FAST-AIR: Fast analytic systems for tracer-gas assessment in indoor research - development and testing of CO_2 tracer-gas system

Harald Andersson[1*], *Mikael* Sundberg[1], *Dario* Senkic[1], *Mats* Sandberg[1] and *Alan* Kabanshi[1]

[1]Department of Building Engineering, Energy Systems and Sustainability Science, University of Gävle, Sweden

Abstract. The time constant of ventilation of rooms in buildings is between 15 minutes (in office spaces) to 2 hours (in residential buildings). Currently, most of the tracer gas system analysers on the market have a minute-based time constant and depending on the channels a cycle of sampling and analysis may take up to 6 minutes, E.g., 6 channel system. Essentially, only mean values are recorded with most present tracer gas analysers. This is a hindrance for detailed temporal analysis of conditions in the room and consequently is does not capture the resolution of the influence of the internal flow on air and contaminant distribution. The current paper presents work on the development and testing of a fast response CO2 tracer-gas system with a time constant of 1 second. In contrast to the present analysers, not only the mean values but also the whole statistical distribution of variables can be recorded, and pulse responses can be analysed. This makes the system viable for measurement and analysis of not only spatial but also temporal distribution of contaminants. For example, recirculating airflow in the room generated by flooding of ventilation air is possible to be measured and thus making it easy to extend the analyses of the process of ventilation far beyond the possibilities with current systems.

1 Introduction

Tracer gas measurement techniques have been a cornerstone in the quantification of ventilation rates since their inception in the 1960s. The fundamental principle of tracer gas methodology involves the introduction of a distinct gas into an air volume, facilitating its subsequent detection and quantification through tracer gas samplers [1]. This technique allows for the precise measurement of air exchange rates, a critical factor in ensuring optimal indoor air quality and energy efficiency in buildings.

The methodologies for tracer gas detection are categorized into passive and active sampling techniques [1]. Passive sampling involves the employment of a chemically reactive substrate, such as a strip or stick, which undergoes a quantifiable chemical reaction upon exposure to the tracer gas. This substrate is later analyzed to determine the extent of its chemical interaction with the tracer gas, thereby providing a measure of gas concentration. In contrast, active sampling techniques utilize mechanical pumps to draw air samples into a chamber equipped with an infrared (IR) sensor. The IR sensor measures the absorption of IR radiation by the air sample, which correlates to the concentration of tracer gas within the chamber. Through this measurement, the quantity of tracer gas present can be accurately determined.

A variety of tracer gases are utilized for ventilation assessment, with carbon dioxide (CO_2), nitrous oxide (N2O), and sulphur hexafluoride (SF6) being among the most commonly employed due to their distinct chemical and physical properties that facilitate detection and measurement [2]. Among the tracer gas methodologies, the pulse method, and the step-down (decay) method are prevalent. The pulse method involves the controlled release of a tracer gas over a designated period, followed by monitoring the peak concentration and its subsequent decay to baseline levels at a detection point, allowing for the determination of air exchange dynamics. Conversely, the step-down method involves a continuous release of tracer gas, which is abruptly halted, and the decay in gas concentration is monitored. Analysis of the decay curve enables the calculation of parameters such as the local mean age of air and the nominal time constant for the space under investigation [3].

Despite the effectiveness of these methods, current tracer gas analysis systems, typically characterized by minute-scale time constants, present limitations in capturing high-resolution temporal variations in air and contaminant distribution within spaces. This limitation is primarily due to the extended sampling and analysis cycles, which may span up to six minutes, depending on the system configuration. As a result, these systems often yield only mean concentration values, insufficient for detailed temporal analysis of indoor environmental conditions [4]. For instance, devices like the Innova series and Bruel & Kjaer [5], have an average data acquisition time of 2-3 minutes, may inadequately

* Corresponding author : Harald.Andersson@hig.se

capture the peak concentrations and temporal dynamics associated with the pulse method. Consequently, there is a compelling need for the development of tracer gas measurement systems featuring rapid response capabilities, which would significantly enhance the precision and utility of ventilation assessments.

2 Technical description

Most of the commonly used tracer gas systems are slow and are expensive, see [4] and the references therein. This section discusses a low-cost and fast tracer gas system called FAST-AIR (fast analytic systems for tracer-gas assessment in indoor research). The proposed FAST-AIR tracer-gas system consists of two parts: The sensor module (data acquisition) and tracer gas seeding system. These two systems are power and controlled independently to facilitate for different tracer gas measurement methods, e.g., the constant injection method, constant concentration method and concentration decay method (which would not require use of the seeding system) [6]. A schematic flow diagram of the system is shown in Figure 1.

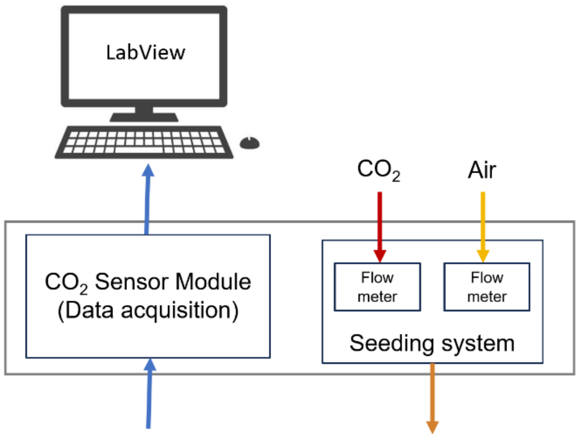

Fig. 1. Overview of tracer-gas system

2.1 The CO_2 sensor module

Common tracer gas system employs SF_6 due to its non-toxic nature and low atmospheric concentration. These systems use infrared photoacoustic spectroscopy sensor modules which are expensive and have a slow data acquisition time. Fu et al. [4] have discussed recent systems which have typically around 45 seconds data acquisition time. This extended acquisition time renders them inadequate for capturing transient peak concentrations effectively as discussed in the study and the references therein.

The proposed system employs a "SenseAir K30" CO_2 sensor, which is low-cost and has a fast response time of 1 second for data acquisition. This sensor offers a measurement range of up to 10000 ppm with an accuracy of +/- 30 ppm and +/- 3% of the reading. Leveraging infrared light absorption within a reflective measurement chamber with a volume of 1 ml, the sensor provides versatility for various sensing and control applications, offering both digital and analogue outputs.

The newly developed system integrates eight sensors across four modules, each offering two measurement channels. This configuration enables independent operation of each module and facilitates instantaneous data acquisition on every measurement channel. Figure 2 gives an overview of the system module.

In free air, the response diffusion time of the sensor stands at 20 seconds, facilitated by the diffusion of air through a membrane enveloping the measurement chamber. However, calibration ports are available to facilitate forced airflow, thereby significantly reducing the time constant. While the precise final time constant awaits empirical measurement, preliminary estimates suggest it to be under 10 seconds.

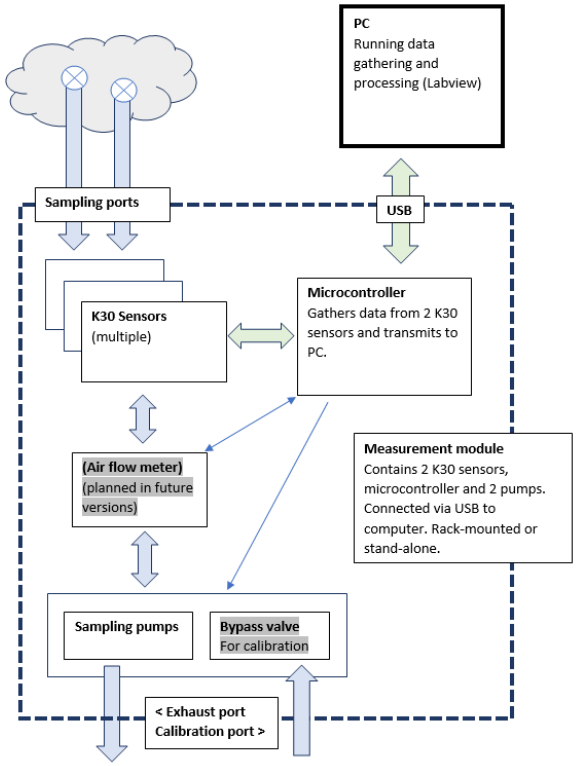

Fig. 2. Overview of a sensor module.

2.1.1 Sampling pump

As a means of forcing the sampled air through the sensor a pump is needed, a suitable pump with a high enough flow to exchange the air in the measurement chamber at least every second is necessary, thus a flowrate of 60 ml/minute minimum is needed. RS components have a miniature diaphragm pump capable of 250 ml/minute that should be suitable. An option is to fit a flow meter.

2.1.2 Communication and control

For communication and control, a digital setup is recommended to minimize addition of more uncertainties in the measured data. The sensor supports digital communication via standard UART and I2C ports, making it compatible with various microcontrollers and computers for data acquisition.

To streamline data handling from multiple sensors, an Arduino microcontroller is employed as a data hub, facilitating data aggregation and transmission to the LabVIEW program. The Arduino is packaging the data more conveniently and transmitting the measurements to the LabVIEW program. LabVIEW program is used due to availability and our previous experience, otherwise other programs with facilities of virtual instruments can also be used.

2.2 Tracer gas seeding system

The tracer gas seeding system is integrated to to facilitate for constant and continuous injection measurement methods. This system allows for the controlled adjustment of the seeding concentration of the tracer gas, which is systematically predetermined by the mixing ratio of compressed ambient air and pure CO_2. The modulation of air and CO_2 flow rates during the dosing process is meticulously regulated by two flow regulators (Omega FMA-1600A series shown in Figure 3) with a precision of ± 0.8%. The effluent from both flow meters is homogeneously combined to achieve a specific seeding CO_2 concentration and flow rate, which is then introduced into the designated room or experimental setup. By rigorously managing the flow rates of both air and CO_2, it is possible to maintain the CO_2 concentration and flowrate at a consistently predetermined level.

Therefore, the system opens for more detailed studies, analysis and research application in fields related to indoor air quality, ventilation efficiency, and the dispersion of airborne contaminants.

Fig. 3 Photo of flow regulators.

2.3 Bill of materials

The total cost for a system with rack of 8 sensors/sampling channel and flow meters is approximately 30,000 SEK (equivalent to €2700), which includes the following bill of materials:

- Senseair K30 CO_2 sensors,
- Arduino microcontroller
- Rack enclosure.
- Various hoses, fittings, and valves.
- Various electrical components, USB cables,
- Sampling pump.
- Module enclosure (Eurorack PCB with 3D-printed assembly and lid)
- Flow meter (note that due to supply shortage of flow meters in the current system, other options can be explored).

3 Measurement Procedure

3.1 System modification and applicability

The FAST-AIR system was tested to assess the system's ability to capture peak concentrations in a setup, specifically designed to investigate rapid transient changes in contaminant concentrations during recirculation and other complex airflow interactions within indoor environments. This evaluation formed the basis of a preliminary experimental investigation, contributing to our broader research project focused on understanding the mechanisms of contaminant transport and infection transmission in indoor spaces.

To Achieve the FAST-AIR tracer gas system was modified to include an innovative sampling globe, integrated seamlessly doser, see schematic diagram in Figure 4. Kabanshi et al. [7] have given explanation on the measurement principles of the sampling globe and doser, and the theory for measurement analysis of local contaminant transfer and evacuation in different zones in the room. This paper underpins the technical foundation for the sampling globe and doser, offering insights into their functional integration within the FAST-AIR system and demonstrates applicability of the system with a brief experimental study.

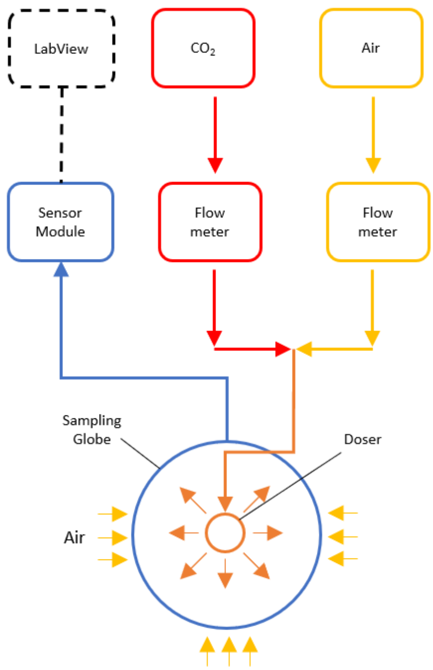

Fig. 4. Schematic diagram of FAST-AIR system with sampling globe and doser.

3.1.1 Sampling globe

In our current measurement setup and experimental framework, we utilize an in-house sampling globe for quantifying transfer probability and local evacuation of contaminants by utilising measurements of transient peak CO_2 concentration in different regions in a room. This setup is used to address the research questions in our ongoing project. Therefore, different sampling methods and systems can be applied which demonstrates the versatility of the FAST-AIR tracer gas system.

The sampling globe comprises eight hollow 3D-printed arms, each with an outer diameter of 8 mm and an inner diameter of 4 mm (see Figure 5). These eight arms are configured as half-circles, measuring 300 mm in length, with 15 sampling apertures (each with a diameter of 0.8 mm) positioned at 20 mm intervals along their length. Notably, the sampling apertures are oriented inward toward the centre of the globe. This design feature ensures that, for our measurement goals, the measured CO_2 concentration reflects an average concentration within the globe, accounting for both inflowing and outflowing air streams.

The globe has a diameter of 191 mm corresponding to a volume of 3.6 litres (0.0036 m^3). The arms are interconnected at both the top and bottom of the globe via a specially designed 3D-printed connector (depicted in Figure 6). This connector comprises eight 4 mm ports to which the individual arms are affixed. These ports serve as conduits directing the sampled air towards a tube connected to the pump of the sensor module, while the top connector also has an independent tube that is used to seed the tracer to the doser.

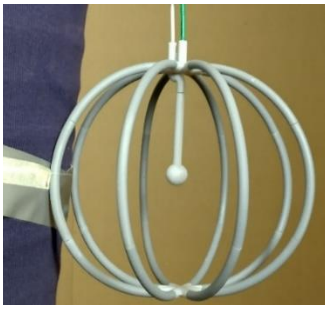

Fig. 5. Photo of sampling globe next to a human heat simulator.

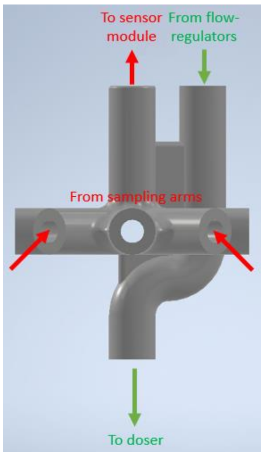

Fig. 6. 3D-Printed Connector.

3.1.2 Doser

Located at the centre of the globe, a doser is suspended from the apex of the top globe connector. As elaborated in section 3.1.1., this connector incorporates an independent tube dedicated to delivering a predetermined concentration of CO_2 tracer gas to initiate the seeding process within the doser, illustrated in Figure 7. The doser comprises eight small apertures, each with a diameter of 0.8 mm, through which jets of tracer gas are emitted outward into the sampling globe. Consequently, these jets promote the thorough mixing of the tracer gas within the globe. We postulated that the turbulent flow generated by the jets within the globe facilitates the dispersion and dilution of the tracer gas, ultimately achieving a uniform concentration throughout the globe. Subsequently, this homogenized concentration is measured by the sampling globe.

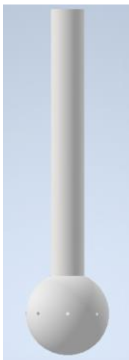

Fig. 7. 3D image of doser.

3.2 Measurement Setup

Measurements were carried out in a climate chamber, 4m (length) x 4m (width) x 2.5m (ceiling height) setup as a study mock-up room. The room is configured with two ventilation systems operated independently and is designed to test displacement ventilation and mixing ventilation. Each ventilation system was operating with 20 l/s air flowrate and supply temperature of 18 °C. This gives the climate chamber a nominal time constant (τ_n) of 33 minutes and 1.8 ACH. The room has four human heat simulators (manikins) representing occupants and each producing 100 W of heat.

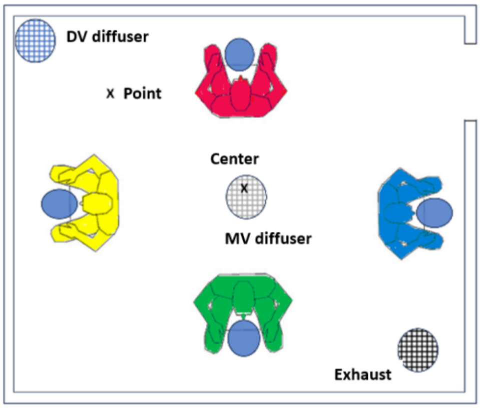

Fig. 8. Measurement setup

CO_2 served as the tracer gas for this study, with concentration measurements taken at a height of 1.1m, corresponding to the mouth region of the simulated occupants. This height was selected to accurately represent the effective inhalation and exhalation zone, a critical domain for evaluating the potential for airborne contaminant or pathogen transmission. The volume encapsulated by the measurement globe around each simulator's mouth region was defined as the effective measurement volume, ensuring relevant data collection for exposure risk. Two tracer gas dosing setups were considered: Continuous injection setup and the burst setup.

3.2.1 Continuous injection setup

In this setup, the blue manikin is the dosing point representing a contaminant source (sick occupant) while the other occupants are susceptible individuals. The dosing gas is set at a rate of 2 L/min of air and 0.1 L/min of pure CO_2. This mixture results in a CO_2 concentration of 48039 PPM (≈4.8%), which is equivalent to a human breath. The mixture is held at a steady concentration by the tracer gas seeding system and continuously released for 3 hours (5 nominal time constants) representing an occupancy and exposure period.

3.2.2 Burst dosing setup

In this setup, a balloon filled with 9.5 Liters of pure CO_2 is burst in the center of the room at a height of 1.1 m. This chosen to assess evolution of contaminants in situation where a person coughs or sneezes or situations where there is a sudden release of contaminants. This creates a different airflow mechanism to that of the continuous injection method and tracking of peak concentrations can help understand such transient airflow dynamics and evolution for each occupant in the room.

4 Measurement results and discussion

The results between the measurement methods are compared for each system and between systems. For readability and simplicity, only concentration results are discussed in this paper. A more detailed analysis on the implications of the results in indoor environment is given in [7].

4.1 Mixing ventilation (MV) system

Under mixing ventilation, a differentiation emerges between the two tracer gas dosing methodologies: continuous dosing exhibits a gradual elevation in gas concentration until a stable equilibrium is achieved, as illustrated in Figure 9 (top). This observation underscores a spatial heterogeneity in concentration distribution, notably at specific locations (e.g., "Red"), despite the anticipation of uniform mixing conditions inherent to mixing ventilation systems. Such spatial disparities are accompanied by minimal temporal fluctuations across all measurement points, indicating a relatively consistent exposure profile across different spatial coordinates within the environment. Furthermore, elevated concentration levels observed at the exhaust outlet suggest a stratified vertical distribution of contaminants, indicating inefficiencies in contaminant removal or uneven air mixing.

On the other hand, the burst dosing technique is characterized by a more pronounced variability, both spatially and temporally, before stabilizing. Immediately following the release (e.g., the bursting of a balloon), concentrations spike at the central point of release, with subsequent peak levels recorded asynchronously across various locations. This pattern of dispersion reveals distinct peak concentrations that diminish over time, indicative of the tracer gas recirculating back the zones. Such a phenomenon, not evident in the continuous dosing method, highlights the dynamic interplay of air currents and the implications this may have on complex behaviour of airborne contaminants under burst dosing conditions.

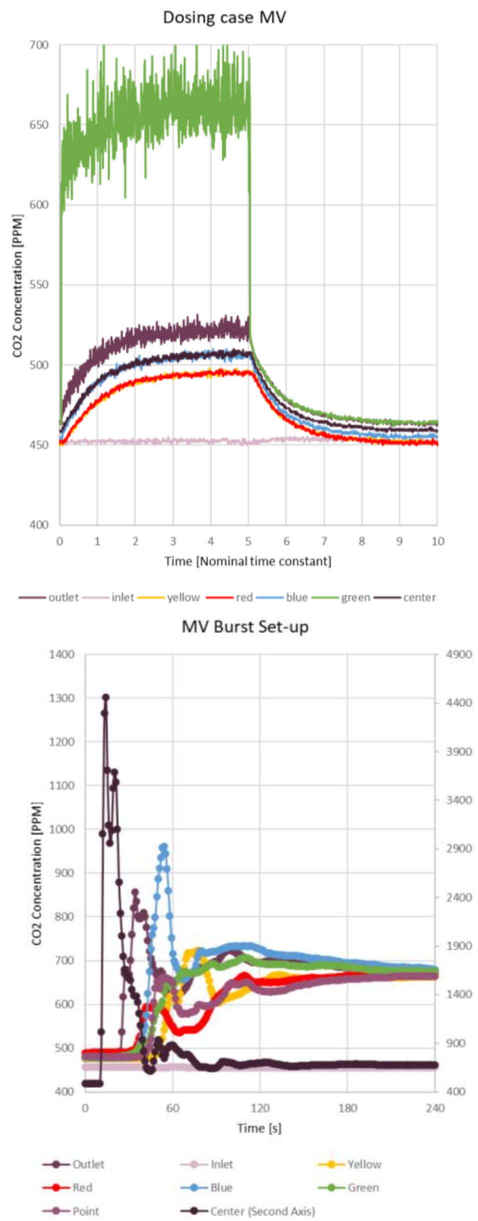

Fig. 9. CO_2 concentration under mixing ventilation for dosing (Top) and burst tracer injection setups (Bottom). Concentration for the center is represented on secondary axis.

4.2 Displacement ventilation (DV) system

Within the context of a displacement ventilation system, pronounced spatial and temporal variations in tracer gas concentration are observed, as shown in Figure 10. The employed dosing methodology reveals significant temporal fluctuations, particularly at the central measurement point under dosing. It is critical to note that this central location lacked a human heat simulator, thereby negating the influence of thermal plumes, which typically serve as a primary driving force for airflow and contaminant dispersion within such ventilation systems (which can be attributed to the stable behaviour under burst methods at the centre, point and outlet).

Spatial disparities in tracer gas concentration under dosing are notably evident at the location marked as "Blue", whereas the measurements at "Red" and "Yellow" locations exhibit a tendency to overlap, suggesting minimal spatial differentiation between these two points. This observation may indicate a homogenization of air and contaminant distribution in these areas, influenced by the layout and operational dynamics of the displacement ventilation system.

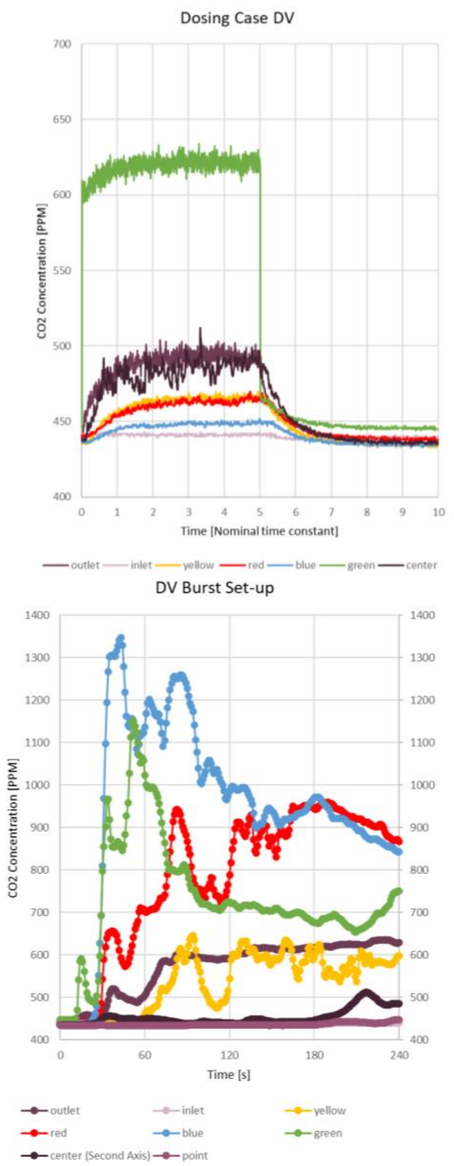

Fig. 10. CO_2 concentration under displacement ventilation: Top shows setup and bottom shows the burst tracer injection setup. Concentration for the centre is represented on secondary axis.

In contrast, the application of the burst dosing method introduces substantial temporal and spatial variability, manifesting independently across different locations within the room. This variability is indicative of significant recirculation patterns, which are attributed to the instabilities associated with thermal plumes generated within the space. Such instabilities contribute to the complex behaviour of airflow and contaminant movement, highlighting the intricate interplay between thermal forces and ventilation effectiveness. The system picks this behaviour under the burst dosing method which can help to understand the critical influence of thermal plumes on the spatial and temporal distribution of contaminants.

4.3 Comparison between ventilation systems.

The mixing ventilation has much higher variations in CO_2-levels for the green manikin compared to displacement ventilation. This indicates higher velocities and turbulence for mixing ventilation than displacement ventilation, compare top Figures 9 and 10. Displacement ventilation on the other hand has much faster decline in CO_2-levels when the dosing is stopped and after 5, at 6 τ_n the displacement ventilation is back at almost nominal CO_2-levels, this means that displacement ventilation is much better than mixing ventilation at evacuating the CO_2 from the occupied zone. Both mixing and displacement ventilation reach a steady state after 2.5 τ_n. At this point it is clear that the transmission affects the manikins differently for displacement and mixing ventilation. For mixing ventilation blue has the highest CO_2-level followed by red and yellow. Whereas for DV blue is almost unaffected, whilst red and yellow have higher levels of CO_2.

The analysis of CO_2 concentration levels under different ventilation strategies reveals distinct differences in airflow dynamics between mixing and displacement ventilation systems. Specifically, the mixing ventilation system exhibits significantly higher fluctuations in CO_2 levels around the green manikin compared to the displacement ventilation system. This observation suggests increased air velocities and turbulence in the mixing ventilation setup, as evidenced by the comparative analysis of Figures 9 and 10 under dosing method. Conversely, displacement ventilation demonstrates a more rapid decline of CO_2 concentrations post-dosing at 5 nominal time constants (τ_n), achieving near-nominal levels after 6 τ_n, indicating higher performance in purging CO_2 from the occupied zone.

Both ventilation strategies attain equilibrium states after approximately 2.5τ_n, highlighting different impacts on contaminant transmission across the manikins. In the scenario of mixing ventilation, the blue manikin records the highest CO_2 concentration, followed by red and yellow. However, under displacement ventilation, the blue manikin experiences minimal impact, while red and yellow exhibit elevated CO_2 levels, suggesting variations in exposure risk dependent on ventilation strategy.

In the context of burst dosing within a mixing ventilation framework, the rapid equalization of CO_2 levels post-dosing is notable. Excluding the inlet, measurement points stabilize at 700 ppm within four minutes, displaying a characteristic pattern of sharp CO_2 concentration spikes followed by declines and subsequent stabilization. For the centre, the outlet and blue the first peak is high but short (less than 15 s).

Displacement ventilation, in contrast, shows immediate and pronounced CO_2 spikes for the blue and green manikins post-burst, with red and yellow experiencing more gradual increases. Notably, the centre point under displacement ventilation exhibits minimal response to the burst, attributed to the positioning of the balloon at the same height. Since the CO_2 has a higher density than the surrounding air it will fall, this results in CO_2 being driven towards the floor, contrasting with the mixing ventilation scenario where higher air velocities facilitate CO_2 dispersion throughout the room.

Overall, the system captures different behaviours and transient peak concentrations under the two considered dosing methods, which is like what is observed in other studies [4]. This underscores the nuanced impact of the response of measurement under different contaminant sources and mechanisms on the assessment of ventilation efficacy and the spatial-temporal distribution of airborne contaminants. As shown the study has a

The results herein underscore the complex interplay between ventilation strategy, spatial configuration, and the dynamics of airflow characteristics in a room. The results show that system has a potential to be used for investigations in complex airflow transient dynamics and will capture behaviour depending on airflow in the room and the investigated method. The observed differences in transient peak concentrations and dispersion patterns between the two ventilation systems mirror those documented in other research of tracer gas systems [4], emphasizing the potential application of FAST-AIR tracer gas system. Further studies are recommended to investigate the limits of the system, time constants and application for different indoor environment setups.

5 Conclusions

As the data shows, a lot of relevant and drastic changes happens within the span of the first four minutes. This information would not be measured with older tracer gas-systems which have longer measurement times (2-3 minutes). Those systems would only give two data points for the first four minutes, the data points would also be averaged over 2-3minutes which would not be able to capture the CO_2-peaks for the occupants (which occur for a relatively short amount of time). A lot of the information necessary to calculate the risk of cross-contamination, exposure times, exposure probability, contamination probability and local purging flowrate happens at fast pace, especially at the beginning of the experiment. Slower tracer gas-system would not be able to collect this data at fast enough rate to calculate these values accurately.

Funding

This work is partly supported by FORMAS (Dnr: 2021-01606) under the project “Ventilation as a strategy to reduce indoor transmission of airborne diseases: Development of new strategies and a risk assessment model”.

References

1. M. H. SHERMAN *Building and Environment*, Vol. 25, No. 4, pp. 365-374, 1990.
2. D. W. Etheridge and M. Sandberg, *Building ventilation: theory and measurement*. Chichester: John Wiley & Sons, 1996.
3. G. Remion, B. Moujalled, M.E. Mankibi. Review of tracer gas-based methods for the characterization of natural ventilation performance: Comparative analysis of their accuracy. *Building and Environment*, (2019)
4. Fu L, Yang M, Niu J, Ren W, You R. Transient tracer gas measurements: development and evaluation of a fast-response SF_6 measuring system based on quartz-enhanced photoacoustic spectroscopy. *Indoor Air*. 2022; 32:e12952. https://doi.org/10.1111/ina.12952
5. Bruel & Kjear Instruction manual for the multi-gas Monitor Type 1302 *Bruel & Kjear* (1990)
6. Laussmann, D.; Helm, D. Air Change Measurements Using Tracer Gases: Methods and Results. Significance of air change for indoor air quality. *In Chemistry, Emissin Control, Radioactive Pollution and Indoor Air Quality*; Mazzeo, N., Ed.; InTech: Rijeka, Croatia, 2011.
7. Kabanshi, A. Andersson, H. Sundberg, M. Senkic, D. Sandberg, M. *ROOMVENT 2024*-Assessing Airborne Infection Risk through a Model of Airflow Evacuation & Recirculation Dynamics