

Indoor Carbon Dioxide Concentrations in Ventilation and Indoor Air Quality Standards

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ABSTRACT

Indoor carbon dioxide (CO₂) concentrations have played a role in discussions of ventilation and indoor air quality (IAQ) since the 18th century. Those discussions have evolved over the years to focus on the impacts of CO₂ concentrations on building occupants, how these concentrations relate to occupant perception of bioeffluents, the use of indoor CO₂ concentrations to estimate ventilation rates, and CO₂-based demand control ventilation. This paper reviews how indoor CO₂ has been dealt with in ventilation and IAQ standards in the context of these issues.

While measured indoor CO₂ concentrations are rarely close to health guidelines, much confusion has resulted regarding CO₂ in ventilation and IAQ standards. For example, an indoor CO₂ concentration of 1800 mg/m³ (roughly equivalent to 1000 ppm_v) has become a de facto standard in many discussions without a sound understanding of its basis or significance. And while there have been anecdotal associations of CO₂ concentrations in this range with occupant symptoms such as stuffiness and discomfort, research results do not support these associations with CO₂ itself. Several studies have shown associations of elevated CO₂ levels with occupant symptoms, but these findings are likely due to lower ventilation rates elevating the concentrations of other more important contaminants along with the CO₂.

The relevance of CO₂ concentrations to ventilation and IAQ standards is based primarily on two factors: their relation to indoor levels of bioeffluents and associated odors, and their relation to ventilation rates per person. Several studies of bioeffluent odor perception in chambers and buildings have shown correlations between dissatisfaction with these odors and both ventilation rate per person and CO₂ level. Also, ventilation rates and indoor CO₂ levels are related based on a single-zone mass balance of CO₂. However, many individuals use CO₂ concentrations to estimate building ventilation rates without understanding the associated mass balance theory and the assumptions on which it is based. This paper reviews these concepts and discusses the role of indoor CO₂ in various ventilation and IAQ standards.

KEYWORDS Carbon dioxide; contaminant limits; demand control ventilation; indoor air quality; standards; ventilation.

1 INTRODUCTION

Indoor CO₂ concentrations have been prominent in discussions of ventilation and IAQ since the 18th century when Lavoisier suggested that CO₂ build-up rather than oxygen depletion was responsible for “bad air” indoors (Klauss, 1970). About one hundred years later, von Pettenkofer suggested that biological contaminants from human occupants were causing indoor air problems, not CO₂. Discussions of CO₂ in relation to IAQ and ventilation evolved since that time, focusing on the following issues: impacts of CO₂ concentrations on building occupants, how these concentrations relate to occupant perception of bioeffluents, the use of indoor CO₂ concentrations to estimate ventilation rates, and the use of CO₂ to control outdoor air ventilation rates. This paper reviews how these issues have been dealt with in ventilation and IAQ standards. The topic is introduced by discussing CO₂ levels in various standards and guidance documents, followed by identification of the primary issues of interest related to indoor CO₂. Those issues are discussed in more detail in subsequent sections.

1.1 Carbon dioxide concentrations in standards and guidelines

While indoor CO₂ concentrations are rarely close to limits in health-based guidelines, much confusion has resulted regarding CO₂ levels in ventilation and IAQ standards. A 2001 review

of ventilation and IAQ criteria in several countries reported that most CO₂ limits are in the range of 1800 mg/m³, although some are as high as 9000 mg/m³ or even 30 000 mg/m³ for short-term exposures (Limb, 2001). ASHRAE Standard 62.1-2013 contains a more recent listing of CO₂ limits in other documents, four of which are equal to 9000 mg/m³ with one at 6300 mg/m³ (ASHRAE, 2013a). Short-term exposure limits tend to be higher, ranging from 18 000 mg/m³ to 54 000 mg/m³. These concentration limits are typically drawn from values developed for industrial environments, which are not applicable to general populations as discussed below. The basis for limits on the order of 1800 mg/m³ is also described later.

ASHRAE Standard 62-1981 contained an indoor CO₂ limit of 4500 mg/m³ for use when applying the performance approach to complying with the standard, i.e., the IAQ Procedure. That limit was changed without explanation to 1800 mg/m³ in 1989. CEN standard 13779 does not contain an indoor CO₂ limit, but has an informative annex that provides default CO₂ concentrations for its four classes of IAQ (CEN, 2007). The highest IAQ class is associated with concentrations about 700 mg/m³ above outdoors, with the lowest class 1800 mg/m³ above outdoors.

Other standards and guidance documents also address indoor CO₂ concentrations. ASTM Standard D6245 does not contain limits on indoor CO₂ concentrations (ASTM, 2012), but notes that adverse health effects from elevated CO₂ have not been observed until concentrations are in the range of 12 600 mg/m³ to 36 000 mg/m³ based on exposures of at least 30 days (ECA, 1992; EPA, 1991). LEED v4 includes requirements for naturally ventilated spaces in which one of three different options for monitoring system performance must be employed (USGBC, 2014). One of those options is to monitor CO₂ concentrations in each thermal zone and to issue an audible or visual alert if the concentration exceeds the setpoint by more than 10 %. LEED v4 refers to Standard 62.1 for the determination of these setpoints, but no values are provided in either document. LEED also awards extra points for monitoring CO₂ concentrations in densely occupied spaces, but again no concentration limits are provided. Other building design standards and guidelines allow for the use of CO₂ in demand control ventilation systems, as described below, but do not necessarily provide indoor concentration limits or setpoints.

Based on consideration of existing standards and guidelines, indoor CO₂ limits are either in the range of 1800 mg/m³ or they are closer to industrial limits on the order of 20 000 mg/m³ or more. Note that measured indoor values tend to be well below these industrial limits. For example, the U.S. EPA BASE study of 100 randomly selected office buildings had a mean peak indoor CO₂ value of 1260 mg/m³, a maximum of about 2200 mg/m³ and a 90th percentile value of 1650 mg/m³ (EPA, 2006). In a study of 56 office buildings in Europe, the average CO₂ concentration ranged from about 900 mg/m³ to about 1400 mg/m³, depending on the country where the buildings were located, with no readings above 2200 mg/m³ (Bluyssen et al. 1996). A more recent study of 37 small and medium sized commercial buildings in California resulted in a mean of the maximum CO₂ concentration of 3031 mg/m³, though the overall mean concentration was only 1168 mg/m³ (Bennett et al. 2011). On the residential side, a study of 108 new homes in California yielded a median indoor CO₂ concentration of 1015 mg/m³ with a range of about 600 mg/m³ to 2000 mg/m³. Higher concentrations have been measured in other residences, including a recent study of 266 dwellings in Tianjin, China, with a median value for the mean CO₂ concentration of about 2500 mg/m³ (Hou et al., 2015). In that study, concentrations in 41 % of children's bedrooms were below 1800 mg/m³, 20 % exceeded 3600 mg/m³, and 6 % exceeded 5400 mg/m³. In another study of residences in Denmark, about one-quarter of the measurements in the bedrooms were above 3600 mg/m³ and 6 % were above 5400 mg/m³ (Bekö et al., 2010). Two studies in school classrooms

showed concentrations as high as 7200 mg/m³, though most were below about 3500 mg/m³ (Coley and Beisteiner, 2002; Bakó-Biró, 2012). Based on this wide range of studies in different countries and different building types, most measured indoor CO₂ concentration are less than 2000 mg/m³, with a small fraction above 5000 mg/m³, but none in the range of health-based industrial exposure limits.

1.2 Questions and issues related to carbon dioxide

In considering indoor CO₂ in the context of ventilation and IAQ standards, a number of issues have been raised and some level of confusion exists. This section outlines those issues as follows, providing context for the discussion what follows:

- Impacts of CO₂ on building occupants
- Relationship of indoor CO₂ and perception of odors from human bioeffluents
- Relationship of indoor CO₂ levels to ventilation rates
- Application of indoor CO₂ levels to controlling outdoor air ventilation

While indoor CO₂ levels are generally far below industrial limits or levels otherwise expected to impact the health and comfort of building occupants, some discussions of indoor CO₂ have referred to the health impacts of exposure to CO₂. It is important for practitioners and other involved with building IAQ to understand how indoor CO₂ levels are associated with occupant health and comfort, and the reasons for any such associations. The second issue listed above concerns the relationship between indoor CO₂ concentrations and the perception of human body odors. This relationship has been studied since the 1930s and has provided the basis for minimum ventilation rates in most ventilation standards and regulations. Those ventilation rates also impact the third issue, the relationship between indoor CO₂ levels and building ventilation rates. In this relationship, CO₂ is simply a tracer gas with a very convenient injection mechanism, i.e., the building occupants. The theory behind tracer gas measurement techniques is well-established, and the assumptions for applying these techniques also apply when using CO₂. Finally, indoor CO₂ levels have been used for many years to control outdoor air ventilation rates based on the actual number of occupants rather than the design occupancy, commonly referred to as demand control ventilation (DCV). This approach has potential benefits for both IAQ and energy efficiency, and the use of DCV in standards is discussed below.

ASTM Standard D6245-12, Standard Guide for Using Indoor Carbon Dioxide Concentrations to Evaluate Indoor Air Quality and Ventilation, which was first issued in 1998, discusses all of these issues (ASTM, 2012). However, per the ASTM definition of a Guide, this document serves as a "... compendium of information or series of options that does not recommend a specific course of action" in order to increase "... awareness of information and approaches in a given subject area" (ASTM, 2014). This is the only standard specific to the interpretation of indoor CO₂ concentrations and addresses all of the issues outlined above, plus some others including the measurement of indoor CO₂ concentrations. However, being a guide, this standard does not contain detailed calculation approaches or specific instructions.

2 IMPACTS OF CO₂ ON BUILDING OCCUPANTS

While indoor CO₂ concentrations in non-industrial buildings are rarely close to any health-based guidelines for industrial environments, much confusion has resulted regarding the health impacts of exposure to CO₂ in buildings. As noted earlier, concentration limits in standards and guidelines for industrial environments are not typically relevant to commercial,

institutional and residential buildings. As noted in the ASHRAE Indoor Air Quality Guide, there are large differences between industrial and non-industrial environments in terms of the composition and concentrations of airborne contaminants (ASHRAE, 2009). For example, industrial workers are typically exposed to high concentrations of specific contaminants, while occupants of non-industrial buildings are exposed to a varied mixture of contaminants for long periods of time. Also, the occupants of nonindustrial environments cover a broad range of age, sex, physical condition and pre-existing health conditions. As stated in the IAQ Guide, “For these reasons the use of industrial guideline values, or fractions of these values, is generally considered inappropriate.” ASHRAE Standard 62.1-2013 also discusses the application of industrial guideline concentrations, noting that they are intended to limit exposure in order to not interfere with work processes, but not to eliminate effects such as odors or mild irritation (ASHRAE, 2013a). In addition, the standard notes that healthy industrial workers will change jobs if the exposure is intolerable, while occupants of non-industrial building occupants have less choice about where they spend their time and include individuals “...who may be more sensitive, such as children, asthmatics, allergic individuals, and the elderly.”

While occupational CO₂ exposure limits are not relevant to non-industrial building environments and indoor concentrations almost never reach those levels, an indoor CO₂ concentration of 1800 mg/m³ has become a de facto standard in many applications without a sound understanding of its basis (Persily, 1997). This reference notes the existence of anecdotal discussions associating CO₂ concentrations in this range with occupant symptoms such as stuffiness and discomfort, but notes that peer-reviewed studies do not support these associations with CO₂ itself. While several studies have shown associations of elevated CO₂ levels with symptoms, absenteeism and other effects (Apte et al., 2000; Shendell et al., 2004; Gaihre et al., 2014), these associations are likely due to lower ventilation rates elevating the concentrations of other contaminants with health and comfort impacts at the same time they are elevating CO₂.

The 1800 mg/m³ CO₂ “guideline value” is commonly attributed to ASHRAE Standard 62. As noted earlier, the 1981 version of that standard contained an indoor CO₂ limit of 4500 mg/m³ for use when applying the performance approach to complying with the standard, i.e., the IAQ Procedure. That limit was changed without explanation to 1800 mg/m³ in 1989, and that value was removed from the standard in 1999. That and subsequent versions of the standard contained an informative appendix explaining that if a space is ventilated at a nominal rate of 7.5 L/s per person, then at steady-state the CO₂ concentration will equal 1800 mg/m³ for assumed values of the CO₂ generation rate per person and the outdoor CO₂ concentration. There is nothing in the standard declaring 1800 mg/m³ or any other CO₂ concentration to be a health or comfort based limit. The 1800 mg/m³ “limit” simply is based on its association with a nominal ventilation requirement of 7.5 L/s per person for control of body odor perception as discussed below. Also, Standard 62 and other ventilation standards contain a range of ventilation requirements for different types of spaces, which will be associated with CO₂ concentrations other than 1800 mg/m³.

While indoor CO₂ concentrations are typically well below values of interest based on health concerns, a recent study has shown evidence of impacts on human performance. A chamber study of individuals completing computer-based tests showed statistically significant decreases in decision-making performance at CO₂ concentrations as low as 1800 mg/m³ (Satish et al., 2012). These experiments were carefully designed to expose the subjects to elevated CO₂ but not to other contaminants. This work has not yet impacted ventilation and IAQ standards, but if the findings are repeated in other studies, it may support future changes.

3 CO₂ AND THE PERCEPTION OF BODY ODOR

There have been many decades of research into outdoor air requirements, which, starting in the second half of the nineteenth century, focused on the control of human body odor associated with the byproducts of human metabolism, often referred to as bioeffluents (Klauss et al. 1970). Building on the seminal work of von Pettenkofer and others, Yaglou et al. (1936) used environmental chambers to investigate ventilation rates required to control the odor from bioeffluents. In these studies, human test subjects rated odor intensity as a function of the ventilation airflow per person. This research found that about 7.5 L/s to 9 L/s per person of ventilation air was needed to dilute body odor to levels judged to be acceptable by individuals entering the room from relatively clean air. Since the time of Yaglou's research, a number of researchers have reported similar results in both laboratory chambers and actual buildings (Cain et al., 1983; Fanger and Berg-Munch, 1983; Iwashita et al., 1990).

Some of these experiments also studied the relationship between CO₂ concentrations and body odor acceptability. The finding that about 7 L/s per person of ventilation controlled human body odor such that about 80 % of unadapted individuals found the odor to be acceptable was accompanied by the result that the same level of acceptability occurred at CO₂ concentrations about 1250 mg/m³ above outdoors. For an outdoor CO₂ level of 630 mg/m³, this indoor concentration roughly corresponds to the commonly cited value of 1800 mg/m³. The relationship between the percentage of subjects dissatisfied with body odor and CO₂ concentrations has been seen experimentally determined in several studies, with the results largely independent of the level of physical activity (Berg-Munch et al., 1986; Fanger and Berg-Munch 1983; Rasmussen et al. 1985). In addition, the relationship did not require that the indoor CO₂ concentration be at steady-state. The lack of a strong dependency on physical activity arises from the fact that humans produce CO₂ and bioeffluents at rates that are roughly proportional to one another. The fact that these relationships do not require the existence of steady-state conditions arises because both CO₂ and odor levels increase at a rate that is primarily dependent on the air change rate of the space in question.

This research supports 1800 mg/m³ of CO₂ as a reflection of body odor acceptability perceived by unadapted visitors to a building. Of course, there are many other contaminants in indoor air that are not associated with the number of occupants, and CO₂ concentration is not a good indicator for those contaminants.

4 CO₂ AND VENTILATION RATES

As discussed previously (Persily, 1997; ASTM, 2012), per person ventilation rates and indoor CO₂ levels are related based on a single-zone mass balance of CO₂. This relationship has been discussed in Standard 62 since 1981, in which the steady-state equation is presented as follows: the outdoor air ventilation rate per person (Q) equals the ratio of the CO₂ generation rate per person (G) to the difference between the indoor and outdoor CO₂ concentrations (ΔC), or $Q = G/\Delta C$. For a ventilation rate of 7.5 L/s per person and a CO₂ generation rate of 0.3 L/min per person, the indoor CO₂ concentration will be about 1200 mg/m³ above outdoors. Using slightly different values of the generation rate, one arrives at the indoor CO₂ concentration value of 1800 mg/m³. This value is often referred to as a CO₂ "limit" erroneously attributed to ventilation standards, but as discussed in earlier, is actually related to

recommended ventilation rates for body odor control under idealized, steady state conditions, not to the health or comfort impacts of the CO₂.

This relationship between CO₂ concentrations and ventilation rates is essentially an application of the constant injection tracer gas method, which has been well-understood for decades (Hunt, 1980), and is often used to estimate ventilation rates without an adequate understanding of its basis. The constant injection method, described in ASTM E741 (ASTM, 2011), involves injecting tracer gas at a constant rate into the space being tested and monitoring the concentration response. Since the so-called peak CO₂ approach is a single-zone steady-state tracer technique, it must abide by the following assumptions to yield a valid air change rate: the CO₂ generation rate is known, constant, and uniform throughout the building being tested; the CO₂ concentration is uniform throughout the building and has achieved steady state; the outdoor CO₂ concentration is known and constant; and, the outdoor air ventilation rate is constant. Given that the method is based on a single-zone mass balance, it can only be used to determine the air change rate of an entire building with a uniform concentration. If the CO₂ concentration varies among rooms, the single-zone approach is not valid and one must employ a multizone mass balance of CO₂ that accounts for the airflows between zones and is far more complicated to apply. Similarly, the steady-state CO₂ value in a single room cannot be used to calculate the ventilation rate of that room if adjoining spaces are at different CO₂ concentrations.

In order for the CO₂ generation rate to be known, constant, and uniform throughout the building, the occupancy level must be known, constant, and uniform. Assuming it is, the CO₂ generation rate can be estimated based on the number and characteristics of the building occupants, that is, their age, size and level of physical activity (ASTM, 2012). However, as noted in that standard, CO₂ generation rates can vary significantly among individuals. Also, the requirement for the CO₂ concentration being at steady state translates to conditions being constant for long enough that a steady-state concentration is achieved. As described in Persily (1997) and ASTM (2012), the time required to achieve steady state depends on the air change rate of the building. For a given air change rate, the concentration will be within 95 % of steady state after three time constants, where the time constant is the inverse of the air change rate. For an air change rate of 1 h⁻¹, it will take 3 h to reach 95 % of the steady-state. For an air change rate of 0.5 h⁻¹, it will take 6 h. During this time, the ventilation rate, occupancy, and outdoor concentration must all be constant. Using a CO₂ concentration before steady state has been achieved will overestimate the air change rate and the associated airflow rate per person, in some cases by significant amounts.

Indoor CO₂ concentrations are clearly related to ventilation rates, but that relationship is complicated by the multizone, transient nature of building airflow systems as well as variations in building occupancy (i.e., CO₂ generation) both temporally and spatially. The relationship is simple under only very specific circumstances, making CO₂ a questionable indicator of ventilation rates.

5 DEMAND CONTROL VENTILATION USING CO₂

Ventilation and IAQ standards allow the use of DCV to control outdoor air ventilation rates; in fact it is required under some circumstances in energy efficiency standards (ASHRAE, 2013b). Under ASHRAE Standard 62.1-2013, the ventilation requirement of a space is the sum of a per-person rate multiplied by the number of occupants plus an area rate multiplied by the floor area of the space. The use of DCV is relevant only to control of the ventilation requirement based on the number of occupants, i.e., the rate based on the floor area must

always be maintained. In practice, The standard allows the use of CO₂ as means to implement DCV, with the outdoor air intake rate controlled using the indoor CO₂ level such that the air intake rate is increased as the CO₂ levels rises and is decreased as it drops, similar to temperature control using a thermostat The setpoint depends on the ventilation rate requirement of the space of interest, which is a function of the space type, the number of occupants and the floor area. Given the requirements in Standard 62.1, setpoints will tend to be higher in densely occupied spaces. However, Standard 62.1 does not contain requirements specific to the application of CO₂ DCV; it simply allows DCV to be used to dynamically reset outdoor air intake flows and mentions CO₂ as an acceptable means of doing so. The application of CO₂ DCV per the standard is described in detail in the Users Manual for the standard (ASHRAE, 2010). Additional information on the application of CO₂-based DCV, specifically setpoint values for different space types, is available in Lawrence (2008).

More specific requirements for the use of CO₂ DCV are contained in California Title 24 and ANSI/ASHRAE/IES/USGBC Standard 189.1 (CEC, 2013; ASHRAE, 2014). Title 24 contains requirements regarding the number of CO₂ sensors, their location and their accuracy. It also specifies that the setpoint be 1080 mg/m³ above the outdoor concentration, which can be measured or assumed to equal 720 mg/m³. Standard 189.1 also contains requirements for sensor location and accuracy, but requires that the outdoor concentration be measured.

6 CONCLUSIONS

This paper summarizes how CO₂ is dealt with in ventilation and IAQ standards, focusing on the impacts CO₂ on building occupants, how CO₂ concentrations relate to occupant perception of bioeffluents, the use of indoor CO₂ to estimate ventilation rates, and the use of CO₂ to control outdoor air ventilation rates. Regarding the impacts of CO₂ on occupants, indoor concentrations are rarely close to limits in health-based guidelines, but much confusion still exists regarding CO₂ levels in ventilation and IAQ standards. Based on studies in different countries and different building types, most measured indoor CO₂ concentrations are less than 2000 mg/m³, with a small fraction above 5000 mg/m³, but none are in the range of health-based industrial exposure limits. Nevertheless, discussions of indoor CO₂ have long referred to the health impacts of exposure to CO₂. Similarly, many have referred to 1800 mg/m³ as a “guideline value” for indoor CO₂ or even a requirement, most commonly attributing it to ASHRAE Standard 62. However, there is nothing in the standard declaring 1800 mg/m³ or any other CO₂ concentration to be a health or comfort based guideline. The notion of an 1800 mg/m³ “limit” is based on its association with a nominal ventilation requirement of 7.5 L/s per person under very specific circumstances as discussed in this paper. Research does exist that associates CO₂ concentrations of 1800 mg/m³ with body odor acceptability of unadapted visitors to a building, but there are many other contaminants in indoor air that are not associated with the occupancy and CO₂ is not a good indicator for those contaminants.

As discussed here, indoor CO₂ concentrations are related to ventilation rates but that relationship is complicated by the multizone, transient nature of building airflow systems as well as variations in building occupancy (i.e., CO₂ generation) both temporally and spatially in buildings. The relationship can be used to estimate ventilation rates from CO₂ concentrations under only very specific and somewhat unusual circumstances, making CO₂ a questionable indicator of ventilation rates. Finally, ventilation and energy efficiency standards allow, in some cases require, the use of CO₂ concentrations to control ventilation rates.

In conclusion, we understand most of the issues related to indoor CO₂ in buildings, with this paper focusing on those issues relevant to ventilation and IAQ standards. Nevertheless, many

practitioners and other users of these standards are still confused regarding these issues. Standards, guidelines and technical papers are available to reduce this confusion, but they only have an impact when read and understood. Other mechanisms need to be employed to get this information where it is needed. Training is one such mechanism. It is also important that technical papers which refer to the use of CO₂ concentrations for measuring ventilation rates or which discuss the place of CO₂ in ventilation and IAQ standards be very carefully reviewed by knowledgeable individuals.

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