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Article *in* Indoor and Built Environment · May 2014

DOI: 10.1177/1420326X13512142

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Original Paper

Indoor and Built Environment

Indoor and Built Environment
2014, Vol. 23(3) 433–448

DOI: 10.1177/1420326X13512142
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The spatial distribution of carbon dioxide in rooms with particular application to classrooms

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Abstract

In most buildings, occupants are the main source of indoor carbon dioxide (CO_2) due to exhalation. Although CO_2 is not considered to pose serious health risks to occupants, elevated levels of CO_2 may serve as an indicator of insufficient ventilation. This study examines how CO_2 is distributed within a complex indoor environment of a classroom and how this distribution is affected by different parameters. Measuring CO_2 concentrations at a single location or height may not act as a true representation of an entire space, unless it is measured in a very small confined space. In this study, it was observed that higher CO_2 concentration values can be found at higher levels in a room and not only at a height between 1 m and 1.2 m as claimed by many researchers. Therefore, if CO_2 concentration levels vary significantly, deviations from the average measured values could become large. It was also found that the CO_2 concentration reflects the dynamic relationship among the occupants, their activity levels and occupancy periods. The findings present a useful contribution for future researchers to efficiently and strategically design experimental set ups with well-organised positioning of sensors for CO_2 monitoring purposes.

Keywords

Classroom, Indoor carbon dioxide, Measurement strategies, Room air distribution, Spatial distribution

Accepted: 17 October 2013

Introduction

Carbon dioxide and ventilation

In ASHRAE 62.1,[1] it is emphasised that CO_2 is not a health concern or a measure for indoor air quality (IAQ) but that its concentration gives information on the levels of pollutants from various human and other sources that affect the indoor environment of a building. Rudnick and Milton[2] suggest that exhaled breath is a vehicle for the release of airborne infectious particles, and thus contributes to the risk of airborne transmission of infections indoors. For such reasons, it is essential to precisely characterise the indoor distribution of air supply in a room under different ventilation strategies. Understanding airflow patterns and CO_2 distribution will help optimise the design of effective ventilation configurations and strategies for controlling the air movement pathways. To the best of our knowledge, no major research studies regarding the variations of CO_2 concentrations resulting from varying occupancy patterns and different ventilation strategies have so far been undertaken in classrooms. This may be due to the high experimental cost of spatial CO_2 distribution measurements required to carry out such studies, especially in large spaces. These problems as well as the

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difficulties with positioning of the CO_2 sampling sensors have prompted the present research.

The range of indoor environmental issues is broad; however, the significance of each issue is dependent on the building type and its use. Due to the increasing evidence of adverse effects caused by poor IAQ, research in this area has increased significantly, particularly in domestic and office buildings. However, no studies specifically concerned with the indoor environment of school buildings have been performed until relatively recently.[3–10] Despite these studies, there is still a lack of information on classrooms occupied by adult students. In a study of IAQ levels in university classrooms with different capacities, Awbi and Pay[11] reported that the IAQ during occupancy periods was very poor. The CO_2 concentration levels in this research exceeded 1000 ppm and in some cases concentrations of more than 5000 ppm were recorded.

Many parameters affect the quality of indoor air within buildings, most of which are in some way related to the presence of pollutants, inadequate ventilation and to personal factors that relate to an individual's perception of air quality.[12,13] Research carried out by Fox et al.[14] at a suburban elementary school in Columbia showed that CO_2 levels, which were found to be within a range of 1017 ppm to 1736 ppm in heavily populated schools, correlated with the levels of airborne bacterial markers. This shows that a considerable proportion of the airborne bacteria emanated from the pupils themselves. In addition to the general environmental factors that affect the air quality in typical public buildings, there are other design parameters and occupancy patterns that make the classroom environment unique. Such parameters include the number of occupants, proximity of students to one another, room design layout, location of teaching equipment and classroom activities (such as student movement). Therefore, it is assumed that university classrooms represent spaces of complex activity which could impact on the IAQ in them.

Previous studies have also shown that classrooms are often inadequately ventilated, with the consequence of increased risks of negative impacts on pupils. Considering that human exhalation is a buoyant jet (due to the elevated temperature) which represents a pulsating and intermittent source of contaminants in space,[15] a larger number of occupants in a classroom will result in a higher CO_2 concentration if insufficient ventilation is provided. In other words, the main source of CO_2 is from exhaled breath and the main mechanism to remove it is through ventilation. Therefore, high levels of CO_2 in classrooms over a sustained period are an indication of low ventilation rates. To highlight this problem, the former Department of Education and Skill in the UK published a design guide on school ventilation (Building Bulletin 101 (BB101), 2006). This document complies with the new Building Regulations Part F – Ventilation[16] in England and Wales.

Current recommendations made by the BB101[17] require purposely ventilation (i.e. controllable devices to supply air to and extract air from a building) to supply external air into all teaching and learning spaces at the rate of:

- a minimum of 3 ls^{-1} per person;
- a minimum daily average of 5 ls^{-1} per person;
- a minimum of 5 ls^{-1} per person at all times and a capability to achieve 8 ls^{-1} per person at any time in a mechanically ventilated building.

It must be noted, however, that, even though not well documented in many countries, recommended fresh air supply rates for classrooms are country-specific that depend on building design and climate. Most ventilation standards specify ventilation rates based on continuous occupancy, but a few (e.g. ASHRAE Standard 62.1, 2010) also consider demand control ventilation rates. This may lead to the presence of higher flow rates than required during some periods, which may cause unnecessary increases in energy consumption. Therefore, when the occupancy in a classroom is transient, not only will there be a significant effect on the variation of CO_2 concentrations but also on the recommendation of suitable ventilation rates by standards.

It is a fact that non-uniformities in CO_2 concentration through a building or a room tend to increase when the sources and controls are localised, or when there is very limited air movement rather than in a well-mixed room air. Given that there are often a continuous variability and fluctuations in the airflow due to the forces of wind or buoyancy, the association of CO_2 concentrations with the opening of windows (source of air supply) is more significant for naturally ventilated classrooms[18–20] than for mechanically ventilated classrooms[21]; hence steady-state conditions are rarely achieved in the former case.[22] It is evident therefore that the connection between ventilation techniques used in a room and CO_2 measurement strategies are not well understood and that guidance is needed for the positioning of CO_2 sensors, especially in naturally ventilated classrooms. In the research presented here, the exhalation of CO_2 was studied in conjunction with the interaction between room airflow patterns resulting from different ventilation systems.

Spatial variability of CO_2 concentration and its impact on sampling points

CO_2 is often used for evaluating the adequacy of classroom ventilation, particularly as it is believed to be related to the dilution of pollutants stemming from human metabolic activity.[23] Evidently, if the ventilation system does not control and maintain CO_2 concentrations at acceptable levels, other indoor contaminants are probably accumulating proportionately. Proper monitoring of CO_2 levels will enable corrections to be made where necessary and consequently improve the IAQ of a space. The measurement strategy for determining CO_2 distribution has a direct impact on our understanding of how CO_2 is distributed within the room and how its distribution is affected by occupants' location and movement, heat sources and room air distribution.

The concentration of CO_2 within a building may vary from location to location due to gravitational settling and a non-uniform airflow field.[24] Other factors that may affect the non-uniformity of spatial distribution are the location and strength of the source (mainly occupants), the types of ventilation systems present and the resulting internal air movements. All these factors will influence the sampling strategy on the choice of representative locations, especially when evaluating the effectiveness of ventilation or control systems.

The CO_2 monitoring and sampling process in this research was carried out in a number of different ways with reliance on published work in the area. For instance, in a research carried out by Coley and Beisteiner,[25] the equipment was wall mounted at a height of about 1.8 m or placed on a bookshelf. Research carried out in Michigan, USA, attempted to place the sampling equipment in representative locations that were secure from tampering – at least 0.6 m above the floor and below the ceiling and at least 0.5 m away from bookshelves and other potentially stagnant areas. Furthermore, locations near doors and windows or over heaters should also be avoided.[26] In a study involving 10 public secondary schools in Athens, the sampling equipment was placed 1.5 m above ground level at several indoor locations in the middle of the classrooms.[27] In another study involving elementary school in Columbia, CO_2 sensors were placed on top of a large cabinet approximately 2.1 m above the floor.[14]

Measuring CO_2 concentrations at a single location or height may not be an accurate indicator, or act as a true representation of the concentration in a space. Realistically, one sampling point in a very small confined space is probably adequate. Fox et al.[14] concluded that a single monitoring location was appropriate for characterising indoor contaminants levels only when HVAC systems were on, i.e. air was being well mixed. However, if the area of a measured room and its occupancy density gradually increases, one sampling point will not be sufficient to provide an accurate value due to the large variation caused by increased pollutant sources and the different distances involved.[22]

In the context of this research, as cited in the ASHRAE Standard 62.1,[1] the breathing zone refers to the region within an occupied space between planes 0.75 m and 1.8 m above the floor and more than 600 mm from the walls or fixed air conditioning equipment. For densely occupied mechanically ventilated spaces (those with a design occupant density greater than or equal to 25 people per $\sim 93.0\ m^2$), Taylor[28] recommends that the CO_2 concentration should be monitored within the space between 0.9 m and 1.8 m above the floor. As cited in Schneider,[29] the ISO1600-1 standard[30] (TC 146/SC 6) discusses suitable sampling locations by recommending the centre of the room at a height of 1.0 m–1.5 m above the floor (breathing zone). In the Standard ASTM D6245-07,[31] it is recommended that indoor air concentrations should not be measured close to people. A distance of 2.0 m from any occupant is sometimes suggested as sufficient to avoid the occupant's effects. However, most researchers (based on a database and questionnaires) prefer heights between 1 m and 1.2 m in the middle of a zone, as a representation.[32]

The accuracy of determining the mean CO_2 concentration in the occupied space could be significantly improved by increasing the number of sampling points. This was demonstrated by research carried out in open plan offices with air conditioning systems,[33] where results showed a strong correlation between the sampling point density and the probability of obtaining the measured quantity at certain confidence levels. Another research carried out in college classrooms reported that due to buoyancy effect of higher respired air from the occupants, CO_2 concentration was observed to be higher at 1.5 m height and that vertical difference were observed.[34] Thus, in order to overcome spatial resolution in a certain area, a large number of both vertically and horizontally distributed measuring sensors are required to generate a mean value that is representative of that particular area. These strategies are important in understanding and predicting airflow fields and the resulting contaminant distributions in ventilated classrooms.

Method

A total of four classrooms located within the University of Reading were selected during the winter term of 2008. According to Melikov,[35] occupied zones in classrooms can be difficult to define due to various activities (such as continuous influx of students due to change in lecturers, etc.) that can take place within the room. In addition, the time spent in the classroom, the varying occupancy numbers and students' seating positions contribute to the challenges in studying the overall IAQ. Therefore in this study, CO_2 concentrations were determined in accordance with the corresponding activity throughout the whole occupancy period, in order to more accurately identify the variations over time.

The general set-up of the gas monitoring system comprises two of the following parts;

1. The CBISS-MK2, 12 channels Intelligent Sampling System with each channel fitted with a solenoid valve, connected to the sampling zone by tubes.
2. A Brüel and Kjaer dual gas analyser (type 3425 B&K INNOVA) with an accuracy of ± 2 ppm.

Both systems were connected for data logging using a laptop linked to the B&K 3425 analyser. During measurements, only 12 points could be monitored at any given time. These 12 points were monitored to analyse the air samples taken from the classroom. This was accomplished by connecting the measuring point to the analyser using a flexible tube, with an inside diameter of 2.4 mm and an outside diameter of 4.0 mm. The lengths of the tubes used were between about 5 m and 7 m, depending on the sampling location. The analyser system used was an accurate, reliable and stable quantitative device with its own microprocessor control.

The test points were sampled in a cycle; one analysing cycle consisted of purging the air in the analyser chamber to ensure a consistent flow of gas before sucking in a new air sample. During the experiments, the sampling order started with random monitoring until it was stabilised. It then followed a sequential cycle of sampling. For instance, when the first cycle started at test point 1, the analysing cycles would then be followed by point 2 through to point 12 and this is known as the analysing loop. The time for a single loop was approximately 10 minutes because the interval between the start of two consecutive sampling channels was less than 1 minute in all the experiments carried out in this research. The reciprocal of the duration of one sampling loop is the sampling rate of a test point, which comprises approximately six loops every 60 minutes. It was impossible to increase the sampling rate of the test points due to a technical restriction.

In the fieldwork tracer gas decay tests using SF_6 were carried out at the end of a monitoring day for different ventilation strategies in accordance with the test methods of E741[36] and the ASTM D6245-07.[31] To reach a uniform concentration in the classroom, the SF_6 gas was injected at several locations in the classroom being investigated, with three fans located at various locations to provide uniform mixing. These fans were switched on for approximately 5–10 minutes to mix the air in the classroom before the decay measurements commenced. The measurements were carried out under the assumption that the room was uniformly mixed. According to Liddament[37] and Fisk et al.,[38] it is always difficult to judge the most appropriate sampling point within the test environment because of the limitations of sampling sensors that are dictated by the available equipment. Ideally, more sampling points are required to reduce the error in data collection. All measurements (including SF_6) were defined and configured on the basis of CO_2 monitoring locations.

In addition, the indoor and outdoor air temperatures monitored during the field work were measured using thermistor temperature sensors. These measurements were collected using Eltek GenII telemetry transmitters, which periodically transmitted data onto a GenII wireless central data logger. Generally, in the experiments carried out in the classrooms, three types of measuring devices were used. These were

1. Built-in temperature and relative humidity (RH) with an accuracy of ± 0.4 K and $\pm 2\%$ (RH) for temperature and humidity, respectively.
2. Thermistors and RH sensors with an accuracy of ± 0.3 K at 23.0°C and $\pm 1.5\%$ for RH.
3. Stainless steel temperature probes equipped with thermistor temperature sensors with an accuracy of ± 0.3 K for an operating range from -50.0°C to 150.0°C.

With regard to the temperature measurement in the classrooms, three sensors were distributed on a vertical pole fixed to each of two trolleys to record the temperature variation with height. These sensors were located at 0.2 m, 1.2 m and 1.8 m above the classroom floor (see Figures 2 and 3). Generally, for thermal comfort measurements, temperature and velocity sensors are located at 0.1 m and 1.1 m above the floor. However, in this research, sensors for temperature and velocity measurements were placed at the same vertical position as the CO_2 sensors to complement these measurements. As stated in the research aim, this study focuses on CO_2 distribution in ventilated rooms and thermal comfort is of secondary concern.

Monitored classrooms

Site and classrooms description. Classrooms with different designs and sizes were chosen for this investigation. The naturally ventilated classroom 2n17 is located in the URS building (building number 33 in Figure 1), which houses the School of Construction Management and Engineering. The mechanically ventilated classroom (Palmer 111) and the one equipped with a windcatcher (Palmer 105) are located in the Palmer Building (Building number 26 in Figure 1) on the first floor of the two- storey building.

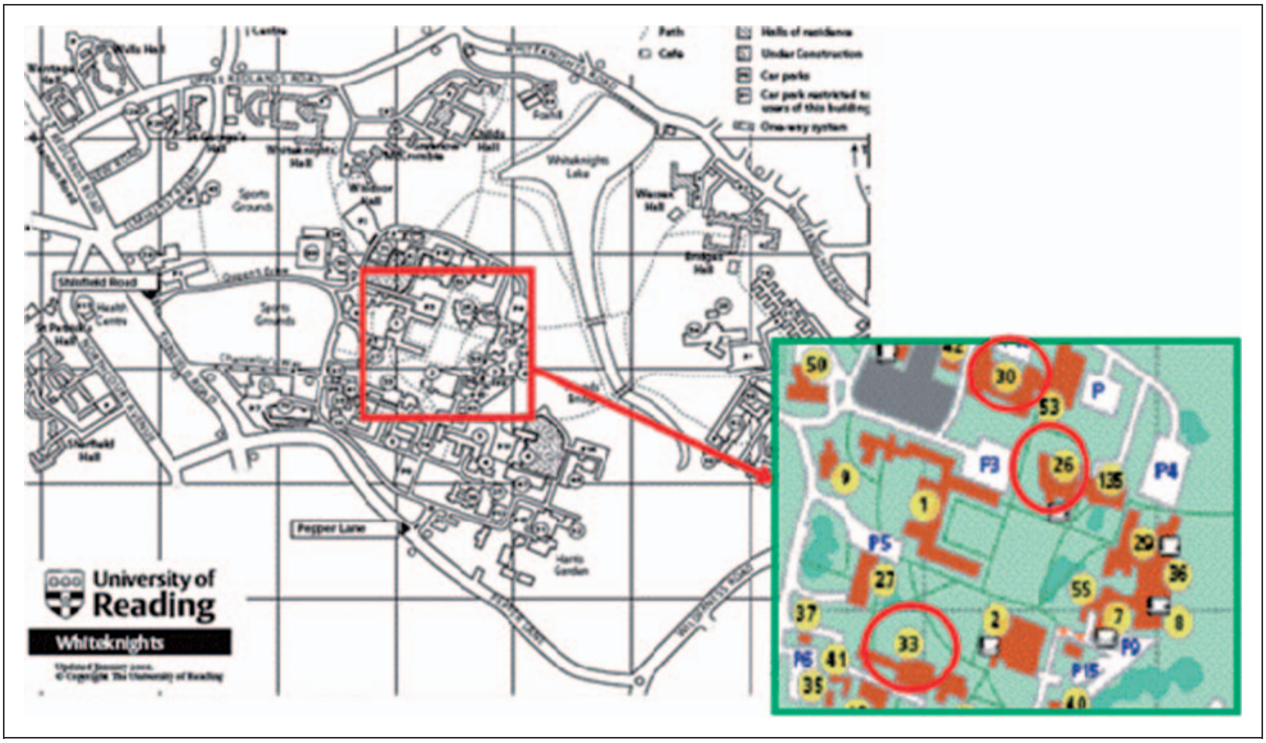

Figure 1. The locations of classrooms used in the monitoring.

Table 1 briefly describes the room sizes, orientations, student capacity (maximum), monitoring period and most importantly, the ventilation strategies applied in each classroom. Two webcams were installed at high strategic locations to capture a whole view of the classroom and to monitor details such as activities of students, seating arrangements and the opening and closing of windows, which are very important factors that influence the levels of CO_2 in classrooms. Due to the unpredictability of weather, such as constantly varying wind speed and direction, the indoor-outdoor temperature, RH and wind speed were measured to give an indication of the conditions in the internal and external spaces. The ambient temperature, wind speed and direction were recorded using the nearest weather observation station (weather station at the Meteorology Department, the University of Reading, is approximately 400 m away from the Palmer building).

Sampling locations. Figures 2, 3 and 4 illustrate the layout of classrooms used in the field measurements. The design of individual classrooms is not the same but they are similar in seating layout. The sensors in all classrooms were placed at heights of 0.2 m, 1.2 m and 1.8 m above floor level. Monitoring at these heights was important in order to investigate the spatial distribution of CO_2 within a seated occupant's surroundings. As illustrated in Figures 2, 3 and 4, measurement poles with a number of sensors (height of sensor in m) were placed at locations A, B, C, D and E in the classrooms.

Data analysis

The experimental data was analysed using both SPSS statistical software and Microsoft Excel to produce descriptive statistical analysis, analysis of variance (ANOVA) with Post-Hoc multiple comparisons and correlation analysis. These analyses were conducted to determine the relationship between the two variables listed below:

1. The occupancy patterns with the ventilation strategies.
2. The CO_2 concentrations with different ventilation strategies.
3. The spatial differences among the 12 sampling points in the classrooms with different ventilation strategies.
4. The relationship between the CO_2 concentration levels and the indoor environmental parameters i.e. temperature, air velocity and RH.

To better understand the variability of the occupancy patterns from one period to another, experiments that were performed in any monitoring day were classified as 'teaching' (T), 'break' (B) and 'non-occupancy' (NO) periods. Measurements were carried

Table 1. Characteristics and description of classrooms.

Classroom specification	URS 2n17	Palmer 111	Palmer 105
Floor area (m^2)	109.25	60.84	74
Volume (m^3)	382.4	173.4	210
Maximum student capacity	70	40	60
Monitoring period	1 week	2 weeks	2 weeks
Windows size (m^2)	1.16 & 1.4	1.12	1.12
Number of panels (position on wall)[a]	4 (back)	5 (side)	6 (side) 6 (back)
Orientation (reference to wall)[b]	North (back)	South (side)	North (side) East (back)
Number of doors	1	1	1
Ventilation strategies	NV	NV	NV
Natural ventilation (NV)			
Natural ventilation –intervention (NV-I[c])	NV-I (door)	NV-I (window)	NV-I (window)
Windcatcher	-	-	Fully open (WC-F)
Mechanical ventilation middle mode extractor fan (MVMM)	-	MVMM	-
Mechanical ventilation middle mode extractor fan –Intervention (MVMM-I[c])	-	MVMM-I	-
Mechanical ventilation full mode extractor fan (MVFM)	-	MMFM	-

[a]Position of side and back walls are illustrated in Figure 2.
[b]Reference to side and back walls in classrooms are relative to the cardinal point.
[c]Intervention involves door or window opening.

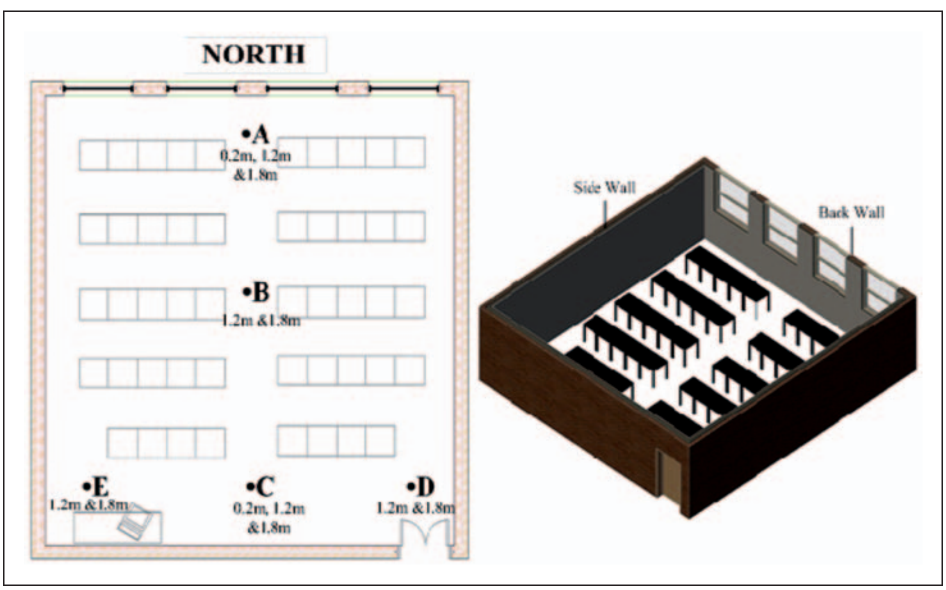

Figure 2. The floor plan and perspective layout of classroom URS 2n17.

out during the day from 8:30 am to 5:30 pm. However, on some occasions when classes were held in the evening, the measurements were continued until the end of the lecture (i.e. till 9:00 pm).

To analyse the spatial differences, ANOVA was used to determine if the differences in the means of CO_2 concentration from various sampling locations (vertical and horizontal locations) were significant, as well as to calculate the 95% confidence limits of the means. The factors affecting the CO_2 mass concentration that were pursued in the study were the type of ventilation system and the locations of all the sampling sensors.

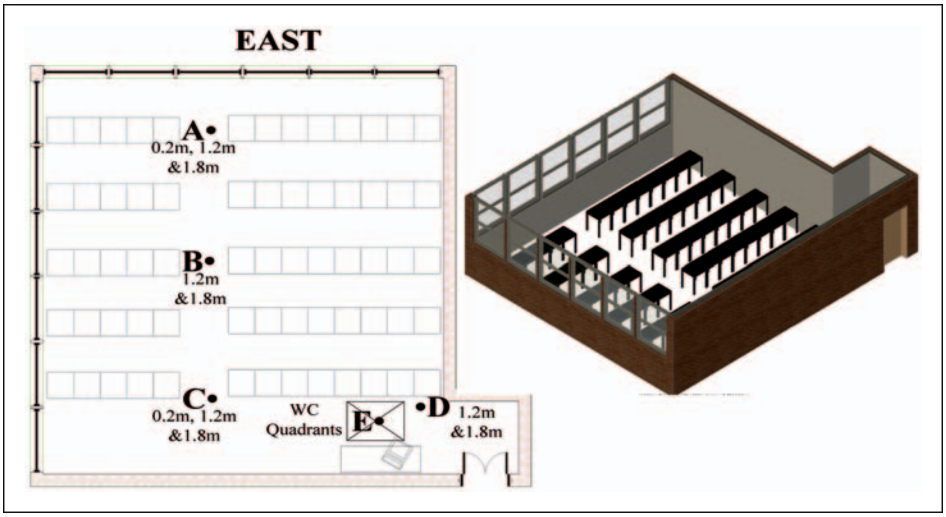

Figure 3. The floor plan and perspective layout of the classrooms 105 in the Palmer Building; the square with X is the location of the windcatcher on the ceiling.

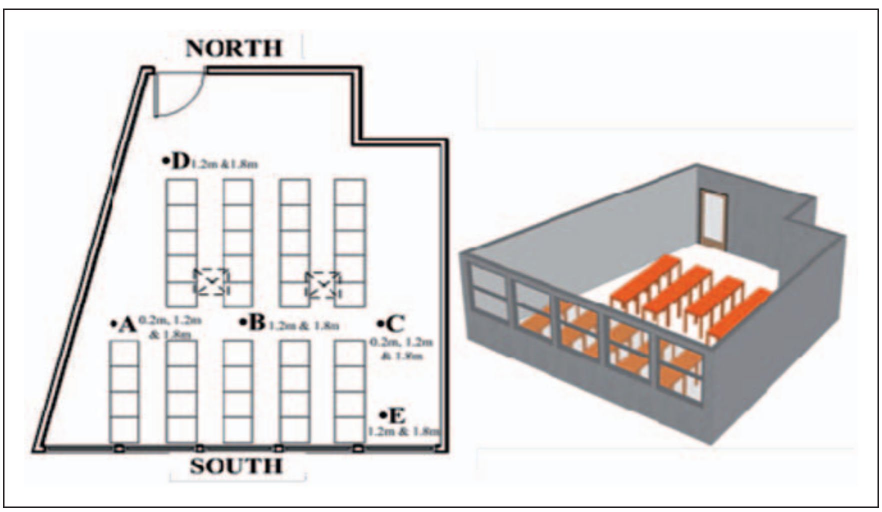

Figure 4. The floor plan and perspective layout of the classrooms 111 in the Palmer Building; the dotted squares are the extractor and supply fans on the ceiling.

However, in most previous multi-location studies researchers did not consider the sensor location as a significant parameter until at least its significance was tested. Therefore in this study, the ANOVA model was used to study the variation of concentrations for both the interactions of location and height of the sampling sensors.

Results and discussions

The distribution of CO_2 concentrations during three different periods

Generally, many researchers reported their results based on the average concentration of data collected. These results could probably be the average concentrations for a few hours, one day, a week or longer monitoring periods. In this study, analysis that considers all three periods: teaching (T), break or swapping classes (B), and non-occupancy (no lectures) (NO) were investigated. In addition, an average value of all three periods (Av) i.e. average of all data collected from the beginning up till the end of the monitoring period was also analysed to observe the differences in CO_2 concentrations.

As shown in Figure 5, for a naturally ventilated classroom the differences between the average values of CO_2 concentrations (Av) throughout the monitoring day and those during the teaching periods (T) only were quite substantial (approximately 680 ppm). The total

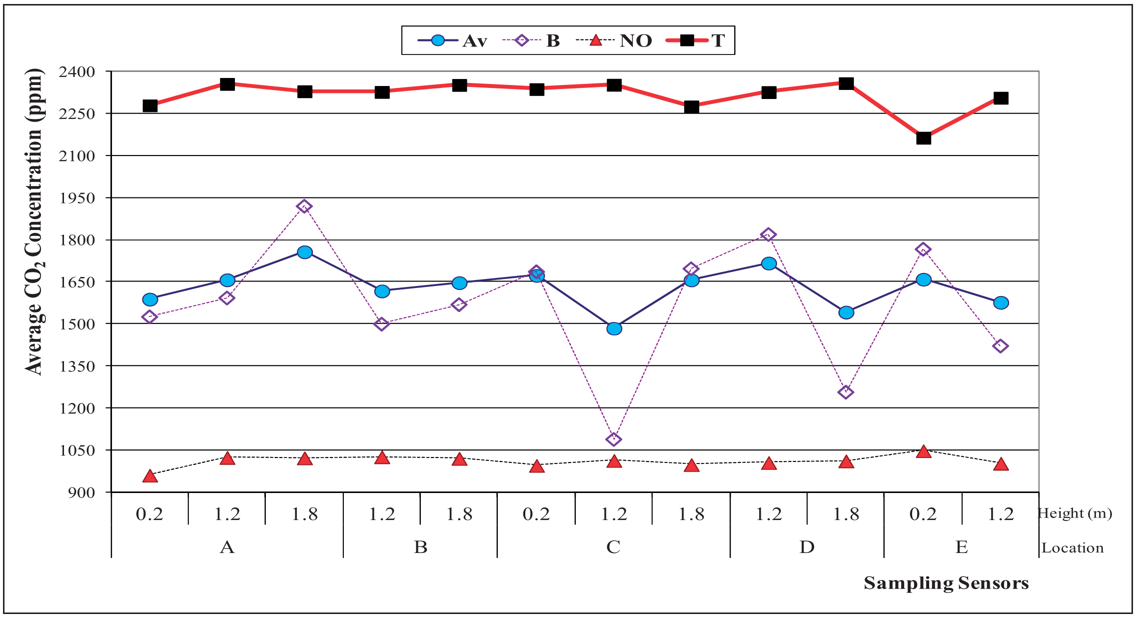

Figure 5. The distributions of average CO_2 concentrations for different monitoring periods in naturally ventilated classroom 111. (Av = average, B = brake, NO = no class, T = teaching).

hours of occupied/teaching period (T) for average of 24 students in the classroom were approximately 5 hours and 40 minutes during the 10 hours of monitoring period. A low air change rate (an average of 0.24 ACH) and stagnant air in the classroom would have caused a substantial variation in the spatial distribution of CO_2 concentrations. Therefore, results presented that were based on average values of the monitoring days might not be accurate for describing the actual condition in the classroom. Hence, for further analysis of the spatial distributions of CO_2 in all classrooms, only data collected during the teaching period would be used. Throughout the monitoring period, the outdoor CO_2 was observed to be within the range of 455 ppm to 537 ppm.

Results of the spatial distribution of CO_2 concentrations with different ventilation strategies

The results for the classrooms were classified under a number of scenarios (cases) involving different ventilation strategies and air change rates as given in Table 2. The air change rate was measured using SF_6 as a tracer gas as described earlier in the method section.

This section discusses the results based on the data that were collected from each of the 12 CO_2 measuring locations. For comparison of the spatial distribution of the CO_2 concentrations as affected by the different cases considered, natural ventilation (NV), mechanical ventilation (MV) and Windcatcher were used. In Table 2, it was observed that when an intervention was introduced in the NV scenario, the impact on ACH was much greater. However, under the scenario of Extract Fan (B_{MI}), intervention results in only marginal increase in ACH as compared to B_M when the extract fan was switched on (a difference of 0.07 ACH). This could have been mainly due to the opening of one window at the side which had probably caused a large influx of air through the window due to the low outdoor air temperature (8.4°C), as listed in Table 3.

Figure 6 shows the relationship between average CO_2 concentrations in a naturally ventilated classroom (Palmer 111) at three elevations and different horizontal positions. The layout of the sensors is as shown in the inset of Figure 6, originally illustrated in Figure 3.

Surprisingly, although windows were opened in the classroom during Case A_{NI}, the variation pattern of CO_2 levels amongst the 12 locations were almost identical except for a steep drop in the CO_2 concentration at a height of 0.2 m in location E for Case A_N. Based on the video evidence, it was observed that not many students were seated at this location throughout the monitored period, hence the lower CO_2 concentration. In addition, the differences between the highest mean value of CO_2 level to the lowest mean value for Case A_N was calculated to be ~200 ppm, while for Case A_{NI} it was ~150 ppm. The difference in these values would have been similar if there was no steep drop at Location E for Case A_N.

As for the intervention in the classroom, the lowest mean values for Case A_{NI} were observed at locations A and E at heights of 0.2 m and at height of 1.8 m for location C. Based on observations, the windows that

Table 2. Types of ventilation strategies applied in classrooms.

Ventilation strategies	Case	ACH	Size (m^2)	Classroom
Natural ventilation with no intervention	Case A_N	0.24	60.84	Palmer 111
Natural ventilation with intervention	Case A_{NI}	0.58		
Extract fan (middle mode speed) with no intervention	Case B_M	3.28		
Extract fan (middle mode speed) with intervention	Case B_{MI}	3.35		
Extract fan (full mode speed) with no intervention	Case B_{FM}	3.65		
Natural ventilation and no intervention	Case C_N	0.63	74	Palmer 105
Natural ventilation with intervention	Case C_{NI}	1.97		
Windcatcher with no intervention	Case D_H	3.1		
Natural ventilation and no intervention	Case E_N	0.78	109.25	URS 2n17
Natural ventilation with intervention	Case E_{NI}	1.20		

Table 3. Averaged indoor and outdoor parameters in classrooms.

Case	Average no. of students (nos)	Indoor CO_2 (ppm)	Indoor temp (°C)	Air. velocity (°C)	Corridor CO_2 (ppm)	Corridor temp (°C)	Out CO_2 (ppm)	Out temp (°C)	Indoor RH (%)	Out RH (%)	Wind dir. (deg)	Wind speed (ms^{-1})
A_N	15	1938	23.4	0.07	671	23.1	465	6.1	30	96	222 SW	5.80
A_{NI}	12	907	21.0	0.08	759	22.7	455	10.1	32	63	223 SW	3.93
B_M	11	1040	20.5	0.05	776	22.5	448	9	31	74	216 SW	3.24
B_{MI}	14	1153	22.0	0.08	1130	23.2	590	8.4	25	58	75 NE	2.30
B_{FM}	12	1020	20.2	0.11	727	22.3	445	11.5	33	86	226 SW	4.26
C_N	16	1354	21	0.02	635	22.0	478	8	36	79	221 SW	3.00
C_{NI}	17	1160	20.3	0.03	849	22.3	484	6.6	34	81	138 SE	2.70
D_H	18	672	16.9	0.09	674	22.1	480	4.5	28	83	122 SE	2.6
E_N	19	1371	22.6	0.06	721	22.3	590	12.6	45	62	232 SW	2.9
E_{NI}	20	1114	22.0	0.07	757	22.0	497	12	43	65	231 SW	3.3

Out: outdoor. All indoor temperatures are based on average of three measuring points (0.2 m, 1.2 m and 1.8 m height from floor level). Wind direction and speed at 10 m height.

were noted by students to be open most of the time were the back two panels and the first panel at the front. As sensors were located fairly close to these windows (~0.7 m from location E and ~ 2.5 m from locations A and E), there would have been a down flow of cool air from the outside (8.8°C) into the classroom, thus displacing warm air at the floor (21.02°C) (typically less than 0.5 m from the floor level). Other sources of air infiltration might also contribute to this effect; notably through cracks and gaps in the fabric. In addition, it was also noted that the seats in this area were not regularly occupied, which further explains the low concentration levels.

Within the classroom, the highest CO_2 concentration was found at about the same height (1.8 m) but for different locations (i.e. A and B). In Case of A_N, the highest mean CO_2 value was at 1.8 m height for location B, followed by that for location A at the same height. Conversely, in Case of A_{NI} the opposite was recorded with the highest value obtained at location A, followed by location B at a height of 1.8 m.

Considering the results for classroom Palmer 111 when mechanically ventilated (see Figure 7), the trend of CO_2 variations among the 12 locations for both B_M and B_{FM} were quite similar, but with greater differences between the lowest concentration (location A at 0.2 m) and the highest concentration of CO_2 (location D at 1.2 m) for B_M case (a difference of 184 ppm). However, with regards to CO_2 concentration build-up, the average levels of CO_2 for B_M with ACH of 3.28 were significantly higher than that for the other two Cases of B_{MI} (ACH 3.35) and B_{FM} (ACH 3.65). This was again attributed to the difference in the number of occupants in this classroom during the

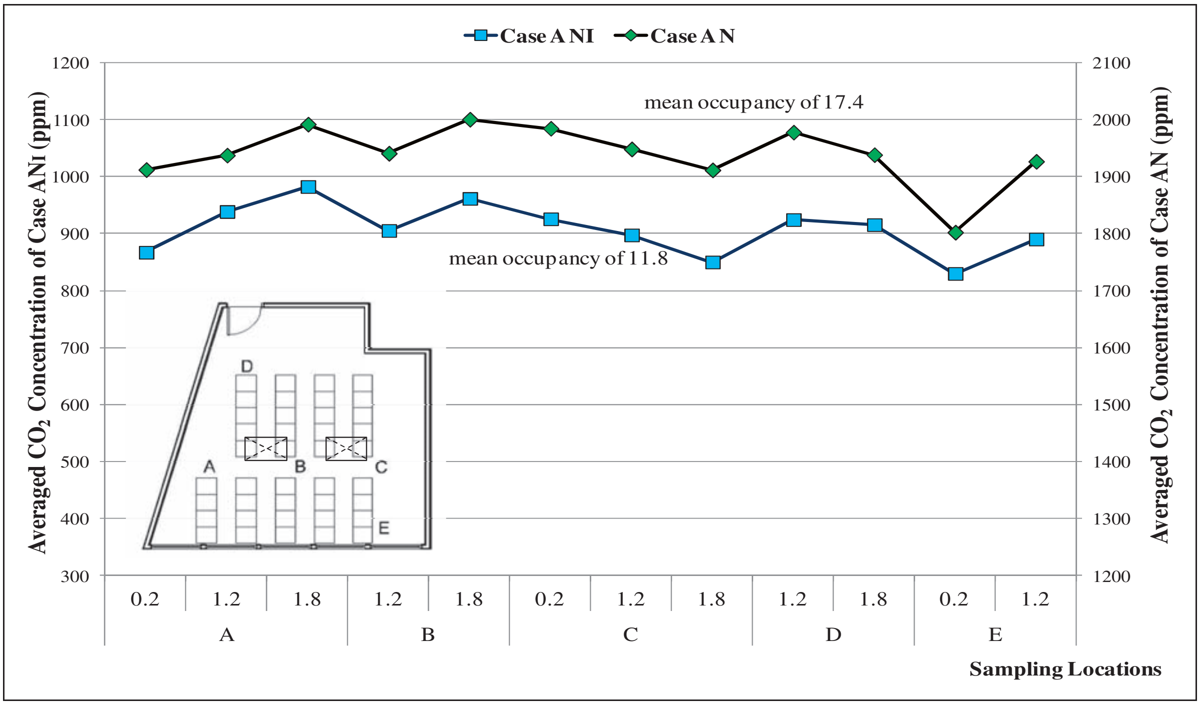

Figure 6. Average CO_2 concentrations at different locations for natural ventilation (classroom Palmer 111).

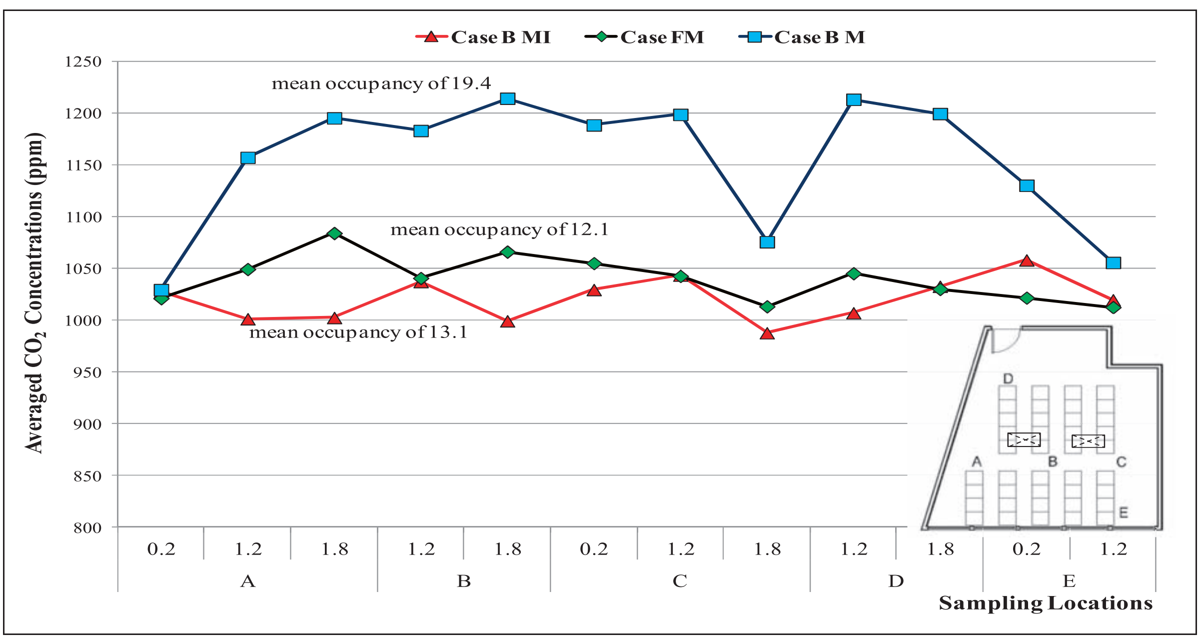

Figure 7. Average CO_2 concentrations at different locations for mechanical ventilation (classroom Palmer 111).

monitoring periods (mean occupancy of 19.4 for B_M compared to 13.1 and 12.1 in Cases of B_{MI} and B_{FM}, respectively).

Based on the ANOVA analysis, a significant difference was recorded amongst the five locations in the classrooms with a p value of <0.05 for both Cases B_M and B_{MI} (see Table 3). However, the effect of mean vertical distribution was observed to be insignificant with a p value of 0.473 and 0.797 for B_M and B_{MI}, respectively. However, in Case of B_{FM} the mean effects of both locations and heights were insignificant (p value >0.05), confirming that the air in the room was well

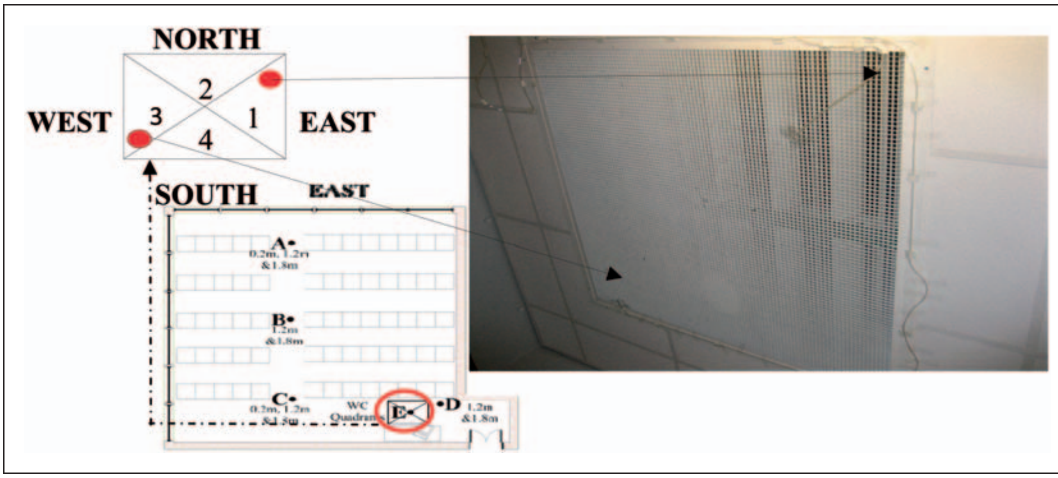

Figure 8. The positioning of CO_2 sampling tubes at the windcatcher quadrants in classroom Palmer 105.

mixed hence placing sampling sensors at any of the locations would not contribute to any errors or inaccuracy in the measurements.

Based on the results given in both Figures 6 and 7, it would appear that if CO_2 sensors were only located at a height of 1.2 m in the centre of the classroom, there would have been a discrepancy of about 2%–8% from the highest mean values given in both figures. The highest difference for the classroom was noted for Case A_{NI}. This therefore, prompts suggestions that there are significant differences in CO_2 concentration with measurement height, which is worthy of further investigation.

Moving now to the results obtained for classroom Palmer 105, the setting up of CO_2 sensors in this room was quite different from the other two classrooms because of the location of the windcatcher. As the performance of the windcatcher greatly depends on the direction and the speed of the wind, extract and supply quadrants within the windcatcher were expected to be changing.[39] Therefore, two sensors, which had been positioned at location E near the side windows in the first week, were moved to locations on the ceiling where the windcatcher damper was placed during the second week of monitoring the CO_2 distribution in this classroom (see the insert of Figure 8).

With the unpredictability of weather and constantly varying wind speed and direction, indoor and outdoor temperature and RH were also measured to provide an indication of the condition of the internal and external environment. Data from the weather station at the Department of Meteorology, University of Reading, which was periodically transmitted to the data logger, were used as complementary measured parameters.

In Figure 9, a steep increase of CO_2 concentrations was observed on Tuesday and Friday of week 1. In particular, it was observed that on Tuesday at about 18:40, where there was no intervention (Case C_N) in the classroom, CO_2 concentrations gradually built-up in the first 2 hours and continued to increase after a short break (a slight drop at 20:30). The steep increase in the build-up of CO_2 (Friday week 1) was due to long lecture periods. In general, it was noted that the high CO_2 concentration was due to the long hours of classroom usage coupled with little ventilation.

With the operation of the windcatcher, the build-up of CO_2 concentration (as illustrated in the Figure 9 for Tuesday and Friday of week 2) was not so high regardless of the number of occupants. For example, on Tuesday week 2, 55 occupants were in the classroom at 16:00 hours for approximately 2 hours, yet the CO_2 concentration was below the acceptable value (<1500 ppm). With regard to the build-up pattern, it was observed that there were significant fluctuations for Case D_H. As stated earlier (refer to Figure 8), two sensors were located at two of the windcatcher's quadrants, which would have been measuring the extract or the supply air into and out of the windcatcher rather than the concentration in the classroom. The measurements at these locations would have contributed to some of the large fluctuations in CO_2 concentration for week 2.

The effect of wind direction on the spatial distribution of CO_2 concentrations

In this section, the effect of the wind direction on the build-up of CO_2 was analysed and discussed. As illustrated in Figure 10, the spatial distribution of CO_2 in the classroom with an operating windcatcher provided some interesting results. Concentration levels were noted to be less at sampling location 12 (dotted red line), which was located at the windward side of one of the windcatcher's quadrants, than those observed at other sampling locations. This was due to the wind direction flowing from South West ($\alpha = 219°$ from the North). The wind speed recorded from the meteorology weather station during the first lecture was about 3.86 ms^{-1} (11:00 to 13:00) and about 5.55 ms^{-1} during the second lecture (14:00 to 16:00).

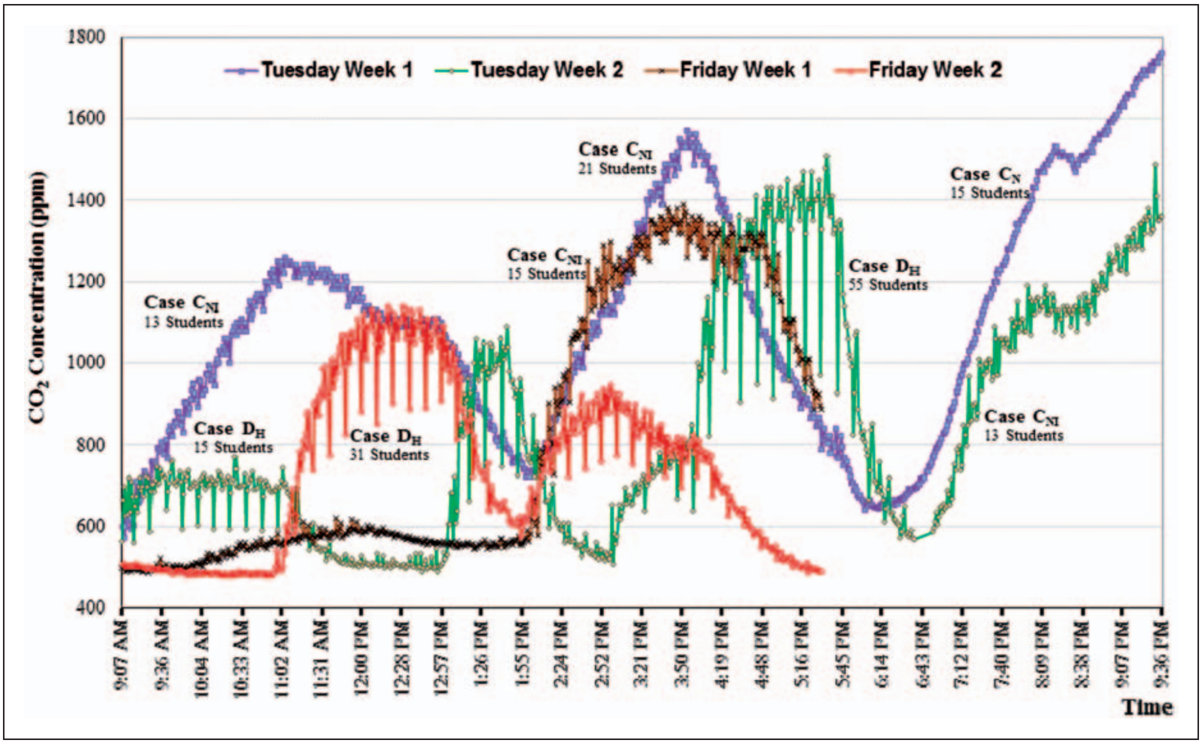

Figure 9. The effect of ventilation strategies and transient occupancy on the build-up of CO_2 concentration (Palmer 105).

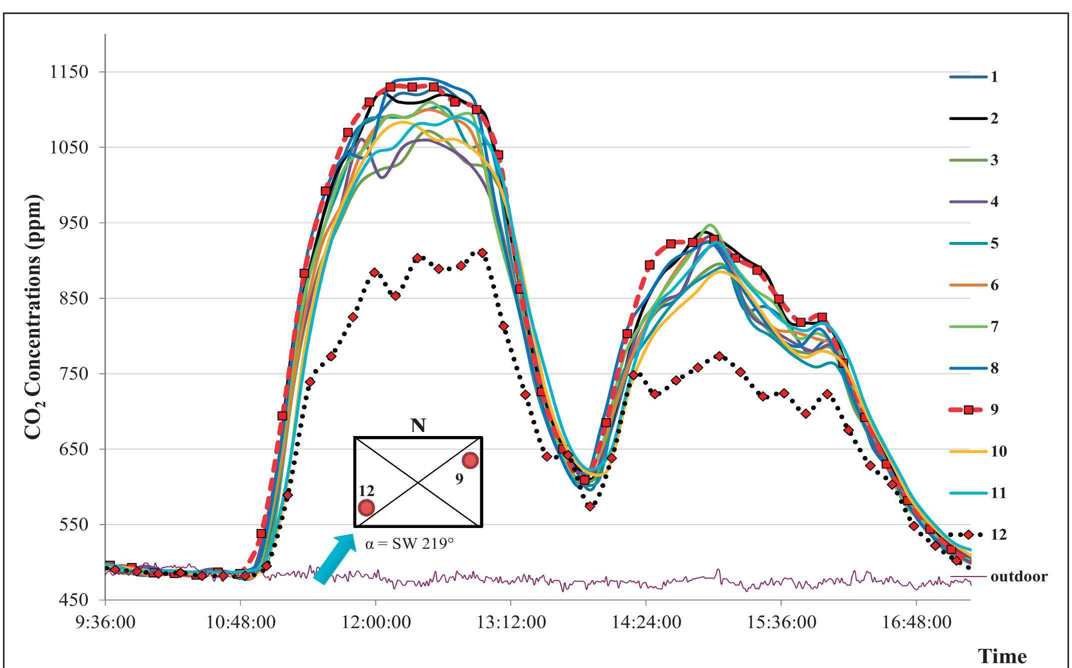

Figure 10. Spatial distribution of CO_2 concentrations for Case D_H with wind direction of 219° (SW).

On the other hand, sensor 9 located at the opposite quadrant recorded a much higher value while the classroom was occupied. During the teaching periods the CO_2 level recorded by sensor 9 was the highest value from all sensors. These results confirmed that the quadrant with sampling sensor 12 was acting as a source of air supply, while that where sensor 9 was located was acting as a source of air extraction. This supports the previous findings of Elmualim and Awbi[4] obtained using wind tunnel tests. However, due to some mixing of supply air with room air in the vicinity of the windcatcher quadrant where sensor 12 was located, it can be seen from Figure 10 that the measured CO_2 concentration was in general higher than the outside concentration.

Comparison of CO_2 spatial distribution for different ventilation strategies

All the cases (A to E) presented in the research were examined to determine the effect of the ventilation strategy on the spatial distribution of CO_2 concentration. Table 4 provides a comparison of ANOVA results for the mean CO_2 concentration for various ventilation strategies. The results illustrate the effect of ventilation strategy on the average CO_2 concentration, which include the significant effects of the 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.

Table 4. Summary of analysis of variance (ANOVA) results for the average CO_2 concentration in various cases of ventilation strategies.

			P-value		
Classroom	Cases	ACH	Location	Height	Location and Height
Palmer 111	Case A_N	0.24	*0.000*	*0.000*	*0.000*
	Case A_{NI}	0.58	*0.000*	*0.008*	*0.000*
	Case B_M	3.28	*0.002*	0.473	*0.001*
	Case B_{MI}	3.35	*0.000*	0.797	*0.000*
	Case B_{FM}	3.65	*0.025*	0.732	*0.002*
Palmer 105	Case C_N	0.63	*0.006*	*0.026*	0.934
	Case C_{NI}	1.97	*0.003*	0.103	0.116
	Case D_H	3.20	0.160	0.287	0.450
URS 2n17	Case E_N	0.78	*0.000*	*0.008*	*0.000*
	Case E_{NI}	1.20	0.974	0.956	0.719

Note: Italic represents a p-value at 5% confidence limit

Palmer 111. The analysis of variance for classroom Palmer 111 shows that the two main effects of sampling (i.e. location and height) on the mean CO_2 values were all significant at a 5% level when the classroom was naturally ventilated. These significant values indicate that there is an effect of each of the independent variables (i.e. location or height) and there is also an effect of how these variables interact (i.e. both location and height).[40] Consequently, it is essential that the effect of ventilation strategies on CO_2 concentration should be tested separately against each type of ventilation and sampling locations (location and height). The resulting interactions for this classroom, namely the mean CO_2 values for both location and height, were found to be significant in all cases.

However, when classroom Palmer 111 was mechanically ventilated, there was an insignificant main effect of the height on the mean CO_2 concentration with a p value >0.05. This shows that overall, the mean CO_2 concentration levels do not vary with sensor height (i.e. 0.2 m, 1.2 m and 1.8 m). It was also noted that with a higher air change rate when the extractor fan was in operation, more uniform CO_2 distribution was produced in the vertical direction. This suggests that in such conditions and if a limited number of sampling locations is desired, the samplers can be distributed anywhere vertically and more samplers can be placed in more horizontal locations at any height. This, however, could not be applied to a naturally ventilated classroom due to the non-uniform mixing of room air. The suggested measuring locations for such a classroom would be at A (back) and B (middle), where most occupants prefer to sit, and vertically at a height of 1.8 m. The mean CO_2 concentration at this height was found to be the highest in most cases.

Palmer 105. For classroom Palmer 105 similar results to those for Palmer 111 with MV ventilation were noted. The variation in the mean CO_2 concentration with height was insignificant in Cases of C_{NI} and D_H with p values of 0.103 and 0.287, respectively. Considering $p = 0.103$ for Case C_{NI}, there was a 1-in-10 chance (i.e. very weak evidence of minimal significance) that the sampled data only agreed with the hypothesis due to chance.[40] This result indicates that when the windcatcher was in operation, the room air was well mixed, signifying that both the main effect of location ($p = 0.160$) and height ($p = 0.287$) of the sampling positions would not produce any significant impact on the measured CO_2 values throughout the monitoring period.

Table 5. Summary of spatial distribution of CO_2 in classrooms with different ventilation strategies.

		Cases									
Location	Height	A_N	A_{NI}	B_M	B_{MI}	B_{FM}	C_N	C_{NI}	D_{DH}	E_N	E_{NI}
	0.2	1912	867	1021	*1029**	1028	*1328**	*1133**	*649**	1245	1140
A	1.2	1937	938	1049	1157	1001	1359	1148	673	1262	1128
	1.8	1991	**982***	**1084***	1195	1002	1374	1172	686	1280	1138
B	1.2	1940	905	1041	1183	1037	1348	1156	669	1273	*1127**
	1.8	**2000***	961	1066	**1214***	999	1361	1185	**695***	**1310***	1143
	0.2	1984	925	1055	1188	1029	1336	1153	665	1302	1138
C	1.2	1948	897	1043	1198	1043	1359	1166	674	1276	1132
	1.8	1911	850	1013	1076	*988**	1341	1134	664	1183	1140
D	1.2	1977	924	1045	1213	1007	**1386***	**1190***	680	1278	1142
	1.8	1938	915	1030	1199	1033	1350	1166	673	1224	1128
E	0.2	*1802**	*829**	1022	1130	**1058***	–	–	–	*1182**	1145
	1.2	1926	890	*1012**	1056	1020	–	–	–	1236	**1146***

Bold*: highest value; *Italic**: lowest value.

URS 2n17. Unlike other classrooms, in URS 2n17 for the intervention case (E_{NI}) the average CO_2 concentrations were essentially the same regardless of the position of the sampling sensors. The area of this classroom was 109.25 m^2 with a maximum occupancy of 70 but was observed to be thinly occupied at most times. Therefore, the seating arrangements may have been mostly random. Another interesting observation for this classroom (Case E_{NI}) was the vertical distribution of CO_2 concentrations. Although the highest value occurred at a height of 1.8 m in location B, the values at this height at locations C and D were observed to be amongst the lowest (see Table 5). The average air velocities recorded by two sensors at two different locations (B and D in Figure 2) was very small ($<0.05\,ms^{-1}$), confirming the presence of stale air. The stratification of CO_2 that was present at some of these locations is a further confirmation of the low ventilation rate at these locations.

In contrast, the overall spatial distributions of CO_2 for Case E_{NI} were statistically not significant with less than 50 ppm variation amongst all sampling sensors. Due to the opening of the door throughout the monitoring period, continuous airflow and recirculation from the corridor would have occurred in this case, thus generating a higher air change rate (1.20 ACH). Thus, for this ventilation strategy, when the door was open the concentration was more uniformly distributed both horizontally and vertically and so a lesser number of samplers would be required for monitoring such a case.

Conclusions

This paper presented results on the effect of ventilation strategy and airflow rate on the build-up and spatial distribution of CO_2 concentrations in classrooms. The major conclusions that could be drawn from the experimental data are as follows:

- The type of ventilation strategy affected the spatial distribution of mean CO_2 concentration.
- The average values of CO_2 concentrations for a whole monitoring period might not be accurately representing the values in the classroom during occupancy. In particular, a low air change rate and the presence of stagnant zones in a classroom (mainly for the natural ventilation cases) would cause a substantial difference between the average concentration values and those existing during teaching periods.
- For all the ventilation strategies used in the classrooms (except for cases when the door was open or when a windcatcher was in operation), the location of sampling position (horizontal distribution) on the measured mean CO_2 concentration was found to be significant.
- The vertical distribution of the mean CO_2 concentration did not vary significantly except for the cases when the classroom was naturally ventilated. However, higher concentration values were found at higher regions (1.8 m height).
- Knowledge of the spatial distribution of CO_2 concentration was important when a limited number of

sampling locations was used. In a classroom, it was found that the samplers should be distributed horizontally within the room, since the concentration would be more likely to vary with distance, e.g. at the back of the classroom and along the aisle between the seating arrangements. In addition, it was found that the seating position of occupants in the room could have a large influence on the CO_2 concentration.

- This study showed that having only one sensor to represent the CO_2 concentration in a room could lead to inaccurate estimations of the average CO_2 level used for monitoring purposes. The choice of sampling locations is very much dependent on the prevailing air movement, and on the type of ventilation strategy.
- The type of ventilation strategy affects the spatial distribution of CO_2. In a classroom with an open door, a more uniform distribution was observed, which was quite opposite to the results obtained from a naturally ventilated classroom with intervention (opening of windows). CO_2 was identified to more likely follow the path of air movement and can be easily distributed by the prevailing airflow due to occupants' interventions (e.g. window or door opening).
- CO_2 concentrations could vary with not only room ventilation condition but also with other parameters such as the number of occupants, occupants' sitting position, occupancy periods, location of air supply and extract openings, external and internal environmental conditions, etc.

Acknowledgements

This work was supported by the Ministry of Education, Malaysia and the University of Malaya.

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