressed in ppm above outdoor level.

Proportional control is applicable to a wide range of occupant densities and patterns. If the design density of the space is under 20 people per 1,000 ft² (roughly 20 people per 100 m²), a proportional control strategy is likely to meet the requirements of Interpretation IC 62-1989-27. This control approach requires a multi-position or proportionally controlled damper, a variable-speed outdoor air intake fan, actuator-driven inlet vanes, or other means of outdoor airflow rate control.

Exponential Control. For applications that have extremely low occupancy densities or have high densities and very large air volumes (e.g., auditoriums, large conference areas), an exponential control approach is recommended. In such spaces, because of the volume of air related to the occupancy of the space, CO₂ buildup will take longer. This potentially means that, in some cases, a proportional control approach will not provide the ideal DCV strategy. This approach controls outdoor air intake based on CO₂ concentrations but adjusts the control output with heightened sensitivity to changes in the indoor CO₂ concentration. An exponential control approach modifies the proportional control algorithm with the addition of a component that changes the controller output by an amount greater than the direct change produced by the sensor input. This type of control can often be implemented using a standard proportional-plus-integral or propor-

tional-integral-derivative control algorithm. In proportional-plus-integral control, the longer the control input remains different from the desired value, the more the controller output will change in order to achieve the desired value. In proportional-integral-derivative control, a derivative term is added to the control algorithm that permits the controller to take anticipatory action, which can help reduce overshoot in certain conditions. (ASHRAE 1995).

Like the proportional control approach, ventilation is modulated between a lower set point (typically 100-200 ppm above outdoor levels) and an upper set point, or anchor point, that represents the equilibrium concentration of CO₂ corresponding to the target per-person ventilation rate of the space. An exponential control approach will introduce a higher rate of outdoor air ventilation sooner, as CO₂ levels begin to rise. The faster ventilation response afforded by this approach can ensure that lag times are met. As with other control approaches, start-up or commissioning of such systems should include procedures to verify compliance with the lag time provisions of Standard 62, set forth in paragraph 6.1.3.4. By monitoring the percent of occupancy and the outdoor air intake flow rate, the actual lag time can be observed. The values for the actual control range should be adjusted to ensure timely delivery of the full design ventilation rate upon increase in occupancy and CO₂ levels.

Other Methods of Control. Other control methods can be developed based on nonequilibrium equations, an increased number of sensors, or other implementation measures or control algorithms to address variances in occupancy between spaces and other factors. There are a number of ways to avoid excessive lag time by causing the ventilation rate to increase more rapidly when indoor CO₂ concentrations increase. A thorough discussion of an alternative approach was provided in the 1996 public review draft by ASHRAE’s Standing Standards Project Committee 62.

As with other approaches to CO₂-based DCV, start-up or commissioning and maintenance of such systems should include procedures to verify compliance with the lag time provisions of Standard 62 set forth in paragraph 6.1.3.4. The values for the actual control range should be adjusted to ensure timely delivery of the full design ventilation rate upon increase in occupancy and CO₂ levels.

Considering Outdoor Levels of CO₂

The CO₂-based DCV approaches discussed above all rely on the outdoor CO₂ concentration. In many locations outdoor levels of CO₂ are fairly stable and vary less than 100 ppm (representing 1 to 2 cfm per person for the control strategies discussed). In these situations an outdoor level of CO₂ concentrations can be assumed that is based on the lowest outdoor concentration observed. If outdoor levels are, in fact, higher at times, the strategy will result in slightly higher ventilation rates on a per-person basis than originally targeted, since the lower set point that initiates an increase of outdoor air intake will be reached sooner after occupancy commences, as will

the upper set point after maximum or near maximum occupancy is reached. Care should be taken to avoid assuming an unrealistically high outdoor CO₂ concentration, as this could result in underventilation.

For locations very close to major highways or in severely polluted cities, outdoor CO₂ levels may vary greatly. Where an automated building control network is in place, it is possible to constantly monitor outdoor CO₂ levels and integrate changing outdoor levels into the CO₂-based DCV approach.

CO₂ is also a major byproduct of combustion from many fuel-fired vehicles, engines, and appliances. Excessive levels of CO₂ in incoming air (e.g., 600-800 ppm) can indicate the presence of combustion fumes. Under these circumstances, a CO₂ sensor can evaluate outdoor air intake and can be used to shut off intake air inlets that are subject to periodic combustion fume entrainment due to loading docks, idling vehicles, or similar sources. Standard 62 provides for this, stating that under certain circumstances, "outdoor air [intake] may be reduced during periods of high contaminant levels, such as those generated by rush hour traffic" (ASHRAE 1990).

Compatibility with Other Building Control Approaches

A CO₂ control strategy can help ensure that adequate ventilation is provided to a building space based on its actual occupancy while reducing costly and unnecessary overventilation. However, CO₂ should not be considered a sole control strategy to deal with comfort or indoor air quality. Other approaches that are compatible with using CO₂ to control ventilation include:

Economizer Control—There should be an override of CO₂ control when there is suitable opportunity to use outdoor air for free cooling.

Control of Non-Occupant-Related Sources—A CO₂ sensor controls ventilation based on human occupancies. Strategies that may be used in conjunction with CO₂ to control non-occupant-related sources of contaminants include:

- operation of a pre-occupancy purge to remove contaminants that may have built up during unoccupied evening hours when the mechanical system is shut off,
- providing a continuous minimum level of outdoor ventilation to control sources,
- use of mixed gas sensors to activate ventilation when the periodic presence of high concentrations of non-occupant-related sources is expected (when cleaning supplies are used or in photocopy rooms or printing plants). There is no broad-based technical foundation for the use of mixed gas sensors to comply with the ventilation rate procedure of Standard 62 while modulating outdoor air intake below rates required by Table 2 of the standard.

As with any HVAC control system, care must be taken to ensure proper application, implementation, and maintenance. When this care is taken, CO₂-based DCV offers effective, effi-

cient control strategies to incorporate into HVAC systems that provide ventilation for acceptable indoor air quality.

METHOD FOR ESTIMATING EXISTING CONSTANT OUTDOOR AIRFLOW RATES

A method for estimating the actual ventilation rates per person in an existing space with constant outdoor airflow rate has been developed based on the widely validated concepts of CO₂ generation rates and indoor CO₂ levels resulting from certain ventilation rates per person. The method is only valid where outdoor airflow rates are constant, and it is not applicable to buildings where there is already variation in outdoor airflow rates. By using the values of CO₂ over time, instead of "snapshot values," CO₂ levels can be used to estimate actual ventilation rates per person, even where equilibrium conditions are not reached due to occupancy fluctuations.

A single CO₂ reading in a space that is below the desired equilibrium value does not guarantee that the desired ventilation rate is being delivered. A high reading does, in the absence of sources for CO₂ other than humans, indicate that the desired ventilation rate is not being delivered. A CO₂ level taken in a space that has not reached equilibrium, but is analyzed as an equilibrium value, will lead to overestimation of the ventilation rate per person (Bearg 1993). Estimates of duration of constant occupancy required prior to the attainment of equilibrium conditions range from one to two hours in spaces with two to five air changes per hour, up to five hours in spaces with one air change per hour (Godish 1995). The failure of many office, school, and theater occupancies, among others, to reach steady state at any time during the occupied periods can lead to erroneous estimations of ventilation rates based on misapplication of equations derived for equilibrium conditions.

The method for estimating the actual ventilation rates per person in an existing space with a constant outdoor airflow rate requires four inputs in addition to a physical description of the space. The actual occupancy at regular intervals, for example, every half-hour, over at least one entire day or occupancy period is recorded. CO₂ is logged in the space over the same occupancy period, and outdoor CO₂ level is determined. Finally, metabolic rates based on occupant activities are estimated.

Using these parameters, the actual curve representing the actual logged CO₂ data is plotted. Then, using simple spreadsheet calculation and graphic capabilities, curves representing predicted CO₂ levels, corresponding to observed occupancy data, and a preliminary estimate of the constant ventilation airflow rates in a space are generated on the same axes as the curve representing the logged CO₂ data. Visual comparison of the predicted versus actual curves indicates whether the preliminary estimated ventilation rate is correct. To facilitate curve matching by visual inspection, offset curves representing different actual ventilation rates can be generated, based on a selected increment in ventilation rate per person.

CO₂ GENERATION RATE

CO₂ production is related to metabolic rate. Under this method for estimating constant ventilation airflow rates, the metabolic rate (in met) must be estimated for the occupants. The 1997 ASHRAE *Fundamentals* gives detailed information on typical metabolic rates in Chapter 8, as well as basic equations for CO₂ generation rates and concentration levels in spaces. Standard 62 also provides a graphic illustration of the relationship between physical activity in met units and CO₂ production in liters per minute (ASHRAE 1990). CO₂ production for office workers at 1.2 met is estimated to be 0.30 liters per minute (0.11 cfm) (Thayer and Benda 1996). Figure D-2, Appendix D of *ANSI/ASHRAE Standard 62-1989* shows a linear relationship between physical activity and CO₂ production, with a value of 0.25 liters per minute (0.088 cfm) CO₂ production corresponding to a physical activity level of 1 met (ASHRAE 1990).

Figure 2 shows this relationship between physical activity and CO₂ production. The higher the level of physical activity, the higher the generation rate of CO₂ by occupants. The figure assumes a constant respiratory quotient, which is the volumetric ratio of CO₂ production and O₂ consumption and varies with physical activity level and dietary intake. The ASHRAE Handbook (ASHRAE 1997) and Standard 62 give 0.83 as a typical value for respiratory quotient. Under these conditions, the relationship between physical activity level and CO₂ production illustrated in Figure 2 represents the following equation:

$$N = 0.25M \left(\frac{1 \text{ minute}}{60 \text{ seconds}} \right) \left(\frac{2.12 \text{ cubic feet per minute}}{1 \text{ liter per second}} \right) \quad (5)$$

where

N = CO₂ production of an occupant, in cubic feet per minute, and

M = physical activity of the occupants, in met units.

Equilibrium CO₂ Levels

Once the CO₂ production of the occupants has been determined, the increase in CO₂ concentration resulting from one minute's respiration by the occupants under fully mixed, steady-state conditions without dilution ventilation can be calculated. Given the initial parts per million CO₂ in the space and knowing the ambient (outdoor) CO₂ level and ventilation rate, the final parts per million CO₂ in the space under fully mixed, equilibrium conditions can be calculated. Equilibrium CO₂ levels for a single control volume or zone can thus be expressed in terms of the ambient CO₂ level, the number of occupants, the activity level of occupants in met units, the space volume, and the outdoor air intake rate. The result corresponds to a two-chamber or mass balance approach in which the space is taken as the control volume and the occupants are taken as an inner volume or chamber within the control volume. The CO₂ level in the space is then determined by the CO₂ entering the space from outdoors, the CO₂ generated by occupants, and the CO₂ leaving the space through the dilution effect of outdoor air intake. The dilution effect can also be thought of as the CO₂ leaving the space in exhaust or exfiltration air.

Using these relationships, plots can be generated of the predicted CO₂ levels in the building with a given fluctuating occupancy level and constant ventilation rate. Figure 5 shows an example with the occupancy schedule plotted as a percent of maximum design occupancy and the constant design ventilation rate per person centered at 20 cfm (10L/s). Increments of 5 cfm (2.5 L/s) result in plotted curves for constant ventilation rates ranging from 10 cfm (5 L/s) to 30 cfm (15 L/s) per occupant based on maximum actual occupancy. The method generates curves corresponding to constant ventilation at total rates that are the product of the per-person rates and the maximum occupancy figure. Then, a predicted curve most closely matching the actual data curve is selected. The process may be repeated as

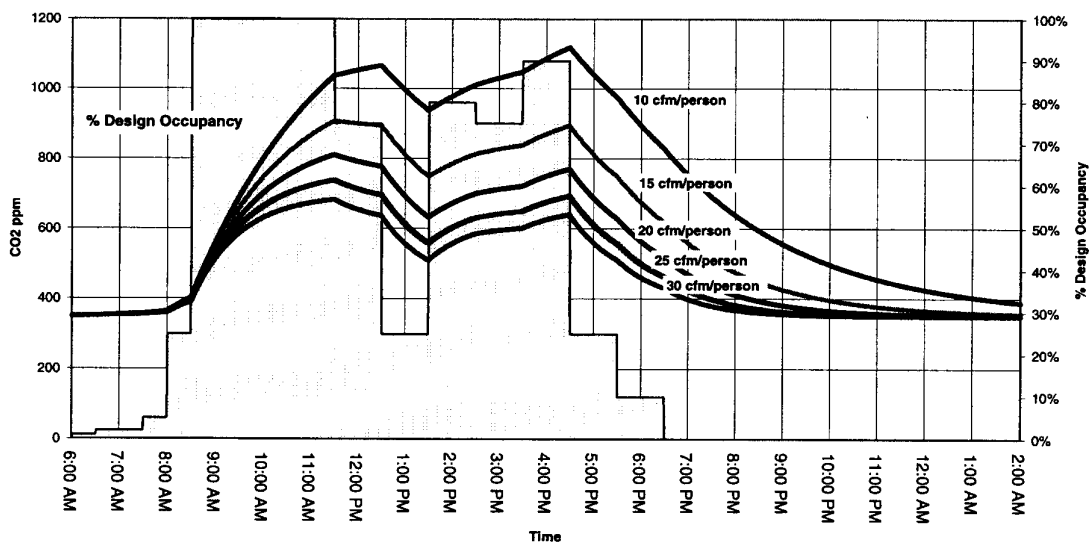


Figure 5 Inside CO₂ levels over time based on different constant airflow rates.

necessary, with different predicted baseline ventilation rates and rate increments selected, and the plot of predicted and actual curves enlarged until a reasonably good match is obtained. The predicted curve most closely corresponding to the actual data curve indicates a reasonable estimate of the actual ventilation rate per person in the occupied space.

The method provides a relatively easy way to estimate the ventilation rates per person in a building. Measuring the CO₂ levels in the space over time and comparing them with an approximation of the predicted levels helps avoid the misleading conclusions that may be inferred when using spot measurements to apply an equilibrium equation to a nonequilibrium value for CO₂ in the space.

LIMITATIONS

If this method is to yield reasonable estimates of ventilation rates, caution must be used when applying this technique to address limitations and minimize inaccuracies inherent in this type of analysis. Limitations include requirements for uniform concentration of CO₂ throughout the space under consideration, isolation from areas with different CO₂ levels, constant outdoor CO₂ concentration, constant outdoor air ventilation rate, accuracy of measurement, representative sampling locations, and accurate occupancy information.

The actual occupancy as a percent of the maximum actual occupancy must be accurately determined. Maximum occupancy should be carefully evaluated during the data-gathering period to ensure that higher occupancies do not occur at other times. Although this will not affect the per-person rate determined using this method, it could result in an underestimate of the ventilation rate per person during periods of maximum occupancy.

Metabolic rates must be accurately estimated to afford reasonable estimates of ventilation rates per person. The CO₂ generation rate can range from under 0.011 cfm (0.0052 L/s) at 1 met to 0.021 cfm (0.010 L/s) at 2 met (Persily 1997). If the building space consists of occupants who are generally participating in similar activities, an average metabolic rate may be determined. In the event that activities vary greatly, a weighted average value may be chosen to accurately represent different levels of activity by the number of occupants so engaged. The method is directly sensitive to erroneous estimates of metabolic rates. A 25% underestimate of the met value for the metabolic rate of occupants will result in an estimate of the ventilation rate that is 25% lower than the actual ventilation rate.

As with any data-gathering exercise, the CO₂ measuring equipment used should be inspected and calibrated carefully. Limits to equipment accuracy introduce uncertainty to the final estimate of ventilation rate per person. Further inaccuracies can be introduced through inappropriate sensor placement within the space or substitution of an inaccurate estimate for an actual measurement of ambient CO₂ levels.

Further work is ongoing to evaluate the sensitivity of the method to erroneous input of occupancy counts and other

parameters. This work will seek to quantify the error introduced with erroneous input.

MODELS FOR THE SELECTION OF CO₂-BASED DCV STRATEGY

It is important for a building owner or designer to be able to verify whether a particular CO₂-based DCV system will meet the requirements of Standard 62. The selection of the appropriate set points, control parameters, and control strategy will all affect the ability of a particular system to meet the provisions of the standard and the criteria of Interpretation IC 62-1989-27.

A spreadsheet computer program has been developed to simulate the impact of CO₂-based DCV in spaces with variable occupancy. The program compares the impact of a fixed continuous ventilation strategy versus a CO₂-based DCV strategy. Using key components of the method previously discussed for correlating actual CO₂ data to estimates of ventilation rate, the model again utilizes a two-chamber or mass balance approach in which the space is taken as the control volume. CO₂ level in the space is then determined by the CO₂ entering the space from outdoors, the CO₂ generated in the space by occupants, and the CO₂ leaving the space through the dilution effect of outdoor air intake. The spreadsheet model can be expanded to allow consideration of local climatic data and energy costs to estimate the economic impact and potential energy savings impact of a CO₂-based DCV strategy.

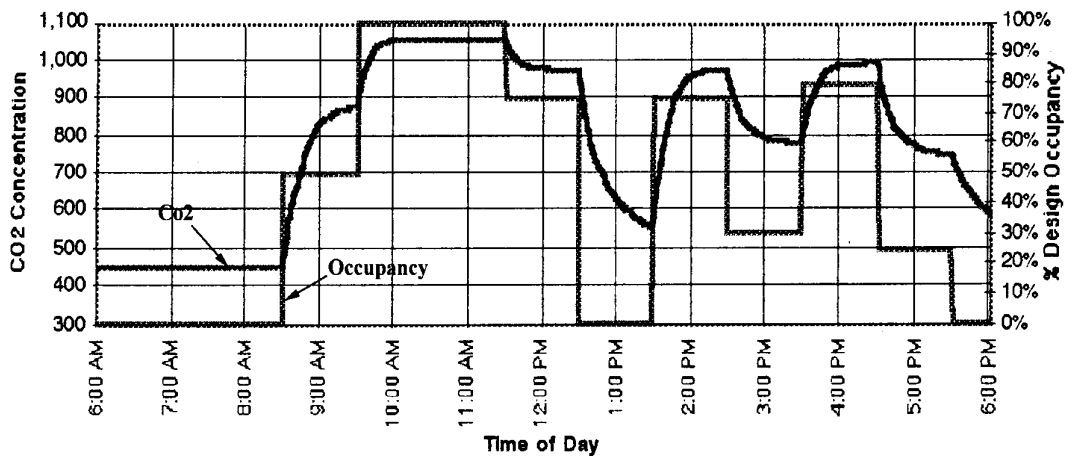
The model allows for inputs that include anticipated infiltration, building pressurization, base ventilation rate, ventilation rate, occupancy, and space volume. The program also allows the user to vary occupancy in the space at half-hour intervals. The program automatically calculates the predicted CO₂ control values based on assumed outdoor levels and target ventilation rate for the space. The ventilation rates and control calculation are based on 60-second intervals and can cover an operating period from 12:01 a.m. to 11:59 p.m. A sample of the input screen is provided in Figure 6. The program is under further development to allow additional inputs, including ventilation effectiveness.

The program output provides two output graphs and one output table. The first graph details occupancy and CO₂ levels in the space as shown in Figure 7. An output table compares the ventilation rate with CO₂-based DCV to constant ventilation at a continuous rate during all occupied hours. The table then provides an estimate of the percentage reduction in ventilation that can be achieved with CO₂ control. If desired, the user can input the continuous ventilation rate derived from the comparison of actual CO₂ measurements in the space and the model discussed earlier in this paper.

The second graphed output of the model, shown in Figure 8, predicts the actual cfm per person ventilation rate, on a minute-by-minute basis, that is delivered to the space. This graph also shows the percent of the maximum ventilation rate provided as occupancy and CO₂ levels change. This information aids in evaluating instantaneous ventilation rates, and comparing totalized outdoor air intake over time under the two

| | |
|---|---|
| Project Description: School Classroom/Meeting Room, 44 people per 1000 sq ft, 15 cfm/person | |
| A. Assumptions (All user inputs Highlighted) | |
| Building Data | Type Of Space: Classroom |
| Occupancy Period In Hours= | 9.0 hrs (from section B) |
| Ceiling Height= | 11.5 ft |
| Floor Area= | 667 sq ft |
| Volume Of Space= | 7670.5 cu ft |
| Outdoor CO2 Concentration = | 450 ppm |
| Design Occupancy Of Space= | 30 people |
| Activity level= | 1.2 MET (1.2 for most applications) |
| Target Per Person Ventilation Rate (Vp) = | 15 cfm/person |
| Total Design Ventilation Rate (Vr) = | 450 cfm |
| Infiltration (as a % of Vr) = | 5% Base Ventilation Rate (as a % of Vr) 20% |
| Infiltration & Base Ventilation in cfm = | 112.5 cfm |
| Control Data Inputs (Open/Close Damper) Note: Press "Command += " Before Changing Data Below | |
| OA Design Ventilation Capacity = | 450 cfm (Ideally should = Vr) |
| Proportional Control Begins | 100 ppm above outside levels |
| Proportional Control Range= | 607 ppm |
| Calculated Data | |
| CO2 Generation Rate/person= | 0.0106 cfm |
| CO2 Equilibrium Control Setpoint for Vp = | 1157 ppm |
| Design Density = | 44.9775 people per 1,000 sq ft |
| Time Periods = | 30 min |

Figure 6 Input variables for CO₂ simulation model.



Calculated Energy Impact Analysis

243,000 of total ventilation design ventilation rate over 9.0 hours
 186,851 of total ventilation with demand control ventilation (including base ventilation rate)
 Savings-----> 56,149 of savings with demand controlled ventilation
 Savings-----> 23% reduction in ventilation without compromising ventilation for air quality

Figure 7 Occupancy assumptions and calculated CO₂ levels from CO₂ DVC simulation program.

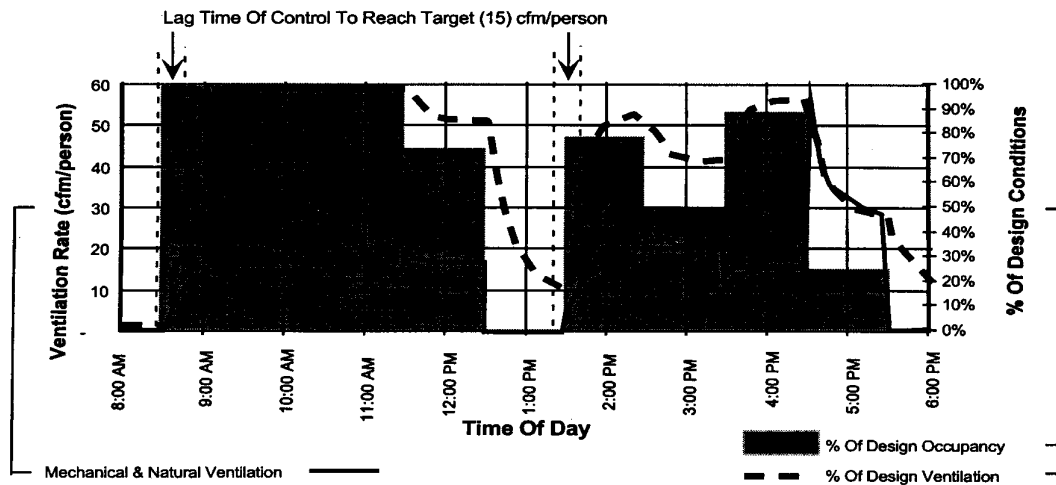


Figure 8 Graphed output from CO₂ DCV simulation program.

different control regimes. This information can also be used to predict control lag times to help predetermine whether the control strategy will maintain target ventilation rates and conform to Interpretation IC 62-1989-27 of Standard 62. Since the lag time is dependent on both the control parameters (e.g., upper and lower set points) and the occupancy patterns, the control parameters can be adjusted as the occupancy patterns are varied to predict the proposed control system's response to different possible occupancy scenarios. Or, with a known and relatively fixed occupancy pattern, the control parameters can be optimized for acceptable lag time, adequate ventilation, and minimization of overventilation. The optimized control parameters can then be used as initial set points in developing a control strategy, for instance, as represented in Equation 4.

Three program versions have been developed, each incorporating different basic control approaches as indicated in Figure 4. One version simulates an on/off ventilation strategy based on a single set point. In this model the user can adjust the dead-band of the sensor to optimize the control strategy. The second version simulates proportional control—modulation of ventilation based on CO₂ levels. Adjustments can be made to the lower and upper set points of the control algorithm to optimize the control strategy for a given space. The third model simulates an exponential control approach.

In the classroom example, represented in Figures 6, 7, and 8, the model compared the ventilation required to meet Standard 62 with continuous ventilation at the design ventilation rate. During the nine occupied hours, continuous ventilation at design occupancy provided 243,000 ft³ of air. A demand-controlled ventilation strategy required 182,000 ft³ of air. The program indicated that overall ventilation air volume would be reduced 25% with the demand-controlled ventilation approach. As demonstrated by the graphed output of the program in Figure 8, ventilation rates during the course of the day are maintained at 15 cfm per person or greater.

The models provide engineers, designers, building managers, and contractors with the means to estimate the impact of providing CO₂-based demand-controlled ventilation to a particular space. When information from this program is combined with local climatic and energy data, it can be used to provide a simple estimate of the actual energy savings and payback of a CO₂-based demand-controlled ventilation strategy. Comparison of program results to actual installations and evaluation of the sensitivity of program results to simplifying assumptions are in progress.

BENEFITS OF CO₂-BASED DEMAND-CONTROLLED VENTILATION

CO₂-based DCV can balance and resolve the traditional conflict between reducing ventilation to save energy while still maintaining ventilation for acceptable indoor air quality. A properly implemented CO₂-based DCV strategy can provide five major benefits.

1. CO₂-based DCV saves energy by reducing costly overventilation when spaces are partially or intermittently occupied. Payback resulting from energy savings can be two years or less for many applications.
2. CO₂-based DCV can help provide a target per-person ventilation rate in the space to help ensure acceptable indoor air quality. In installations where air intakes would otherwise be set to meet an arbitrary percentage of the design ventilation rate (e.g., 15% open), CO₂-based DCV can help ensure that ventilation rates of the space meet the target per-person rates based on actual occupancy. Actual occupancy may be very different from the initial design occupancy.
3. CO₂-based DCV is not particular about where outdoor air is coming from. If adequate outdoor air is being introduced by natural air leakage, an open window, or a leaky damper set,

it will reduce the amount of outdoor air that would otherwise be delivered by the mechanical ventilation system.

4. A CO₂-based DCV system can be adjusted to maintain any desired ventilation rate, whether that be 15 cfm per person or 50 cfm per person.
5. CO₂-based DCV can help improve control of comfort conditions by reducing outdoor air intake when feasible in extreme outdoor conditions. Reduced outdoor air intake in hot, humid climates can improve humidity control; reduced outdoor air intake in cold conditions can help maintain indoor humidity.

CONCLUSIONS

CO₂-based DCV, when applied in spaces subject to variable or intermittent occupancy or in spaces where actual occupancies are greatly below design occupancy, can reduce unnecessary overventilation while ensuring that target per-person ventilation rates are met. A recent interpretation for *ANSI/ASHRAE Standard 62-1989* has affirmed that CO₂-based DCV systems comply with the standard as long as certain conditions are met. CO₂-based DCV systems use CO₂ as a control input to modulate ventilation below the maximum total outdoor air intake rate while still maintaining the required ventilation rate per person. Details have been provided on proper application of CO₂-based DCV.

Using CO₂ data logged over time in an occupied space, it is possible to estimate the ventilation rate of a continuously ventilated space, even if equilibrium levels have not been reached, provided that occupancy age, activity level, and varying densities within the space over time are known. A method of estimating constant outdoor air intake flow rates has been detailed. This method helps overcome the pitfalls inherent in using spot CO₂ measurements to estimate ventilation rates.

Once the actual ventilation rates within a space are known, it is possible to estimate the ventilation reduction impact of a CO₂-based DCV approach using a simple spreadsheet model. This model also assists a designer or building owner to predict whether a particular CO₂-based DCV strategy meets the requirements of ANSI/ASHRAE interpretation

IC 62-1989-27 and *ANSI/ASHRAE Standard 62-1989*. Two important criteria for any CO₂ control strategy are that the targeted per-person ventilation rate is met at all times and that during periods of changing occupancy the lag times as prescribed in Standard 62 are met.

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