Demand Control Ventilation Using CO_2

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Carbon dioxide (CO_2)-based demand controlled ventilation (DCV) is increasingly used to modulate outside air ventilation based on real-time occupancy. Its use could potentially become as common as thermostatic control is today. This article summarizes the current state of the art in CO_2-based ventilation control including a brief discussion of the technology used, its reliability and how it is best applied. Like any control approach, the success of a CO_2-based DCV application is dependent on how it is engineered and installed.

Properly installed, CO_2 DCV can reduce unnecessary over-ventilation that might result if air intakes are set to provide ventilation for a maximum assumed occupancy. This approach, equally applicable to retrofit or new construction can save energy while ensuring that ASHRAE Standard 62 ventilation rates are maintained at all times.

CO_2 and Ventilation

The basis of using CO_2 for ventilation control is established in well-quantified principles of human physiology. All humans, given a similar activity level, exhale CO_2 at a predictable rate based on occupant age and activity level. This relationship is described in Appendix D of ANSI/ASHRAE Standard 62-1999.[2] As a result, CO_2 can be used as a good indicator of human bioeffluent concentration and/or occupancy (i.e., doubling the number of people in a space will approximately double CO_2 production).

CO_2 is one of the most common gases found in our atmosphere. As a point of reference, concentrations in the center of the Pacific Ocean atop Mauna Loa Hawaii have been measured at 366 ppm[1] and is considered to be the benchmark for the lowest concentration found worldwide. In urban areas, outside concentrations generally have been in the 375 to 450 ppm range.

Because CO_2, like all gases, will rapidly diffuse in outside air, variations in concentrations in a particular location are generally less than 50 ppm and tend to be seasonal in nature. CO_2 is also one of the most plentiful byproducts of combustion (9% to13% by volume) and as a result, outside air measurements can be affected by extremely localized sources of combustion such as exhaust flues or running vehicles. Measurement of outdoor CO_2 levels above 500 ppm may indicate that a significant combustion source is nearby.

An indoor CO_2 measurement provides a dynamic measure of the balance between CO_2 generation in the space, representing occupancy and the amount of low CO_2-concentration outside air introduced for ventilation. The net effect is that it is possible to use CO_2 concentration to determine and control the fresh air dilution rate in a space on a per person basis.

Figure 1 shows how CO_2 would build up in a low density, office-type space assuming outside levels of 400 ppm. Each line represents how CO_2 concentrations would rise depending on the ventilation rate per person. The point at which concentrations level off represents the equilibrium point where the CO_2 produced by people is in balance with the dilution rate to the space. These balance points are universal to all occupant densities for spaces occupied by adults in an office-type activity level (1.2 met [70 W/m^2]). The balance point that occurs is relative or additive to the outdoor concentration.

Any ventilation rate established on a per-person basis will have a corresponding equilibrium point that can serve as an anchor for a ventilation control strategy using CO_2-based DCV. This does not mean that the control strategy waits for the equilibrium level to be reached before ventilation is introduced. The equilibrium point is only one input into the development of the DCV strategy.

CO_2 is not considered harmful nor a contaminant at the levels of 400 to 2,000 ppm normally found in buildings. In fact the eight-hour exposure limit to CO_2 established for industrial environments by OSHA is more than 5,000 ppm and the 15 minute threshold limit value is 30,000 ppm, far above that experienced in most com-

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mercial buildings or residences. Perceptions of poor air quality associated with elevated CO_2 levels are more indicative of the buildup of other indoor contaminants as a result of reduced per person ventilation in a space rather than the direct effect of CO_2. For HVAC applications, CO_2 is best used as an indicator for outside air ventilation on a per person basis.

Another important point to clarify is the relationship between CO_2 production and body odor. CO_2 levels will increase or decrease in relation to human metabolic activity. Since CO_2 is a good indicator of human metabolic activity, it could also be used as a tracer for other human emitted bioeffluents.

CO_2 can be used to measure or control any per-person ventilation rate, regardless of the perceived level of bio-effluents or body odor in a space. In fact, the 1,000 ppm guideline for CO_2 used in Standard 62-1989 is the equilibrium level for 15 cfm/person (7 L/s) assuming a 300 ppm outside level of CO_2. Unfortunately, the 1,000-ppm level has become obsolete as measured urban-background CO_2 concentrations have risen over the past five to six decades to closer to 400 ppm. Concentrations of 1,100 ppm would often be more indicative of 15 cfm/person (7 L/s).

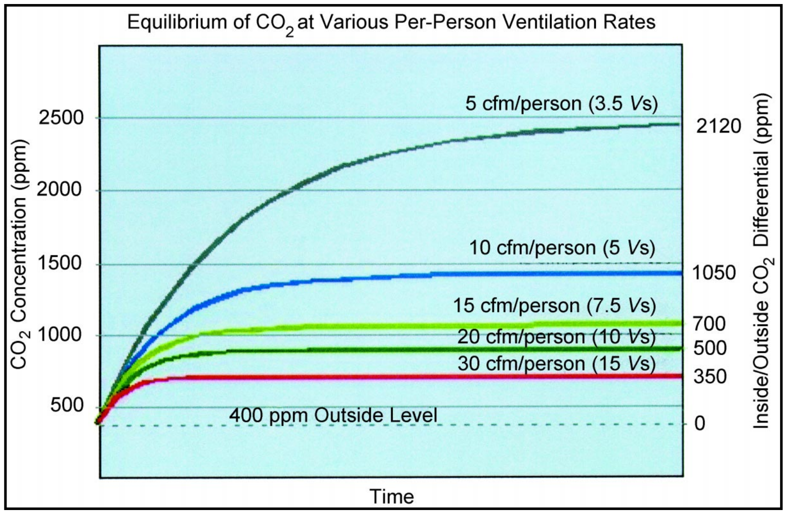

Figure 1: Equilibrium of CO_2 at various per-person ventilation rates.

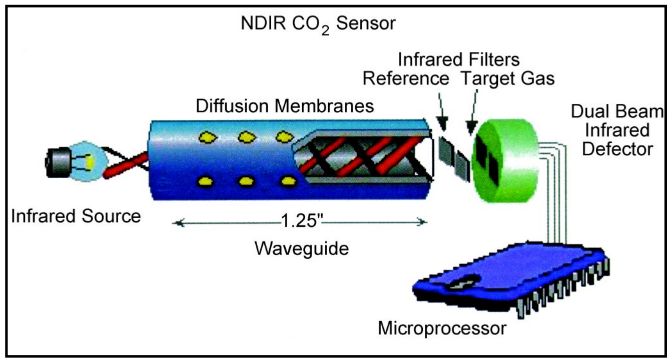

Figure 2: Non-dispersive infrared detection (NDIR) CO_2 sensor.

History of CO_2 in Codes and Standards

One of the first references to CO_2 measurement and ventilation was in a mechanical engineer's handbook published first in 1916 by McGraw-Hill. Even at this early point in the last century, the handbook established the fundamental relationship between outside air ventilation and CO_2 concentrations that forms the basis today for CO_2 DCV.[3] The handbook recommended that "…CO_2 levels should not exceed 8 or 10 parts in 10,000," or in modern measure, 800 to 1,000 ppm. The authors also have found reference in the New York City Building Code of 1929 that rooms not ventilated directly by windows should have ventilation "…methods capable of maintaining a carbon dioxide content of the air of not more than one part in one thousand [1,000 ppm]."[4]

More recently, ANSI/ASHRAE Standard 62-1989 indicated that "comfort (odor) criteria are likely to be satisfied when the ventilation rate is set so that 1,000 ppm of CO_2 is not exceeded."[5] For some designers, this phraseology generated some confusion as to the best application of CO_2 for air quality and ventilation control. As a result, the CO_2 provisions in the standard have been the subject of seven of the 28 interpretations requested of Standard 62-1989. In 1997, one of the authors submitted interpretation IC 62-1989-27, which clarified many of the issues related to the use of CO_2 for ventilation control.[6] A copy of this interpretation is provided with all copies of Standard 62-1999.

A brief summary of the key points of the IC 62-1989-27 interpretation that should be considered in designing a CO_2 DCV strategy in accordance with Standard 62 is provided. For further clarification, the reader should refer directly to the interpretation or a paper presented at the 1998 ASHRAE summer meeting, "Application of CO_2 Based Demand Controlled Ventilation Using ASHRAE Standard 62: Optimizing Energy Use and Ventilation."[7]

- The use of CO_2 control may be applied as part of the ventilation rate procedure under provisions for intermittent and variable occupancy (sec. 6.1.3.4) but does not affect the calculation of the design occupancy or design ventilation rate.
- The CO_2 control strategy can be used to modulate ventilation below the design ventilation rate while still maintaining *Table 2* ventilation rates (e.g., 15 cfm [7 L/s] per person). Sensor location and selection of control algorithm should be based on achieving the rates in *Table 2*. The control strategy should also be developed considering inside/outside CO_2 differential.
- The control strategy must provide adequate lag time response as required in the standard.
- If CO_2 control is used, the design ventilation rate may not be reduced to consider peak occupancies of less than three hours (often called diversity). In other words, the variable provision of 6.1.3.4 cannot be applied to lower the estimated maximum occupancy for the purpose of reducing the design ventilation rate while using DCV.
- CO_2 filtration or removal methods other than dilution cannot be implemented in the space.
- A base ventilation rate should be provided during occpied periods to control for non-occupant related sources.

In ANSI/ASHRAE Standard 62-1999, changes have been made from the previous version to eliminate reference to the absolute level of 1,000 ppm CO_2. Instead, refer to maintaining an inside/outside differential. In reference to the 15 cfm/person (7 L/s) minimum ventilation rate the standard now has established a 700 ppm inside/outside differential in place of the 1,000 ppm absolute level.

Model building codes have addressed the use of CO_2 for ventilation control. Model building codes serve as a reference for most state and local codes. The current version of the International Mechanical Code (IMC) addresses systems operation in Section 403.3.1[8] and states that "The minimum flow rate of outdoor air that the ventilation system should be capable of supplying during its operation shall be permitted to be based on the rate per person indicated in Table 403.3 and the actual number of occupants present." In the commentary provided as a reference to the code by the IMC, use of CO_2 for ventilation control is provided as an example of a way to modulate ventilation based on occupancy.[9] The IMC is currently referenced by the BOCA building code and will be the mechanical code of reference as the three major Model Building Codes (BOCA, UBC, SBC) are harmonized into a single code in the near future.

CO_2 Measurement Technology

Even though the principles governing the relationship between CO_2 and ventilation control have been well known since at least 1916, technology to measure and control CO_2 reliably and cost effectively is a relatively recent development. The first inexpensive CO_2 sensors designed specifically for ventilation control in HVAC applications appeared on the market in 1990. Sold at one-tenth the price of technical and scientific instrumentation of that time, the sensors performed remarkably similar in that accuracy was excellent but long-term drift of the sensor required calibration annually or more frequently. While this is tolerable in technical and scientific applications, the need for frequent calibration provided an unexpected added cost for the HVAC-related applications and discouraged their widespread use.

Most sensor technology used to measure gases is interactive in that the target gas to be measured must physically or chemically interact with the sensor. This can result in sensor degradation requiring periodic replacement or calibration. Because CO_2 is so inert, conventional interactive technology cannot be used. As a result, most commercially available CO_2 sensors use some form of infrared-based detection. This is because different gases absorb infrared energy at specific and unique wavelengths in the infrared spectrum. Currently, two technologies are used for infrared measurement of gases in HVAC applications. Both have the potential for low cost but have distinctly different operational characteristics.

Non-Dispersive Infrared Detection

Sensors based on the principal of Non-Dispersive Infrared Detection (NDIR) look for the net increase or decrease of light that occurs at the wavelength where CO_2 absorption takes place. The light intensity is then correlated to CO_2 concentrations. *Figure 2* provides an example of a typical NDIR sensor where ambient air is allowed to diffuse into a sample chamber that contains a light source at one end and a light detector at the other. A selective optical filter is placed over the light detector to only admit light at the specific wavelength where CO_2 is known to absorb light.

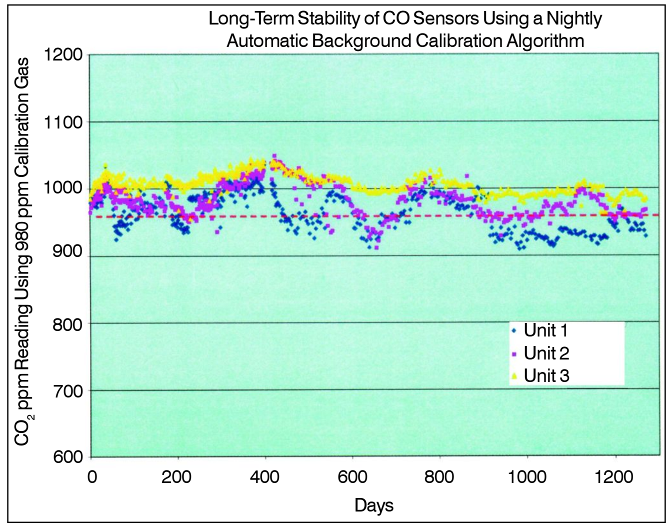

Figure 3: Long-term stability of CO_2 sensors using a nightly automatic background calibration algorithm.

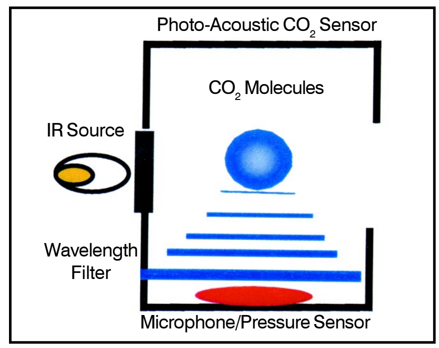

Figure 4: Photo-acoustic CO_2 sensor.

Though not common in all IR sensors, this illustration shows a second detector in the assembly that is covered by an optical filter tuned to a wavelength where there is no gas absorption. This second detector and filter is used as a reference to correct for changes in the optics of the sensor over time that may result in sensor drift. An important consideration in the design of this type of sensor is to minimize or eliminate sensor drift that may occur because of particle buildup in the sensor and/or aging of the light source. One method of minimizing particle buildup is to use a gas permeable membrane that will facilitate diffusional movement of gas molecules but will block out larger particulates that may change the sensor optics.

Aging of the infrared source is one of the most significant factors in sensor drift. It can be minimized by selection of sources with stable characteristics and compensated for by corrective algorithms that adjust for light source aging. The dual-beam approach shown in *Figure 2* is one method of compensating for changes to the sensor optics resulting from both aging and particle buildup.

Another approach involves having the sensor calibrate itself on a nightly basis when the space is unoccupied, and inside levels drop to baseline outside levels. *Figure 3* shows the results of over three years of operation of three sensors using a nightly automatic baseline calibration where the sensor accuracy was checked on a regular basis with a calibrated gas of 980 ppm CO_2. Sensor accuracy remained well within a ±50 ppm over the duration of the test period showing that good long-term stability is achievable with this type of sensor.

Photo-Acoustic CO_2 Sensors

Another type of infrared technology used to measure CO_2 is called photo-acoustic sensing. This type of sensor uses a chamber open to the atmosphere and exposes air in the chamber to flashes of infrared light specific to the gas absorption wavelength for CO_2. This flashing light causes the CO_2 gas molecules to vibrate as they absorb infrared energy. A small microphone in the chamber monitors this vibration and then microprocessors in the sensor calculate the CO_2 concentration.

Figure 4 shows a schematic of a photo-acoustic sensor. This type of sensor is not as sensitive to dirt and dust but can be affected by the same light source aging characteristics of NDIR sensors. Photo-acoustic sensor accuracy can also be affected by vibration and atmospheric pressure changes. More accurate sensors often will use a pressure sensor to correct for the range of pressures found in HVAC measurement applications.

Cost of CO_2 Sensors

Use of CO_2 sensors for demand controlled ventilation has dramatically increased over the past three years, which has stimulated a significant drop in sensor pricing. Three years ago, CO_2 sensors were considered a specialty control product at a price of \$400 to \$500 per sensor. A typical contractor price for a CO_2 sensor today has dropped approximately 50%. It is likely that this trend in price reduction will continue as the use of CO_2 sensors is expanded. Some manufacturers are offering CO_2 and temperature sensing combined making installation easier and reducing sensor manufacturing costs by sharing components.

Installation Guidelines

The following are some general guidelines that can be used when designing a CO_2 DCV installation.

Control Strategy. The objective of a CO_2 control strategy is to modulate ventilation to maintain target cfm/person ventilation rates based on actual occupancy. The strategy should allow for reduced overall ventilation during periods of occupancy that are less than full occupancy and as a result save energy. Typical control approaches have used a proportional or proportional-integral control algorithm to modulate ventilation between a base ventilation rate established for non-occupant-related sources and the design ventilation rate for the space. Typically, modulation of outside air above base ventilation begins when indoor CO_2 is 100 ppm above outside levels. Modulation of ventilation based on CO_2 levels continues to the point where at the CO_2 equilibrium level for the target ventilation rate, the design ventilation rate is provided.

Duct vs. Wall Mount. Generally, it is recommended that sensors be installed in the occupied space rather than in ductwork. This is because return air tends to be an average of all spaces being conditioned and may not be representative of what is actually happening in a particular space.

Duct sensors are best used where a single space or multiple spaces with common occupancy patterns are being ventilated. The most common areas for installation are directly in the return air ductwork or inside the return air plenum just before it enters the air handler. For systems with return air plenums (rather than ductwork), leakage of outdoor air through the building envelope or from supply air ducts traveling through the plenum, may affect readings. In this case, sensors should be located in the space or where leakage is not a factor.

Location of Wall-Mount Sensors. Criteria for placement of wall-mount sensors are similar to those for temperature sensors. Avoid installing in areas near doors, air intakes or exhausts or open windows. Because people breathing on the sensor can affect the reading, find a location where it is unlikely that people will be standing in close proximity (2 ft [0.6 m]) to the sensor. One sensor should be placed in each zone where occupancy is expected to vary. Sensors can be designed to operate with VAV based zones or to control larger areas up to 5,000 ft^2 (465 m^2) (if an open space).

DCV in Multiple Spaces. Control systems are being designed that use CO_2 and temperature for control of comfort and ventilation at the zone level. In this approach, wall-mount sensors that provide feedback to the local VAV box and central control system monitor all major zones and critical spaces. This approach allows real-time control of ventilation based on actual occupancy and ventilation efficiency versus relying on an estimate of occupancy patterns and density at the time of design, long before the building is actually in use. In some cases, this control approach may allow temporary deviation of temperature to meet zone ventilation requirements.

CO_2 sensing can also simplify outdoor air control as it can replace the need for active flow measurement and control that is otherwise normally needed to maintain the required minimum OA intake as the system supply flow varies from maximum to minimum.

Multiple Occupancy Zones with One Fresh Air Control. In some cases, particularly in retrofit applications, a single air handler will serve multiple spaces that have very different occupancy patterns (e.g., a school or building floor plan). In these applications, if a duct-mounted sensor is used, it will sample the average of all the spaces and may not control levels based on the actual conditions in the space. By considering an average of all spaces, this approach cannot ensure that target per person rates established by local codes or Standard 62-1999 would be met in all spaces (often termed "critical" spaces). As a result, the use of duct sensors in this application would likely not meet the requirements of local codes and Standard 62-1999.

An effective, but slightly more costly approach, is to install a wall-mount sensor in each of the occupied spaces. Each sensor output is then sent to a signal transducer that will read all the sensors and pass through one signal that represents the sensor with the highest reading to the air handler. As a result, ventilation rates will be controlled to ensure the most critical space is always adequately ventilated. This approach also can be used with large spaces such a retail establishments or large floor plates on multiple story buildings.

When to Use Outside Air Sensing. CO_2-based demand controlled ventilation is based on the principle that the differential between inside and outside concentrations can give an indication of the ventilation requirement rate in the space. As a general rule of thumb, a differential of 700 ppm is indicative of a ventilation rate of 15 cfm/person (7 L/s). An inside/outside differential of 500 ppm is indicative of a 20 cfm/person (9 L/s) ventilation rate.

For most applications, outside air can be assumed to be at 400 ±50 ppm. As a result, most control strategies will work well if the designer or installer assumes outside levels are at 400 ppm. Even if outside concentrations are higher than 500 ppm, and 400 is used as the assumed outside level, the only impact will be that the space will be slightly over ventilated by about 2 cfm/person (0.9 L/s) during those periods when outside levels are elevated. Since the lowest levels are approximately 366 ppm,[1] a conservative maximum under-ventilation effect of assuming a 400 ppm outside level is less than 1 cfm per person (0.47 L/s).

Elevated outside CO_2 levels are generally due to the presence of localized combustion sources such as vehicles, power plants, or building exhausts. If elevated levels are measured, it may be a function of the location of outside air intakes related to localized combustion sources. If deemed necessary by the designer, CO_2 sensors are available for mounting in outdoor air that can be used to ensure that ventilation rates are controlled based on a real-time differential between inside and outside concentrations.

Compatibility with Other Control Approaches. The use of CO_2 control is highly complementary with other building control approaches such as economizer control and pre-occupancy purging, or use of temperature or humidity limits on outdoor air intakes. For example, a call for economizer control should override a CO_2 DCV control because there is economic benefit to use outside air for cooling.

Benefits of CO_2 DCV

CO_2-based DCV does not affect the design ventilation capacity required to serve the space; it just controls the operation of the system to be more in tune with how a building actually operates.

- Excessive over-ventilation is avoided while still maintaining good IAQ and providing the required cfm-per-person outside air requirement specified by codes and standards. The authors have observed operational energy savings of $0.05 to $0.15 per square foot annually. This observation has been verified in a recent literature review on CO_2 control that cited studies where energy savings form DCV control approaches ranged from 5% to 80% versus a fixed ventilation strategy.[10] System paybacks can range from a few months to two years and are often substantial enough to help pay for other system or building upgrades.
- The payback from CO_2 DCV will be greatest in higher density spaces that are subject to variable or intermittent occupancy that would have normally used a fixed ventilation strategy (e.g., theaters, schools, retail establishments, meeting and conference areas).
- In spaces with more static occupancies (e.g., offices), CO_2 DCV can provide control and verification that adequate ventilation is provided to all spaces. For example, a building operator may arbitrarily and accidentally establish a fixed air intake damper position that results in over or under ventilation of all or parts of a space. A CO_2 control strategy can ensure the position of the intake air dampers is appropriate for the ventilation needs and occupancy of the ventilated space at all times. This may save additional energy when outside air intakes are arbitrarily set to over-ventilate.
- In some buildings, infiltration air or open windows may be a significant source of outside air. A CO_2 sensor will consider the contribution of infiltration in a space and only require the mechanical system to make up what is necessary to meet required ventilation levels. These savings are in addition to those quoted earlier.
- When integrated with the appropriate building control strategy, ventilation can be controlled zone by zone based on actual occupancy. This allows for the use of supply air from under-occupied zones to be redistributed to areas where more ventilation or cooling is needed.
- A CO_2 control strategy can be used to maintain any per-person ventilation rate. As a result this approach is highly adaptable to changing building uses and any changes that may occur in future recommended ventilation rates.
- CO_2 DCV can provide the building owner/manager with valuable information about occupancy trends.

Summary

CO_2 demand control ventilation is a real-time, occupancy-based ventilation approach that can offer significant energy savings over traditional fixed ventilation approaches, particularly where occupancy is intermittent or variable from design conditions. Properly applied, it allows for the maintenance of target per-person ventilation rates at all times. Even in spaces where occupancy is static, CO_2 DCV can be used to ensure that every zone within a space is adequately ventilated for its actual occupancy. Air intake dampers, often subject to maladjustment, or arbitrary adjustments over time can be controlled automatically avoiding accidental and costly over or under ventilation.

Measurement and control technology using CO_2 sensors is quickly evolving to a stage of maturity where cost and reliability will likely approach that of conventional temperature measurement and control in the near future. As a result, the use of CO_2 as an indoor comfort, ventilation and air quality control parameter has the potential to be as widely used as temperature and humidity measurements are today. There also exists a good opportunity to reduce energy consumption due to reduced ventilation requirements at varying occupancy rates.

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