Indoor Carbon Dioxide Concentrations in Ventilation and Indoor Air Quality Standards

Andrew Persily

National Institute of Standards and Technology
100 Bureau Drive, MS8600
Gaithersburg, Maryland USA
andyp@nist.gov

ABSTRACT

Indoor carbon dioxide (CO_2) 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 CO_2 concentrations on building occupants, how these concentrations relate to occupant perception of bioeffluents, the use of indoor CO_2 concentrations to estimate ventilation rates, and CO_2–based demand control ventilation. This paper reviews how indoor CO_2 has been dealt with in ventilation and IAQ standards in the context of these issues.

While measured indoor CO_2 concentrations are rarely close to health guidelines, much confusion has resulted regarding CO_2 in ventilation and IAQ standards. For example, an indoor CO_2 concentration of 1800 mg/m^3 (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 CO_2 concentrations in this range with occupant symptoms such as stuffiness and discomfort, research results do not support these associations with CO_2 itself. Several studies have shown associations of elevated CO_2 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 CO_2.

The relevance of CO_2 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 CO_2 level. Also, ventilation rates and indoor CO_2 levels are related based on a single-zone mass balance of CO_2. However, many individuals use CO_2 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 CO_2 in various ventilation and IAQ standards.

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

1 INTRODUCTION

Indoor CO_2 concentrations have been prominent in discussions of ventilation and IAQ since the 18th century when Lavoisier suggested that CO_2 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 CO_2. Discussions of CO_2 in relation to IAQ and ventilation evolved since that time, focusing on the following issues: impacts of CO_2 concentrations on building occupants, how these concentrations relate to occupant perception of bioeffluents, the use of indoor CO_2 concentrations to estimate ventilation rates, and the use of CO_2 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 CO_2 levels in various standards and guidance documents, followed by identification of the primary issues of interest related to indoor CO_2. Those issues are discussed in more detail in subsequent sections.

1.1   Carbon dioxide concentrations in standards and guidelines

While indoor CO_2 concentrations are rarely close to limits in health-based guidelines, much confusion has resulted regarding CO_2 levels in ventilation and IAQ standards. A 2001 review of ventilation and IAQ criteria in several countries reported that most CO_2 limits are in the range of 1800 mg/m^3, although some are as high as 9000 mg/m^3 or even 30 000 mg/m^3 for short-term exposures (Limb, 2001). ASHRAE Standard 62.1-2013 contains a more recent listing of CO_2 limits in other documents, four of which are equal to 9000 mg/m^3 with one at 6300 mg/m^3 (ASHRAE, 2013a). Short-term exposure limits tend to be higher, ranging from 18 000 mg/m^3 to 54 000 mg/m^3. 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/m^3 is also described later.

ASHRAE Standard 62-1981 contained an indoor CO_2 limit of 4500 mg/m^3 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/m^3 in 1989. CEN standard 13779 does not contain an indoor CO_2 limit, but has an informative annex that provides default CO_2 concentrations for its four classes of IAQ (CEN, 2007). The highest IAQ class is associated with concentrations about 700 mg/m^3 above outdoors, with the lowest class 1800 mg/m^3 above outdoors.

Other standards and guidance documents also address indoor CO_2 concentrations. ASTM Standard D6245 does not contain limits on indoor CO_2 concentrations (ASTM, 2012), but notes that adverse health effects from elevated CO_2 have not been observed until concentrations are in the range of 12 600 mg/m^3 to 36 000 mg/m^3 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 CO_2 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 CO_2 concentrations in densely occupied spaces, but again no concentration limits are provided. Other building design standards and guidelines allow for the use of CO_2 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 CO_2 limits are either in the range of 1800 mg/m^3 or they are closer to industrial limits on the order of 20 000 mg/m^3 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 CO_2 value of 1260 mg/m^3, a maximum of about 2200 mg/m^3 and a 90th percentile value of 1650 mg/m^3 (EPA, 2006). In a study of 56 office buildings in Europe, the average

CO_2 concentration ranged from about 900 mg/m^3 to about 1400 mg/m^3, depending on the country where the buildings were located, with no readings above 2200 mg/m^3 (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 CO_2 concentration of 3031 mg/m^3, though the overall mean concentration was only 1168 mg/m^3 (Bennett et al. 2011). On the residential side, a study of 108 new homes in California yielded a median indoor CO_2 concentration of 1015 mg/m^3 with a range of about 600 mg/m^3 to 2000 mg/m^3. 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 CO_2 concentration of about 2500 mg/m^3 (Hou et al., 2015). In that study, concentrations in 41 % of children's bedrooms were below 1800 mg/m^3, 20 % exceeded 3600 mg/m^3, and 6 % exceeded 5400 mg/m^3. In another study of residences in Denmark, about one-quarter of the measurements in the bedrooms were above 3600 mg/m^3 and 6 % were above 5400 mg/m^3 (Bekö et al., 2010). Two studies in school classrooms showed concentrations as high as 7200 mg/m^3, though most were below about 3500 mg/m^3 (Coley and Beisteiner, 2002; Bakó-Biró, 2012). Based on this wide range of studies in different countries and different building types, most measured indoor CO_2 concentration are less than 2000 mg/m^3, with a small fraction above 5000 mg/m^3, but none in the range of health-based industrial exposure limits.

1.2   Questions and issues related to carbon dioxide

In considering indoor CO_2 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 CO_2 on building occupants
- Relationship of indoor CO_2 and perception of odors from human bioeffluents
- Relationship of indoor CO_2 levels to ventilation rates
- Application of indoor CO_2 levels to controlling outdoor air ventilation

While indoor CO_2 levels are generally far below industrial limits or levels otherwise expected to impact the health and comfort of building occupants, some discussions of indoor CO_2 have referred to the health impacts of exposure to CO_2. It is important for practitioners and other involved with building IAQ to understand how indoor CO_2 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 CO_2 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 CO_2 levels and building ventilation rates. In this relationship, CO_2 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 CO_2. Finally, indoor CO_2 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 CO_2 concentrations and addresses all of the issues outlined above, plus some others including the measurement of indoor CO_2 concentrations. However, being a guide, this standard does not contain detailed calculation approaches or specific instructions.

2   IMPACTS OF CO_2 ON BUILDING OCCUPANTS

While indoor CO_2 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 CO_2 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 CO_2 exposure limits are not relevant to non-industrial building environments and indoor concentrations almost never reach those levels, an indoor CO_2 concentration of 1800 mg/m^3 has became 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 CO_2 concentrations in this range with occupant symptoms such as stuffiness and discomfort, but notes that peer-reviewed studies do not support these associations with CO_2 itself. While several studies have shown associations of elevated CO_2 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 CO_2.

The 1800 mg/m^3 CO_2 "guideline value" is commonly attributed to ASHRAE Standard 62. As noted earlier, the 1981 version of that standard contained an indoor CO_2 limit of 4500 mg/m^3 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/m^3 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 CO_2 concentration will equal 1800 mg/m^3 for assumed values of the CO_2 generation rate per person and the outdoor CO_2 concentration. There is nothing in the standard declaring 1800 mg/m^3 or any other CO_2 concentration to be a

health or comfort based limit. The 1800 mg/m^3 "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 CO_2 concentrations other than 1800 mg/m^3.

While indoor CO_2 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 CO_2 concentrations as low as 1800 mg/m^3 (Satish et al., 2012). These experiments were carefully designed to expose the subjects to elevated CO_2 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   CO$_2$ 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 CO_2 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 CO_2 concentrations about 1250 mg/m^3 above outdoors. For an outdoor CO_2 level of 630 mg/m^3, this indoor concentration roughly corresponds to the commonly cited value of 1800 mg/m^3. The relationship between the percentage of subjects dissatisfied with body odor and CO_2 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 CO_2 concentration be at steady-state. The lack of a strong dependency on physical activity arises from the fact that humans produce CO_2 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 CO_2 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/m^3 of CO_2 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 CO_2 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 CO_2 levels are related based on a single-zone mass balance of CO_2. 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 CO_2 generation rate per person (G) to the difference between the indoor and outdoor CO_2 concentrations (ΔC), or $Q = G/\Delta C$. For a ventilation rate of 7.5 L/s per person and a CO_2 generation rate of 0.3 L/min per person, the indoor CO_2 concentration will be about 1200 mg/m^3 above outdoors. Using slightly different values of the generation rate, one arrives at the indoor CO_2 concentration value of 1800 mg/m^3. This value is often referred to as a CO_2 "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 CO_2.

This relationship between CO_2 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 CO_2 approach is a single-zone steady-state tracer technique, it must abide by the following assumptions to yield a valid air change rate: the CO_2 generation rate is known, constant, and uniform throughout the building being tested; the CO_2 concentration is uniform throughout the building and has achieved steady state; the outdoor CO_2 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 CO_2 concentration varies among rooms, the single-zone approach is not valid and one must employ a multizone mass balance of CO_2 that accounts for the airflows between zones and is far more complicated to apply. Similarly, the steady-state CO_2 value in a single room cannot be used to calculate the ventilation rate of that room if adjoining spaces are at different CO_2 concentrations.

In order for the CO_2 generation rate to be known, constant, and uniform throughout the building, the occupancy level must be known, constant, and uniform. Assuming it is, the CO_2 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, CO_2 generation rates can vary significantly among individuals. Also, the requirement for the CO_2 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 CO_2 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 CO_2 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., CO_2 generation) both temporally and spatially. The relationship is simple under only very specific circumstances, making CO_2 a questionable indicator of ventilation rates.

5 DEMAND CONTROL VENTILATION USING CO_2

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 CO_2 as means to implement DCV, with the outdoor air intake rate controlled using the indoor CO_2 level such that the air intake rate is increased as the CO_2 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 CO_2 DCV; it simply allows DCV to be used to dynamically reset outdoor air intake flows and mentions CO_2 as an acceptable means of doing so. The application of CO_2 DCV per the standard is described in detail in the Users Manual for the standard (ASHRAE, 2010). Additional information on the application of CO_2–based DCV, specifically setpoint values for different space types, is available in Lawrence (2008).

More specific requirements for the use of CO_2 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 CO_2 sensors, their location and their accuracy. It also specifies that the setpoint be 1080 mg/m^3 above the outdoor concentration, which can be measured or assumed to equal 720 mg/m^3. 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 CO_2 is dealt with in ventilation and IAQ standards, focusing on the impacts CO_2 on building occupants, how CO_2 concentrations relate to occupant perception of bioeffluents, the use of indoor CO_2 to estimate ventilation rates, and the use of CO_2 to control outdoor air ventilation rates. Regarding the impacts of CO_2 on occupants, indoor concentrations are rarely close to limits in health-based guidelines, but much confusion still exists regarding CO_2 levels in ventilation and IAQ standards. Based on studies in different countries and different building types, most measured indoor CO_2 concentrations are less than 2000 mg/m^3, with a small fraction above 5000 mg/m^3, but none are in the range of health-based industrial exposure limits. Nevertheless, discussions of indoor CO_2 have long referred to the health impacts of exposure to CO_2. Similarly, many have referred to 1800 mg/m^3 as a "guideline value" for indoor CO_2 or even a requirement, most commonly attributing it to ASHRAE Standard 62. However, there is nothing in the standard declaring 1800 mg/m^3 or any other CO_2 concentration to be a health or comfort based guideline. The notion of an 1800 mg/m^3 "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 CO_2 concentrations of 1800 mg/m^3 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 CO_2 is not a good indicator for those contaminants.

As discussed here, indoor CO_2 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., CO_2 generation) both temporally and spatially in buildings. The relationship can be used to estimate ventilation rates from CO_2 concentrations under only very specific and somewhat unusual circumstances, making CO_2 a questionable indicator of ventilation rates. Finally, ventilation and energy efficiency standards allow, in some cases require, the use of CO_2 concentrations to control ventilation rates.

In conclusion, we understand most of the issues related to indoor CO_2 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 CO_2 concentrations for measuring ventilation rates or which discuss the place of CO_2 in ventilation and IAQ standards be very carefully reviewed by knowledgeable individuals.

7   ACKNOWLEDGEMENTS

8   REFERENCES

Apte, M.G., Fisk, W.J., and Daisey, J.M. (2000). Associations Between Indoor CO_2 Concentrations and Sick Building Syndrome Symptoms in US Office Buildings: An Analysis of the 1994-1996 BASE Study Data. Indoor Air, (10) 246-57.

ASHRAE. (2009). Indoor Air Quality Guide. Best Practices for Design, Construction, and Commissioning. American Society of Heating, Refrigerating and Air-Conditioning Engineers.

ASHRAE. (2010). 62.1 User's Manual. American Society of Heating, Refrigerating and Air-Conditioning Engineers.

ASHRAE. (2013a). ANSI/ASHRAE Standard 62.1-2013, Ventilation for Acceptable Indoor Air Quality. American Society of Heating, Refrigerating and Air-Conditioning Engineers.

ASHRAE. (2013b). ANSI/ASHRAE/IES Standard 90.1-2013, Energy Standard for Buildings Except Low-Rise Residential Buildings. American Society of Heating, Refrigerating and Air-Conditioning Engineers.

ASHRAE. (2014). ANSI/ASHRAE/IES/USGBC Standard 189.1-2014, Standard for the Design of High-Performance Green Buildings. American Society of Heating, Refrigerating and Air-Conditioning Engineers.

ASTM. (2011). Standard Test Method for Determining Air Change in a Single Zone by Means of a Tracer Gas Dilution. E741-11, ASTM International, West Conshohocken, Pennsylvania.

ASTM. (2012). Standard Guide for Using Indoor Carbon Dioxide Concentrations to Evaluate Indoor Air Quality and Ventilation. D6245-12, ASTM International, West Conshohocken, Pennsylvania.

ASTM. (2014). Form and Style for ASTM Standards. ASTM International, West Conshohocken, Pennsylvania.

Bakó-Biró, Zs., Clements-Croome, D.J., Kochhar, N., Awbi, H.B., and Williams, M.J. (2012). Ventilation Rates in Schools and Pupils' Performance. Building and Environment, (48) 215-223.

Bekö, G., Lund, T., Nors, F., Toftum, J., and Clausen, G. (2010). Ventilation Rates in the Bedrooms of 500 Danish Children. Building and Environment, (45) 2289-2295.

Bennett, D., Wu, X., Trout, A., Apte, M., Faulkner, D., Maddalena, R. and Sullivan, D. (2011). Indoor Environmental Quality and Heating, Ventilating, and Air Conditioning Survey of Small and Medium Size Commercial Buildings. CEC-500-2011-043, California Energy Commission.

Berg-Munch, B., Clausen, G., and Fanger, P.O. (1986). Ventilation Requirements fo rthe Conrol of Body Odor in Spaces Occupied by Woman. Environment International, (12) 195-199.

Bluyssen, P.M., Fernandes, E.O., Groes, L., Clausen, G., Fanger, P.O., Valbjørn, O., Bernhard, C.A., and Roulet, C.A. (1996). European Indoor Air Quality Audit Project in 56 Office Buildings. Indoor Air, (6) 221-38.

Cain, W.S., Leaderer, B.P., Isseroff, R., Berglund, L.G., Huey, R.J., Lipsitt, E.D. and Perlman, D. (1983). Ventilation Requirements in Buildings: I. Control of Occupancy Odor and Tobacco Smoke Odor. Atmospheric Environment, (17) 1183-1197.

CEC. (2013). Building Energy Efficiency Standards for Residential and Nonresidential Buildings, Title 24, Part 6, California Energy Commission.

CEN. (2007). Ventilation for non-residential buildings - Performance requirements for ventilation and room-conditioning systems. EN 13779, European Committee for Standardization.

Coley, D.A. and Beisteiner, A. (2002). Carbon Dioxide Levels and Ventilation Rates in Schools. International Journal of Ventilation, (1) 45-52.

ECA. (1992). Guidelines for Ventilation Requirements in Buildings, European Collaborative Action Report No. 11, EUR1449EN. Luxemborg Office for Official Publications of the European Communities.

EPA. (1991). Introduction to Indoor Air Quality. A Reference Manual, U.S. Environmental Protection Agency, U.S. Public Health Service, National Environmental Health Association, EPA/400/3-91/003.

EPA. (2006). BASE Data on Indoor Air Quailty in Public and Commercial Buildings. 402-C-06-002, United States Environmental Protection Agency.

Fanger, P.O. and Berg-Munch, B. (1983). Ventilation Requirements for the Control of Body Odor. Proceedings of Engineering Foundation Conference on Management of Atmospheres in Tightly Enclosed Spaces, American Society of Heating, Refrigerating, and Air-Conditioning Engineers, 100-106.

Gaihre, S., Semple, S., Miller, J., Fielding, S., and Turner, S. (2014). Classroom Carbon Dioxide Concentration, School Attendance, and Educational Attainment. Journal of School Health, (84) 569-74.

Hou, J., Sun, Y., Kong, X., Wang, P., Zhang, Q., and Sundell, J. (2015). Ventilation Rate in Dwellings And Its Association With Children's Health In Tianjin, China. Proceedings of Healthy Buildings Europe 2015, Eindhoven, The Netherlands, Paper ID473.

Hunt, C.M. (1980). Air Infiltration: A Review of Some Existing Maesurement Techniques and Data. In Building Air Change Rate and Infiltration Measurements, ASTM STP 719. C.M. Hunt, J.C. King and H.R. Treschsel, Eds., American Society for Testing and Materials, 3-23.

Iwashita, G., Kimura, K., Tanabe, S., Yoshizawa, S., and Ikeda, K. (1990). Indoor Air Quality Assessment Based on Human Olfactory Sensation. Journal of Architectural Planning and Environmental Engineering, (410) 9-19.

Klauss, A.K., Tull, R.H., Roots, L.M., and Pfafflin, J.R. (1970).History of the Changing Concepts in Ventilation Requirements. ASHRAE Journal, (12) 51-5.

Lawrence, T. (2008). CO_2 Criteria for Monitoring Outdoor Air. ASHRAE Journal, (50,12) 18-27.

Limb, M.J. (2001) A review of international ventilation, airtightness, thermal insulation and indoor air quality criteria. TN 55. Coventry, Great Britain: Air Infiltration and Ventilation Centre.

Persily, A.K. (1997). Evaluating Building IAQ and Ventilation with Indoor Carbon Dioxide. ASHRAE Transactions, (103, 2) 193-204.

Rasmussen, C., Clausen, G.H., Berg-Munch, B., and Fanger, P.O. (1985). The Influence of Human Activity on Ventilation Requirements for the Control of Body Odor. Proceedings of CLIMA 2000 World Congress on Heating, Ventilating and Air-Conditioning, (4) 357-362.

Satish, U., Mendell, M.J., Shekhar, K., Hotchi, T., Sullivan, D., Streufert, S., and Fisk, W.J. (2012). Is CO_2 an indoor pollutant? Direct effects of low-to-moderate CO_2 concentrations on human decision-making performance. Environmental Health Perspectives, (120) 1671-7.

Shendell, D.G., Prill, R., Fisk, W.J., Apte, M.G., Blake ,D., and Faulkner, D..(2004) Associations Between Classroom CO_2 Concentrations and Student Attendance in Washington and Idaho. Indoor Air, (14) 333-41.

USGBC. (2014). LEED v4 for Building Design and Construction. U.S. Green Building Council.

Yaglou, C.P., Riley, F.C., and Coggins, D.I. (1936). Ventilation requirements. ASHVE Transactions, (42) 133-162.