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ARTICLES

Application of Indoor CO_2 in Response to the Pandemic

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In response to the COVID-19 pandemic, there have been many recommendations to monitor indoor CO_2 concentrations. However, the technical basis for these recommendations and stated concentration limits are not always clear. This article discusses the application of indoor CO_2 during the pandemic and identifies opportunities for improvement.

Keywords: carbon dioxide, guidance, infectious disease, health, ventilation

The COVID-19 pandemic highlighted the importance of ventilation in mitigating the spread of airborne infectious diseases. As a result, many organizations have made recommendations for improved ventilation [1-2]. These include increased ventilation rates, higher efficiency filtration,

and portable air cleaners. Real-time monitoring of indoor CO_2 concentrations is also recommended as an indicator of ventilation adequacy [3-5]. However, guidelines for CO_2 monitoring vary, and their technical bases are not fully described in all these recommendations. In addition, CO_2 has been used in modeling and experimental studies motivated by the pandemic.

The relationship of indoor CO_2 to ventilation and indoor air quality (IAQ) has a long history, dating back centuries. These discussions have evolved to include 1) the relationship between CO_2 and bioeffluent odors, 2) the impacts of CO_2 on building occupants, 3) the use of CO_2 as a tracer gas to measure air change rates and ventilation performance, and 4) outdoor air intake control using CO_2 concentrations. Recently, CO_2 has also been discussed in response to the pandemic in relation to the risks of airborne disease transmission. The ASHRAE Position Document on Indoor Carbon Dioxide [5] describes the relationship of CO_2 to ventilation and IAQ, documenting the solid knowledge base that exists to support the application of CO_2 monitoring and analysis. This article summarizes how CO_2 monitoring and simulation have been applied in response to the COVID-19 pandemic. Only limited references are provided, with a more complete list available in reference 6. The authors are pursuing a more comprehensive scoping review that will be published later this year.

CO₂ applications in studies of COVID

In response to COVID-19, there have been several research studies and guidance documents describing the use of indoor CO_2, which are all based on established concepts. However, the technical basis for the applications, recommendations, and supporting documents is not always clear. This review considered these applications, including tracer gas measurements of air change rates and ventilation performance, CO_2 as an indicator or proxy of infection risk, indoor CO_2 concentrations as indicators of ventilation or IAQ, and recommendations on the use of CO_2 monitoring.

As an indication of increased interest in CO_2, **Figure 1** plots the number of papers published by year, based on Web of Science searches, using the terms "carbon dioxide ventilation building" and the same terms with the addition of "disease" OR "infectious". The number of papers related to CO_2 and ventilation in buildings has been increasing since 2014, with another increase in 2021, presumably due to the COVID-19 pandemic.

The number of papers that mention "disease" OR "infectious" increased even more dramatically in 2021.

Tracer gas measurements of air change rates and ventilation performance

Many field studies have measured air change rates using standard single-zone tracer gas decay or constant injection, with the latter assuming steady-state CO_2 concentration. These measurements have been conducted in various settings, such as schools, gyms, buses, and retail buildings, to evaluate transmission risk or IAQ. In addition, some measurements have been done using transient or integral mass balance analyses that are not standardized. Some studies have been conducted in naturally ventilated spaces, but applying tracer dilution methods to these spaces can be challenging due to the difficulty in achieving uniform tracer gas concentrations. A few studies used CO_2 as a tracer gas to measure air change rates in laboratory chambers for air cleaner performance testing. These environments are well-controlled, making measurements easier and the results more likely to be valid.

However, these studies involving air change rate estimation vary in their discussion of key assumptions and inputs. For example, some studies lack detail on the CO_2 generation rate, which varies based on occupancy. In addition, some use measured outdoor CO_2 concentrations, while others use an assumed value, which may not be reliable given variations in outdoor concentrations. Another critical assumption is that these tracer gas methods assume the space being studied behaves as a single zone, but most studies do not mention or justify this assumption. Finally, measurement uncertainty is not usually reported, making it difficult to interpret results.
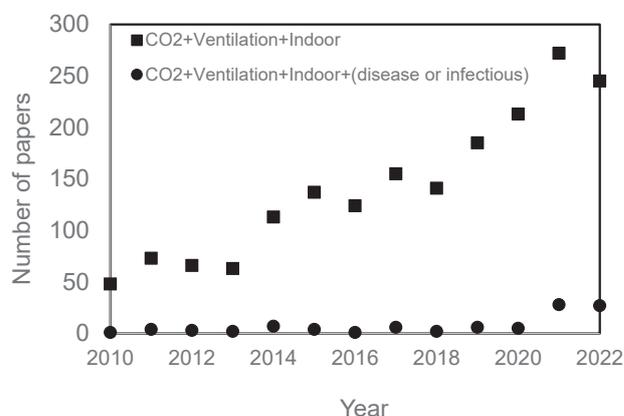

Figure 1. Number of papers related to indoor CO_2 as a function of year (as of 23 Feb 2023).

Indicator of exposure or infection risk

Several studies have used CO_2 as an indicator or proxy for exposure to infectious aerosols or infectious risk through measurements in the field of test chambers and simulations using computational fluid dynamics (CFD). Experimental studies have been conducted in various space types, including concert halls, healthcare facilities, and laboratory chambers. Some studies simultaneously measured CO_2 and airborne particle concentrations to study their relationship, while others used CO_2 concentration as an indicator of exposure or risk using the Wells-Riley equation. Others present CO_2 as a risk indicator without explaining the basis for the connection. Many studies employ the concept of rebreathed air, and some focus on the impact of specific activities like breathing, talking, or signing or features such as ventilation rates, physical partition, and filtration.

Several modeling studies have used CO_2 as an indicator of aerosol exposure and infection risk, using CFD to examine the impact of air distribution. Others used mass balance modeling to evaluate CO_2 variations in space and time as exposure or risk indicators, sometimes acknowledging that there is no direct evidence correlating CO_2 concentrations with virus-containing aerosol levels.

While CO_2 has been used as a surrogate for infectious aerosols, arguments exist for and against. Some reasons for using CO_2 as a surrogate include the ability to capture the fate and transport of fine droplets and simplicity. Reasons against include differences in particle dynamics from gases, two-phase airflow of infectious aerosols, and the inability to capture differences between particles with aerodynamic diameters relevant to virus transmission.

Measurement of indoor CO_2 as an indicator of ventilation and IAQ

Many field studies of infection risk or building performance during the pandemic have included measurements of CO_2 concentrations, generally as metrics of ventilation and IAQ. However, the links between CO_2, ventilation, and IAQ are not always explained. In many cases, ASHRAE Standard 62.1 [8] is cited as the source of concentration limits of 1000 ppm$_v$ or 700 ppm$_v$ above outdoors, despite the standard not containing either value. Other studies cite CO_2 limits in documents associated with the country where the measurements were conducted.

These studies include a survey of the indoor environments in taxis in Paris before and after the lockdown and an examination of the effectiveness of ventilation in buses in Spain. Other studies present assessments of ventilation and IAQ in a fitness club, a concert hall, and some mechanically ventilated buildings. Many of these studies simply report the measured CO_2 concentrations, sometimes compared to a local limit, but generally do not discuss the value of CO_2 as a ventilation or IAQ metric. As discussed in [6], indoor CO_2 concentrations are not good indicators of overall IAQ but can serve as a measure of ventilation using tracer gas concepts as discussed above.

CO_2 measurement for ventilation monitoring or control

Several studies using CO_2 measurement or analysis have been conducted to investigate strategies for monitoring or controlling building ventilation. While these studies generally do not quantify infection risk, they are motivated by the need to manage risk. For example, one proposed feedback control strategy uses CO_2 monitoring as a function of scheduled airing periods, class duration, and masking to manage infection risk in naturally ventilated classrooms. Another used metabolism-based ventilation control to reduce infection risk and energy use in gymnasiums. Others reviewed CO_2 monitoring and ventilation recommendations, noting the challenges in linking CO_2 concentration to infection rates and identifying concentration limits for different spaces.

Indoor CO_2 concentration monitoring

As noted in the ASHRAE Indoor CO_2 Position Document [6], there are numerous recommendations, and in some cases requirements, to monitor indoor CO_2 concentrations to manage the risks of airborne infection, often with a reference concentration for comparison or compliance. These concentrations are based on CO_2 as an indicator of ventilation or as a direct or indirect indicator of infection risk, but the rationales presented are not always clear.

Indoor CO_2 limits have been established for decades for managing generic IAQ and sick building syndrome symptoms, usually around 1,000 to 1,500 ppm$_v$. During the pandemic, several organizations, and governments have recommended monitoring indoor CO_2 concentrations as an indicator of outdoor ventilation rates [2-4]. However, measured CO_2 concentrations are not considered reliable proxies for the risk of airborne exposure to the SARS-CoV-2 virus [9].

Many of these indoor CO_2 limits are based on CO_2 as an indicator of the outdoor ventilation rates, which implicitly involves using CO_2 as a tracer gas requires a target ventilation rate. However, the bases for these limits are not always explained. CO_2 limits based can be estimated using the requirements of ventilation standards, e.g., CEN 16798 [10] or some other ventilation rate intended to control transmission. The CO_2 limits that have been issued generally do not differentiate between space types, occupant characteristics, or required ventilation rates, despite their impact on indoor concentrations. A space-specific CO_2 metric for ventilation has been developed that considers the space, occupants, and target ventilation rate [11], which can be applied using an online tool called *QICO_2* [12].

Conclusions

This article summarized the application of indoor CO_2 in response to the COVID-19 pandemic. CO_2 has been used as a tracer gas to estimate air change rates and as an indicator of ventilation or IAQ, which are not new concepts. Some studies have focused on CO_2 as a proxy for airborne infectious aerosols. However, these applications do not always reflect a complete understanding of the relevant mass balance theory, building ventilation, and IAQ. The studies reviewed in this summary reinforce the need for better guidance on the use of indoor CO_2, including measurement protocols and research on CO_2 emissions by building occupants, indoor CO_2 concentrations, and the relationship between indoor CO_2 and airborne disease transmission. ∎

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