The spatial distribution of carbon dioxide in an environmental test chamber

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ABSTRACT

The spatial distribution of CO2 level in a classroom carried out in previous field work research has demonstrated that there is some evidence of variations in CO2 concentration in a classroom space. Significant fluctuations in CO2 concentration were found at different sampling points depending on the ventilation strategies and environmental conditions prevailing in individual classrooms. However, how these variations are affected by the emitting sources and the room air movement remains unknown. Hence, it was concluded that detailed investigation of the CO2 distribution need to be performed on a smaller scale. As a result, it was decided to use an environmental chamber with various methods and rates of ventilation, for the same internal temperature and heat loads, to study the effect of ventilation strategy and air movement on the distribution of CO2 concentration in a room. The role of human exhalation and its interaction with the plume induced by the body’s convective flow and room air movement due to different ventilation strategies were studied in a chamber at the University of Reading. These phenomena are considered to be important in understanding and predicting the flow patterns in a space and how these impact on the distribution of contaminants. This paper attempts to study the CO2 dispersion and distribution at the exhalation zone of two people sitting in a chamber as well as throughout the occupied zone of the chamber. The horizontal and vertical distributions of CO2 were sampled at locations with a probability that CO2 variation is considered high. Although the room size, source location, ventilation rate and location of air supply and extract devices all can have influence on the CO2 distribution, this article gives general guidelines on the optimum positioning of CO2 sensor in a room.

1. Introduction

The use of Carbon dioxide (CO2) as an indicator of indoor air quality (IAQ) and as a tracer gas to estimate air exchange rates in buildings is widely applied by many researchers nowadays. Although it is present in the atmosphere, CO2 gas that is generated by room occupants or released from cylinders is sometimes used as a tracer gas in ventilation research due to its low cost and safety consideration. However, in an enclosed space, the indoor CO2 is usually associated with the presence of occupants. Exhaled breath from occupants involved in a sedentary level of activity contains some 4–5% of CO2 – this equates to about 0.01 grams per seconds (g/s) (about 0.005 L/s) [1]. Although CO2 may not be considered to pose serious health effects, some research has indicated that individuals in schools with high CO2 concentration tend to report drowsiness, lethargy and a general sense that the air is stale [2]. ASHRAE states that comfort criteria with respect to human bioeffluents (odour) are likely to be satisfied if the ventilation strategy results in an indoor CO2 concentration of less than 700 ppm above the outdoor air concentration. CO2 concentrations in outdoor air typically range from 300 to 400 ppm. Keeping levels less than 700 ppm above the outdoor air concentration is an indication that sufficient outdoor air is being brought into the environment which will help control other pollutants at acceptable levels.

In a typical building, the constant emission of CO2 by occupants is diluted by outside air introduced by mechanical ventilation and infiltration of air through leakage and openings such as windows. If the CO2 concentrations from outside air are known, the difference between inside and outside CO2 concentrations can indicate the amount of outside air being introduced to a space on the basis of litres per second per person (l/s/p). Currently most national codes express ventilation rates requirements on this basis. Thus it is seen that the CO2 concentrations have considerable importance in studying the IAQ.

The desire for thermal comfort and acceptable indoor air quality usually provides conflicting constraints on the ventilation system. While a high ventilation rate may increase the removal of gaseous...
contaminant, it may result in cold draught. On the other hand, a low ventilation rate may not be sufficient to remove the indoor contaminants. Even if the ventilation rate is enough to achieve optimum thermal comfort and IAQ conditions inside the building, this does not guarantee that the air will be well mixed inside the ventilated space. Ventilation air is not only to dilute the contaminant but also acts as carrier of gaseous and particulate matter, provide of fresheness, and to some extend is an indicator of the effectiveness of the HVAC system.

Previous researches have confirmed that the measurement and the analysis of indoor CO₂ concentration could be useful for understanding IAQ and ventilation [3–6]. However, the spatial distribution of indoor pollutants and CO₂ has not been adequately addressed in the literature primarily due to being time consuming, high experimental cost involved and the lack of funding for conducting such studies. Yet this information is essential in designing pollutants control and ventilation systems in buildings. Most importantly, this information is vital for future researchers to efficiently and strategically design the experimental setup with well-organized positioning of sensors which is essential for producing meaningful information to represent the mean CO₂ concentration in the room which is required for monitoring purposes. By measuring CO₂ source, and applying the mass balance theory, the air change rate can be estimated from the CO₂ decay rate. Some earlier studies used the indoor CO₂ concentration to estimate ventilation rates with an assumed average CO₂ production rate per occupant [4]. Persily [7] examined strategies based on CO₂ concentration to evaluate building ventilation rates. A simplified technique for measuring ventilation rate is by employing a steady-state mass balance or equilibrium analysis under certain circumstances. Recently, the use of CO₂ balance strategies to calculate air exchange rate has become popular as a result of its simplicity and low cost. A study of the dynamic evaluation of air flow rates for a variable air volume (VAV) system using both CO₂ and SF₆ as tracer gases proved that metabolic CO₂ produced by occupants can be used as a means to evaluate real time air flow rates [8,9].

Smith [9] noted that the ventilation equations are very sensitive to errors in input data and other variables such as time varying ventilation rates, non-homogeneous mixing, and uncertainties associated with CO₂ measurements and production rate. Therefore, proper monitoring of CO₂ levels may allow the uncertainties to be corrected, leading to better estimation of CO₂ concentrations, hence improved air quality. The measurement strategy for determining CO₂ distribution is of utmost importance for not only identifying the sources of CO₂ but also how it is distributed in the room and affected by occupants' movement, heat sources, as well as room air distribution strategy. Hence, measuring concentration at a single location or height may not be an accurate indicator or act as a representative for the whole measured space due to large variations caused by the strength of pollutant sources and distances involved [10]. The spatial distribution of CO₂ level in classrooms carried out in a previous field work research has demonstrated that there is some evidence of variations in CO₂ concentration within a classroom size and ventilation strategy [11]. However, how these variations are affected by the emitting sources remains largely unknown. Fig. 1 shows that there is a significant difference in spatial distribution of CO₂ among sampling locations measured in one of the classrooms involved. Significant variations of CO₂ concentration were found at different sampling points as well as in the average value of CO₂ during the occupancy period.

In Fig. 1, the significant difference among the sampling locations is represented by a P-value for horizontal distribution (location: A, B, C, D, E) which is 0.037 and a P-value for vertical distribution (height: 0.2, 1.2 m and 1.8 m) of 0.217. The variations were found to be dependent on the ventilation strategies and environmental conditions prevailing in individual classrooms which cause the non-uniform distributions of CO₂ and other pollutants concentrations. Previous studies [12,13] also showed that the non-uniform distributions of pollutants in the vicinity of an occupant are due to thermal plume around the human body. Occupants’ movements, their breathing level and the overall air flow pattern are also seen to be the cause of the non-uniform distribution in a space.

Undeniably, it still remains unclear how different ventilation strategies affect the distribution of CO₂ concentration in classrooms. Therefore this paper aims to describe some of the laboratory work which was carried out in an environmental chamber to investigate the spatial distribution of CO₂ concentrations with different ventilation strategies. The role of human exhalation was also studied in the chamber including the interaction between different air flows and the plume induced by a human body and its interaction with convective flow and turbulence due to different ventilation strategies.

2. Methodology

2.1. Experimental setup

The overall focus of this research is on classroom environments but the part which will be discussed here is mainly based on experimental studies conducted under transient conditions in a full-scale test chamber with different ventilation strategies. This chamber comprises of two compartments, one compartment (environment control room) houses the air conditioning unit and the second compartment is the working area with dimensions of 2.78 × 2.78 × 2.3 m (ceiling height). The air conditioning of the environment control room is provided by and air handling unit with its compressor housed outside the chamber which is capable of cooling the compartment to −5 °C or also heating it up to 35 °C. The heating and cooling are controlled by a cooling coil, fan and heater. A PID temperature controller is used to control the temperature of the room to the desired value. An air handling unit cools and heats the air supply to the desired value for the working compartment. The air is then supplied to the working compartment from the required air supply devices depending on the ventilation strategy selected and the required air flow rate. One wall or part of the wall in this compartment has heating panels that can safely heat the wall to about 50 °C.

Figs. 2 and 3 show photographs and an illustration of the experimental chamber, the air handling unit (AHU) and the AHU control panel. The illustration in Fig. 3 shows how the air is drawn into and out of the Chamber (working compartment). The fan shown in the figure supplies the ventilation air from the laboratory to the AHU and then to the working compartment. Air is uniformly mixed in the AHU, heated or cooled and the fan then delivers it into the chamber room at the required flow rate and temperature. The inlet vent to the working compartment is a rectangular slot with measurement of 400 mm long × 65 mm high at a height of 2.18 m above the floor. The circular outlet with circular vent has a radius of 50 mm.

Four typical situations of air distribution methods have been identified and experiments were carried out involving two average size students at 1.0 metabolic rate each. The four situations used in the measurements are listed below with the abbreviation stated in the brackets that is used in the results afterwards. Three air flow rates of 8 L/s (1.61 air change rate (ACH)), 4 L/s (0.72 ACH) and no mechanical ventilation (0.04 ACH) were employed in this research.

1. Natural condition (No Vent): Both the inlet and the outlet openings in the chamber were sealed using ducting tape. Although the inlet and outlet were sealed, the air handling unit was still in operation in order to cool the wall adjacent to the
working chamber. Therefore, it was possible that air entered the working chamber through air leakage paths in the chamber envelop due to imperfect sealing, which was quite difficult to achieve as there were many fixtures in the chamber. The concentration decay method was used to measure air leakage through the chamber by measuring the CO₂ concentration decay after the occupants evacuated the chamber. Only concentration values at 1.2 m height in all locations were used to measure the decay.

2. Air recirculation (RC 8 L/s): Re-circulated air was supplied into the working compartment via the inlet located at a height of 2.18 m above the floor with the air flow rate adjusted to 8 L/s. An extract opening on the same side of the inlet wall was used to suck the air from the test chamber and re-circulate it into the chamber again (see Fig. 3).

3. Fresh air supply (FA 4 L/s): The damper in the environment control room was open to allow fresh air from outside the chamber to enter into the test compartment. This air flows into the working area and circulates into the chamber. The air flow rate was set at 4 L/s.

4. Fresh air supply (FA 8 L/s): Fresh air flow rate set at 8 L/s.

In this study, mixing ventilation is used for ventilating the working compartment and it would be expected that spatial gradients in contaminant concentration will be present. In many mixing ventilation studies, it is expected that there will be a relatively a large entrainment region around the supply air jet where velocity values are 0.2 m/s or higher. Hence, to avoid draught in the occupied zone, it is important that the supply air jet does not directly enter the occupied zone of the room. There are several methods that can be used to prevent excessive air velocities in the occupied zone, while achieving good mixing. In this study, a plate was fixed at the bottom of the inlet diffuser to deflect the supply air jet upwards towards the ceiling and use the coanda effect to avoid

Fig. 1. Spatial distribution of CO₂ concentration in naturally ventilated classroom.

Fig. 2. (a) Environmental Chamber, (b) Air handling unit, (c) Air handling control panel.
the risk of down draught in cooling situations [14]. The coanda effect is commonly associated with room ventilating systems. It can be described by the vortex accompanying the inlet jet which causes the flow to deflect and overcome the downward buoyancy effects on it. Furthermore, due to induction, the temperature of the air jet decays rapidly to the room temperature. The attachment of the jet to the ceiling is due to the low pressure created by the formation of a vortex as shown in Fig. 4(b). It is therefore expected that such arrangement will create a flow pattern without excessive air velocities in the occupied zone, but will still achieve sufficient mixing of the jet with chamber air. However, due to the relatively large size of inlet opening in the chamber (0.026 m²), the air supply velocity for an air flow rate of 8 L/s is approximately 0.3 m/s which is rather low for a ceiling supply. As a result, the air jet may have plunged into the occupied zone at these or lower air flow rates instead of wall jet developing over the ceiling. However, this should not cause too much influence on the CO₂ distribution in most of the occupied zone.

2.2. Measurements

The CO₂ concentrations and personal exposure were measured using a 12-channel gas analyzer type Bruel & Kjaer 1302 (accuracy approximately ±2%). These concentrations were measured at several locations and heights in the chamber (Fig. 5). Horizontally, the sampling points were surrounding the occupants (A) left, (B) front, (C) back (D) right and (E) occupant sitting position. Vertical sampling points were placed at 1.2 m and 1.8 m height at all horizontal locations representing the breathing zone height for seated and standing occupants respectively. Due to the limited number of sampling locations (12 in total), only two sampling points at 0.2 m height were placed at location (B) front and (D) right. These were selected to obtain concentration levels close to the floor.

In this study a single gas analyzer with 12 inlet ports is located outside of the test room and the air samples are taken from the test points in the working chamber through thin tubes by suction. The test points were sampled in cyclic order. The time interval between the start of two consecutive analyzing cycles was 1 min in all experiments conducted. As there are 12 test points, every test point is sampled every 12 min. Due to the length of the sampling tubes, an optimum duration of the sampling period initial tests were carried out to determine the required suction and purging periods with the sampling tubes connected to the sampler.

The gradients in temperatures and air speed were measured by using 4-wire PRT sensors and Dantec ‘Multi-channel Flow analyzer’ which are also located at the same points as the CO₂ sensors. Generally, for thermal comfort measurements temperature and velocity sensors are located at 0.1 m and 1.1 m above the floor.

Fig. 3. The Air handling unit in operation and the sitting layout of the occupants.

Fig. 4. (a) A plate fixed below the supply air diffuser to direct the air flow to the ceiling, (b) A sketch showing the Coanda effect on the inlet jet.
However in this research, sensors for temperature and velocity measurements were placed at the same vertical position as the CO\textsubscript{2} sensors to complement these measurements. This study is not related to thermal comfort but focuses on CO\textsubscript{2} distribution in ventilated rooms. In total 12 sensors were used for measuring the spatial distribution of CO\textsubscript{2}, 16 velocity sensors to measure the air flow in the chamber and 12 PRT Sensors to monitor the temperature distribution in the chamber. The positions of all the sensors are shown in Fig. 5.

As mentioned earlier, this research was carried out after the field work study which was done in classrooms. In this experimental study, the two student occupants in the working chamber were requested to sit in their position and do normal classroom work within a 3-h period for each sampling day. Fig. 6 shows the seating position of the two undergraduate students in the central area of the chamber. On occasions when movements occurred such as standing, stretching or walking, students reported it in a log book given to them. However, small hand movements were not recorded.

3. Data analysis

Section 4 presents the results for: (1) the buildup of CO\textsubscript{2} concentration and (2) spatial CO\textsubscript{2} distribution. The analysis to obtain the desired results were carried out using statistical analysis of variance (ANOVA) to determine if the differences in the means from the 12 sampling locations were significant with 95% confidence limits of the mean. This included the significant effects of vertical mean values at all horizontal locations for assessing the horizontal distribution, and the mean values of all the horizontal locations for the vertical distribution assessment. In addition, the significance of the concentration variation at individual points was assessed. This was to provide guidelines on vertical and horizontal variations in CO\textsubscript{2} concentrations as each factor (location and height) may have a different effect on the global distribution. All these results will be discussed and compared for the four ventilation strategies explained earlier.

Under steady-state room conditions, the local ventilation effectiveness ($E_i$) was calculated using the following equation:

$$E_i = \frac{C_e - C_s}{C_i - C_s}$$

where $C_e$ is contaminant concentration in the exhaust diffuser, $C_s$ is contaminant concentration in the supply diffuser, and $C_i$ is contaminant concentration in the indoor measured points. Eq. (1) is the definition of relative ventilation effectiveness given by Sandberg [15] and it expresses how the effect of ventilation varies for different locations in the room. It is a measure of dispersion and its value is always positive and can be greater than unity. It is equal to unity when there is a perfect mixing, i.e. the concentration throughout the room is uniform and equal to the exhaust concentration.

Fig. 5. (a) A plan view showing the positioning of velocity transducers (V), PRT sensors (T) and Carbon dioxide sensors (C) inside the chamber; (b) A perspective view of the chamber.

Fig. 6. (a) The chamber with measuring equipment and occupants’ sitting positions, (b) 2 × 100 W bulbs representing occupant’s heat to maintain steady-state temperature before occupants enter the chamber.
However, in this article, No Vent and RC 8 L/s were not used for predicting the ventilation effectiveness. Based on the findings explained in the next section, it was found that the instrument readings of CO2 concentration taken over a 3-h period for both these strategies, did not reach constant readings, as shown in Fig. 7. The CO2 readings continuously increased, which means that the sampling time required to obtain the true mean concentration is very difficult to predict.

4. Results and discussion

4.1. Buildup of CO2 concentration with different ventilation strategies

As explained earlier, the measurements were carried out in a 3 h period of occupancy. Fig. 7 shows the CO2 concentration buildup in the chamber with different ventilation strategies applied. The lines of CO2 buildup refer to all the horizontal and vertical sampling points in the chamber. The initial concentration in the chamber room when the occupants started to enter it varies, thus the measured concentration were corrected by deducting and normalizing the initial concentrations to the background level, 400 ppm to provide direct comparison between the ventilation strategies.

Predictably in a room with no openings, the air change rate would be very low as there is no appreciable amount of air flowing in or out of the room; hence the buildup of CO2 levels will be greater. This is reflected in the uppermost inclined graph of CO2 concentration in Fig. 7. In addition, it was observed that in the first 30 min, the buildup of CO2 was comparable for all ventilation strategies but diverged significantly later on. In the first hour (dotted line), it can be seen that the concentration for the RC 8 L/s and No Vent continue to buildup parallel to each other, reaching approximately 1618 ppm and 1956 ppm after 1 h respectively. Whereas, the FA 8 L/s and FA 4 L/s concentrations are seen to be at the lower range (1220 ppm and 1375 ppm) and continue settling towards a constant value of 1430 ppm for the FA 8 L/s after 90 min and 1890 ppm for FA 4 L/s at the end of the 3-h session.

The top incline line in Fig. 7 shows that the concentration of CO2 in the unventilated chamber increased more rapidly when compared to the other cases and reached a value of 4146 ppm at the end of the 3-h session. In comparison, for the higher air flow rates (4 L/s and 8 L/s) used in the other three situations, the CO2 concentration buildup has a lower inclination. However, despite the high air flow rate, the CO2 buildup for the RC 8 L/s case, was parallel to the No Vent case as a result of air recirculation in the room. The differences in the CO2 concentration at the end of the measurement periods compared to the No Vent condition are 708 ppm, 2256 ppm and 2746 ppm for RC 8 L/s, FA 4 L/s and FA 8 L/s respectively. As expected, when fresh air is supplied, the CO2 concentration was found to be much lower throughout the measurement period reaching almost a constant value towards the end of the session. In the case of FA 8 L/s, taking the steady-state value of CO2 concentration in the chamber of about 1430 ppm, and an average outside concentration of 400 ppm, the CO2 exhaled by two occupants was calculated to be about 0.00824 L/s. As would be expected, these tests show that with fresh air supplied to the chamber the buildup of CO2 will stabilize and reach a steady-state level after a long period.

4.2. Influence of the ventilation strategy on the spatial distribution of CO2

The local ventilation effectiveness ($E_l$) can give an indication of the CO2 concentration at that location. The velocity fields given in Table 1 can also be used to analyze the local value of ventilation effectiveness at all sampling points as shown in Fig. 8. This figure shows that the ventilation effectiveness for all the sampling points indicate slightly smaller variation for the case of FA 8 L/s (range 0.98–1.06) compared to the FA 4 L/s case (range 0.95–1.1). For both these cases, it was found that the local ventilation effectiveness is less than 1 in the upper regions of the occupied zone (1.8 m), and at locations B (front) and C (back), see Fig. 5. Besides these 2 locations, low ventilation effectiveness also occurs at the upper region in location D and at the breathing level (1.2 m) for FA 4 L/s. This can also be associated with the low velocities (<0.05 m/s) in all those regions giving rise to higher CO2 concentration. However, the overall ventilation effectiveness for the occupied zone in the two cases was greater than 1 ($E > 1$) which indicates that a good mixing of room air has occurred.

In the analysis that follows, the CO2 distribution profiles were measured at the points identified earlier for the horizontal and vertical distributions of the sampling points. To compare the effect
of the ventilation on the spatial distribution of CO₂, the average CO₂ concentration throughout the 3 h period for all 4 ventilation strategies were considered (Fig. 9).

Presented in Fig. 9 and Table 1 are the summary of the analyses and results of the spatial distribution of the average CO₂ concentration for all four ventilation strategies that were carried out in the chamber. Based on the analyses in Fig. 9, it was found that the lowest average CO₂ concentration lies at a height of 0.2 m for all cases except for the case of FA 4 L/s which was slightly lower at 1.8 m height in location A. Although at standard temperature and pressure, the density of carbon dioxide is around 1.98 kg/m³, which is about 1.5 times that of air, in this scenario the gas did not sink to a lower height due to its diffusion with other gases present. This suggests that CO₂ gas is carried upwards to the upper region of the occupied zone by the air movement in the room and thermal stratification. Because the exhaled CO₂ is warmer than the surrounding air in the chamber, thermal stratification was observed at the upper region of the occupied zone (Table 1). Indeed, in all four situations, the highest CO₂ concentrations were found to be at the same location as the highest value of the air temperature in the chamber (see Table 1). On the other hand, the lowest concentrations occurred closer to wall A (see Fig. 5(b) at 0.2 m height in all situations except for FA 4 L/s at 1.2 m height which correspond to the low temperature at that point. This may be due to the operation of the air handling unit which cools the wall adjacent to the working chamber.

The resulting spatial distributions of CO₂ concentration for all ventilation strategies show that most of the highest values occur at 1.8 m height and not at the breathing zone level as might be expected. In addition, it was found that the highest peak of CO₂ concentration in each situation lies at the back of the occupant’s sitting position (location C). At this position also a higher temperature is observed that could be attributed to the heat emitted from a fluorescent light on the side wall at approximately 2.13 m height. It may also be due to convective currents from the body plumes towards the back wall. In addition, as shown in Table 1, in the upper part of the room, a low velocity region (<0.05 m/s) occurs which may be due to the relatively stagnant air that is expected to be contaminated because it originates from thermal plumes due to occupants and equipment. Furthermore, internal air recirculation is also expected to occur in this region due to re-entrainment of air by the heat plumes. Generally, areas with higher temperature indicate more stagnant air conditions.

With regards to the statistical analysis of variance, the average CO₂ concentration among the sampling locations (horizontal) was significantly different only for the case of No Vent. At FA 8 L/s, FA 4 L/s and RC 8 L/s, the average CO₂ concentration was not significantly different among the locations, signifying that higher ACH produced
better mixing (Table 2). This is further confirmed by the highest and the lowest difference between maximum and minimum CO2 concentration which are 77 ppm and 76 ppm for FA 8 L/s and RC 8 L/s respectively. On the contrary, the vertical distributions of CO2 in all cases were found to be significantly different (P < 0.05) except for FA 8 L/s. The aforementioned results suggest that for FA 8 L/s, the average CO2 concentration was essentially uniform both horizontally (P-value = 0.628) and vertically (P-value = 0.288). In such case, a lower number of samplers would be required to estimate the average concentration in a room as compared to what will be required for other ventilation strategies. Interestingly, for RC 8 L/s, although the ventilation rate was similar to FA 8 L/s, due to the recirculation system, the pairwise comparison test for the vertical sampling points shows a strong significant difference (P-value = 0.37). In addition, the average of CO2 concentrations in the vertical measuring points (0.2 m, 1.2 m and 1.8 m) of No Vent and FA 4 L/s, also show significantly different means with a P-values of 0.006 and 0.008 respectively. Thus, if limited number of sampling location is desired for these ventilation arrangements, the samplers should be located at two or more elevations. With such results, it is assumed that in a larger space, an even more significant difference in the mean vertical CO2 distributions may occur in most situations. As for horizontal distribution, a significant difference in the mean concentration may occur in larger rooms with low ventilation or less mixing as the concentration at the horizontal sampling locations seems to be significantly different for the lower air flow rates. On the whole, the highest mean difference found in this research was approximately 123 ppm (No Vent) which is considered to be small but this is due to the confined size of the chamber which limits the distribution and dispersion of CO2 by the air movement.

5. Conclusions

This study showed that having only one sensor to represent the CO2 concentration in a room may lead to inaccurate estimations of the average CO2 level used for monitoring purposes. For accurate assessment of CO2 concentrations in a ventilated room several sampling sensors located at various vertical and horizontal locations may be necessary. Although in this study, the size of the chamber is considerably smaller (17.75 m3) than normal rooms, the variations found in the spatial distribution of CO2, with the difference between the maximum and the minimum concentration was in the range of 76–123 ppm. This is due to the dispersion of CO2 itself which varies with room conditions and variables such as the occupancy level, occupant sitting position, the air flow rate, location of the inlet and outlet air terminals, external and internal environmental conditions, etc. In general, relatively uniform CO2 concentration patterns were found in an environment with mixing ventilation with higher air flow rates than with reduced rates. As could be expected, the local ventilation effectiveness was also observed to be higher at most sampling locations in a room with higher air flow rates. The local ventilation effectiveness was found to be lower at the upper region of the occupied zone (1.8 m) in locations B and C for both FA 8 L/s and FA 4 L/s. Apart from these locations, lower ventilation effectiveness was also found at the breathing level for FA 4 L/s case. This was substantiated by the low velocity (<0.05 m/s) at all these locations. However, the average ventilation effectiveness in the occupied zone for both FA 8 L/s and FA 4 L/s was found to be greater than 1. It has not been possible to determine the values of ventilation effectiveness for RC 8 L/s and No Vent as the CO2 concentration in the chamber did not reach a steady-state value after 3-h of monitoring.

Results confirm that the type of ventilation strategies is an important parameter which determines the distribution of CO2 concentrations, due to the fact that they generate different air flow patterns and thus different spatial concentration patterns. In this research, it was observed that the highest mean of CO2 concentration lies at a higher region in the room (1.8 m) and not as might be expected at the breathing zone (1.2 m). Interestingly, the location of the concentration peaks was also seen to be accumulated at the back of the occupants in all ventilation strategies except for RC 8 L/s. In this case however, the difference between the highest peak concentration in region (B) of the room and concentration at other locations (A and C) were very small (<5 ppm). In such a case, it may be reliable to have one sensor as a representative for a fairly small

Table 2

<table>
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<tr>
<th>Ventilation methods</th>
<th>Dependent variable</th>
<th>No vent</th>
<th>FA 4 L/s</th>
<th>RC 8 L/s</th>
<th>FA 8 L/s</th>
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<td>94 ppm</td>
<td>77 ppm</td>
<td>76 ppm</td>
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* 95% Confidence level of the mean difference.
room. However, non-uniform spatial distributions of CO\textsubscript{2} were observed with low air flow rates. This finding implies that thermal plumes and temperature gradients are important phenomena in transporting and driving the CO\textsubscript{2} distribution from the breathing zone or above causing CO\textsubscript{2} stratification. Generally, knowledge of the spatial gradient of the CO\textsubscript{2} concentration is important when limited number of sampling locations is to be used for monitoring. In conclusion, the choices of sampling locations depend on the prevailing air movement, hence on the type of ventilation strategy used. The ventilation rates not only significantly affect the average CO\textsubscript{2} concentration in the room but also have a direct effect on the uniformity of the distribution. CFD simulations would be helpful to obtain a better understanding of the air flow patterns and the distribution of CO\textsubscript{2} concentrations in a room which could also offer guidance on locating sensors to obtain average concentrations in the room. This study will be undertaken in future as continuation of this research.

References


