Carbon Dioxide

Special Topics in Indoor Air Quality: Carbon Dioxide

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ONTARIO SOCIETY OF PROFESSIONAL ENGINEERS

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Background

Given that the air we breathe has a direct impact on our health, it is important to be aware of **Indoor Air Quality (IAQ)** and take measures to maximize it. Depending on the jurisdiction, there may be regulations in place, such as an occupational health and safety act, which empowers employees[1,2] to be involved in the collection of air quality measurements or given access to IAQ documents. Depending on the context, different types of air quality measurements and interventions may be implemented.

Air quality is dependent on several factors including, but not limited to, temperature, humidity, carbon dioxide, particulate matter, and volatile organic compounds.[3] No single measurement tool can evaluate all these parameters, and not all measurement types are required or appropriate in all scenarios. Certain measurement types are more practical and commonly carried out than others, such as temperature and humidity.

Because of the common need to measure temperature and humidity, these functions are often found in consumer devices. While these devices may not be as precise as laboratory-calibrated devices, the consensus is that they can be used by non-experts in air quality evaluations. Similarly, consumer devices are now available to measure carbon monoxide, particulate matter, and carbon dioxide. All these devices have limitations. Whenever possible, these measurements should be verified, repeated, and done in consultation or comparison to expert work.

Indoor carbon dioxide (CO_2) concentrations can indicate the level of human activity and the effectiveness of ventilation in a space. CO_2 is produced and exhaled by human beings at different rates, depending on their activity level. The measured indoor CO_2 concentration is a sum of the CO_2 in the outdoor environment around a building (specifically close to the air intake of the HVAC system) topped up by the CO_2 produced by the metabolic activity of humans.[4] CO_2 concentration is one of several parameters that could be considered when assessing and controlling appropriate ventilation and indoor air quality.

Acceptable Indoor CO_2 Concentrations

In general, non-industrial settings with good ventilation levels will reflect a carbon dioxide level typically below 1000 parts per million (ppm). If poorly ventilated, these same indoor spaces can have carbon dioxide readings in a range from 1000 to 3000 ppm. That said, several factors can affect these readings, and factors such as time of day, occupancy levels, temperature, humidity, weather, levels of particulate matter, and volatile organic compounds can all be factored in. As such, the best practice is to concurrently monitor outdoor and indoor conditions, including carbon dioxide levels, and to consider

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[1] Government of Ontario, "Guide to the Occupational Health and Safety Act ." Accessed: May 29, 2024. [Online]. Available: https://www.ontario.ca/document/guide-occupational-health-and-safety-act

[2] CCOHS, "CCOHS: Prevention and Control of Hazards," Canadian Centre for Occupational Health and Safety. Accessed: May 29, 2024. [Online]. Available: https://www.ccohs.ca/oshanswers/prevention

[3] D. Poppendieck, "So you want to buy an indoor air quality monitor." Accessed: May 29, 2024. [Online]. Available: http://poppendieck.com/IAQ/Consumer%20IAQ%20Monitors.html

[4] R. Stumm, "Revisiting the 1,000 PPM CO_2 Limit," ASHRAE J, vol. 64, no. 6, Jun. 2022, Accessed: Mar. 15, 2024. [Online]. Available: https://web.p.ebscohost.com/abstract?direct=true&profile=ehost&scope=site&authtype=crawler&jrnl=00012491&AN=157174532&h=g3/RVhuyHWJvtq1w4ptmC6REpmY6aCkwe5gP230NncoZVeU1hLoI%2Bk/67sJqQcDnrLDueYJxIjG1AoggkKePPQ%3D%3D&crl=c&resultNs=AdminWebAuth&resultLocal=ErrCrlNotAuth&crlhashurl=login.aspx%3Fdirect%3Dtrue%26profile%3Dehost%26scope%3Dsite%26authtype%3Dcrawler%26jrnl%3D00012491%26AN%3D157174532

taking appropriate actions when the CO_2 differential exceeds 600 ppm or more.

When CO_2 levels are high, it can generally be inferred that the rate at which outdoor air enters the room is insufficient for the occupancy and activity types in that room. Implementing demand-controlled ventilation systems that adjust airflow based on occupancy and indoor air quality measurements can help maintain optimal CO_2 levels. However, while high CO_2 concentrations can provide us with a good indication that the ventilation is insufficient, it is more difficult to infer that ventilation is sufficient when CO_2 levels are low. A low CO_2 concentration does not necessarily mean good IAQ. In non-industrial settings where CO_2 is primarily generated by occupant breathing, it is at best an indicator of outdoor air ventilation rate per person.[5]

Periodic monitoring of multiple indoor air quality parameters is recommended to ensure a holistic assessment of indoor environmental conditions. It is also recommended to invest in continuous indoor air quality monitoring systems to promptly identify deviations from recommended CO_2 levels and take corrective actions.

The effects of exposure to CO_2 on overall health, wellness, learning, and work performance have been widely studied. For instance, the correlation between CO_2 and **Sick Building Syndrome** has long been observed.[6] Several studies have shown, at minimum, a correlation between the presence of CO_2 at dosages representative of typical non-industrial settings (e.g., 1,000 to 5,000 ppm) and negative health, cognitive, and performance effects.[7] Among some of the important suggested negative health effects due to CO_2 dosages under 5,000 ppm are bone demineralization, kidney calcification, oxidative stress, and mild hypercapnia.[8]

Results from these studies have tended to be inconsistent, prompting justifiable calls for further research.[9] However, despite limitations in the current state of scientific literature, in the context of occupational health and safety organization and legislation, concentrations above 5,000 ppm are considered significant. The Canadian Centre for Occupational Health and Safety (CCOHS) sets CO_2 exposure limits to:[10]

1. 5,000 ppm (time-weighted average), and
2. 30,000 ppm (short-term limit).

CO_2 dosage levels above 5,000 ppm have often been linked to important health consequences. In controlled environments such as those experienced by astronauts, visuomotor performance issues

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[5] A. Persily et al., "ASHRAE's New Position Document on Indoor Carbon Dioxide," 2022, *International Society of Indoor Air Quality and Climate*. Accessed: Mar. 15, 2024. [Online]. Available: https://orbit.dtu.dk/en/publications/ashraes-new-position-document-on-indoor-carbon-dioxide

[6] M. G. Apte, W. J. Fisk, and M. J. Daisey, "Associations between indoor CO_2 concentrations and sick building syndrome symptoms in U.S. office buildings: an analysis of the 1994-1996 BASE study data," *Indoor Air*, vol. 10, no. 4, pp. 246–257, 2000, doi: 10.1034/J.1600-0668.2000.010004246.X.

[7] T. A. Jacobson, J. S. Kler, M. T. Hernke, R. K. Braun, K. C. Meyer, and W. E. Funk, "Direct human health risks of increased atmospheric carbon dioxide," *Nature Sustainability* 2019 2:8, vol. 2, no. 8, pp. 691–701, Jul. 2019, doi: 10.1038/s41893-019-0323-1.

[8] J. Guillermo et al., "Associations between acute exposures to PM2.5 and carbon prospective observational study dioxide indoors and cognitive function in office workers: a multicountry longitudinal ," *Environ Res*, 2021, doi: 10.1088/1748-9326/ac1bd8.

[9] A. Persily et al., "ASHRAE's New Position Document on Indoor Carbon Dioxide," 2022, *International Society of Indoor Air Quality and Climate*. Accessed: Mar. 15, 2024. [Online]. Available: https://orbit.dtu.dk/en/publications/ashraes-new-position-document-on-indoor-carbon-dioxide

[10] CCOHS, "CCOHS: Prevention and Control of Hazards," Canadian Centre for Occupational Health and Safety. Accessed: May 29, 2024. [Online]. Available: https://www.ccohs.ca/oshanswers/prevention

have been observed at 12,000 ppm, and headaches have been observed with CO_2 levels of 20,000 to 30,000 ppm.[11] At levels around 100,000 ppm, it has been found that CO_2 can cause "convulsions, coma, and death."[12,13]

The OSPE CO_2 Calculator

The contexts discussed above are only some of the many indoor environments in which carbon dioxide monitors can be used as tools for air quality monitoring. The **Ontario Society of Professional Engineers (OSPE)** calculator, based on data from **ASHRAE 62.1** and the **Canadian Standards Association (CSA)**, is available to provide threshold values in many types of indoor environments. It can be found here.

Alternatively, the US-based **National Institute of Standards and Technology (NIST)** has developed the **Quick Indoor CO_2** metric analysis tool, QICO_2, which can be found here.

Use of Indoor CO_2 as a Metric of IAQ

The tradition of measuring CO_2 as a proxy for general air quality is over 150 years old.[14] The presence of CO_2 – particularly in indoor spaces – often correlates with the presence of other air pollutants and it is often proportional to the number of people and, to a degree, the type of physical activity undertaken by those people.[15]

Measuring carbon dioxide is useful as it provides us with at least four forms of information, both direct and indirect, discussed in further detail below.

(i) Carbon dioxide dosage (direct)

Low levels of CO_2 are not harmful, but very high levels can be a concern.[16] In industrial workplaces, the measurement of CO_2 can be directly used to determine if the trace gas concentration (dosage) is too high. When values of CO_2 are near or above 5,000 ppm, it is reasonable to consider the possibility that levels of CO_2 are at or approaching toxic levels. Measurement of CO_2 provides us with direct, quantified information to inform exposure-related risk-mitigation processes.[17]

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[11] H. R. McGregor et al., "Brain connectivity and behavioral changes in a spaceflight analog environment with elevated CO_2," *Neuroimage*, vol. 225, p. 117450, Jan. 2021, doi: 10.1016/J.NEUROIMAGE.2020.117450.

[12] N. J. Langford, "Carbon dioxide poisoning," *Toxicol Rev*, vol. 24, no. 4, pp. 229–235, 2005, doi: 10.2165/00139709-200524040-00003.

[13] A. Persily et al., "ASHRAE's New Position Document on Indoor Carbon Dioxide," 2022, *International Society of Indoor Air Quality and Climate*. Accessed: Mar. 15, 2024. [Online]. Available: https://orbit.dtu.dk/en/publications/ashraes-new-position-document-on-indoor-carbon-dioxide

[14] M. Von Pettenkofer, "'Pettenkofer, Max von: Über den Luftwechsel in Wohngebäuden.'" Accessed: Mar. 15, 2024. [Online]. Available: https://www.digitale-sammlungen.de/de/view/bsb10767804?page=5

[15] A. Persily et al., "ASHRAE's New Position Document on Indoor Carbon Dioxide," 2022, *International Society of Indoor Air Quality and Climate*. Accessed: Aug. 20, 2024. [Online]. Available: https://orbit.dtu.dk/en/publications/ashraes-new-position-document-on-indoor-carbon-dioxide

[16] N. J. Langford, "Carbon dioxide poisoning," *Toxicol Rev*, vol. 24, no. 4, pp. 229–235, 2005, doi: 10.2165/00139709-200524040-00003.

[17] Canadian Centre for Occupational Health and Safety, "Chemical Profiles," 2024, Accessed: Mar. 15, 2024. [Online]. Available: https://www.ccohs.ca/oshanswers/chemicals/chem_profiles/carbon_dioxide.html

(ii) General air quality (indirect)

From the perspective of general air quality, the measurement of carbon dioxide in indoor environments is an indicator of both hydrocarbon fuel combustion and biological metabolism.[18] It complements other air quality measurements like particulate matter, carbon monoxide, and ozone. In outdoor air, CO_2 concentration is about 400 ppm, while indoors, 1,000 ppm is generally viewed as acceptable. A commonly accepted guideline is to maintain indoor CO_2 concentrations below 1,000 ppm. For better indoor air quality, aim for CO_2 concentrations closer to the outdoor level, around 400-600 ppm.[19]

(iii) Ventilation rates (indirect)

CO_2 measurements may be used to make correlations to determine ventilation rates or air change rates. Because people exhale CO_2 at predictable rates based on gender, age, and activity, the difference between indoor and outdoor CO_2 levels can be used to determine the outdoor airflow per person.[20] This can be used to verify if ventilation rates are compliant with targets or regulations. The outdoor airflow per person can be calculated from the formula:

$$V_{outdoor} = \frac{N \cdot 1{,}000{,}000}{C_{space} - C_{outdoor}}$$

Where N is the rate of CO_2 generation per person, measured in litres/second, typical values for CO_2 generation values can be used.[21,22] Additionally, C_{space} is the CO_2 concentration in the space being evaluated and Coutdoor is the CO_2 concentration outdoors. Both are assumed to be measured in ppm, hence the constant of one million in the numerator.[23]

The OSPE calculator provides details on what the target CO_2 should be in different spaces to comply with current standards set by ASHRAE and CSA.

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[18] R. Stumm, "Revisiting the 1,000 PPM CO_2 Limit," ASHRAE J, vol. 64, no. 6, Jun. 2022, Accessed: Mar. 15, 2024. [Online]. Available: https://web.p.ebscohost.com/abstract?direct=true&profile=ehost&scope=site&authtype=crawler&jrnl=00012491&AN=157174532&h=g3/RVhuyHWJvtq1w4ptmC6REpmY6aCkwe5gP230NncoZVeU1hLoI%2Bk/67sJqQcDnrLDueYJxIjG1AoggkKePPQ%3D%3D&crl=c&resultNs=AdminWebAuth&resultLocal=ErrCrlNotAuth&crlhashurl=login.aspx%3Fdirect%3Dtrue%26profile%3Dehost%26scope%3Dsite%26authtype%3Dcrawler%26jrnl%3D00012491%26AN%3D157174532

[19] A. Persily et al., "ASHRAE's New Position Document on Indoor Carbon Dioxide," 2022, *International Society of Indoor Air Quality and Climate*. Accessed: Aug. 20, 2024. [Online]. Available: https://orbit.dtu.dk/en/publications/ashraes-new-position-document-on-indoor-carbon-dioxide

[20] A. Persily and L. de Jonge, "Carbon dioxide generation rates for building occupants," *Indoor Air*, vol. 27, no. 5, pp. 868–879, Sep. 2017, doi: 10.1111/INA.12383.

[21] P. Wolkoff, "Indoor air humidity, air quality, and health – An overview," *Int J Hyg Environ Health*, vol. 221, no. 3, pp. 376–390, Apr. 2018, doi: 10.1016/J.IJHEH.2018.01.015.

[22] M. J. Mendell, A. G. Mirer, K. Cheung, M. Tong, and J. Douwes, "Respiratory and Allergic Health Effects of Dampness, Mold, and Dampness-Related Agents: A Review of the Epidemiologic Evidence," *Environ Health Perspect*, vol. 119, no. 6, p. 748, Jun. 2011, doi: 10.1289/EHP.1002410.

[23] Ontario Society of Professional Engineers, "OSPE Air Quality Calculator." Accessed: Mar. 13, 2024. [Online]. Available: http://ospe-calc.herokuapp.com/

CO_2 sensors are commonly found in the control systems of modern building HVACs.[24,25] The **Demand-Controlled Ventilation** mode of modern HVAC systems typically uses CO_2 levels at a building-wide or building-area context to modulate ventilation. While the CO_2 feedback signals are not typically available to individual building users, CO_2 monitoring can be done on a room-by-room basis to determine whether ventilation in an occupied space is adequate.[26,27] While this kind of CO_2 measurement can provide valuable insight regarding air changes in a particular space, carrying out the measurements and analyzing the time-variant data requires skill and experience, which may put it outside the capability or scope of practice of typical building users.

(iv) Risk of airborne disease transmission (indirect)

CO_2 monitoring can be used to conduct risk analysis in the context of airborne disease transmission, such as in the case of COVID-19. In this scenario, in-situ CO_2 measurement can be used as a proxy for the probability of transmission of disease, albeit with large uncertainties[28] due to factors such as population transmission rates, mask usage, air filtration, or other hygiene measures. Despite the uncertainties, "[all] else being equal, higher CO_2 concentrations correspond to lower outdoor air ventilation rates and potentially an increased [likelihood] of airborne transmission."[29] As such, CO_2 measurement provides a valuable, if imperfect, tool in airborne transmission risk analysis.

Use of CO_2 Monitors

Due to the ability of CO_2 monitors to verify outdoor airflow rates, steady-state CO_2 concentration can be used to confirm if ventilation systems are providing sufficient outdoor air, as required by ASHRAE 62.1. It is important to note that different spaces have different activities, densities, required ventilation rates, and age groups, resulting in variations of expected steady-state CO_2 concentrations between 600 ppm and 2500 ppm, depending on the space. For specific values, one may refer to the **OSPE Air Quality Calculator**.

It is recommended to analyze trends over time, rather than single measurements, to identify problematic spaces. Several factors can affect CO_2 levels and result in readings that do not reflect ventilation quality. For instance, if occupancy is low and CO_2 generation is minimal, outdoor air can infiltrate the building envelope and mask poor mechanical ventilation, resulting in low CO_2 levels. In addition, initial CO_2 levels in vacant spaces may be lower, and they may rise over time before reaching a steady-state level within one to two hours. Weather patterns can also impact ambient (outdoor) CO_2 levels temporarily, resulting in artificially low measurements due to higher levels of infiltration. The presence of individuals near a CO_2 sensor, especially if they exhale near it, can cause a temporary spike in CO_2 readings.

[24] D. Södergren, "A CO_2-controlled ventilation system," *Environ Int*, vol. 8, no. 1–6, pp. 483–486, Jan. 1982, doi: 10.1016/0160-4120(82)90066-6.
[25] Shan. K. Wang, *Handbook of Air Conditioning and Refrigeration*. 2000.
[26] Q. Huang, T. Marzouk, R. Cirligeanu, H. Malmstrom, E. Eliav, and Y.-F. Ren, "Ventilation rate assessment by carbon dioxide levels in dental treatment rooms," *medRxiv*, p. 2021.02.04.21251153, Feb. 2021, doi: 10.1101/2021.02.04.21251153.
[27] S. Batterman, A. Cincinelli, and T. Martellini, "Review and Extension of CO_2-Based Methods to Determine Ventilation Rates with Application to School Classrooms," *International Journal of Environmental Research and Public Health 2017*, Vol. 14, Page 145, vol. 14, no. 2, p. 145, Feb. 2017, doi: 10.3390/IJERPH14020145.
[28] Z. Peng and J. L. Jimenez, "Exhaled CO_2 as a COVID-19 Infection Risk Proxy for Different Indoor Environments and Activities," *Environ Sci Technol Lett*, vol. 8, no. 5, pp. 392–397, May 2021, doi: 10.1021/ACS.ESTLETT.1C00183.
[29] "ASHRAE's New Position Document on Indoor Carbon Dioxide — Welcome to DTU Research Database." Accessed: Mar. 13, 2024. [Online]. Available: https://orbit.dtu.dk/en/publications/ashraes-new-position-document-on-indoor-carbon-dioxide

It is also important to note that CO_2 levels can be affected by metabolic activity. For instance, occupants entering and leaving a space, as well as engaging in other high metabolic activities, can lead to higher CO_2 levels. Engaging in lower metabolic activities, such as sitting quietly, can lead to a decrease in CO_2 levels. When you have many occupants in an enclosed space with insufficient ventilation, the CO_2 levels will rise. Combustion in the space, like a burning candle or the use of any gas appliance, can also increase CO_2 levels.

Various technologies are available to sense CO_2 levels, with **Non-Dispersive Infrared (NDIR)** sensors being the most accurate method. Sensors must comply with accuracy requirements (±75 ppm) outlined in ASHRAE 62.1-2022.6.2.6.1.3 [89]. Most CO_2 sensors available on the market have an accuracy of at least ±50 ppm. As a result, when these sensors are used, a reading of 800 ppm is not different from a reading of 750 or 850 ppm. When selecting a CO_2 sensor, it is also important to consider factors such as how it performs in different humidity conditions, how frequently the sensor measures CO_2, how long the battery lasts, and how the measurement is stored. This information is generally provided by the sensor manufacturer.

CO_2 sensors are typically installed in return or supply ducts to provide an average CO_2 level for all supplied spaces. However, this method assumes perfect air distribution, which may not always be the case. Some spaces may be oversupplied with outdoor air while others are undersupplied, leading to variations in CO_2 levels. Additionally, short-circuiting can cause lower CO_2 levels in the return air when air from the supply duct goes directly to the return duct without mixing with the air in the space. This can result in return air CO_2 levels that do not accurately reflect the CO_2 level in the space, potentially leading to inadequate ventilation in certain areas.

To accurately assess ventilation within different zones, CO_2 monitors should be positioned in the breathing zone, which is the area where occupants breathe. This gives a reading that represents the average conditions in the room. It's important to avoid placing monitors near supply grills, windows, and doors, as these locations may provide cleaner air streams that are not representative of overall averages throughout the room. Monitors also shouldn't be placed too close to individuals or other CO_2 sources, such as combustion sources, as they may measure the exhaled CO_2 plumes from occupants or emissions from other sources.

It is also critical to recalibrate CO_2 monitors on a schedule as indicated in the device manual to ensure accurate measurements. For transparency and disclosure, CO_2 monitors should have visible displays to notify occupants of the air quality, ideally accompanied by a sign indicating the target CO_2 levels and what to do when the targets are not met. The OSPE calculator can be used to determine the expected steady-state CO_2 concentration for a given space, which can help ensure compliance with current ventilation requirements.

Sensor Specifications, Placement, and Measurement Strategies

Concerning measurement strategies, implementations, and sensor specifications, it is advisable that, whenever possible, one should consult experts in ventilation, filtration, and/or air quality, such as a professional engineer or an industrial hygienist. If that is not possible or practical, then one should follow best practices for the environment under test conditions and strive to follow manufacturer guidelines. In all cases, seek to maximize accuracy and precision, comparing the state of air quality indoors with that outdoors and recording relevant factors at the time of measurement, such as time of day, occupancy levels, weather, and events that could have an impact on air quality. Measurements should be recorded and communicated openly and transparently, engaging those affected in meaningful discussions for the maximization of indoor air quality.

The proposed legislation **Bill 140** that was put forward in 2023 in the **Ontario Legislature** provides a good example of suggested strategies for carbon dioxide monitoring for public schools and childcare centres.[30] These carbon dioxide monitoring devices should have a visible display and be based on non-dispersive infrared or better sensing technology. Furthermore, a process for recalibration on an annual basis should be factored into their use.

The proposed legislation includes the following:

1. Monitors must be installed in the occupied space rather than in the ductwork.
2. Monitors must be installed between 1.3 and 1.5 metres above the finished floor.
3. Monitors must be located away from ventilation equipment, windows, and doors.
4. Monitors must be located at least 1.5 metres away from occupants.
5. Monitors must be powered to ensure continuous monitoring.

The outdoor carbon dioxide levels should be monitored concurrently. The indoor carbon dioxide levels should not exceed 600 ppm above the levels measured outdoors.

It is also recommended that a "traffic light" signaling system be adopted which considers the differential between indoor and outdoor values and that:

1. Spaces that are 200 ppm or more below the maximum threshold for carbon dioxide shall be indicated in green.
2. Spaces that are within 200 ppm of the maximum threshold shall be indicated in yellow.
3. Spaces that are at or above the maximum threshold shall be indicated in red.

Conclusion

CO_2 concentration is one of several parameters that could be considered when assessing and controlling appropriate ventilation and indoor air quality. Measurements carried out with them should be made with care, openness, and transparency. Whenever possible these measurements should be verified, repeated, and in consultation or comparison to expert work. In non-industrial settings, good ventilation levels will reflect a carbon dioxide level typically below 1,000 ppm, although it can vary based on several factors. In settings such as schools and childcare facilities, rather than an absolute threshold, a differential of less than 600 ppm between indoor and outdoor carbon dioxide levels should be targeted. Values in other settings can vary.

[30] "Bill 140, Improving Air Quality for Our Children Act, 2023 - Legislative Assembly of Ontario." Accessed: Aug. 20, 2024. [Online]. Available: https://www.ola.org/en/legislative-business/bills/parliament-43/session-1/bill-140

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