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CO_2 monitoring to assess ventilation rate: practical suggestions from a laboratory study

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Abstract. Several recent studies have demonstrated that ventilation plays an important role in the transmission of SARS-CoV-2 (the coronavirus that causes COVID-19) in public buildings, such as schools. However, there are no clear rules on how to assess the ventilation performance in classrooms, especially during a pandemic. Therefore, the main objective of this study was to develop guidance to assess the ventilation performance under different ventilation regimes. A full-scale laboratory study was conducted in the Experience room of the SenseLab, where CO_2 concentrations were monitored at 19 locations (18 indoors and one outdoors) simultaneously and recorded every 30 seconds by HOBO® CO_2 loggers. The experiment was conducted under four different ventilation regimes: '600 m^3/h mixing', 'open windows', 'no ventilation', and 'open windows and door'. Each regime lasted 50 minutes, which is approximately the duration of one normal lesson at Dutch secondary schools. Six (three males and three females) healthy subjects were invited to participate in this experiment as CO_2 sources. Results showed that CO_2 concentrations varied significantly between different measurement locations in the same classroom, especially under natural ventilation conditions. This demonstrates the need of monitoring the CO_2 concentration, next to outdoors, at more than one location in a classroom. The finding of this study could contribute to a standardized way of monitoring CO_2 concentrations and the assessment of ventilation performance of an occupied space.

Keywords. CO_2 concentration, ventilation regimes, classrooms, monitoring guidance.
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1. Introduction

After being proved and confirmed by many scientists, the airborne transmission of SARS-CoV-2 transmission has finally been accepted as the dominant transmission route by the whole world [1-3]. Along with that, people have begun to raise concerns over the indoor air quality (IAQ) and ventilation [4, 5]. Increasing ventilation has been listed as one of the main measures against the spread of SARS-CoV-2 by many governments. However, how do we know whether the ventilation is enough or how to assess the ventilation efficiency? According to previous studies, CO_2 concentration has usually been taken into account as the indicator of the amount of ventilation or for IAQ [6-8]. Because CO_2 measurement devices are easily usable, relatively cheap, and reasonable accurate, CO_2 is widely used to estimate ventilation rate in spaces [8, 9], and the history of using CO_2 as an indicator of the ventilation performance can be traced back to more than 160 years ago [10]. Besides, several studies suggested CO_2 can be seen as the proxy of COVID-19 infection risk [7, 11-13]. because both infected aerosols and CO_2 are mainly originating from human exhalation. For example, by using monitored CO_2 concentrations, Burridge et al. [12] established a predictive and retrospective model to estimate the risk of airborne infection in regularly occupied spaces, such as office or school classrooms.

However, despite the widely use of CO_2-based methods, there is no consistent guidance for CO_2 monitoring. The selection of measurement locations of and number of sensors mainly depends on researchers' personal experiences, and therefore varied a lot among previous studies [14-16]. For example, in some studies the CO_2 concentration was measured at only one indoor location per room [17, 18], while others conducted the measurement at three or four locations to get more accurate ventilation rates [19, 20]. Additionally, the height of measurement point was also not consistent. In studies conducted by Mumovic et al. [21], Clements-Croome et al. [22], and Turanjanin et al. [23], the sensors/devices were placed at the height of 1.1m above the floor, while the height was set to 1.2m in studies conducted by Hou et al. [17] and Krawczyk et al. [24].

According to the lab study carried out by Mahyuddin et al. [25], CO_2 was not distributed homogeneously in the investigated classrooms, therefore, monitoring CO_2 at only one location might lead to inaccurate result, and the selection of monitoring location should depend on the ventilation regimes. To accurately assess the ventilation rate in an occupied space, a unified and detailed CO_2 monitoring protocol including different strategies that are applicable for different ventilation regimes is needed. Therefore, in this study a full-scale experiment with multiple measurement locations in the SenseLab [26] was conducted to better understand the CO_2 distribution in a room under different ventilation regimes, and developed a consistent CO_2 monitoring guidance, based on the results.

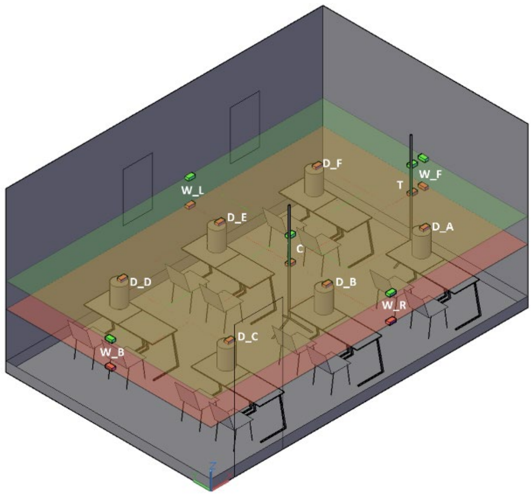
2. Methods

2.1 study design

The full-scale experiment was conducted in the Experience room (6.5 (l) × 4.2 (b) × 2.6 (h)) of the SenseLab [26] (See Fig. 1). Six healthy subjects, including three males and three females, volunteered to participate in this experiment. They were asked to remove their masks after seated [27]. The average age of them was 27 ±2 years old. Prior to the study, all subjects gave informed consent to participate in the experiment, and they were able to leave the Experience room at any time in the case they were not feeling comfortable.

Fig. 1 – Experimental setting.

19 measurement locations (18 indoors and one outdoors) were selected in this study. As shown in Fig. 2, six of them ('D_') were on top of six desks at 1.1m above the floor, two of them were in the centre ('C') / front ('F') of the room at 1.1m and 1.6m respectively, and the last eight of them were on the four walls ('W_'), also at 1.1m and 1.6 m. CO_2 concentrations at all these locations were measured every 30 seconds using HOBO® CO_2 loggers (which have an accuracy of ±50 ppm ±5% of reading in the range of 0-5000 ppm).



Note: measurement locations at 1.1m were marked in red and at 1.6m were marked in green.

Fig.2 - Measurement locations in the experience room.

The same measurement was repeated four times under four different ventilation regimes: (1) mixing ventilation with a ventilation rate of 600 m^3/h (in which air come from four 600 × 600 mm grills on the ceiling and exhaust from the perforated plinth on the short side of the room); (2) natural ventilation with windows open; (3) no ventilation; and (4) natural ventilation with both door and windows open. Each tested condition lasted 50 minutes. To reset the CO_2 concentration to the default level (close to the outdoor level), a ten-minute break (during which occupants left the room and the ventilation was set as 120m^3/h mixing ventilation) was inserted between each of two test periods. According to the weather report, the outdoor condition on the experiment day was 16 °C, 63%, and with 13 km/h north wind [28].

2.2 Data analysis

All collected data was imported and analysed using SPSS version 26.0 (SPSS Inc. Chicago, IL, USA) in the following steps. First, the average CO_2 concentration of all the indoor locations were compared among the last ten measurements (i.e. the last five minutes) of each test periods using one-way ANOVA to check whether they reach a steady state. Second, the average (standard deviation) CO_2 concentration during the last five minutes of each period at each location was analysed with descriptive statistics. Third, CO_2 concentrations were compared between different ventilation regimes with one-way ANOVA. Then, the average CO_2 concentrations were compared among different horizontal locations at 1.1m and 1.6m, separately, using one-way ANOVA. Finally, using paired samples t-test, the difference of CO_2 concentrations between two heights was compared at five locations (four walls and the centre), separately.

3. Results and Discussion

3.1 CO_2 concentrations under different ventilation regimes

According to the results collected from this study, the trends in CO_2 variation over time at all indoor locations were similar. Take the centre location (1.1m) as an example, as shown in Fig. 3, when the ventilation regime was '600 m^3/h mixing', the CO_2 concentration was relatively steady and low. During 'open windows' regime, the CO_2 concentration increased at the beginning but reached a relatively steady state at the end. When there was 'no ventilation', the CO_2 concentration increased significantly and continuously during the whole period. With the 'open door and windows', the CO_2 concentration was similar to concentration under the '600 m^3/h mixing' condition, but with slightly more fluctuations. According to the one-way ANOVA test result, the CO_2 concentration varied significantly between these four ventilation regimes ($F(3, 676) = 8522$, $p < 0.001$). The Bonferroni test showed that there was a significant difference of CO_2 concentration between almost every two ventilation regimes, except for between '600 m^3/h mixing' and 'open door and windows'. The CO_2 concentration during these two ventilation regimes were much lower than with the other two regimes. This indicated that natural ventilation, under certain conditions, could achieve a similar ventilation effect as mechanical ventilation.

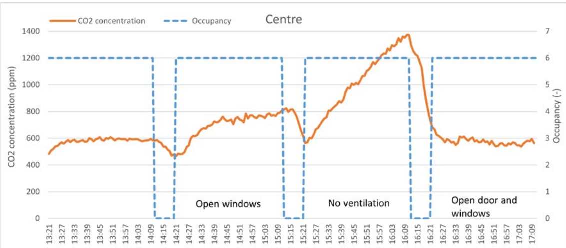
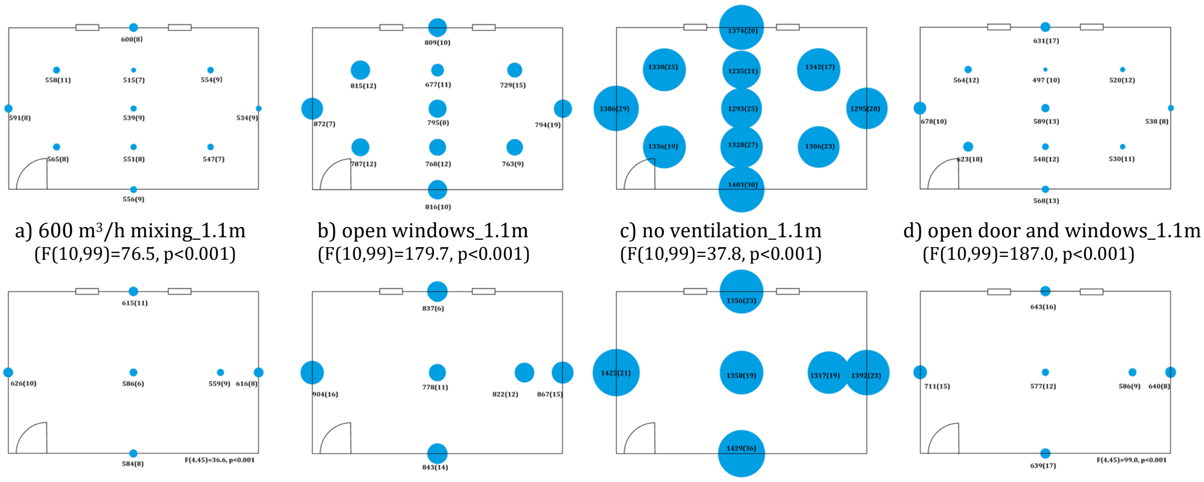


Fig. 3 - CO_2 variation over time at one location.

Additionally, it can be seen from the figure that the CO_2 concentration could reach to a relatively steady state at the end of all test periods, except for the third period- 'no ventilation'; the CO_2 concentration hardly reached a plateau. Nevertheless, the results collected during the last five minutes seemed closest to the steady-state concentration. Besides, results of the one-way ANOVA test showed that the average CO_2 concentration collected from all indoor locations did not vary significantly among the last ten measurements (i.e. last five minutes) of all the periods, which indicated the CO_2 concentration during the last five minutes of all test periods could be considered as stable. Therefore, the following analyses were all based on the results collected during the last five minutes of each test period.

3.2 CO_2 distribution under different ventilation regimes

Fig. 4 illustrates the horizontal distribution of CO_2 concentrations at 1.1m and 1.6m in the Experience room under different ventilation regimes. The diameter of circles represents the difference of the average CO_2 concentration between each indoor measurement location and the outdoor location. Different colours of circles represent different ventilation regimes: red represents '600 m^3/h mixing'; green represents 'open door and windows'; yellow represents 'open windows'; and blue represents 'no ventilation'. As shown in these figures, the CO_2 concentration was not evenly distributed in the Experience room. According to the one-way ANOVA test results (see the values mentioned below the subtitles), the CO_2 concentration did vary significantly between different locations ($p<0.05$), especially under natural ventilation conditions (where higher F-values were found). Generally speaking, CO_2 concentrations measured on the wall were relatively higher than the other locations. Moreover, the lowest CO_2 concentration was always observed at location D_E, while the highest CO_2 concentration on the back wall (W_B), no matter under which ventilation regime.



a) 600 m^3/h mixing_1.1m ($F(10,99)=76.5$, $p<0.001$)
b) open windows_1.1m ($F(10,99)=179.7$, $p<0.001$)
c) no ventilation_1.1m ($F(10,99)=37.8$, $p<0.001$)
d) open door and windows_1.1m ($F(10,99)=187.0$, $p<0.001$)
e) 600 m^3/h mixing_1.6m ($F(4,45)=36.6$, $p<0.001$)
f) open windows_1.6m ($F(4,45)=240.4$, $p<0.001$)
g) no ventilation_1.6m ($F(4,45)=34.0$, $p<0.001$)
h) open door and windows_1.6m ($F(4,45)=99.0$, $p<0.001$)

Fig. 4 - CO_2 distribution in the Experience room.

Note: the numbers under the circles are the average (standard deviation) CO_2 concentrations measured at each location during the last five minutes.

To further identify the vertical distribution of CO_2 concentration, results collected from the locations with two different heights were compared with each other (1.1m vs. 1.6m). As shown in Table 1, in most cases, t(9) was negative and the p value was less than 0.05, which means the CO_2 concentration was significantly higher at 1.6m than it at 1.1m, no matter under which ventilation regimes. This vertical distribution might be caused by the thermal plume produced by occupants. Given the fact that students spend most of their time sitting, instead of standing, the CO_2 concentration at 1.1m (the breathing height of a sitting person) should be paid more attention to in field studies.

Tab. 1 - Comparisons of CO_2 concentrations between two heights for different ventilation regimes.

Location	600 m^3/h mixing	Open windows	No ventilation	Open windows and door
C	t(9)=-12.3 (**< 0.001**)	t(9)= 5.2 (**0.001**)	t(9)= -8.8 (**< 0.001**)	t(9)= 2.1 (0.065)
W_F	t(9)=-23.7 (**< 0.001**)	t(9)=-20.9 (**< 0.001**)	t(9)=-14.0 (**< 0.001**)	t(9)=-32.3 (**< 0.001**)
W_R	t(9)=-6.9 (**< 0.001**)	t(9)=-5.8 (**< 0.001**)	t(9)=-5.2 (**0.001**)	t(9)=-16.3 (**< 0.001**)
W_B	t(9)=-8.3 (**< 0.001**)	t(9)=-7.1 (**< 0.001**)	t(9)=-6.8 (**< 0.001**)	t(9)=-6.4 (**0.004**)
W_L	t(9)=-3.6 (**0.006**)	t(9)=-7.0 (**< 0.001**)	t(9) = 2.8 (**0.021**)	t(9)=-3.3 (**0.010**)

Note: all results were obtained from independent t-tests; p-values are shown in paratheses; results in bold means statistically significant difference ($p < 0.05$).

3.3 Proposed CO_2 monitoring guidance

According to the above-mentioned results, the CO_2 concentration was not well mixed, neither horizontally nor vertically, in the Experience room. Therefore, results collected from one measurement location might be inaccurate. However, in occupied classrooms, it is also infeasible to monitor CO_2 concentration at too many locations as this current study did. Thus, if the condition permits, according to the worst-case design principle [29], priorities are suggested to be given to the locations on walls since higher CO_2 concentrations were always measured on walls. If the CO_2 concentration on the wall could meet the requirement, so could the CO_2 concentration in the whole classroom. Moreover, the risk of equipment damage by students was relatively lower on walls than other locations, and in that case, locations on the front wall and back ball were recommended since they are usually farthest from the students' activity zone.

Additionally, to get an accurate result, the outdoor CO_2 concentration should also be monitored, and the number of occupants, open windows and open doors should be recorded during the monitoring period since all this information could cause a remarkable difference in CO_2 concentrations/ventilation rates in classrooms.

4. Conclusions

To understand the CO_2 distribution in a classroom setting, CO_2 concentrations were measured at 18 indoor (and one outdoor) locations simultaneously in the Experience room of the SenseLab, under four different ventilation regimes. Based on the measurement results, this study concluded that only one measurement location might lead to inaccurate results, especially under natural ventilation regimes. Therefore, for future field studies, to get a better understanding of the ventilation/IAQ in classrooms, at least two CO_2 measurement locations on walls (especially the front and the back wall) at 1.1m should be selected in natural ventilated classrooms, while in mechanical ventilated classrooms (with both supply and exhaust), one measurement point seems enough because CO_2 is relatively well-mixed under this ventilation regime. In addition, outdoor CO_2 concentration was also suggested to be monitored, and the number and behaviour of occupants during the measurement should be recorded.

5. Remark

More detailed results and discussion of this study were published in the journal 'Indoor and Built Environment' [30].

6. Acknowledgement

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Data Statement

The datasets generated during and/or analysed during the current study are not available because more analysis will be conducted based on these datasets but the authors will make every reasonable effort to publish them in near future.