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Evaluating Building IAQ and Ventilation with Indoor Carbon Dioxide

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ABSTRACT

A number of approaches exist to evaluate building ventilation and indoor air quality. In some situations, the measurement and analysis of indoor carbon dioxide concentrations can be useful for understanding indoor air quality and ventilation. On the other hand, oversimplified descriptions of measurement procedures based on carbon dioxide have been presented, and there have been many instances in which indoor carbon dioxide concentration measurements have been misinterpreted and misunderstood. This paper describes various applications of carbon dioxide concentrations for evaluating building air quality and ventilation and the factors that need to be considered in their use. While carbon dioxide concentrations do not provide a comprehensive indication of indoor air quality, they can be used to indicate the acceptability of a space in terms of human body odor. Also, under some circumstances carbon dioxide can also be used to estimate building air change rates and percent outdoor air intake at an air handler. These uses of indoor carbon dioxide concentrations, and the situations in which their use is appropriate, are described. In addition, the factors that must be considered when using indoor carbon dioxide concentrations in these ways are also described. These factors include building and ventilation system configuration, occupancy patterns, nonoccupant carbon dioxide sources, time and location of air sampling, and instrumentation for concentration measurement.

INTRODUCTION

There are a number of situations in which it is useful to evaluate building ventilation and indoor air quality. These situations include building commissioning, proactive building management, diagnosis of indoor air quality complaints, and investigation of building energy consumption. A number of techniques are available to perform such evaluations, and some of these techniques involve the measurement and analysis of indoor carbon dioxide concentrations to evaluate specific aspects of indoor air quality and ventilation. However, as with all measurement techniques, the user needs to understand the procedure being employed and must use it properly to obtain reliable information.

The usefulness of carbon dioxide in understanding indoor air quality and ventilation in buildings is based on two concepts. One is the fact that people emit carbon dioxide at a rate that depends on their size and their level of physical activity. The other factor is that when the indoor carbon dioxide concentration is elevated above the outdoor level, it can be used as a tracer gas to study building ventilation using a number of well-established tracer gas measurement techniques.

There have been cases in which oversimplified descriptions of measurement procedures have been presented and in which indoor carbon dioxide concentration measurements have been misinterpreted and misunderstood. For example, a study of the indoor environment within office buildings reported no association between high ventilation rates, 15 L/s and 32 L/s per person (30 cfm and 64 cfm per person), and the rates of occupant symptoms (Menzies et al. 1993). However, the reported ventilation rates were based on the analysis of indoor carbon dioxide concentrations using a simple mass balance equation based on an assumption of steady-state conditions. The existence of steady-state conditions was not mentioned in describing the measurements and data interpretation. If the carbon dioxide concentrations in the buildings were not at steady state, the actual ventilation rates could have been much lower—by as much as 50% (Dols and Persily 1995). Other misunderstandings concerning indoor carbon dioxide concentrations include statements that describe carbon dioxide as an indicator of overall indoor air quality, that express health concerns for indoor concentrations above 1,800 mg/m^3 (1,000 ppm(v)), and that imply if the carbon dioxide concentration in a space is below 1,800 mg/m^3 (1,000 ppm(v)) then the space complies with ASHRAE Standard 62-1989 (Persily 1993).

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This paper describes various approaches to using indoor carbon dioxide concentrations to understand building indoor air quality and ventilation. The relationship between carbon dioxide concentrations and indoor air quality is discussed, with an emphasis on the experimentally demonstrated relationship between concentration and the acceptability of human body odor in occupied spaces. A number of approaches in which carbon dioxide can be used as a tracer gas to determine building ventilation parameters are also described. Much of the material in this paper is based on a provisional standard on the use of indoor carbon dioxide concentrations to evaluate indoor air quality and ventilation (ASTM 1996).

CARBON DIOXIDE GENERATION RATES

Both the relationship between indoor carbon dioxide concentrations and indoor air quality and the relationship between carbon dioxide and ventilation are based on the rate at which people generate carbon dioxide. People generate carbon dioxide, and consume oxygen, at a rate that depends primarily on their level of physical activity and their size. The relationship between activity level, size and the rates of carbon dioxide generation and oxygen consumption is discussed in *ASHRAE Fundamentals* (ASHRAE 1993) and is summarized below.

The rate of oxygen consumption, V_{O_2}, in L/s, of a person is given by the following equation:

$$V_{O_2} = \frac{0.00276 A_D M}{(0.23RQ + 0.77)}. \tag{1a}$$

A_D is the DuBois surface area in m^2, which is described below. When using inch-pound (I-P) units, A_D is in ft^2 and V_{O_2} is in cfm, and Equation 1a takes the form

$$V_{O_2} = \frac{0.000543 A_D M}{(0.23RQ + 0.77)} \tag{1b}$$

where RQ is the respiratory quotient, i.e., the relative volumetric rates of carbon dioxide produced to oxygen consumed. M is the level of physical activity, or the metabolic rate per unit of surface area, in mets (1 met = 58.2 W/m^2 = 18.5 Btu/h·ft^2). A_D, the DuBois surface area in m^2, can be estimated by the following equation:

$$A_D = 0.203 H^{0.725} W^{0.425} \tag{2a}$$

where H is the body height in m and W is the body mass in kg. When using inch-pound units, A_D is in ft^2, H is in ft, W is in lb, and Equation 2a takes the form

$$A_D = 0.660 H^{0.725} W^{0.425}. \tag{2b}$$

For an adult of average size, A_D equals about 1.8 m^2 (19 ft^2). Additional information on body surface area is available in the EPA's *Exposure Factors Handbook* (EPA 1989). The value of RQ depends on diet, the level of physical activity, and the physical condition of the person and is equal to 0.83 for an adult of average size adult engaged in light or sedentary activities. RQ increases to a value of about 1 for heavy physical activity, about 5 met. Given the expected range of RQ, it has only a secondary effect on carbon dioxide generation rates.

The carbon dioxide generation rate of an individual is therefore equal to V_{O_2} multiplied by RQ. Figure 1 shows oxygen consumption and carbon dioxide generation rates as a function of physical activity for an average-sized adult with a surface area of 1.8 m^2 (19 ft^2) and RQ = 0.83.

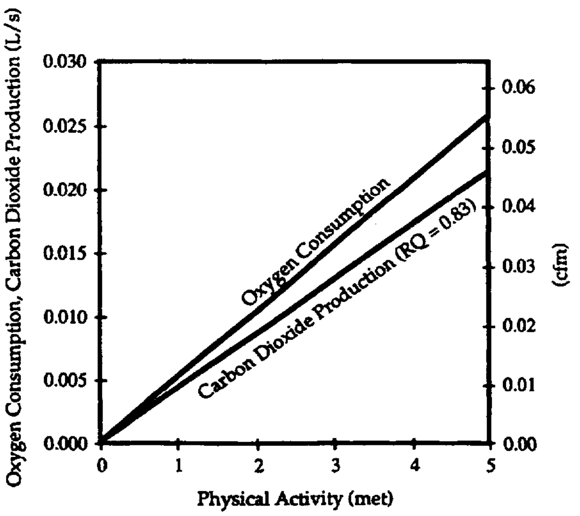

Figure 1 *Carbon dioxide generation and oxygen consumption as a function of physical activity.*

Based on Equation 1, the carbon dioxide generation rate corresponding to an average-sized adult engaged in office work (1.2 met) is about 0.0052 L/s (0.011 cfm). However, the generation rate depends strongly on activity level and can cover a range from less than 0.0050 L/s (0.011 cfm) at 1 met to as high as 0.010 L/s (0.021 cfm) at about 2 met for the occupants of an office building. The carbon dioxide generation rate for a child with A_D = 1 m^2 (11 ft^2) and a physical activity level of 1.2 met is equal to 0.0029 L/s (0.0061 cfm). When making calculations that use the carbon dioxide generation rate in a building, one must consider the level of physical activity and the size of the building occupants. Chapter 8 of *ASHRAE Fundamentals*, "Physiological Principles and Thermal Comfort" (ASHRAE 1993), contains typical met levels for a variety of activities. Some of these values are reproduced in Table 1.

Oxygen depletion is sometimes cited as a cause of indoor air quality complaints in buildings. Based on the oxygen consumption rates determined with Equation 1, it can be shown that oxygen depletion due to low ventilation rates is not typically an issue of concern. Given an activity level corresponding to office work, about 1.2 met, the oxygen consumption rate of an individual equals 0.006 L/s (0.013 cfm). At an outdoor air ventilation rate of 7.5 L/s (16 cfm) per person, the steady-state indoor oxygen concentration is reduced from its typical outdoor level of 21% to 20.9%. At 2.5 L/s (5.3 cfm) and 0.5 L/s (1 cfm) per person, the indoor oxygen concentration is

TABLE 1
Typical Met Levels for Various Activities

Activity	Met
Seated, quiet	1.0
Reading and writing, seated	1.0
Typing	1.1
Filing, seated	1.2
Filing, standing	1.4
Walking at 0.9 m/s (2 mph)	2.0
House cleaning	2.0-3.4
Exercise	3.0-4.0

reduced to 20.8% and 19.8%, respectively. Health effects do not generally occur until oxygen levels decrease to less than 19.5% (NIOSH 1987), which corresponds to an outdoor air ventilation rate of 0.4 L/s (0.8 cfm) per person.

CARBON DIOXIDE AND INDOOR AIR QUALITY

Indoor carbon dioxide concentrations have been referred to as an indicator of indoor air quality, often without describing a specific association between carbon dioxide and indoor air quality. There are a number of relationships that could be implied in discussing carbon dioxide and indoor air quality; these include the health effects of elevated carbon dioxide concentrations, the impact of carbon dioxide on occupant perceptions of the indoor environment, the relationship between carbon dioxide concentrations and the concentrations of other indoor contaminants, and the relationship between carbon dioxide and outdoor air ventilation rates. In addition, references are often made between carbon dioxide concentrations of 1,800 mg/m^3 (1,000 ppm(v)) and ASHRAE Standard 62-1989. While some of these relationships are relatively well understood, and in some cases well founded, others have not been documented experimentally or theoretically. In other words, indoor carbon dioxide concentrations can be used to indicate specific and limited aspects of indoor air quality but are not an overall indicator of the quality of indoor air.

Carbon dioxide is not generally considered to be a health concern at the concentrations that typically occur indoors. The time-weighted average threshold limit value (based on an 8-hour exposure and a 40-hour work week) for carbon dioxide is 9,000 mg/m^3 (5,000 ppm(v)), and the short-term exposure limit (15-minute exposure) is 54,000 mg/m^3 (30,000 ppm(v)) (ACGIH 1995). A number of studies at elevated concentrations, about 5% carbon dioxide in air or 90,000 mg/m^3 (50,000 ppm(v)), have been performed, and the lowest level at which effects have been seen in humans and animals is about 1%, i.e., 18,000 mg/m^3 (10,000 ppm(v)) (EPA 1991). Indoor carbon dioxide concentrations will not reach these levels except when the ventilation rate is extremely low, about 1 L/s (2 cfm) per person for 9,000 mg/m^3 (5,000 ppm(v)) and less than about 0.2 L/s (0.4 cfm) per person for 54,000 mg/m^3 (30,000 ppm(v)).

Associations between carbon dioxide concentrations and occupant perceptions of the indoor environment in terms of comfort and irritation are complex because they combine several different issues, including the comfort impacts of the carbon dioxide itself, associations between carbon dioxide levels and the concentrations of other contaminants, and the relationship between carbon dioxide and ventilation. A number of peer-reviewed studies of occupant symptoms have shown no significant relationship between the prevalence of symptoms and carbon dioxide concentrations (Hodgson et al. 1991; Jaakkola et al. 1991; Skov et al. 1987, 1990). However, some indoor air quality investigators associate indoor carbon dioxide concentrations from 1,100 mg/m^3 (600 ppm(v)) to 1,800 mg/m^3 (1,000 ppm(v)) or higher with perceptions of stuffiness and other indicators of discomfort and irritation (Bright et al. 1992; Rajhans 1983; Bell and Khati 1983). These associations are often based on anecdotal observations of the investigator or on informal occupant surveys. It may be that the observed associations between carbon dioxide and occupant comfort are due to other factors, such as thermal comfort or the concentrations of other contaminants in the space. However, as discussed below, there is a demonstrated correlation between indoor carbon dioxide concentrations and the level of acceptability of the space in terms of human body odor.

The relationship between carbon dioxide concentrations and the concentrations of other indoor contaminants depends on the characteristics of the sources of these other contaminants. As discussed earlier, the rate at which carbon dioxide is generated in a space depends on the number of people in the space, their size, and their level of physical activity. If other contaminants are generated at a rate that also depends on the occupancy level in the space, then carbon dioxide may be a good indicator of the concentrations of these contaminants. However, only some contaminants are generated at a rate that depends on occupancy, and many contaminant sources are not a function of occupancy at all. For example, emissions from building materials and furnishings and the intake of outdoor contaminants by the ventilation system do not depend on the number of occupants in a space. Regardless of the indoor carbon dioxide level, the concentration of contaminants emitted by occupant-independent sources may be high, low, or in between and the carbon dioxide concentration will not provide any information on their concentration. This fact can limit the usefulness of carbon dioxide-based demand-controlled ventilation.

The relationship between carbon dioxide and outdoor air ventilation rates is well understood and is based on the consideration of carbon dioxide as a tracer gas (Persily and Dols 1990). Based on the mass balance of a tracer gas in a building, measured carbon dioxide concentrations can be related to information on the rate of carbon dioxide generation in the space to determine some ventilation characteristics of a building. Later in this paper, a number of approaches to determining building ventilation performance are described that are based on the use of occupant-generated carbon dioxide as a tracer gas. All else being equal, if the ventilation rate in a space decreases, then the indoor carbon dioxide concentration will increase. However, to make a quantitative estimate of ventilation based on measured carbon dioxide concentrations, one must employ a specific tracer gas technique that is appropriate to the conditions that exist in the building.

Carbon Dioxide and ASHRAE Standard 62-1989

A common misunderstanding exists that if indoor carbon dioxide concentrations in a building are maintained below 1,800 mg/m^3 (1,000 ppm(v)), then the building is in compliance with ASHRAE Standard 62-1989. ASHRAE Standard 62-1989 contains two paths to compliance—the ventilation rate procedure and the indoor air quality procedure. The ventilation rate procedure requires that one determine the design ventilation rate of a building based on the space use in the building, the number of occupants, and the outdoor air requirements for various space-use categories contained in Table 2 of the standard. The ventilation rate procedure also contains requirements for contaminant levels in the outdoor air and that no unusual contaminants or sources exist. While compliance with the outdoor air requirements of the ventilation rate procedure is likely to maintain indoor carbon dioxide concentrations below 1,800 mg/m^3 (1,000 ppm(v)), the other requirements of the procedure must also be met to achieve compliance with the standard.

The indoor air quality procedure contains a guideline for indoor carbon dioxide concentrations of 1,800 mg/m^3 (1,000 ppm(v)), but the standard also contains limits for four other contaminants of predominantly outdoor origin in Table 1 of the standard and three other indoor contaminants in Table 3. In addition, one must keep all other known contaminants of concern below specific levels, and a subjective evaluation is required for those contaminants for which no objective measures of acceptability are available.

Carbon Dioxide Concentrations and Body Odor Acceptability

At the same time people are generating carbon dioxide, they are also producing odor-causing bioeffluents. Similar to carbon dioxide generation, the rate of bioeffluent generation depends on the level of physical activity. Bioeffluent generation also depends on diet and on personal hygiene (such as the frequency of bathing). Because both carbon dioxide and bioeffluent generation rates depend on physical activity, the concentrations of carbon dioxide and the odor intensity from human bioeffluents in a space exhibit a similar dependence on the number of occupants and the outdoor air ventilation rate.

Experimental studies have been conducted in chambers and in occupied spaces in which people evaluated the acceptability of the air in terms of body odor (Berg-Munch et al. 1986; Cain et al. 1983; Fanger and Berg-Munch 1983; Fanger 1988; Iwashita et al. 1990; Rasmussen et al. 1985). These experiments studied the relationship between outdoor air ventilation rates and odor acceptability and are a major consideration in developing the ventilation rate recommendations in ventilation standards. Some of the experiments also studied the relationship between carbon dioxide concentrations and the acceptability of the air in the space in terms of odor.

These studies have concluded that about 7 L/s (15 cfm) of outdoor air ventilation per person will control human body odor such that roughly 80% of unadapted persons (visitors) will find the odor to be at an acceptable level. The same level of odor acceptability was found to occur at carbon dioxide concentrations that are about 1,250 mg/m^3 (700 ppm(v)) above the outdoor concentration, which at a typical outdoor level of 630 mg/m^3 (350 ppm(v)) yields an indoor carbon dioxide concentration of 1,880 mg/m^3 (1,050 ppm(v)). These considerations yield the commonly discussed guideline value for carbon dioxide of 1,800 mg/m^3 (1,000 ppm(v)) (ASHRAE 1989). The differential between indoor and outdoor levels of 1,250 mg/m^3 (700 ppm(v)) is a measure of acceptability with respect to body odor, irrespective of the outdoor carbon dioxide concentration. Figure 2 shows the percent of unadapted persons (visitors) who are dissatisfied with the level of body odor in a space as a function of the carbon dioxide concentration above that outdoors (CEC 1992). People adapt quickly to bioeffluents. For adapted persons (occupants), the ventilation rate per person to provide the same acceptance is approximately one-third of the value for unadapted persons (visitors) and the corresponding carbon dioxide concentrations above outdoors are three times higher (Berg-Munch et al. 1986; Cain et al. 1983).

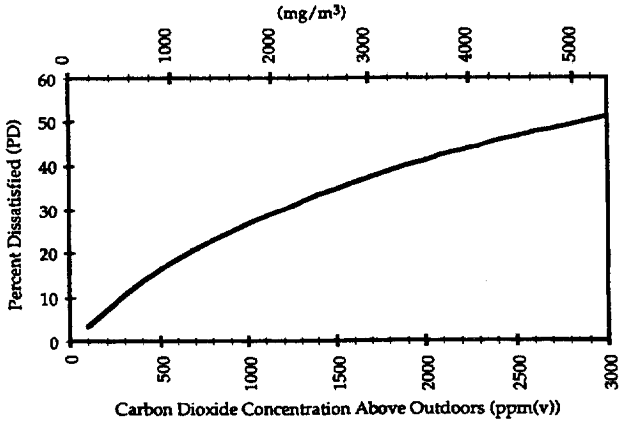

Figure 2 Percent of visitors dissatisfied as a function of carbon dioxide concentration (CEC 1992).

The relationship between percent dissatisfied and carbon dioxide concentrations for visitors shown in Figure 2 was seen experimentally (Berg-Munch et al. 1986; Fanger and Berg-Munch 1983; Rasmussen et al. 1985), and the correlation was not strongly dependent on the level of physical activity. In addition, the relationship did not require that the indoor carbon dioxide concentration be at equilibrium. The relationship described in Figure 2 can also be derived based on the experimentally determined relationship between percent dissatisfied and outdoor air ventilation rates in L/s (cfm) and the relationship between outdoor air ventilation rates and equilibrium carbon dioxide concentrations that is described later in this paper.

While carbon dioxide concentrations can be an appropriate means of characterizing the acceptability of a space in terms of body odor, as stated earlier, they do not provide information on the concentrations of contaminants from other pollutant sources such as building materials, furnishings, and occupant activities. And while maintaining carbon dioxide concentrations within 1,250 mg/m^3 (700 ppm(v)) of outdoor levels should provide acceptable perceived air quality in terms of human body odor, it does not necessarily imply adequate control of these other pollutant sources.

EVALUATION OF BUILDING VENTILATION

There are a number of different approaches in which indoor carbon dioxide concentrations can be used to evaluate building ventilation. These approaches include the determination of the percent outdoor air intake at an air handler and the determination of building air change rates using tracer gas decay and equilibrium analysis. These three techniques are described in the following sections.

Percent Outdoor Air Intake

The percentage of outdoor air in the supply airstream of an air handler can be determined using carbon dioxide as a tracer gas based on mass balances of air and tracer at the air handler (Gothe et al. 1988; Olcerst 1994). The value of the percent outdoor air intake can then be used to estimate outdoor air intake rates, which is particularly helpful when the outdoor air intake rate is difficult to measure directly using a pitot tube or hot-wire anemometer traverse. In these situations, the outdoor air intake rate is obtained by multiplying the measured value of the percent outdoor air intake by the value of the supply airflow rate measured, for example, with a pitot traverse of the supply air duct.

The percent outdoor air intake of an air handler is equal to the volumetric airflow rate of outdoor air into the air handler, Q_o, divided by the airflow rate of supply air being delivered by the air handler, Q_s. These airflow rates, and the recirculation airflow rate, Q_r, are shown schematically in Figure 3. Based on a mass balance of air and carbon dioxide at the air handler, the percent outdoor air intake is given by the following equation:

$$\%OA = 100 \times \frac{(C_r - C_s)}{(C_r - C_{out})} \qquad (3)$$

where

$\%OA$ = percent outdoor air intake,

C_r = carbon dioxide concentration in the recirculation airstream of the air handler,

C_s = carbon dioxide concentration in the supply airstream of the air handler, and

C_{out} = carbon dioxide concentration in the outdoor air.

When using this approach, C_r can be measured in the return duct, which is often more accessible than the recirculation duct. C_s should be measured at the air handler, as far downstream of where the outdoor and return airstreams mix. Care must be exercised to ensure that the values of C_r and C_s are truly representative of the average concentrations in these airstreams. Multipoint sampling may be necessary to verify the representativeness of these concentrations. Typical variations in indoor CO_2 concentrations with time are generally not a problem in the determination of %OA; however, C_r and C_s should be measured over the shortest time possible. Measurements of C_r and C_s made within about 10 minutes of each other usually will be adequate.

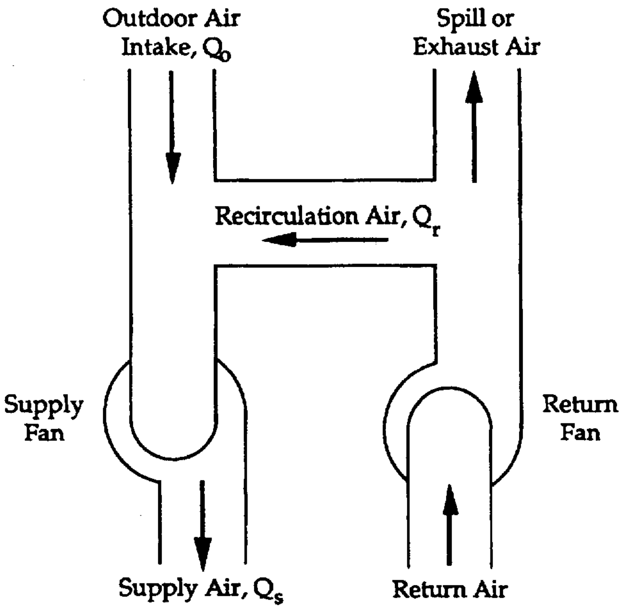

Figure 3 *Air-handling system schematic..*

The precision in the percent outdoor air intake determined with Equation 3 can be estimated using Equation 4:

$$\Delta\% = \%OA \sqrt{\frac{(\Delta C_r^2 + \Delta C_{out}^2)}{(C_r - C_{out})^2} + \frac{(\Delta C_r^2 + \Delta C_s^2)}{(C_r - C_s)^2}} \qquad (4)$$

where

$\Delta\%$ = precision of the percent outdoor air intake,

ΔC_r = precision of the measured carbon dioxide concentration in the recirculation air,

ΔC_s = precision of the measured carbon dioxide concentration in the supply air,

ΔC_{out} = precision of the measured carbon dioxide concentration in the outdoor air.

Equation 4 only accounts for the precision of the measured concentrations and neglects any bias due to calibration and operator errors. The magnitude of the difference between C_r and C_{out} is the main factor affecting the precision in %OA, with large values of this difference increasing the precision of %OA. This difference can be maximized by making the concentration measurements well into the occupied period of the day, when the indoor carbon dioxide concentration has increased well above the outdoor concentration.

The use of carbon dioxide concentrations to determine the percent outdoor air intake is similar to the use of an energy balance to determine the percent outdoor air intake from the air temperatures in the supply, return, and outdoor airstreams. The so-called "temperature balance" method has been described in many places, but it has two major drawbacks. First, the value of the percent outdoor air intake will be associated with a large measurement uncertainty when the return and outdoor air temperatures are close together (Persily 1994). Depending on the value of the percent outdoor air intake and the uncertainty in the air temperature measurement technique, an uncertainty in the percent outdoor air intake of 50% to 100% can exist when the outdoor air temperature is within 10°C (18°F) of the return air temperature. Another problem with the temperature balance method is the existence of imperfect mixing of the outdoor and return airstreams and the difficulty in determining the supply air temperature upstream of the heating or cooling of the supply airstream. The carbon dioxide approach avoids the first problem as long as the measurements are made after the indoor carbon dioxide concentration has increased sufficiently above the outdoor level, i.e., after the building has been occupied for several hours. The second problem is also less of a concern with carbon dioxide because the supply concentration can be measured farther downstream of where the return and outdoor airstreams mix without any impact from the heating and cooling coils.

Tracer Gas Decay Measurements of Building Air Change Rates

Whole-building air change rates can be measured using the tracer gas decay technique in which occupant-generated carbon dioxide is used as a tracer gas and the measurement is conducted after the occupants leave the building. ASTM Standard E741 (ASTM 1995) contains a test method for tracer gas decay measurements of air change rates in a single zone, which determines the total rate at which outdoor air enters a single-zone space divided by the volume of that space. This outdoor air change rate includes both infiltration through leaks and other openings in the building envelope and intentional outdoor air intake through mechanical ventilation systems. This test method applies to single-zone spaces, defined in the standard as a space or set of spaces wherein the tracer gas concentration can be maintained at a uniform level and which exchange air only with the outdoors.

In the tracer gas decay technique, a tracer gas is released into a space to obtain a uniform tracer concentration throughout the space being tested. The decay in tracer gas concentration is monitored over time, and the air change rate is determined from the rate of concentration decay. If the air change rate is constant, then the tracer gas concentration, $C(t)$, decays, assuming a zero concentration outdoors, according to

$$C(t) = C_0 e^{-It} \tag{5}$$

where

t = time, h;

C_0 = tracer gas concentration at $t = 0$; and

I = air change rate, h^{-1}.

The air change rate, I, is equal to the outdoor airflow rate into the space (intake and infiltration) divided by the volume of the space, V. Tracer gas concentrations measured in decay tests are usually analyzed by taking the natural logarithm of each side of Equation 5 to yield

$$\ln C(t) = \ln C_0 - It. \tag{6}$$

The value of I can be determined with least-squares linear regression to calculate the slope of the line for a series of concentration readings over time.

The average air change rate can also be determined over a time period, from t_1 to t_2, using the following equation:

$$I = \frac{[\ln C(t_2) - (\ln C(t_1))]}{(t_2 - t_1)} \tag{7}$$

where $C(t_1)$ is the tracer gas concentration at the beginning of the time period and $C(t_2)$ is the concentration at the end of the period.

When using occupant-generated carbon dioxide to conduct a tracer gas decay test, the requirements of ASTM E741 must be followed. These requirements cover test equipment, sampling duration and frequency, uniformity of tracer gas concentration in the space being tested, and calculation methods. However, using the tracer gas decay technique with occupant-generated carbon dioxide involves some considerations not explicitly covered in ASTM E741. For example, the decay technique is based on the assumption that there is no source of tracer gas in the building, which, in the case of carbon dioxide, means that the building is unoccupied. In practice, an occupancy density of one person per 1,000 m^2 (10,000 ft^2) or less should not impact the measurement results. In addition, the tracer gas decay technique as described in ASTM E741 assumes that the outdoor tracer gas concentration is zero, which is not the case with carbon dioxide. However, if the outdoor concentration is constant during the decay measurement, then the tracer gas decay technique can be used by substituting the difference between the indoor and the outdoor concentrations for the indoor concentration in the analysis contained in ASTM E741. Standard E741 also requires that the concentration measurement precision be better than ±5% of the concentrations during the decay. When using carbon dioxide as a tracer gas, this precision requirement must be applied to the difference between the indoor and outdoor carbon dioxide concentrations.

In most buildings it takes some time for all of the occupants to leave the building, and during this time the indoor carbon dioxide concentration will decay. The indoor carbon dioxide concentration when the building is finally unoccupied depends on the concentration in the building when the occupants start leaving, the amount of time it takes for them to leave, and the outdoor air change rate of the building. Depending on the values of these parameters, the indoor carbon dioxide concentration may be too low once the building is unoccupied to perform a reliable tracer gas decay measurement.

ASTM E741 also requires that the indoor tracer gas concentrations at multiple points within the building differ by less than 10% of the average concentration in the building. When using carbon dioxide, this concentration uniformity requirement should be applied to the difference between the indoor and outdoor concentrations. It may be difficult to meet this uniformity requirement in buildings with large spatial variations in occupancy and/or outdoor air delivery rates.

Carbon dioxide can also be released into an unoccupied building to perform a tracer gas decay test when occupant generation of carbon dioxide is insufficient to increase the indoor concentration. In this case, one should refer to ASTM E741 for guidance on tracer gas injection.

Estimating Ventilation Rates Using Equilibrium Analysis

Under some circumstances indoor carbon dioxide concentrations can be used to estimate outdoor air ventilation rates based on the constant injection tracer gas technique. The application of the constant-injection technique using occupant-generated carbon dioxide is sometimes referred to as equilibrium carbon dioxide analysis. ASTM E741 contains a test method for constant-injection tracer gas decay measurements of air change rates in a single zone. Equilibrium carbon dioxide analysis is a special case of the constant-injection approach described in the ASTM standard.

The constant-injection technique in ASTM E741 involves injecting tracer gas into a single-zone space at a constant and known rate. The gas is distributed in the zone such that it meets a concentration uniformity criterion. The tracer gas concentration in the zone is then measured in real time. The average outdoor airflow rate into the zone during some time interval is calculated from the average concentration during that interval, the tracer gas injection rate, the zone volume, the length of the time interval, and the tracer gas concentrations measured at the beginning and end of the interval.

A constant-injection tracer gas measurement performed in accordance with ASTM E741 determines the total rate at which outdoor air enters a single-zone space. As with tracer gas decay measurements, the outdoor air entry includes both infiltration through leaks and other openings in the building envelope and intentional outdoor air intake through mechanical ventilation systems. Also, as with tracer gas decay, this test method applies to single-zone spaces.

The equilibrium carbon dioxide analysis approach is a special case of the constant-injection technique described in ASTM E741 in which the outdoor airflow rate is constant, the outdoor tracer gas concentration is nonzero and constant, the indoor carbon dioxide concentration is at equilibrium, there is a constant generation rate of carbon dioxide in the space, and there are no mechanisms of carbon dioxide loss other than ventilation. In this approach, the outdoor airflow rate is given by Equation 8a:

$$Q_o = \frac{1.8 \times 10^6 G}{(C_{in,eq} - C_{out})} \tag{8a}$$

where

Q_o = outdoor airflow rate into the space, L/s;

G = carbon dioxide generation rate in the space, L/s;

$C_{in,eq}$ = equilibrium carbon dioxide concentration in the space, mg/m^3; and

C_{out} = outdoor carbon dioxide concentration, mg/m^3.

For inch-pound units, with the flows in cfm and the carbon dioxide concentrations in ppm(v), Equation 8a takes the following form:

$$Q_o = \frac{10^6 \times G}{(C_{in,eq} - C_{out})}. \tag{8b}$$

Equations 8a and 8b can be written in terms of the outdoor airflow rate per person by substituting the carbon dioxide generation rate per person for G. In this case, the outdoor airflow rate per person is given by Equation 9a:

$$Q_p = \frac{1.8 \times 10^6 G_p}{(C_{in,eq} - C_{out})} \tag{9a}$$

where

Q_p = outdoor airflow rate per person into the zone, L/s per person, and

G_p = carbon dioxide generation rate in the zone per person, L/s per person.

Again, if the flows are in cfm and the carbon dioxide concentrations are in ppm(v), then Equation 9a takes the form:

$$Q_p = \frac{10^6 \times G_p}{(C_{in,eq} - C_{out})}. \tag{9b}$$

The validity of Equations 8 and 9 is based on several requirements and assumptions related to the single-zone tracer gas mass balance on which the equations are based. First, the zone to which the procedure is being applied is assumed to act as a single zone with respect to carbon dioxide concentration, i.e., the carbon dioxide concentration throughout the zone is uniform. ASTM E741 specifies that the tracer gas concentration at representative locations throughout the zone differ by less than 10% of the average concentration for the zone. The existence of concentration uniformity can be verified by measuring the indoor carbon dioxide concentration throughout the zone being tested. The measurement points should be well distributed both horizontally and vertically in the zone being tested, including points in the individual rooms comprising the zone and multiple locations within the individual rooms.

Equations 8 and 9 also require that the zone being tested be isolated from any other zones in the building in terms of airflow unless those zones are at the same carbon dioxide concentration as the zone being tested. That is, there can be no airflow into the zone being tested from any other zones with a different carbon dioxide concentration (except the outdoors). In practice, this requirement means that these equations cannot be applied to an individual room unless the concentration in the rest of the building minus the outdoor concentration is within 10% of the average carbon dioxide concentration difference in the zone being tested. For rooms that do not meet this 10% criterion, one must demonstrate that there is no significant airflow from such rooms to the test zone. This lack of airflow can be demonstrated using smoke at the airflow paths between rooms.

The approach also requires that the carbon dioxide generation rate be constant and known. This requirement means that the number of occupants in the space and the rate at which they generate carbon dioxide are constant for a sufficiently long period while the concentration builds up to equilibrium. When using Equation 8, one needs to know the number of occupants and their average carbon dioxide generation rate. When using Equation 9, one only needs the average carbon dioxide generation rate per person. Determination of the average carbon dioxide generation rate requires consideration of the activity level and size of the occupants as discussed earlier.

The derivation of Equations 8 and 9 is also based on a constant outdoor carbon dioxide concentration. This requirement is generally not a problem, but the outdoor concentration must be measured prior to and during the measurement of the indoor equilibrium concentration. It is not sufficient to assume that the outdoor concentration is at a typical value such as 630 mg/m^3 (350 ppm(v)). Outdoor carbon dioxide concentrations can range from about 550 to 900 mg/m^3 (300 to 500 ppm(v)), depending on the time of day, season of the year, weather patterns, and building location.

Equations 8 and 9 are based on the additional assumption that the outdoor air ventilation rate is constant. Therefore, one must understand and consider the factors affecting the ventilation rate of the space being tested. These factors include outdoor weather conditions and the operation and control of any mechanical ventilation system. If the space is mechanically ventilated, the control system may modulate the rate of outdoor air intake based on the weather. These control systems can also vary intake rates based on time of day, interior air temperatures, and other factors. If the building is mechanically ventilated, the outdoor air intake controls must be understood, and the system operation status and the intake damper position must be determined prior to and during the carbon dioxide concentration measurements to verify that they are not changing.

This approach also requires that the indoor carbon dioxide concentration be at equilibrium, meaning that the indoor carbon dioxide generation rate, the outdoor carbon dioxide concentration, and the outdoor airflow rate are constant for a sufficiently long period of time such that the indoor concentration stabilizes to a constant value. At this point, the rate at which carbon dioxide is generated in the space plus the rate at which carbon dioxide enters from the outdoors is equal to the rate at which carbon dioxide leaves the space via ventilation.

The time required to reach equilibrium depends only on the outdoor air ventilation rate of the space divided by the volume of that space, sometimes referred to as the outdoor air change rate in units of air changes per hour (h^{-1}). This relationship can also be described in terms of the time constant of the space, which is equal to the inverse of the outdoor air change rate. If the carbon dioxide generation rate (occupancy level), outdoor concentration, and ventilation rate are all constant and the indoor carbon dioxide concentration starts at the outdoor concentration, then it takes three time constants for the difference between the indoor and outdoor concentrations to reach 95% of its equilibrium value. Figure 4 is a plot of the calculated buildup of indoor carbon dioxide concentration for several different air change rates, assuming an outdoor concentration of 630 mg/m^3 (350 ppm(v)) and an occupant density typical of office space.

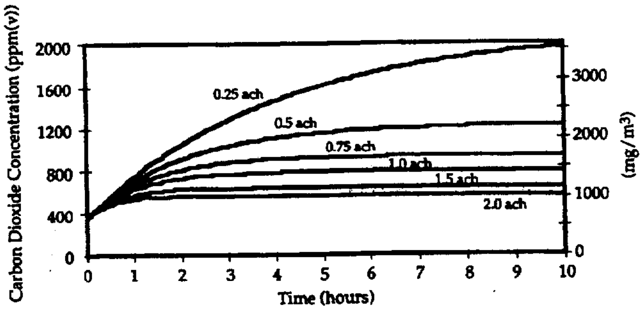

Figure 4 *Calculated carbon dioxide build up.*

At an air change rate of 0.25 h^{-1}, it takes 12 hours of constant occupancy to reach 95% of the equilibrium carbon dioxide concentration difference. This air change rate corresponds to about 3 L/s (6 cfm) per person and an occupant density of 7 people per 100 m^2 (1,000 ft^2) of floor area and is not uncommon in office buildings under minimum outdoor air intake (Persily 1989). At 0.75 h^{-1} (corresponding to about 10 L/s [20 cfm] per person and more typical of office building ventilation rates), it takes four hours for the indoor concentration to reach 95% of equilibrium. At high air change rates, well above 1 h^{-1}, equilibrium is reached in three hours or less.

In a classroom with 30 people per 100 m^2 (1,000 ft^2) of floor area and an outdoor air ventilation rate of 7.5 L/s (15 cfm) per person, the air change rate is about 3.2 h^{-1}. Under these conditions it will take only about one hour to reach 95% of the equilibrium carbon dioxide concentration difference. If the outdoor air ventilation rate is 2.5 L/s (5 cfm) per person, then the air change rate will be 1.08 h^{-1}, and it will take about 2.8 hours to reach 95% of equilibrium.

In practice, the equilibrium requirement can be considered to be met when the change in the indoor-outdoor concentration difference over one hour is less than the amount determined with Equation 10a:

$$\Delta C_{eq} = \frac{324 \times 10^6 G}{V} \tag{10a}$$

where

ΔC_{eq} = change in indoor-outdoor concentration difference, mg/m^3;

G = carbon dioxide generation rate in the zone, L/s; and

V = volume of the zone, L.

When using inch-pound units, with the flows in cfm, the volume in ft^3, and the concentration difference in ppm(v)), Equation 10a takes the form:

$$\Delta C_{eq} = \frac{3 \times 10^6 G}{V}. \tag{10b}$$

The values of both G and V in Equations 10a and 10b need only be approximate.

In an office space with an average carbon dioxide generation rate of 0.0052 L/s (0.011 cfm) per person, an occupant density of 7 people per 100 m^2 (1,000 ft^2), and a ceiling height of 3 m (9.8 ft), Equation 10 yields a rate of change in the indoor carbon dioxide concentration of 39 mg/m^3 (24 ppm(v)) over one hour to verify the existence of equilibrium. For a classroom with an average carbon dioxide generation rate of 0.0029 L/s (0.0061 cfm) per person, an occupant density of 30 people per 100 m^2 (1,000 ft^2), and a ceiling height of 2.5 m (8.2 ft), Equation 10 yields a rate of change in the indoor carbon dioxide concentration of 113 mg/m^3 (67 ppm(v)) over one hour to verify the existence of equilibrium. Continuous monitoring of indoor carbon dioxide concentrations can be useful for determining if equilibrium conditions exist. However, one must still monitor building occupancy and ventilation system operation to ensure that these parameters are also not changing.

When Equations 8 and 9 are used to estimate outdoor air ventilation rates, the precision of these ventilation rates should be estimated and reported. These estimates of the precision are based on the precision of the carbon dioxide generation rate and of the carbon dioxide concentration measurements. The precision of the outdoor airflow rate into the zone determined with Equation 8 can be estimated using Equation 11:

$$\Delta Q_o = Q_o\left[\left(\frac{\Delta G}{G}\right)^2 + \frac{2\Delta C^2}{(C_{in,eq} - C_{out})^2}\right]^{0.5} \tag{11}$$

where

ΔQ_o = precision of the outdoor airflow rate into the zone, L/s (cfm);

ΔG = precision of the carbon dioxide generation rate in the zone, L/s (cfm); and

ΔC = precision of the carbon dioxide concentration measurement, mg/m^3 (ppm(v)).

The precision of the outdoor airflow rate per person, Q_p, determined with Equation 9 can be estimated using Equation 12:

$$\Delta Q_p = Q_p\left[\left(\frac{\Delta G_p}{G_p}\right)^2 + \frac{2\Delta C^2}{(C_{in,eq} - C_{out})^2}\right]^{0.5} \tag{12}$$

where

ΔQ_p = precision of the outdoor airflow rate per person, L/s (cfm) per person and

ΔG_p = precision of the carbon dioxide generation rate per person, L/s (cfm) per person.

The precision of the measured carbon dioxide concentration, ΔC, can sometimes be obtained from the manufacturer's literature. Alternatively, one can determine the measurement precision based on laboratory and field calibrations. ASTM Standard D3249 (ASTM 1990) contains a discussion of issues related to measurement accuracy of air analyzers.

The precision of the carbon dioxide generation rate per person, ΔG_p, depends on the uncertainty in the size and level of physical activity of the building occupants. Equation 1 can be used to estimate the precision of ΔG_p based on the uncertainties in A_D and M using standard calculation procedures for the propagation of error. For example, if A_D = 1.8 m^2 (19 ft^2) with an uncertainty of 0.1 m^2 (1 ft^2) and M = 1.2 met with an uncertainty of 0.1 met, the carbon dioxide generation rate will equal 0.0052 L/s (0.011 cfm) with an uncertainty of 0.0005 L/s (0.001 cfm). The precision in the carbon dioxide generation rate, G, for a group of people in the space is based on the uncertainties in the average carbon dioxide generation rate per person and the number of people.

The use of the equilibrium analysis approach requires the consideration of sources of carbon dioxide in the space other than people as well as carbon dioxide removal mechanisms. Other sources include combustion processes in or near the space; carbon dioxide removal mechanisms include large numbers of plants. The existence of other sources will increase carbon dioxide concentrations, and these elevated concentrations could be interpreted as lower ventilation rates. The existence of removal mechanisms will decrease carbon dioxide concentrations and lead to the conclusion that the ventilation rate is higher than its actual value. There is no practical way to adjust for the existence of significant sources or removal mechanisms; therefore, carbon dioxide concentrations measured in these circumstances cannot generally be used to estimate ventilation rates reliably.

Even if the indoor carbon dioxide concentration has not yet reached equilibrium, Equations 8 and 9 can be used to determine an upper bound on the ventilation rate. For example, if the difference between the indoor and outdoor carbon dioxide concentrations at equilibrium is 1,170 mg/m^3 (650 ppm(v)) and the carbon dioxide generation rate in the space is 0.5 L/s (1.1 cfm), then Equation 8 yields a ventilation rate of 770 L/s (1,690 cfm). However, if the indoor concentration is not yet at equilibrium, then Equation 8 can still be used to determine that the ventilation rate is no higher than 770 L/s (1,690 cfm). In other words, these equations can be used to confirm the inadequacy of ventilation but not necessarily its adequacy.

Mass Balance Approaches to Calculating Ventilation Rates

Indoor carbon dioxide concentrations have also been used to calculate building ventilation rates based on an analysis of the carbon dioxide mass balance equation without the simplifying assumptions of steady state or a constant generation rate (Penman 1980; Penman and Rashid 1982; Persily and Dols 1990; Smith 1988; Turiel and Rudy 1980). These approaches have employed either a differential or integral form of the mass balance equation. The use of these equations involves a nonlinear curve-fitting approach to analyzing the measured data which is generally employed only in research studies.

CONTINUOUS MONITORING OF INDOOR CARBON DIOXIDE

Continuous monitoring of indoor carbon dioxide concentrations using a data-logging device can be useful in investigations of building ventilation and indoor air quality. Such monitoring generally lasts one or more days and can be useful in the outdoor air, air handler return ducts, and occupied spaces.

Continuous monitoring of indoor carbon dioxide concentrations can be used to determine if equilibrium conditions exist, as discussed in conjunction with the equilibrium analysis approach. However, to verify the existence of equilibrium, one must monitor building occupancy and ventilation system operation to ensure that these parameters are also constant. Continuous monitoring can also be used to determine the actual peak carbon dioxide concentrations in a building or a space within a building.

Continuous monitoring can also be used to determine building occupancy patterns, i.e., when the occupants of a building or a zone within a building arrive and leave. If the building or zone ventilation rate is relatively constant, variations in indoor carbon dioxide concentrations can be used to indicate when the building or space is occupied and to provide some indication of the occupancy level.

Continuous monitoring of indoor carbon dioxide concentrations can also be used to monitor HVAC system operation in some situations. If the occupancy of a building or zone is relatively constant, variations in the carbon dioxide concentration can be used to indicate modulations in outdoor air ventilation rates due to economizer operation or modulation of variable-air-volume (VAV) systems.

CARBON DIOXIDE MEASUREMENT ISSUES

While there is currently no standardized test method for measuring indoor carbon dioxide concentrations, some guidance is available on measuring these concentrations. Due to the possibility of instrument drift over time and the impacts of travel on instrument performance, it is important that the instrument calibration be checked in the field before and after the carbon dioxide concentration measurements. The field check should include challenging the device with two calibration gases with nominal concentrations of about 550 and 1,800 mg/m^3 (300 and 1,000 ppm(v)).

Many carbon dioxide concentration measurement instruments require a "warm-up" period for their operation to stabilize. The manufacturer's instructions should be consulted for the appropriate warm-up time. Some carbon dioxide concentration measurement instruments are affected by the temperature and relative humidity. The manufacturer's instructions should be consulted for the suggested operating conditions.

When using indoor carbon dioxide concentrations for the purposes described in this paper, the outdoor carbon dioxide concentration must be measured. Due to the existence of local variations in the outdoor carbon dioxide concentration and the possibility of exhaust air entrainment, the outdoor carbon dioxide concentration should be measured where the outdoor air is brought into the ventilation system serving the space. If the space is not mechanically ventilated, then the outdoor concentration should be measured near those vents, windows, and other openings through which outdoor air would be expected to enter the space.

The outdoor concentration should be measured several times before, during, and after the indoor carbon dioxide concentration measurements to determine a reliable value of the outdoor concentration and to verify its stability. Hourly measurements of the outdoor concentration should be sufficient. If the instrument measuring the carbon dioxide concentration is sensitive to temperature, this effect must be taken into account when measuring outdoor carbon dioxide concentrations.

Indoor carbon dioxide concentration sampling locations should be selected to ensure a representative concentration value that is not unduly biased by the carbon dioxide sources (people) and ventilation air with a low concentration. Indoor sampling locations should be selected by making measurements at multiple locations in the space and identifying one or more locations that yield a representative value. The carbon dioxide concentration in an occupied space will generally not be uniform due to the high carbon dioxide concentration in the air exhaled by people, about 72,000 mg/m^3 (40,000 ppm(v)). Therefore, the indoor concentration should not be measured close to people. A distance of about 2 m (6 ft) from occupants is probably sufficient to avoid these effects. Indoor sampling locations should also be selected to avoid the low concentration air entering the space through open windows and supply air vents.

The indoor carbon dioxide concentration can be measured at a return or exhaust vent serving the space to obtain an approximate average concentration for the space. If there are multiple return or exhaust vents in the space, it may be necessary to sample at multiple vents to identify a vent that yields a representative value. Concern has been expressed about this approach due to the possibility of supply air short-circuiting to the return, resulting in a low return air concentration.

CONCLUSIONS

The measurement and interpretation of indoor carbon dioxide concentrations can provide useful information on building indoor air quality and ventilation. However, when evaluating indoor air quality and/or ventilation using carbon dioxide, the user must understand the technique being employed and verify its applicability to the building and situation at hand.

While indoor carbon dioxide concentrations have been shown to be a reliable indicator of the acceptability of a space in terms of human body odor, there is little evidence supporting the use of carbon dioxide as a comprehensive indicator of indoor air quality. Many building studies have shown no significant relationship between carbon dioxide concentrations and the prevalence of occupant symptoms. Also, many contaminant sources are not associated with occupancy levels, and their concentrations will not be associated with carbon dioxide levels. The analysis of carbon dioxide concentrations can be used to obtain information on building ventilation performance based on a number of tracer gas techniques, but the assumptions associated with these techniques must be understood and validated by the user.

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