The Relationship Between Indoor Air Quality and Carbon Dioxide

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ABSTRACT

In some situations, measurements of indoor CO_2 concentrations can be used to assess indoor air quality and ventilation. However, oversimplified descriptions of measurement procedures based on CO_2 have been presented, and there have been many cases where indoor CO_2 concentrations have been misinterpreted. This paper describes the relationship of indoor CO_2 concentrations to building air quality and ventilation, with a focus on how CO_2 can be used to evaluate air quality and ventilation performance. While CO_2 concentrations do not provide a comprehensive indication of indoor air quality, they can be used to assess the acceptability of a space in terms of human body odor. Also, under some circumstances CO_2 can be used to evaluate building ventilation, specifically air change rates and percent outdoor air intake.

INTRODUCTION

A variety of techniques are available to evaluate building ventilation and indoor air quality, and some of these techniques involve the measurement and analysis of indoor CO_2 concentrations. However, there have been cases where oversimplified descriptions of CO_2-based measurement procedures are presented and indoor CO_2 concentrations are misinterpreted. Some common misunderstandings include characterizations of CO_2 as an indicator of overall indoor air quality, health concerns about concentrations above 1800 mg/m^3, and implications that CO_2 concentrations below 1800 mg/m^3 imply compliance with ASHRAE Standard 62-1989 (1-2).

The relationship of CO_2 to indoor air quality and ventilation is based on two concepts. One is that people emit CO_2 at a rate that depends on their size and their level of physical activity, as discussed in the ASHRAE Fundamentals Handbook (3). The second concept is that CO_2 can be used as a tracer gas to study building ventilation when its indoor concentration is elevated above outdoors. This paper describes the relationship between CO_2 and indoor air quality, with a focus on the experimentally-demonstrated relationship between concentration and the acceptability of human body odor in occupied spaces. In addition, approaches in which CO_2 can be used as a tracer gas to determine building ventilation parameters are described. The material in this paper is based in part on a provisional standard on the use of indoor CO_2 concentrations to evaluate indoor air quality and ventilation that has recently been published by ASTM (4).

CARBON DIOXIDE AND INDOOR AIR QUALITY

Indoor CO_2 is sometimes referred to as an indicator of indoor air quality without describing a specific association between CO_2 and air quality. A number of potential relationships exist including the health effects of elevated CO_2 concentrations, the impact of CO_2 on occupant perceptions of the indoor environment, the relationship between CO_2 concentrations and the concentrations of other indoor contaminants, and the relationship between CO_2 and outdoor air ventilation rates. In addition, references are often made between CO_2 concentrations of 1800 mg/m^3 and ASHRAE Standard 62-1989 (1).

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 h exposure and a 40 h work week) for CO_2 is 9000 mg/m^3, and the short-term exposure limit (15 min exposure) is 54 000 mg/m^3 (5). A number of studies at elevated concentrations, about 5% CO_2 in air or 90 000 mg/m^3, have been performed, and the lowest level at which effects have

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been seen in humans and animals is about 1%, that is 18 000 mg/m^3 (6). Indoor CO_2 concentrations will not reach these levels unless the ventilation rate is very low, about 1 L/s per person for 9000 mg/m^3 and less than 0.2 L/s per person for 54 000 mg/m^3.

Associations between CO_2 concentrations and occupant perceptions of the indoor environment are more complex because they combine several issues including the comfort impacts of CO_2 itself, associations between the concentrations of CO_2 and other contaminants, and the relationship between CO_2 and ventilation. A number of peer-reviewed studies of occupant symptoms have shown no significant relationship between the prevalence of symptoms and CO_2 concentrations (7-10). However, some indoor air quality investigators associate indoor CO_2 concentrations from 1100 mg/m^3 to 1800 mg/m^3 or higher with perceptions of stuffiness and other indicators of discomfort and irritation, generally based on anecdotal observations or informal occupant surveys (11). These associations between CO_2 and occupant comfort may be due to other factors, such as thermal comfort or the concentrations of other contaminants.

The relationship between the concentrations of CO_2 and other indoor contaminants depends on the sources of these other contaminants. The rate at which CO_2 is generated in a space depends on the number of people, their size and their level of physical activity. If other contaminants are generated at a rate that also depends on the occupancy level, then CO_2 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, for example emissions from building materials and contaminants entering a building from outdoors. Carbon dioxide concentrations do not provide any information on the concentration of contaminants emitted by occupant-independent sources.

The relationship between CO_2 and outdoor air ventilation rates is well understood and is based on the consideration of CO_2 as a tracer gas (12). Under some circumstances, using a mass balance of CO_2 in a building, measured CO_2 concentrations can be used to determine some building ventilation parameters. All else being equal, if the ventilation rate in a space decreases then the CO_2 concentration will increase. However, to make quantitative estimates of ventilation parameters based on measured CO_2 concentrations one must employ a specific tracer gas technique that is appropriate to the conditions that exist in the building. Specific approaches to determining building ventilation performance are described later in this paper.

A common misunderstanding exists that if CO_2 concentrations are below 1800 mg/m^3, then the building complies with ASHRAE Standard 62-1989 (1). The Ventilation Rate Procedure in the standard is based on outdoor air ventilation rates requirements, not on the maintenance of indoor CO_2 levels. It also contains requirements for contaminant levels in the outdoor air and that no unusual contaminants or sources exist. The Indoor Air Quality Procedure contains a CO_2 guideline of 1800 mg/m^3, as well as limits for four contaminants of predominantly outdoor origin and three other indoor contaminants. One must also keep all other contaminants of concern below specific levels, and there is a requirement for the subjective evaluation of contaminants for which no objective measures of acceptability are available. Therefore, maintaining CO_2 levels below 1800 mg/m^3 does not mean that a building is in compliance with the standard.

Carbon Dioxide Concentrations and Body Odor Acceptability

At the same time people generate CO_2, they also produce odorous bioeffluents. Similar to CO_2, the rate of bioeffluent generation depends primarily on the level of physical activity. 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 (13-18). These experiments studied the relationship between ventilation rates and odor acceptability, and have been a major consideration in the development of ventilation standards. Some of the experiments also studied the relationship between the acceptability of a space in terms of body odor and CO_2 concentrations.

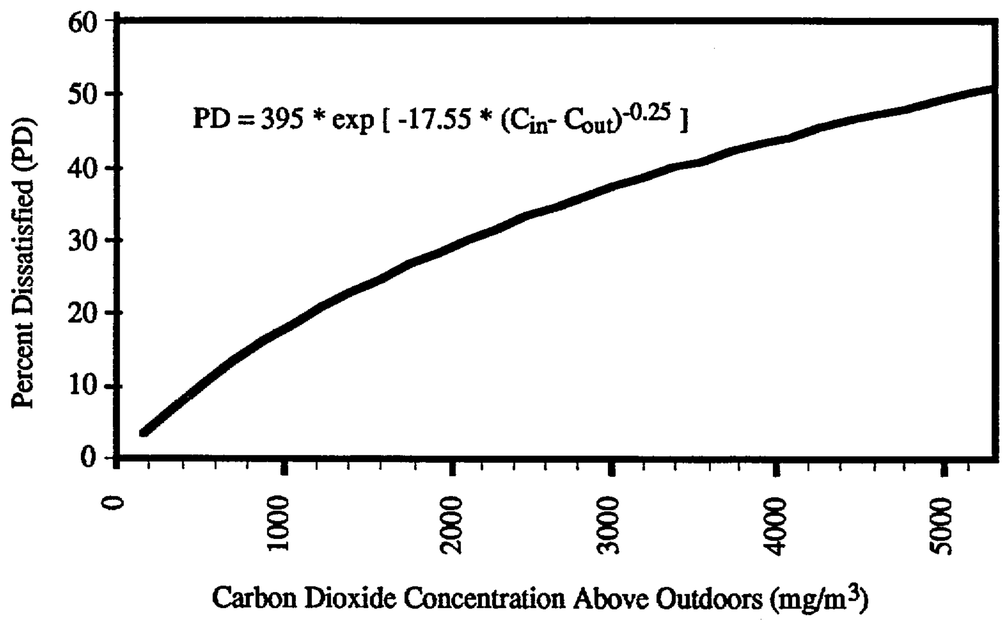

Figure 1 Percent of Visitors Dissatisfied versus Carbon Dioxide Concentration (19)

These studies concluded that about 7 L/s of outdoor air per person will control body odor such that roughly 80% of unadapted persons (visitors) will find the odor at an acceptable level. The same level of acceptability was found to occur at CO_2 concentrations about 1250 mg/m^3 above outdoors, which at a typical outdoor level of 630 mg/m^3 yields an indoor concentration of 1880 mg/m^3. These considerations yield the common CO_2 guideline of 1800 mg/m^3. Figure 1 shows the percent of visitors dissatisfied with the level of body odor in a space versus the CO_2 concentration above outdoors (19). For adapted persons (occupants), the ventilation rate per person to provide the same acceptance is about one third the value for visitors, and the CO_2 concentrations above outdoors are three times higher (13-14). While CO_2 concentrations can be an appropriate means of characterizing the acceptability of a space in terms of body odor, they do not provide information on the control of contaminants from other pollutant sources such as building materials, furnishings and the outdoors. And while maintaining CO_2 concentrations within 1250 mg/m^3 of outdoors should provide acceptable perceived air quality in terms of human body odor, it does not necessarily imply adequate control of other pollutants.

CARBON DIOXIDE AND BUILDING VENTILATION

There are several approaches for using indoor CO_2 concentrations to evaluate ventilation, including the determination of the percent outdoor air intake at an air handler and the determination of building air change rates.

Percent Outdoor Air Intake

The fraction of outdoor air in the supply airstream of an air handler can be determined from measured CO_2 concentrations in the supply, return and outdoor airstreams. The value of the percent outdoor air intake can be used to estimate outdoor air intake rates by multiplying the percent outdoor air intake by the value of supply airflow rate measured, for example, with a pitot traverse. The percent outdoor air intake of an air handler is equal to the outdoor air intake rate of the air handler divided by the supply airflow rate delivered by the air handler. Based on mass balances of air and CO_2 at the air handler, the percent outdoor air intake is given by

$$\%OA = 100 \times \frac{(C_r - C_s)}{(C_r - C_{out})} \quad (1)$$

where %OA = percent outdoor air intake,and C_r, C_s and C_{out} = the CO_2 concentrations in the recirculation, supply and outdoor airstreams in mg/m³. The main factor affecting the precision in %OA is the magnitude of the difference between C_r and C_{out}, with large values of this difference increasing the precision of %OA. This difference can be maximized by measuring the concentrations well into the occupied period of the day when the indoor concentration has increased well above the outdoor concentration.

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 CO_2 is used as a tracer gas and the measurement is conducted after the occupants leave the building. ASTM Standard E741 (20) contains a test method for using tracer gas decay to determine the air change rate of a single-zone space. This air change rate includes both infiltration through leaks and openings in the building envelope and outdoor air intake by ventilation systems. Single-zone spaces are defined in the standard as spaces where the tracer gas concentration is uniform 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. Standard E741 describes the analysis of tracer gas concentrations to determine building air change rates. When using occupant-generated CO_2 to conduct a tracer gas decay test, the requirements of ASTM E741 need to be followed in the areas of 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 CO_2 involves issues not explicitly covered in ASTM E741. One critical issues is that in most buildings it takes some time for all of the occupants to leave the building, and during this time the indoor CO_2 concentration will decay. The indoor concentration when the building is finally unoccupied depends on the concentration when the occupants start leaving, the amount of time it takes them to leave, and the building air change rate. Depending on the values of these parameters, the indoor CO_2 concentration may be too low once the building is unoccupied to perform a reliable decay measurement. Other issues are described in ASTM PS40 (4).

Estimating Ventilation Rates Using Equilibrium Analysis

Under some circumstances indoor CO_2 concentrations can be used to estimate outdoor air ventilation rates based on the constant injection tracer gas technique. The constant injection technique, also described in ASTM E741, involves injecting tracer gas into a single-zone space at a constant and known rate. The constant injection technique, when used with occupant-generated CO_2, is sometimes referred to as equilibrium analysis. As with tracer gas decay, the measured air change rate includes both infiltration and intake, and the test method applies to single-zone spaces. In this approach, the outdoor airflow rate is given by Equation (2).

$$Q_o = \frac{1.8 \times 10^6\,G}{(C_{in,eq} - C_{out})} \qquad (2)$$

where Q_o = outdoor airflow rate into the zone in L/s, G = CO_2 generation rate in the zone in L/s, $C_{in,eq}$ = equilibrium CO_2 concentration in the zone in mg/m³, and C_{out} = outdoor CO_2 concentration. Equation (2) can used to determine the outdoor airflow rate per person by substituting the CO_2 generation rate per person for G.

The validity of Equation (2) is based on several assumptions related to the single-zone tracer gas mass balance on which the equation is based. First, the zone to which the procedure is being applied acts as a single-zone with respect to CO_2 concentration as specified in ASTM E741, that is the CO_2 concentration in that zone is uniform. The procedure also requires that the zone being tested is isolated from any other zones in the building in terms of airflow, unless those zones are at the same CO_2 concentration as the zone being tested. The approach also requires that the CO_2 generation rate is constant and known. This requirement means that the number of occupants in the space is constant for a sufficiently long period of time while the concentration builds-up to equilibrium. Equation (2) is also based on a constant outdoor CO_2 concentration, which is generally not a problem, and that the outdoor air ventilation rate is constant.

This approach also requires that the indoor CO_2 concentration is at equilibrium, meaning that the indoor CO_2 generation rate, the outdoor CO_2 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. The time required to reach equilibrium depends on the outdoor air change rate of the space in units of air changes per hour (h^{-1}). At an air change rate of 0.25 h^{-1}, it takes 12 h of constant occupancy to reach 95% of the equilibrium CO_2 concentration difference. This air change rate corresponds to about 3 L/s per person and an occupant density of 7 people per 100 m^2 of floor area, and is not uncommon in office buildings under minimum outdoor air intake (21). At 0.75 h^{-1} (corresponding to 10 L/s per person and more typical of office building ventilation rates), it takes 4 h 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. Even if the indoor CO_2 concentration has not yet reached equilibrium, Equation (2) can be used to determine an upper bound on the ventilation rate. In other words, this equation can be used to confirm the inadequacy of ventilation but not necessarily its adequacy.

Mass Balance Approaches to Calculating Ventilation Rates

Indoor CO_2 concentrations have also been used to calculate building ventilation rates based on an analysis of the CO_2 mass balance equation without assuming steady-state or a constant generation rate (12, 22-25). These approaches have employed both differential and integral forms of the mass balance equation. The use of these equations involves nonlinear curve fitting to analyze the measured data and are generally employed only in research studies.

CONCLUSIONS

The measurement and interpretation of indoor CO_2 concentrations can provide information on building indoor air quality and ventilation. However, one must understand the technique being employed and verify its applicability to the building and situation at hand. While indoor CO_2 concentrations have been shown to be reliable indicators of the acceptability of a space in terms of human body odor, there is little justification for using CO_2 as a comprehensive indicator of indoor air quality. Many studies have shown no significant relationship between CO_2 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 CO_2 levels. The analysis of CO_2 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 by the user.

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