Application of Indoor Carbon Dioxide During the COVID-19 Pandemic

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ABSTRACT

In response to the COVID-19 pandemic, many organizations have recommended improved ventilation to reduce the risk of indoor airborne infectious disease transmission. These recommendations include increasing outdoor air rates and filtration efficiencies, as well as verifying that ventilation systems are operating as intended. There have also been many recommendations to monitor indoor CO_2 concentrations as indicators of ventilation or infection risk, in some cases with quantitative concentration limits. However, the technical basis for these recommendations to monitor CO_2 and, more importantly, the basis for the concentration limits are not always clear. CO_2 monitoring and analysis has also been used in many research studies of the risks of airborne disease transmission and the potential effectiveness of mitigation measures. This paper reviews research applications of indoor CO_2, as well as recommendations for CO_2 monitoring and interpreting measured concentrations issued during the pandemic. As described in the paper, some of the research applications and recommendations employ CO_2 as an indicator of the adequacy of outdoor air ventilation rates, essentially an application of well-established tracer gas measurement methods. In other cases, CO_2 is used as a proxy for exposure to infectious aerosols. In yet other cases, the motivation for measuring indoor CO_2 concentrations and recommended levels is not well explained. This paper reviews the application of indoor CO_2 in response to pandemic and raises several questions regarding their technical basis and the potential for improvement.

KEYWORDS

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

1 INTRODUCTION

In response to the COVID-19 pandemic and in anticipation of future airborne infectious diseases, the importance of ventilation as a control option to manage disease transmission has been widely recognized. Many organizations have made recommendations on building and ventilation system operation, as well as changes to existing standards and guidance (ASHRAE, 2022a; CDC, 2021; REHVA, 2021; WHO, 2021). These recommendations include engineering approaches such as increased ventilation rates, enhanced particle filtration, and the use of portable air cleaners, as well as administrative controls such as face coverings and distancing. Many organizations have also recommended, or suggested consideration of, monitoring indoor CO_2 concentrations in real-time as an indicator of the adequacy of ventilation (EMG-SPI-B, 2021; EPA, 2022; REHVA, 2021). Recommendations for CO_2 monitoring vary in the degree to which they include a description of their technical bases and in specified guideline concentrations. In addition, CO_2 has also been used in modelling and experimental research studies motivated by the pandemic.

The application of CO_2 to the topics of ventilation and indoor air quality (IAQ) is not new, with some of the earliest discussions occurring many centuries ago. Those discussions have evolved over time to focus on 1) how CO_2 concentrations relate to occupant perceptions of bioeffluent odors, 2) the impacts of CO_2 exposure on building occupants, 3) the use of CO_2 as a tracer gas to measure air change rates and other aspects of ventilation performance, and 4) outdoor air intake control using CO_2 concentrations (i.e., demand control ventilation or DCV). More recently, CO_2 has been discussed and employed in the context of managing the risk of airborne infectious disease transmission. All of these topics are discussed in the recent ASHRAE Position Document on Indoor Carbon Dioxide (ASHRAE, 2022b). Research into the application of CO_2 to ventilation and IAQ continues with recent focuses on DCV (Lu et al., 2022) and metrics (Persily, 2022; Wargocki et al., 2021). In addition, the ASHRAE Position Document recommends research on the health and performance impacts of CO_2, indoor CO_2 concentration measurement including sensor performance, the relationship of CO_2 to airborne infectious disease transmission, and other topics. ASTM Standard D6245 (2018) is a guide to the use of CO_2 for evaluating ventilation and IAQ and addresses many of the topics covered by the Position Document. Therefore, a solid knowledge base exists to support the application of CO_2 monitoring and analysis in practice, including to airborne disease transmission. The objective of this paper is to review how CO_2 monitoring and simulation have been applied in response to the pandemic in research and in recommendations. It is not intended to be a systemic literature review, but examples of each application are discussed.

2 CO_2 APPLICATIONS IN STUDIES OF COVID

In response to the COVID-19 pandemic, there have been a number of research studies and guidance documents in which indoor CO_2 has been applied or mentioned. Most of these applications use well-established concepts that have been described previously (ASHRAE 2022b). However, in some cases the technical bases for the applications or recommendations and the supporting discussion are not always clear, which has led to the continuation of longstanding confusion regarding the relationship of indoor CO_2 to ventilation and IAQ (Persily, 1997). This paper reviews these applications, citing examples of each and in some cases noting how CO_2 could be used more rigorously. These applications include tracer gas measurements of air change rates and ventilation performance (section 2.1), the use of CO_2 as an indicator or proxy of infection risk (2.2), measurement and reporting of indoor CO_2 concentrations as indicators of ventilation or IAQ (**Error! Reference source not found.**), and recommendations on the use of CO_2 monitoring (2.4). One study, which does not fall into these categories, examined the accumulation of exhaled CO_2 behind face masks in a study of potential breathing difficulty and discomfort associated with wearing face coverings (Huo and Zhang, 2021).

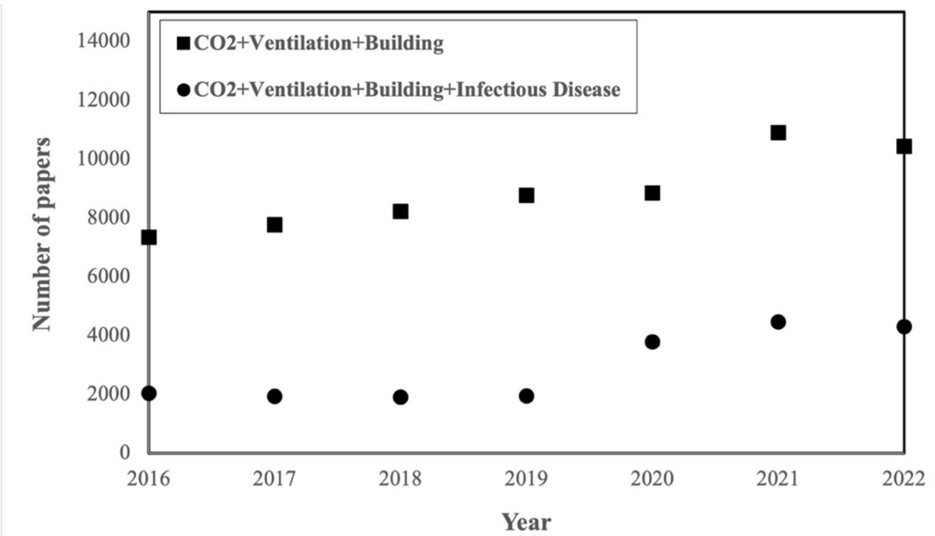

Figure 1: Number of papers related to indoor CO_2 as a function of year

As an indication of increased interest in CO_2, Figure 1 is a plot of the number of papers published by year, based on Google Scholar searches, using the phrase " 'carbon dioxide' ventilation building" and the same phrase with the additional term "infectious disease." The 2022 value is adjusted using the number of papers identified on 22 August 2022 and assuming the number of papers per day will be constant for the year. Interestingly, the number of papers without "infectious disease" has been increasing since 2016, perhaps due to the availability of lower-cost sensors and interest in the impacts of CO_2 exposure on humans (ASHRAE 2022b). However, there was a definite increase in 2021, presumably due to the pandemic generating more interest in indoor CO_2. The lower line, which includes "infectious disease," was more stable over the first four years, with a clear increase starting in 2020.

2.1 Tracer gas measurements of air change rates and ventilation performance

Many reported air change rate measurements in field settings used single-zone tracer gas decay or constant injection (ASTM, 2011), with the latter typically assuming the CO_2 concentration is at steady state. These measurements have been made in studies intended to evaluate transmission risk or to assess IAQ in schools, gyms, buses, retail buildings, and other spaces (Bain-Regious et al. 2022, Deol et al. 2021, Miranda et al. 2021, Querol et al. 2021, Schibuola and Tambani 2021; Shinohara et al. 2022; Ye and Zhang 2022). Others have employed transient or integral mass balance analyses that are not standardized (Blocken et al. 2021, Li et al. 2021, Nusseck et al. 2020). Some measurements have been conducted in naturally ventilated spaces, e.g., Styczynski et al. (2021), which investigated a number of healthcare areas. It should be noted that applying tracer gas dilution methods to naturally ventilated spaces can be challenging given the potential difficulty in achieving the required levels of tracer gas concentration uniformity in such spaces.

Two studies used tracer gas dilution to determine the air change rate in laboratory chambers used to study air cleaner performance (Kong et al.2022, Zeng et al. 2021). Such environments are more well-controlled than spaces in buildings, making the measurements more straightforward and likely to yield valid results. In fact, a standard method of testing portable air cleaners within employs tracer decay to verify the airtightness of the test chamber (AHAM, 2019). CO_2 has been used as a tracer gas to quantify air distribution in a test space to study aerosols emitted by speaking (Singer et al. 2021), but this is a less common application.

These studies vary in the thoroughness of their discussion of key assumptions and inputs required to estimate air change rates. For example, the analysis of peak CO_2 concentrations using the constant injection tracer approach requires the rate at which CO_2 is generated in the space. Not all studies explain the basis of the generation rate used in sufficient detail to judge its reasonableness, which is critical as CO_2 generation rates vary depending on the number of occupants in a space, their characteristics (i.e., age, body mass, gender), and their level of physical activity. Also, some studies involve measurements of outdoor CO_2 concentrations while others use an assumed value, with the latter being questionable given known variations in outdoor concentrations as a function of time, season, and locality. A key assumption in applying these tracer gas approaches is that the space being studied behaves as a single zone. This assumption is required by all of the tracer gas methods employed in these studies and means that a single tracer gas concentration can be used to characterize the space of interest, i.e., that the concentration is sufficiently uniform in the space. Also, single-zone methods do not account for air or tracer transported to and from zones adjacent to the zone being tested. In general, spaces within buildings are not isolated from other spaces, leading to potential errors in air change rate measurements that can be difficult to quantify. Most studies do not mention this assumption or the justification for its use. Finally, these studies generally do not report the measurement uncertainty associated with reported air change rates, making it difficult to interpret the results and understand their significance. Note that the ASTM (2011) tracer gas dilution test method describes how to estimate these uncertainties.

2.2 Indicator or proxy of exposure or infection risk

Several studies have used CO_2 as an indicator or proxy of exposure to infectious aerosols or infection risk. These include field measurements in occupied buildings and test chambers as well as simulations using computational fluid dynamics (CFD) and other modelling approaches. Experimental studies have been conducted in a range of spaces, including concert halls and healthcare facilities (Beato-Arribas et al. 2015; Lu et al. 2021; Schade et al. 2021; Styczynski et al. 2021; Ye and Zhang 2021), as well as laboratory chambers (Good et al. 2021; Kappelt et al. 2021; Parhizkar et al. 2022; Zhang and Bluyssen 2022). Many of these studies involved the simultaneous measurement of CO_2 and airborne particle concentrations to explore the relationship between the two. In other studies, CO_2 was monitored with the concentration used as an indicator of exposure or risk. Sometimes the connection was described in detail, in many cases using the Wells-Riley equation, but in others CO_2 was presented as an indicator of exposure and/or risk without explaining the basis for the connection. Many studies employed the concept of rebreathed air (Rudnick and Milton 2003). Some studies focused on the impact of specific activities, such as breathing, talking, and singing, or features such as physical partitions, ventilation rates, and filtration.

A number of other studies used modelling approaches applying CO_2 as an indicator of aerosol exposure and infection risk. Several of these used CFD to study the relationship in detail (Xiaoping et al. 2011; Castellini et al 2022; Su et al. 2022a; Rivas et al. 2022). The first three references studied the impacts of air distribution, while the fourth also studied exposure on semi-indoor terraces. Other studies used more general mass balance modelling approaches to evaluate CO_2 variations in space and time as an exposure or risk indicator (Cammarata and Cammarata 2021; Li and Cai 2022; Peng and Jimenez 2021; Shinohara et al. 2022. Stabile et al. 2021). Tung et al. (2021) used CO_2 to study potential disease transmission between units in a multifamily building. Barone et al. (2022) modelled the impact of ventilation strategies on infection risk and indoor CO_2 levels in railway coaches and their effect on energy, cost, and atmospheric CO_2 emissions. Boonmeemapasuk and Pochai (2022) developed an infection risk model using CO_2 as an indicator of exhaled aerosols to study disease transmission and vaccine efficacy in an outpatient room. While acknowledging that there is no direct evidence correlating CO_2 concentrations with virus-containing aerosol levels, Nusseck et al. (2020) measured CO_2 generation rates associated with a number of vocal and instrumental musical activities to support ventilation assessments geared towards reducing infection risk.

Ai et al. (2020) discussed the use of CO_2 as a surrogate for infectious aerosols, summarizing arguments for and against. The reasons why CO_2 and other tracer gases might be a good surrogate include: if fine droplets are responsible for disease transmission, then tracer gases can adequately capture their fate and transport; studies exist showing that tracer gases can be "good enough" for characterizing particle dynamics; and, tracer studies, both experimental and simulation, are less complex. On the other hand, counterarguments include the following: particle dynamics are different from those of gases due to the effects of gravity, inertia, and deposition onto surfaces; particle airflow is two-phase, given that infectious aerosols are composed of both solids and liquid; tracer gases cannot simulate coagulation, evaporation, and resuspension of particles; and tracer gases cannot capture the differences between particles over the range of aerodynamic diameters relevant to virus transmission.

2.3 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, although the links between CO_2, ventilation and IAQ are not always explained. In many cases, ASHRAE Standard 62.1 (ASHRAE 2019) is cited as the source of concentration limits of 1000 ppm_v or 700 ppm_v above outdoors, despite the fact that the standard does not contain either value (ASHRAE 2022b). Other studies cite CO_2 limits in documents associated with the country where the measurements were conducted.

Among these studies was a survey of the indoor environments in taxis in Paris before and after lockdown (Hachem et al. 2021), an examination of the effectiveness of ventilation in buses in Spain (Querol et al. 2021), and evaluations of the impacts of ventilation operation and natural ventilation in schools (Kuwahara and Kim 2022, Miranda et al. 2021). Other studies presented assessments of ventilation and IAQ in a fitness club (Peixoto 2021), a concert hall (Kitamura et al. 2021), a "green" commercial building (Su et al. 2022b), and a number of mechanically ventilated buildings (Lastovets et al. 2022). Many of these studies simply report the measured CO_2 concentrations, sometimes comparing to a local limit, but generally not questioning the value of CO_2 as a ventilation or IAQ metric. As discussed in ASHRAE (2022b), 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 in section 2.1.

2.4 CO_2 measurement for ventilation monitoring or control

There have been several studies using CO_2 measurement or analysis 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 that risk. Stabile et al. (2021) conducted a simulation study of infection risk in a high school classroom as a function of ventilation strategy (including periodic airing), class duration, and masking. They proposed a feedback control strategy using CO_2 monitoring to schedule airing periods in naturally ventilated classrooms. Based on another simulation study, Wang et al. (2022) proposed a metabolism-based ventilation control method for gymnasiums to reduce infection risk and energy use, while Li and Cai (2022) suggested a CO_2-based DCV approach. Kitamura et al. (2021) studied CO_2 concentrations during a musical performance in a concert hall and noted the potential benefits of displaying real-time concentrations to concertgoers. Estrella et al. (2021) and Eykelbosh (2021) reviewed studies and recommendations on CO_2 monitoring, noting the challenges in identifying concentration limits for different spaces and in linking CO_2 concentration to infection rates. Similarly, Lu et al. (2021) considered CO_2 monitoring for hospitals, recommending the installation of systems to provide warnings of poor ventilation, while Olsiewski et al. (2021) noted the use of CO_2 above 1000 ppm_v as a proxy for inadequate ventilation in schools. Based on measurements of ventilation and CO_2 in buses, Querol et al. (2021) recommended monitoring CO_2 and occupancy for improving ventilation, noting the need to also monitor outdoor concentrations. Two recent reviews of occupancy behavior modelling and ventilation approaches respectively also discussed selected CO_2 concentration guidelines (Deng et al. 2022; Franceschini and Neves, 2022)

3 INDOOR CO_2 CONCENTRATION MONITORING

As noted in the ASHRAE Indoor CO_2 Position Document (ASHRAE 2022b), there are numerous recommendations, and in some cases requirements, to monitor indoor CO_2 concentrations to manage the risks of airborne infection. These recommendations and requirements often include a reference concentration for comparison or for more formal compliance. Many of these concentrations are based on CO_2 as an indicator of ventilation and the associations of low-ventilation rates with increased risk (WHO 2021). Other limits are based on CO_2 as a direct or indirect indicator of infection risk, though the rationale for those limits is not always clearly described. A complete review of all pandemic-motivated CO_2 limits is beyond the scope of this paper, but a summary is presented here.

Indoor CO_2 limits have existed for decades, generally based on the management of generic IAQ concerns and sick building syndrome symptoms (Health Canada 2021; Toyinbo et al. 2022). These limits have tended to be on the order of 1000 ppm_v but range as high as about 1500 ppm_v. Of particular note is the 1000 ppm_v limit in Japan that was issued in 1970; since then, thousands of buildings have been tested annually to determine if they comply (Hayashi et al. 2020). During the COVID-19 pandemic, many additional recommendations have been made to monitor indoor CO_2 concentrations. Among the many organizations and government bodies making these recommendations, the Centers for Disease Control and Prevention (CDC 2021) in the United States, the Federation of European Heating, Ventilation and Air Conditioning Associations (REHVA 2021) in Europe; and Environmental Modelling Group and Scientific Pandemic Insights Group on Behaviours (EMG/SPI-B 2021) in the United Kingdom have provided guidance on using CO_2 as an indicator of outdoor ventilation rates. However, AIVC (2020) noted a measured "CO_2 concentration does not indicate with much certainty that the occupants of a building are safe from airborne exposure to the SARS-CoV-2 virus and is not recommended as a reliable proxy of the risk of airborne exposure to the virus." Some recommendations differentiate between spaces with an elevated risk of infection based on occupant density or activities likely to increase the rate at which people generate respiratory aerosols. Mandatory CO2 concentration limits have also been issued by some governments, e.g., Belgium (BFG 2021). A website displays a world map showing where and how CO_2 is being monitored to manage the risk of airborne transmission, including guideline values that have been issued by governments and other organizations (AIREAMOS, 2022)

Many of these indoor CO_2 limits are based on CO_2 as an indicator of the outdoor ventilation rate per person, which implicitly involves the use of CO_2 as a tracer gas along with 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. ASHRAE Standard 62.1, which are not based on the control of airborne disease transmission, 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. For example, the steady-state CO_2 concentrations corresponding to the ventilation requirements and default occupancy densities in Standard 62.1 range from about 1000 ppm_v in office spaces and classrooms with younger students to between 1500 ppm_v and 2000 ppm_v in restaurants, lecture classrooms, and retail spaces to above 2500 ppm_v in conference rooms and auditoriums. A space-specific CO_2 metric for ventilation has recently been developed that allows the user to identify target CO_2 levels based on the space, occupants, and target ventilation rate (Persily 2022), and an online tool, *QICO2*, is available to facilitate its application (Persily and Polidoro 2022).

4 CONCLUSIONS

This paper summarized the application of indoor CO_2 to ventilation and IAQ studies motivated by the COVID-19 pandemic. Many of these studies used CO_2 as a tracer gas to estimate air change rates or as an indicator of ventilation or IAQ. These applications are not new to the pandemic as they have been used for decades (ASHRAE 2022b). Others have focused on CO_2 as a proxy or indicator of airborne infectious aerosols exhaled by building occupants. This concept is not new either but has been the subject of more work in the last two years. As has been the case for decades (Persily 1997), these applications of CO_2 have not always reflected a sound technical understanding of the relevant mass balance theory, the significance of human CO_2 exposure, and the relevance of indoor CO_2 to overall IAQ. For example, the studies employing CO_2 as a tracer gas are variable in terms of how well they reflect awareness of established measurement standards. These studies include varying levels of detail and thoroughness in describing the measurement methodology, limited discussion and confirmation of key assumptions including that the space is behaving as a single zone, and a lack of measurement uncertainty in reported values.

In summary, the application of indoor CO_2 in light of the pandemic reflects much of the confusion that has existed for decades. For example, many papers cite ASHRAE Standard 62.1 as a reference for an indoor CO_2 limit of 1000 ppm_v, or 700 ppm_v above outdoors, despite the fact that the standard last contained the 1000 ppm_v value in 1989 and never contained a 700 ppm_v limit (ASHRAE 2022b). The studies cited in this summary reinforce the need for improved guidance on the application of indoor CO_2, including concentration measurement protocols, as well research on the use of CO_2-based DCV, CO_2 emission rates of building occupants, measurement of indoor CO_2 concentrations including sensor performance and location, and the relationship of indoor CO_2 to airborne infectious disease transmission.

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