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Spatial distribution of CO_2 Impact on the indoor air quality of classrooms within a University

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ABSTRACT

Indoor air quality (IAQ) remains a public and global concern. While CO_2 does not pose health risks to occupants, high CO_2 levels indicate insufficient ventilation, potentially accumulating pollutant concentrations. In buildings, occupants are identified as the main source of indoor carbon dioxide (CO_2) through exhalation. Standard classrooms may have occupant density between 1.8 and 2.4m^2/person. Therefore, the IAQ of classrooms and lecture theatres remain a concern. This study investigated airflow and contaminant (using CO_2 as a proxy) distribution in two classrooms modelled using CFX a Computational Fluid Dynamics (CFD) software, verified against experimental measurements. The model provides the visualization of flow patterns so that the effects of external and internal flow fields in the classroom can be studied. The results show that there are large differences in classroom indoor ventilation performance due to the effects of wind direction and wind speed on building surface wind pressure from outdoor wind speeds. Windward high-pressure surfaces and leeward vortices created by building shading promote indoor air quality in buildings with windcatcher openings. The concentration distribution of CO in the classrooms showed an upward convergence with the thermal plume generated by the respiratory differences of the personnel and the temperature of the lighting equipment. The results of this study have important implications for improving classroom design guidelines for school buildings, especially in terms of ventilation strategies and air quality monitoring.

1. Introduction

Indoor air Quality (IAQ) has been a global concern for decades. Since most people spend up to 90 % of their time indoors [1], the adverse effects of poor IAQ are far-reaching. As reported by users [2], despite the varied and often elusive nature of their complaints, air quality is a major role due to indoor pollutant levels are often higher than outdoor pollutant levels. In indoor environments, exposure to high levels of airborne pollutants, such as organic dust, can lead to pulmonary diseases [3]. The range of indoor environmental issues is of a broad nature, yet the significance of each issue fluctuates across different buildings [2]. Owing to mounting evidence of adverse outcomes attributed to poor IAQ, the importance of research in this area has increased significantly, particularly in residential and office.

Nevertheless, studies specifically concerned with the indoor environment of school buildings have not been performed until recently [4,5]. Despite these advancements, scant research has been reported on classrooms utilized by adult students. Numerous

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studies have documented sub-optimal IAQ levels in university classrooms with different capacities during occupancy periods [6,7]. Furthermore, Fox et al. [3] found CO_2 concentrations in a suburban elementary school in Columbia to range from 1017 ppm to 1736 ppm in heavily occupied schools. This correlation was observed with airborne bacterial levels, indicating a significant portion of the bacteria originated from the students themselves. Consequently, CO_2 concentration exceeded 1000 ppm and, in some cases, concentrations were recorded to be more than 5000 ppm, which contradicts concentration levels of 700 ppm stated by ASHRAE [6,7]. Daisey et al. [8] revealed that many classrooms are not adequately ventilated, which can lead to accumulation of bio effluents from room occupants and various gasses and particulate pollutants associated with building materials, classroom activities, and general housekeeping. In this paper, the exhalation of CO_2 is studied together with the interaction taking place between airflows from different ventilation systems. This is because of the complex indoor environments of classrooms which are influenced by many factors including number of students, activities, and seating arrangements. Hence, ventilation studies in classroom environments have increasingly become important.

Previous research has shown no relationship between CO_2 and sick building syndrome (SBS) complaints [9,10]. Ventilation and CO_2 concentration does not directly affect occupant health or perception outcomes. Yet the rate of ventilation and amount of CO_2 concentration affect indoor environmental conditions including air pollutant concentrations that, in turn, may impact the occupants' health or perceptions [11,12]. Higher CO_2 concentrations are associated with increased frequency of health symptoms [13,14]. Even though CO_2 may not be considered to pose serious health effects, reports on mild sickness and discomfort have been observed [15]. Some research indicates that in schools, high CO_2 concentrations tend to lead to drowsiness, lethargy [16], difficulties in complex decision making [17] and a general perception that the air is stale [13]. Indoor concentrations above 1400 ppm, or that which exceeds the outdoor concentration by at least 1000 ppm, has also been known to cause headaches and respiratory problems, stuffiness, inattention, unpleasant odours, lethargy, and general discomfort [18,19]. In another study, it was found that if the indoor CO_2 concentration is 1000 ppm higher than outdoor concentration, an increase of 10–20 % in student absenteeism was noticed in the average annual daily attendance [20].

Using ventilation rates of CO_2 as an indicator for IAQ, ASHRAE [21] recommends that indoor CO_2 concentrations must be maintained at or below 700 ppm above the ambient level in schools. Elevated levels of CO_2 may serve as an indicator of insufficient number of air changes in that environment. As noted by Leephakpreeda et al. [22], this may be because CO_2 is a human waste and if concentrations are controlled at the desired level, then other pollutants will be controlled at acceptably low levels as well. In addition, a study carried out by Kozar [23] and Liu et al. [24] also found that Muramic acid which serves as a marker for bacterial levels in indoor air, correlated with CO_2 in occupied classrooms. The likelihood of airborne infection transmission can be estimated using continuous CO_2 (exhaled breath) measurements and a risk equation derived by Rudnick & Milton [25]. Exhaled breath contains approximately 40, 000 ppm of CO_2 compared with the estimated 350 ppm in the outdoor air. Airborne infections can only be acquired by inhaling air that has been previously exhaled. Because occupants are the dominant indoor source of CO_2, the increase in indoor CO_2 concentration above the outdoor concentration is considered as a good surrogate for the indoor concentrations of bio effluents (i.e. body odours).

In many buildings, the occupants themselves are a major source of indoor air contamination, due to human activities which results in Carbon Dioxide (CO_2) exhalation amongst others. Considering that human exhalation is a buoyant jet with a pulsating intermittent nature, this has an initial elevated temperature that acts as a contaminant source in space [26]. Therefore, increased numbers of occupants in a classroom will result in a higher CO_2 concentration if ventilation provision is insufficient over a sustained period. In an enclosed space, exhaled breath from occupants involved in sedentary level of activity contains 4 %–5 % of CO_2, equating to approximately 0.01 gs^{-1} or about 0.005 l^{-1} [27]. When there are high concentrations of CO_2, internally generated pollutants can also build up collectively [28].

On the one hand, a primary factor contributing to these scenarios is the high variability in occupancy density higher education classrooms. Consequently, variations in CO_2 concentrations must be identified by conducting studies. More so since, human beings are considered to act as flow obstacles, their movement disturbing the stratification of the ventilated room [26]. In ventilated rooms, this is mainly significant in the case of physical activity including movement of students or lecturers. However, most ventilation standards (for instance ANSI/ASHRAE Standard 62.1–2016 [21]) specify ventilation rates based on continuous occupancy. This may indicate the presence of higher flow rates, which may then bring about unnecessary increases in energy consumption. 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 specification of relevant ventilation standards.

On the other hand, Shendell et al. [13] identified ventilation rates in at least 50 % of the classrooms falling below the 7.5 $l\ s^{-1}$ per person. This rate represents the minimum threshold prescribed by numerous standards. In instances such as this when the level of ventilation is insufficient, toxins and other pollutants may reach an undesirable level, whereas if it is excessive there will be unnecessary loss of energy from the space, especially when the external air temperature is lower than the internal air temperature [8]. In addition, low ventilation rates [29,30] and high indoor air temperatures [31] has been shown to affect the student's learning performance. Additionally, in other research carried out in environmental chambers and in occupied buildings, there were agreements that ventilation rates of about 7.5 l^{-1} per person (of outdoor air) would control human body odour such that approximately 80 % of un-adapted person (visitors) would find the odour at an acceptable level [32]. As stated in the ASTM Recommended Guide [32], it is evident that body odours in a room will not be harmful to most people if the CO_2 associated with humans is maintained at less than 650 ppm above background levels. The potential for increased risks of contracting certain communicable respiratory illness such as influenza and common colds in classrooms with low ventilation rates is also of particular concern [33].

Based on ventilation efficiency concepts discussed by Sung and Kato [34,35], it is concluded that local CO2 concentration is beneficial. The ventilation efficiency index of air-induced in void space was estimated using CFD. Using estimated germicides in the CFD model, it quantitatively indicated the ability to transport fresh air from the upper level to the lower-level void space diluting and expelling pollutants discharged within the zone. In addition, from the ultraviolet (UV) dose the researchers demonstrated results calculated from the UV distribution intensity. However, from the context the UV dose near the supply port was observed to be low but the air is relatively fresh. This also shows the importance of UV for local pollutants, as air movement carries airborne pollutants from sources. This also highlights the importance of the location of local pollutants. Although the approach by Sung and Kato [34,35] may provide ventilation efficiency, the application of UV was not considered in this research however techniques requiring the application of CFD was developed.

Generally, the control, monitoring, and prediction of indoor environmental conditions is complex, especially given the growth of new design standards of IAQ and thermal comfort [36,37]. Experimental measurements have conventionally provided a means of evaluating critical zones, although in many cases, cost and time limitations rule out its use [38]. For most research output, Computational Fluid Dynamics (CFD) has been used to predict air movement in ventilated spaces in analysing the preliminary and actual stages of design. Without any doubt, predicting indoor air distribution by means of CFD has contributed to advances in building ventilation system design [39]. Other researchers have highlighted using CFD codes to numerically solve equations that govern air movement, heat transfer and the distribution of chemical species of internal and external flows [40,41].

Rudnick & Milton [25] stated that exhaled breath is a vehicle for the release of airborne infectious particles, and thus contributes to the risk of airborne transmission of infection indoors. In indoor environments, exposure to high levels of airborne pollutants such as organic dust can lead to pulmonary diseases [3]. It is envisaged that an increased outdoor air supply can reduce the airborne transmission of infection for some common respiratory illnesses including influenza [42].

1.1. Effects of occupancy density and increased risks

One of the main contributing factors that result in such scenarios is due to the high variability of occupancy density in higher education classrooms. In effect, variations in CO_2 concentrations must be identified by conducting studies. More so since, human beings are considered to act as flow obstacles, their movement disturbing the stratification of the ventilated room [26].

Indoor concentrations above 1400 ppm, or that which exceeds the outdoor concentration by at least 1000 ppm, has also been known to cause headaches and respiratory problems, stuffiness, inattention, unpleasant odours, lethargy, and general discomfort [18, 19]. Person to person transmission of infections through the recirculated air of a room is also another potential source of significant morbidity [42–44]. The likelihood of airborne infection transmission can be estimated using continuous CO_2 (exhaled breath) measurements and a risk equation derived by Rudnick & Milton [25]. Exhaled breath contains approximately 40,000 ppm of CO_2 compared with the estimated 350 ppm in the outdoor air. Airborne infections can only be acquired by inhaling air that has been previously exhaled. As a result of this, CO_2 is used as a marker and would be useful to relate infection risk directly to the rebreathed fraction.

1.2. Numerical models

A pioneering work on indoor airflow simulation using CFD techniques was conducted by Nielsen [45], followed by Chan [42] and Zhu et al., [46]. In these, CFD models were developed and used to calculate the spatial distributions of the mean age and mean residual lifetime of air in the environment and to evaluate the efficiency of ventilation systems. The challenges when using CFD models is because, airflows in rooms are characterised as being non-isothermal, turbulent, three dimensional and transient. In this paper, CFD models were developed and used to calculate the spatial distributions of the mean age and mean residual lifetime of air in the environment and it was used to evaluate the efficiency of ventilation systems verified against experimental measurements.

2. Methods

Despite extensive studies identifying CO_2 concentration levels as indicators of ventilation adequacy relative to occupancy and metabolic activity, there is sparse information regarding the use of field-measured CO_2 concentrations to estimate ventilation rates and CO_2 generation rates for a particular space. According to Persily and Dols [47], using CO_2 to evaluate ventilation effectiveness requires certain assumptions and unique conditions to obtain reliable information. Generally, this field lacks a simple and quick method for estimating air change rates and CO_2 concentrations. Guidance on the matter of achieving good IAQ is needed because the frequently used tracer gas technique, though significant, can be difficult to implement and it is not always economically viable. Furthermore, there has been widespread misunderstanding and misuse of CO_2 during tracer gas evaluations [47]. In principle, on-site measurements in an enclosed environment (i.e. office, classroom or bedroom) provides the most realistic data concerning airflow and air quality. However, due to the variability of outdoor conditions (i.e. CO_2 concentrations, wind speed and directions, etc.) which affect the velocity and control of air movement within the measured spaces, making an estimation using quantitative analysis can be difficult and inaccurate.

To overcome this, a numerical model to visualise the spatial distribution of CO_2, in addition to the evaluation and assessment of CO_2 monitoring in classrooms was carried out. This was performed with different ventilation strategies encountered during the experimental studies throughout the fieldwork tests and within a controlled environment in an environmental chamber (hereafter referred to as the chamber). A numerical model using ANSYS-CFX was created to carry out further quantitative analysis. The emphasis of the model was based on the variation of the impacts determined by several sampling sensors within different locations.

In this paper, experimental methods used to investigate the air movement and spatial distribution levels of CO_2 in both classrooms [48] and a test chamber [49], provided in-situ data and useful information for the CFD validation. However, due to the complexity of indoor airflows (i.e. low mean air velocity of less than 0.2 ms^{-1}) it makes experimental investigation also extremely difficult. In addition, experimental accuracy is also principally determined by the quality of the sensors and equipment used, whereas the accuracy of numerical solutions is dependent on the quality of the discretisation and boundary condition used [50]. The conditions and the modelling of the spatial distributions of CO_2 in the chamber and some of the classrooms studied, is modelled using the ANSYS CFX 18.0 to determine the most physically realistic combination of mass and energy transport models, fluid properties and boundary conditions. To develop a good understanding of the differences between the turbulence models, a detailed simulation and analysis of the flow in the chamber has been performed. Based on these simulations, various parameters were compared and validated with experimental data to assess the extent of deviation as well as the trend [50].

2.1. Modelling of the atmospheric boundary layer (ABL) in CFD

Considering these parameters, the turbulent nature of airflows in rooms has always been 'a bone of contention' when researchers are modelling turbulent flows. Unfortunately, no single turbulence model is universally accepted for all categories of problems. This is because, the choice of models depends on the application, level of accuracy required, the available computational resources and the computation time available for a simulation. The accuracy of CFD modelling depends on many factors, such as discretisation schemes, numerical methods, boundary conditions, and turbulence models [51,52]. These include a zero-equation model (0-eq) [53], a Low Reynolds number (LRN) k-ε model [54], a renormalization group (RNG) k-ε model [55], a Shear Stress Turbulence k-omega (SST k-ω) model [56], a large-eddy-simulation model (LES) [57] and a few others.

The modelling of the atmospheric boundary layer (ABL) in CFD was based on specifying appropriate inlet and wall boundary conditions. Simulating the two classrooms at the University of Reading (Palmer 105 and Palmer 111) were carried out in two parts, first the wind flow and velocity around the building where the classrooms are situated was determined. This simulation was carried out under steady state conditions. Secondly the spatial distributions of CO_2 in the classroom influenced by the wind flow and impact on the outer wall are calculated. For this situation, a transient calculation was carried out using the input parameters from the steady-state results as the initial boundary conditions. To model the external and internal flow fields, it was necessary to model the effect of other buildings which are situated close to the monitored building in the simulated ABL. The construction of these domains was mapped using the layout of the university campus. From the results presented by Mahyuddin et al. [50], the RNG turbulence model was used as it performs significantly better than the SST and standard k-ε model. In addition, a simplified geometry representing human shape (cylinder) is used in this context since both CFD predictions using computational simulated person (CSP) and simplified geometry correspond well with the experimental results [50].

A fixed air temperature of 15.0 °C was specified throughout the flow domain. The reference pressure was set to 0 Pa to reduce

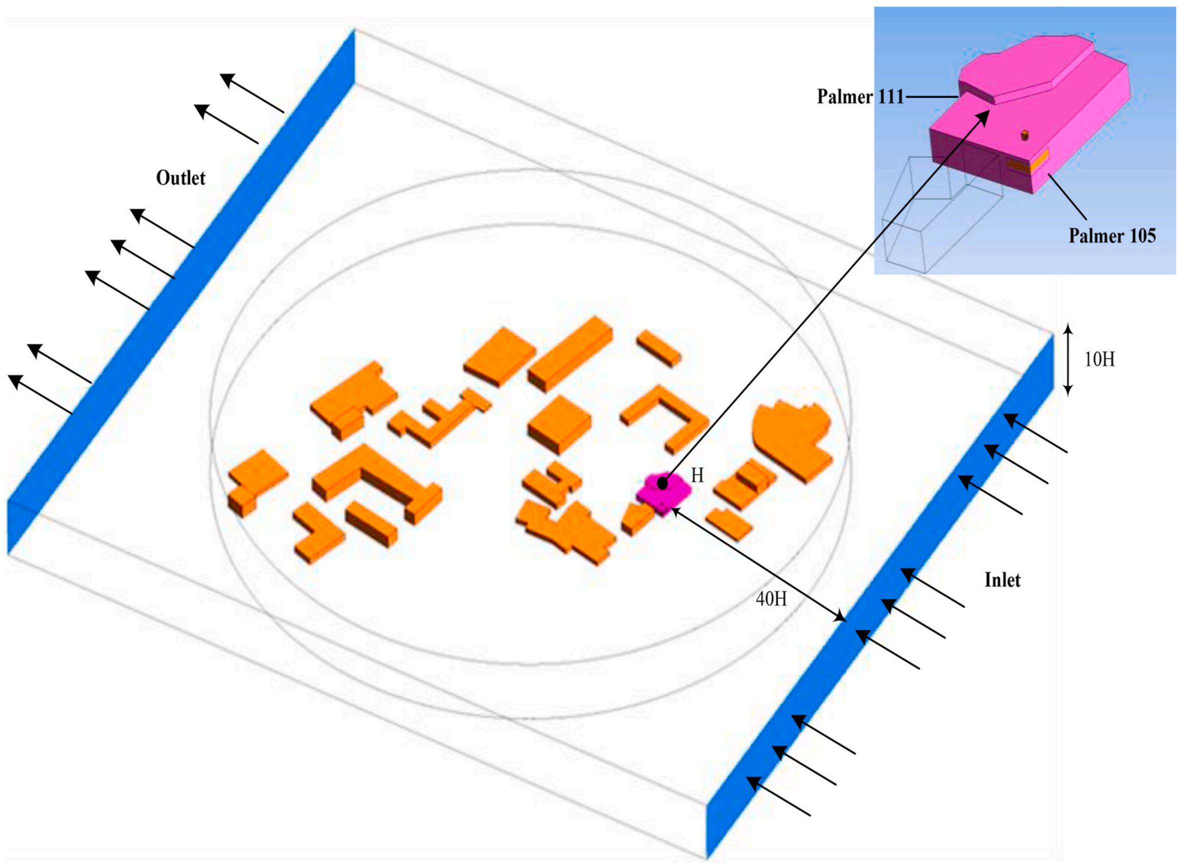

Fig. 1. The computational domain of the building used in the CFD simulation.

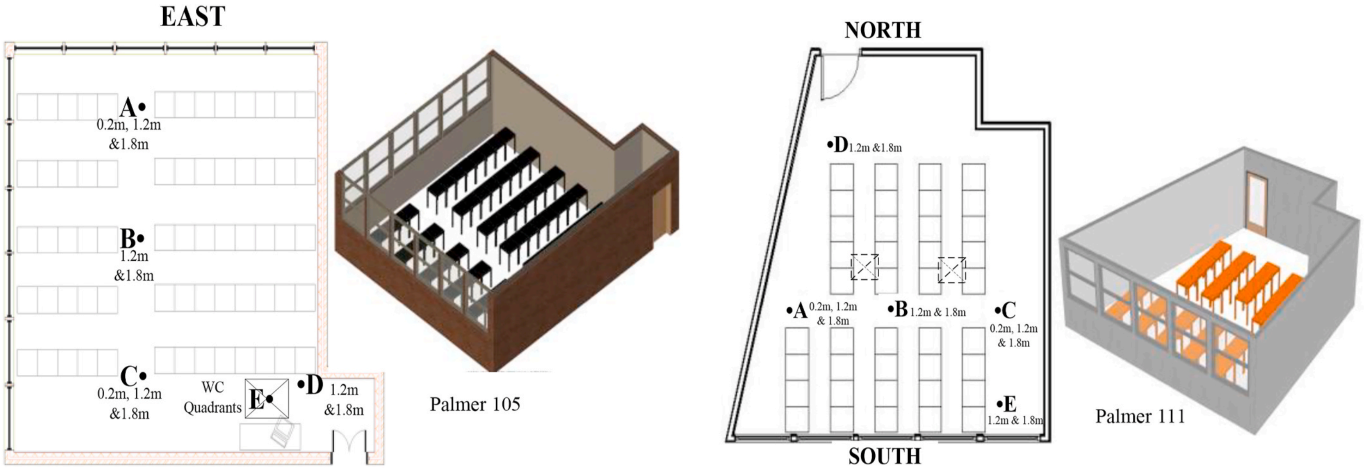

Fig. 2. The floor plan and perspective layout of classroom Palmer 105 (left) with a square (E) indicating the location of the windcatcher (WC) on the ceiling. Palmer 111 (right) with dotted squares are the extractor and supply fans on the ceiling.

rounding errors since the flow was incompressible. The inlet boundary conditions were specified based on recommendations by Richards et al. [58]. Equations (1)–(3) were used to define the inlet boundary conditions.

$$u = \frac{u_*}{\kappa} \ln\left[\frac{z}{z_0} + 1\right] \tag{1}$$

$$\kappa = \frac{{u_*}^2}{\sqrt{C_\mu}} \tag{2}$$

$$\varepsilon = \frac{{u_*}^3}{\kappa(z + z_0)} \tag{3}$$

where **u** is the stream wise velocity component, $\boldsymbol{k}$ is turbulent kinetic energy and turbulent eddy dissipation $\boldsymbol{(\varepsilon)}$. $\boldsymbol{\kappa} = 0.4$ is the Von Karman's constant, u* is the wall friction velocity, $\boldsymbol{z}$ = height above the ground, $\boldsymbol{z_0}$ = roughness height which depends on the prevailing terrain condition which in this study, a terrain of grass 0.25 m (a common value for rough surface with varying heights and scattered obstacles at relative distance.) is used and $\boldsymbol{C\mu} = 0.09$ which is a model constant of standard $\boldsymbol{k}$-$\boldsymbol{\varepsilon}$ model.

2.2. Modelling of the external flow field around the full-scale building in the ABL

The computational domain was built so that the edges of the inlet, outlet and domain did not interfere with the flow region of interest (i.e. around and within the structure of the Palmer.

building). The terrain of the modelled site is flat and open. The external conditions and the weather data was obtained from the Universities onsite observatory where weather observations have been collated data since 1901. The modelled buildings were placed inside a circular block shaped domain, representing the interface between the buildings and the external conditions (i.e. inlet and out), the bigger rectangular domain (Fig. 1). The inlet and outlets are modelled on opposite sides of this domain that can be rotated to suit the wind direction. If the direction of the wind flow had to be changed, only the outer rectangular domain would be rotated by the angle of the wind direction. The domain outlet was positioned at a distance downstream from the test building. In this model, the value of the reference velocity at a height 10 m above the ground was taken to be 4.80 ms −1 from 0° N and 3.24 ms −1 with direction from 216° SW for Case zones Palmer 105 and Palmer 111 respectively.

The height (H) of the Palmer Building in Fig. 1, is 7 m from the ground. A height of 10H (70 m) equivalent was used between the ground level of the Palmer Building and the top of the flow domain while 40H (280 m) was used between the domain inlet and the windward face of Palmer Building. A grid comparison was also performed (coarse, medium and fine mesh) to justify the numerical results obtained from the simulation. To investigate these factors, a steady state simulation was performed for all three grids with the flow field computed each with twice the number of grid points in X, Y and Z direction. The outlet distance from the nearest building is 25H (175 m). The overall domain had a total number of 13,030,278 elements meshed using three different unstructured meshes, 9,715,559 number of elements for Tetrahedral mesh type, 3,247,736 for Prisms and 66,983 for Pyramids mesh type. A steady-state solution for the flow field around the building based on the above mesh sizes was obtained. Convergence was achieved when the maximum residual curve for each transported quantity was less than 10^{-4}, staying constant over a significant period. A high-resolution scheme was used to discretise the advection terms.

2.3. Transient simulation of the classrooms

In both CFD models (for Palmer 105 and 111), students were represented in the respective classrooms according to the seated layout. The number and location of the student seats were 15 and 17 sedentary occupants in Palmer 105 and 111, respectively. These locations were modelled based on field work measurements developed by Mahyuddin and Awbi [48], not highlighted in this paper. Fig. 2 shows the layout of the classrooms used for field work. The design of the individual classrooms varies but the seating layout considered is similar. The selection of measurement point locations exhibits variability in the present research. For densely occupied mechanical ventilated spaces (with design occupant density greater than or equal to 25 people per 93 m^2), CO_2 concentration must be monitored within the space between 0.9 m and 1.8 m above the floor [59]. As cited in Schneider [60], the ISO standard (TC 146/SC 6) suitable sampling locations are recommended for the centre of the room at a height of 1.0 m–1.5 m above the floor (breathing zone). In ASTM D6245-07, it was discussed that the indoor concentration should not be measured close to people to prevent false readings. Therefore, a proposed distance of 2 m from any occupant is sufficient to avoid these impacts. Maldonado and Woods [61] discuss three main factors that influence the relative magnitude of the concentrations as follows.

a) The location and strength of the source,
b) The internal air movements within building zones
c) The type and location of the air supply and return terminals.

For years, countries including Canada, Japan, Korea, Singapore, Sweden, UK, and USA have conducted IAQ studies aiming to set standards and guidelines, resulting in different regulations and guidelines evolving. However, representative locations of CO_2 sampling sensors are still relative and reliant upon the professional judgement of assessors.

In practice, there is a great variability in the positioning of sampling locations by various researchers to characterise indoor CO_2 concentrations. There were several other researchers who carried out measurements in rooms using one representative point at various heights, for instance 1 m height [62,63], 1.2 m height [64,65], 1.5 m [66,67] and a few other no distinct height above the floor level.

Conversely other research chose not to mention the specific location but only stated the breathing zone as recommended by some of the guidelines [13,68]. Furthermore, there were considerable number of researchers who did not declare the sampling strategies used for monitoring CO_2 levels and the sensor location [62,68].

In research carried out in open plan offices with air conditioning systems in Hong Kong, Mui et al. [69], cited the need for accuracy in determining the mean concentration of occupied space could be significantly improved by increasing the number of sampling points. In this study, a total of 17 'representative' sampling locations were measured throughout a one-year monitoring period. These representative locations were distributed within multi-zone locations. From the results the magnitude and variation were used to study the significance of the average spatial distribution of CO_2 concentration within the zone. It was concluded that the CO_2 concentrations varied at different locations with a spatial average of 868 ± 135 ppm.

Considering all the above-mentioned relationship between CO_2 and its applications in IAQ control, these debates will continue from different schools of thought. However, in this paper the focus is not to agree or disagree with these "health impacts", but rather to develop a standardise measurement procedure. It is well known that the non-uniformities in the distribution of air and building occupancy can present difficulties in finding representative locations for sensors [69]. Nevertheless, identifying appropriate locations where the highest concentrations of contaminants occur and reducing the number of sampling points can save both time and cost [70]. This however is not without technical difficulties such as calibration, resources and manpower [71].

All sampling devices used to obtain data were located at locations A, B, C, D and E (i.e. sensor height in m). These were then used as boundary conditions for the respective models.

Based on observations carried out in the two classrooms, the numbers and locations of the students' sitting arrangement were identified. These locations were modelled based on the fieldwork measurements. The boundary conditions for both Cases are summarised in Table 1.

3. Results and discussion

The design, preparation and implementation using computational simulations of the external flow and wind-induced ventilation have been discussed in the preceding section. The estimates of the atmospheric pressure and velocity profile around the test structure were discussed and measured for the two different wind directions starting with the modelled profiles of the ABL.

3.1. Wind direction from 0° N – Classroom Palmer 105

The presence of an ABL was shown to affect both the external velocity flow field and the surface pressure distribution around the test classrooms (Figs. 3 and 4). The shaded contour plots from the CFD results (Figs. 3 and 4) present velocity (ms^{-1}) and pressure (Pa). Nejat et al. [72], Ai & Mak [38] showed that the performance of windcatcher for natural ventilation applications in buildings (based on a commercial 'Windcatcher' design) is influenced by the wind speed and direction. In this study, the windcatcher on the roof of Palmer 105 was also modelled to visualise the conditions in the classroom influenced by the flow fields of the external conditions. When the mean wind meets the windward face of the classroom structure, the velocity gradient leads to increased wind speeds at the top of the windward face as illustrated in Fig. 3, which is due to the flow separation at the edge of the roof line. Above this line, flow patterns illustrated with a plane across the windcatcher demonstrates higher velocities and flow patterns into the classroom.

The distribution of the external surface pressure is illustrated in Fig. 4. In this case, one of the windows was modelled as opened to investigate the air movement in the classroom and the pressure gradient that could be expected in the room. The maximum peak pressure as observed on the front surface of the structure corresponds to the stagnation point where flow is brought to rest. Using RNG k-ε model, the peak pressure is predicted to be slightly underneath the roof line, while low pressure distribution ~ −3.0 Pa occurs along the leading edge of the roof closer to the windward edge of the roof. The surface pressures close to the ventilation openings were also found to vary. When openings were present, the pressure just above and below the windward face opening was higher, which agrees with the observations made by Potter [73]. The variation in pressure impacts the air flow patterns around the windcatcher and hence

Table 1
Summary of boundary conditions used in the research case study buildings.

Turbulence model	RNG *k-ε* model			
Wall treatment	Nonslip, standard logarithmic wall function			
Numerical Schemes	The High-Resolution transient scheme which uses the second order accuracy.			
Walls			***Case 1***	***Case 2***
	Front wall	Fixed Temperature	19.0 °C	Adiabatic
	Back wall	Fixed Temperature	18.2 °C	Adiabatic
	Left wall	Fixed Temperature	18.6 °C	Adiabatic
	Right wall	Fixed Temperature	19.0 °C	Adiabatic
	Ceiling	Fixed Temperature	19.5 °C	Adiabatic
	Floor	Fixed Temperature	18.5 °C	Adiabatic
Heat Sources	Lamp	Fixed Temperature	37.0 °C	37.0 °C
Human	Body	Fixed Temperature	33.7 °C	33.7 °C
Tables		Adiabatic		
Inlet	Air supply	Mass flow	rate0.161 kg s^{-1}	0.016 kg s^{-1}
		Fixed temperature	17.0 °C	16.0 °C
	Nose	Mass flow rate 0.000164 kg s^{-1}, exhaled air temperature at 34.0 °C, turbulence intensity 5 %, direction of exhalation x = -0.88 y = - 0.88, z = 0.00 (ms^{-1}), 4.0 % of CO_2 concentration volume		

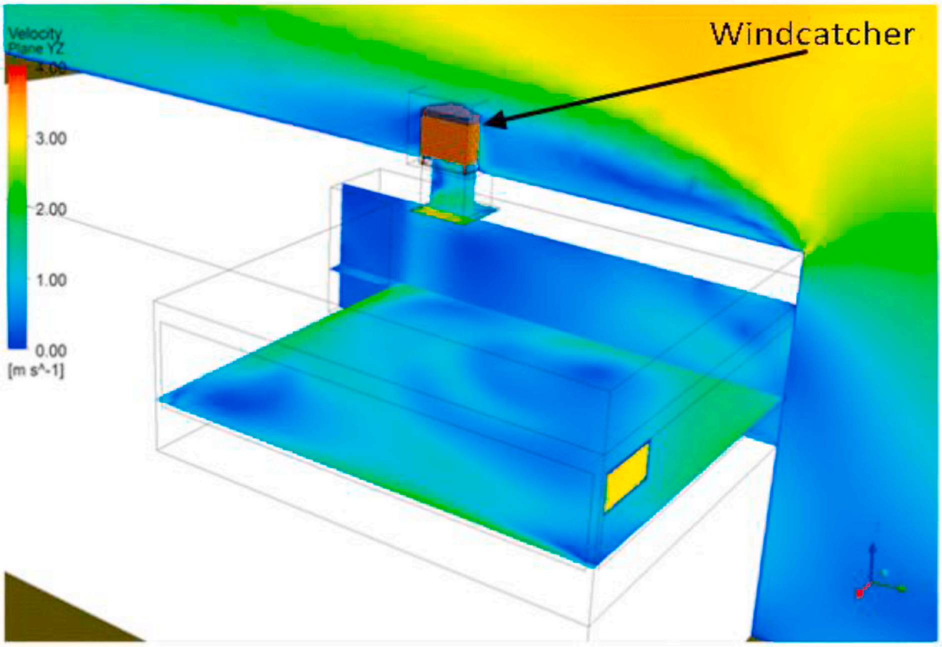

Fig. 3. The velocity contour plot in and around the test structure: classroom Palmer 105.

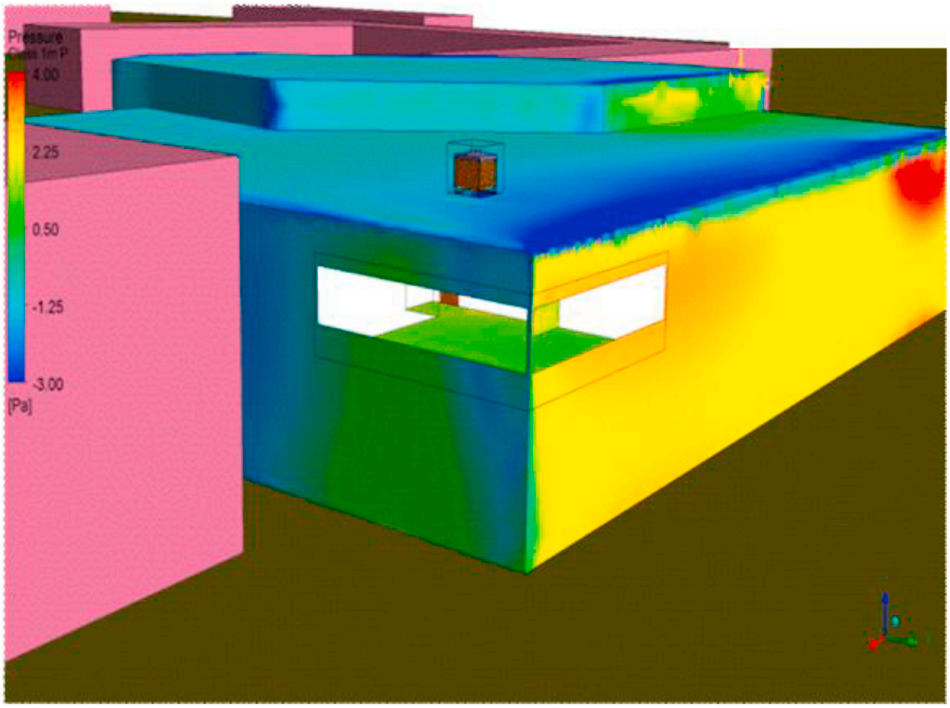

Fig. 4. The external wind pressure distribution predictions around classroom Palmer 105. Windows are closed.

supplied to the classroom.

3.2. *Wind direction from 216° SW – Classroom Palmer 111*

The steady-state results for Palmer 111 are different from that of Palmer 105. Due to the wind direction and the location of the classroom in the domain, different velocity and pressure flow fields were observed. In this case, the wind direction was from the

Southwest (216° SW) of the building domain, where other buildings were within the flow domain territory. From the observed flow patterns, it was observed that the flow fields and the pressure distributions were significantly different, due to the obstruction of the buildings within the flow domain. Fig. 5 illustrates the velocity contour along a plane cutting through Palmer 111. Higher air velocity from the windward side (3.24 ms^{-1}) gradually decreasing towards the opposite end and a much lower air velocity observed nearer to the buildings.

The presence of the vortex on the front surface and the position of a stagnation point at the wall of Palmer 111 led to significantly different pressure distribution. Below this stagnation point, air is forced to move down the surface until reaching the ground which results in a lower velocity. In addition, pressure distribution streamlines along the lateral plane across Palmer 111 is illustrated in Fig. 6. The peak negative pressure which is less than −10 Pa is observed at the leeward side of the building. Regarding the windward side, a slightly higher pressure is observed (∼−6 Pa) though this is clearly different from that of Palmer 105. It is also observed that when the flow is incident on the wall of Palmer 111, there is a separation zone in the upstream corner, with the re-circulation.

3.3. Transient simulation of classrooms palmer 105 and palmer 111

Prior to evaluating the quality of indoor environmental parameters such as spatial CO_2 distributions, air temperature and air velocity, it was important to understand the flow field around the Case classrooms. The flow around these structures are complex and a great deal of information can be inferred. Unfortunately, due to the lack of data for the urban environment around these buildings, it was difficult to draw definite conclusions. Therefore, to carry out investigations in the classrooms, key findings (i.e. surface pressure distribution and velocity profile) were used in the initial data needed for the transient conditions.

After simulating the airflow patterns for a duration of which convergence was reached, the results obtained were analysed. Two vertical planes were created; one at the section corresponding to the opening of the windcatcher quadrant (z = 1.2 m) and second, around the occupants (z = 7.2 m) as illustrated in Fig. 7. The relative reference pressure (0.7 Pa) was taken from the external flow field in the ABL simulation results (see the insert in Fig. 7).

To allow air movement into the classroom (via infiltration) a rectangular opening between windows was added to the flow domain (Fig. 8). Based on experimental measurements, air infiltration rate of 0.63 ach was incorporated as inlet boundary conditions. The velocity contours in these planes are observed to be higher towards the ceiling and towards the windcatcher. This was due to convection currents from heat sources rising from the occupant's plumes and the lights. The plume flows are shown to spread laterally on reaching the ceiling. In addition, the inlet flow jet through the back wall was observed causing a rise in velocity at the lower region (Fig. 7). The downstream flow towards the floor is also due to the temperature difference from the outdoor (15.0 °C) and the classroom (average of 18.8 °C).

In Fig. 8, the layer of high CO_2 concentration is driven by the buoyancy force produced by the manikins' thermal plumes. At this instance, natural convection around the human body is of particular interest since it interacts with respiration flows where, in a mixing ventilation condition, the exhaled air is entrained upwards by the warm plumes near the body. Hence, higher CO_2 concentrations are observed flowing towards the ceiling of the classroom. Fig. 9 shows the average values of normalised CO_2 concentrations at various sampling locations positioned across the room at different heights. The spatial distributions of CO_2 were based on 12 sampling sensors,

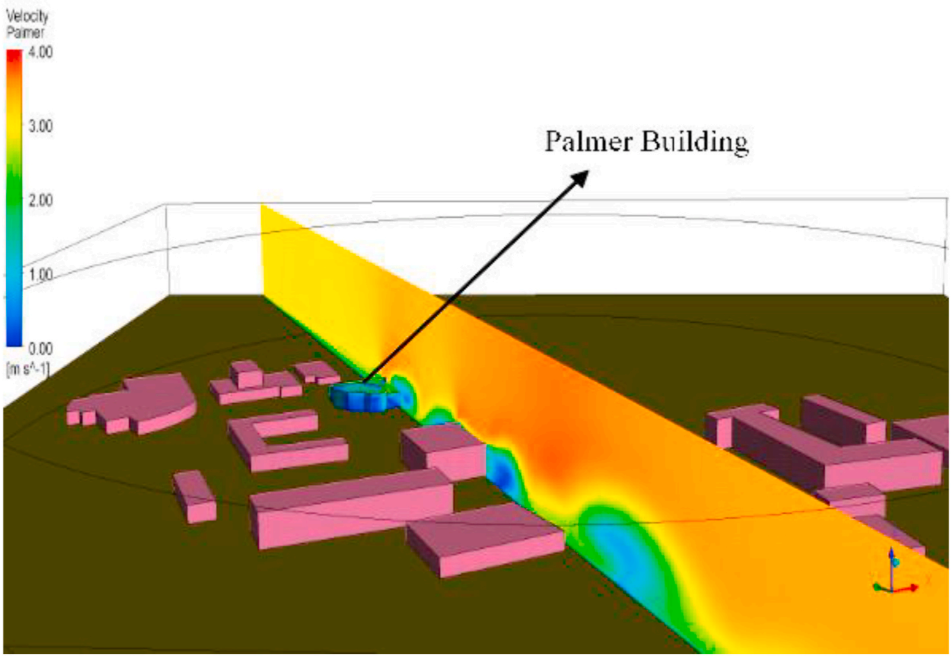

Fig. 5. Velocity distribution predictions across classroom 111 and adjacent buildings.

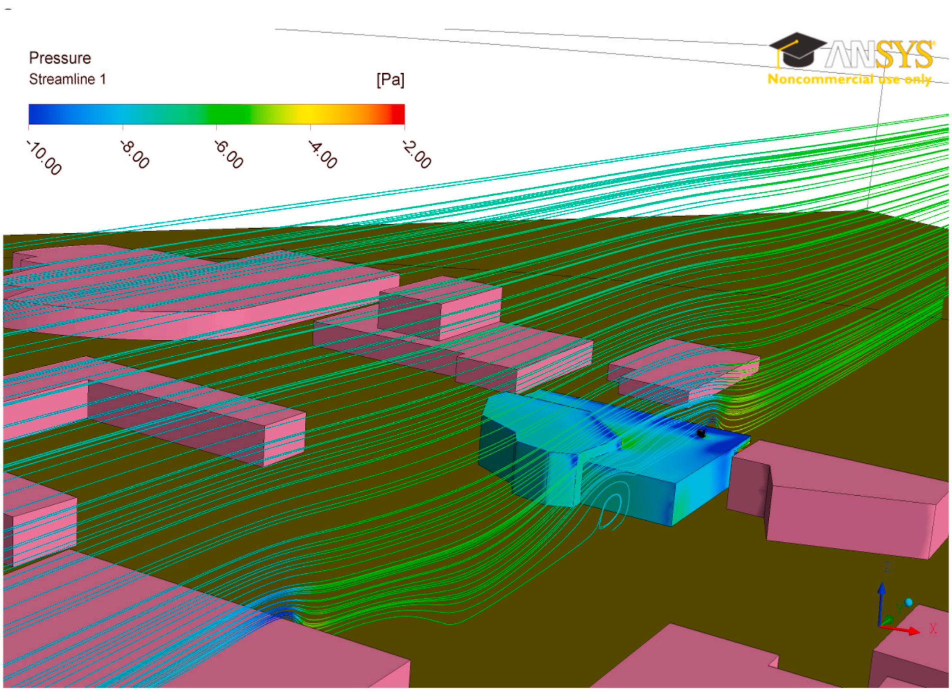

Fig. 6. The streamline patterns of the flow over the test cube: Classroom Palmer 111.

positioned at locations similar to points in Fig. 2. However, in this CFD simulation, CO_2 concentrations are only calculated at 10 locations. Two sampling sensors located within two quadrants of the windcatcher (location E, Fig. 2) were not considered. This is because this model did not integrate the performance of the sensors in the windcatcher.

From Fig. 9, in most locations the trend of the spatial distributions of CO_2 was comparable except for location A (back of the classroom) at the height of 0.2 m and 1.2 m, and location B (middle of the classroom) at the height of 1.2 m. Although the concentrations are slightly lower at location A, it is noted that the trend of the average CO_2 are similar. In location B, the CFD simulation also underestimated the average value by approximately 50 ppm. In general, these findings agree with the measured results in Palmer 105. Therefore, in a naturally ventilated classroom, it would be essential to locate sensors at varying locations as the variations in the mean CO_2 concentration with the different heights and locations were significant.

Similar to the CO_2 distribution, the average indoor air temperature of the predicted calculations (Fig. 9) is also observed to achieve good agreement with the measurements. Although the CFD calculations slightly underestimated the temperatures in the classroom, the differences are not significant. A difference of approximately 0.6 °C is underestimated at location A at the height of 0.2 m. A possible explanation to this finding is that the cooler outdoor air penetrating into the classroom via the air infiltration openings would have been well mixed with the indoor conditions hence flowing down towards the floor. This would then flush and reduce the CO_2 concentrations at this location upwards, reducing the temperature at this location.

The simulation trends illustrated in Fig. 10 are of good agreement with the measurements. The insert in this figure illustrates the build-up of CO_2 during the day of monitoring with varying number of students at different lecturing sessions. To compare the CFD simulation and the measured values, the first hour (i.e. shaded area of the insert) with 15 students was selected. Based on these findings, it is evident that the accuracy of the values used for the boundary conditions in the CFD simulations was adequate to further simulate the spatial distributions of CO_2 in this classroom with the same environmental conditions.

Unlike the findings obtained in Palmer 105, the simulated prediction from palmer 111 were not in agreement with the measurements. A marked difference in the average temperature profiles can be observed in the comparison as plotted in Fig. 11. The predicted simulations have significantly overestimated the air temperature in the classroom with a maximum difference of ~1.7 °C in location C (Front) at the height of 0.2 m. A possible explanation for this inconsistency is probably due to the specification of the wall's boundary temperatures. As no external flow data was measured during the field work, it was not possible to fully validate these parameters.

Therefore, the wall boundary conditions were set up as adiabatic (Table 1) instead of specifying the actual temperatures of the room surfaces as in Palmer 105. In addition, an initial value for the classroom temperature was assigned to be 20.6 °C which was based on the average initial room temperatures measured. Unlike the variations with the temperature, the average CO_2 concentration predicted in Palmer 111 agrees with the experimental results except for the value obtained in location A (back) at the height of 0.2 m. An underestimation of ~80 ppm is observed. The spatial CO_2 distribution pattern is also observed to be comparable for most locations.

Fig. 12 shows the velocity distribution in the classroom at the end of the duration (1-h). The air speed at the side wall (contour planes) along the windows is observed to be high due to the air infiltration opening. Locations above the occupants and their

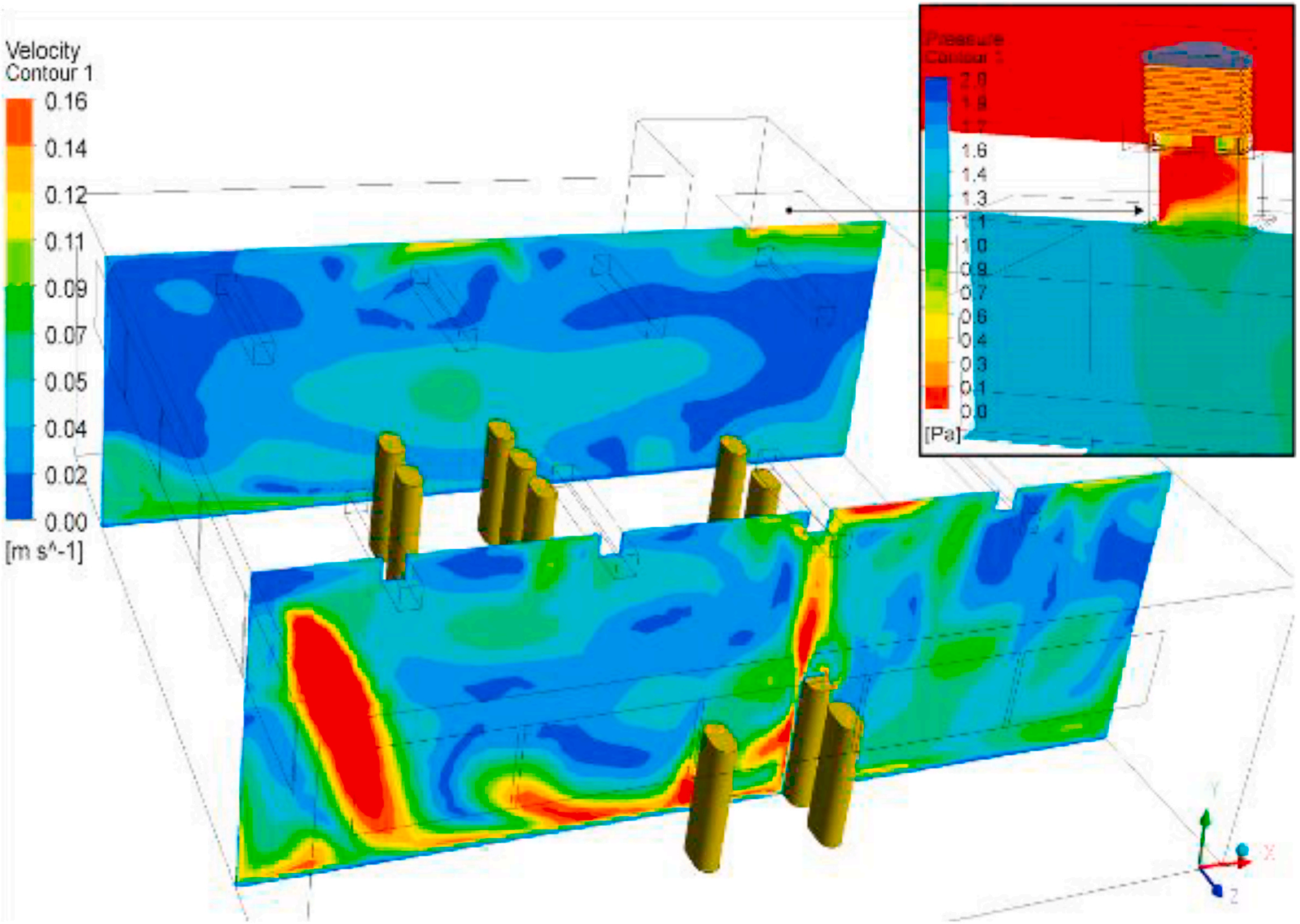

Fig. 7. The airflow pattern in classroom 105 in vertical planes z = 1.2 m and 7.2 m.

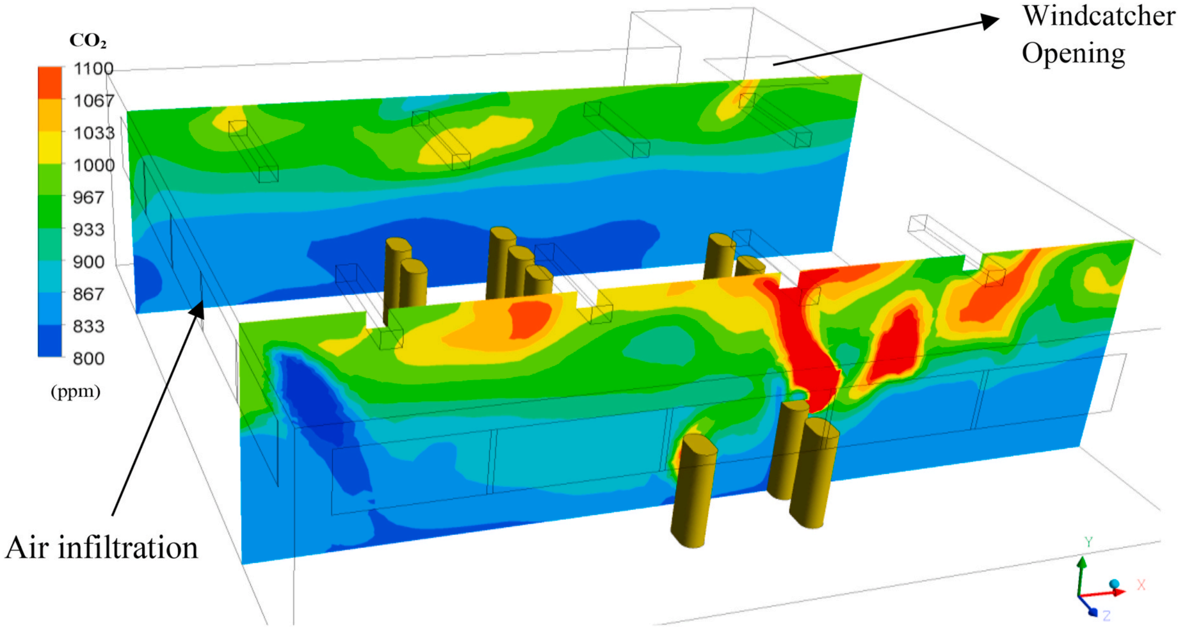

Fig. 8. The CO_2 concentration distribution pattern in classroom 105 for vertical planes z = 1.2 m and 7.2 m.

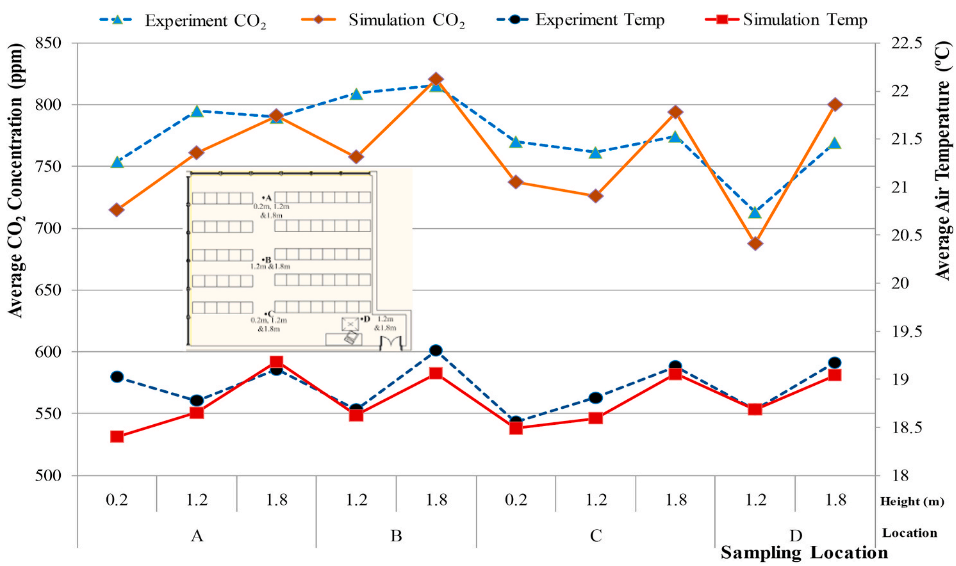

Fig. 9. Comparison of CO_2 and temperature distribution levels in classroom 105: results from fieldwork measurements and CFD predicted simulation.

surrounding as well as at the extract fan outlet also show high velocities due to buoyancy flow and the effect of the thermal plumes.

In this simulation, it is demonstrated that the exhalation flow may indeed intensify because of density differences causing high concentrations within localised zones. This is evident as the results of CO_2 distributions at the height of 1.2 m (Fig. 13b) in the classroom shows that high concentrations accumulate locally instead of rising, which is due to positive buoyancy flow (see Fig. 13c). However, another observation of the distributions of CO_2 concentration at 1.2 m shows high values at the breathing zone, i.e. seen to be transported behind the breathing manikins. This high concentration would probably penetrate the breathing zone of the manikins seated at the back. This effect of air movement in a room should be avoided as the concentration of CO_2 could also be linked with contaminant source.

Differences in the spatial distributions of CO_2 can be observed, although CO_2 concentrations, are normally low at lower regions (0.2 m), while the concentrations at the back of the classroom is significantly lower compared to other locations at that level (Fig. 13a). This would have been due to the entrainment of warm air from the corridor via infiltration below the door forcing the accumulated CO_2 concentration from the corridor region to enter towards the side. This effect can be seen in Fig. 13b where the high concentrations of

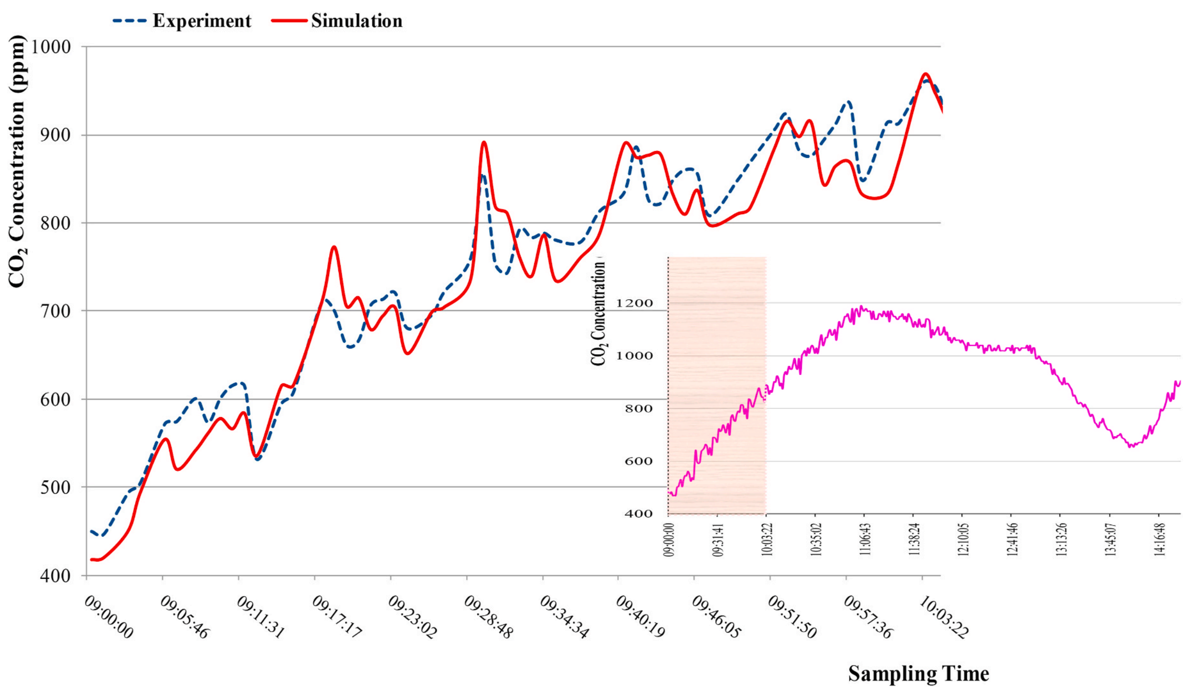

Fig. 10. Comparison of the CO_2 concentrations build-up in classroom Palmer 105: results from fieldwork measurements and CFD predicted simulation.

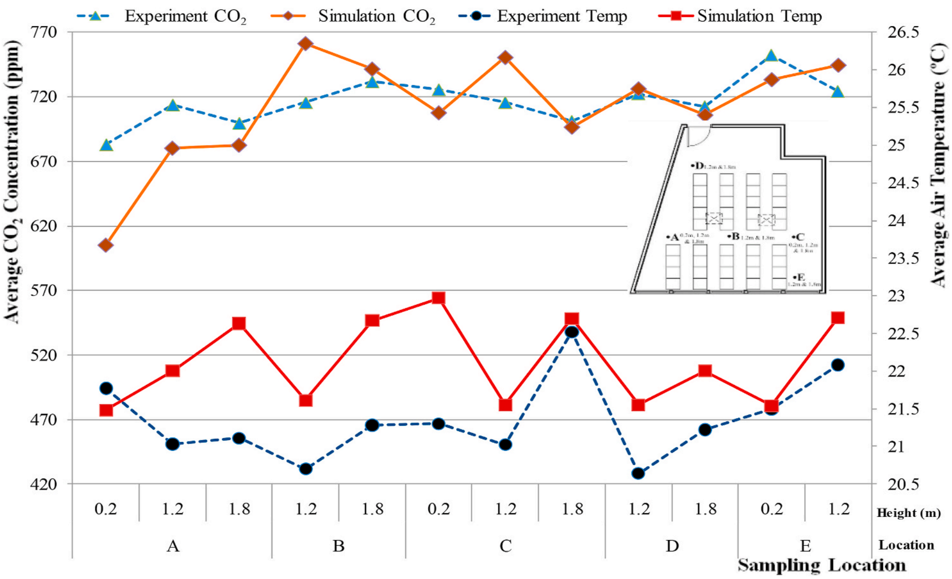

Fig. 11. Comparison of CO_2 spatial distribution levels (ppm) in classroom 111: results from fieldwork measurements and CFD predicted simulation.

exhaled CO_2 from the occupants in the back row tend to move towards this side. Higher concentrations are also observed to be flowing towards the extract fan (location E, see Fig. 2).

The findings indicate that when the extract fan is switched on, better vertical stratification and distribution was produced, and significant variations occurred across the horizontal planes. These results suggest that if a limited number of sampling sensors is desired, the samplers can be vertically distributed anywhere (i.e. above 1.2 m height) but more samplers are needed within a few horizontal locations to ensure accurate predictions of flow patterns within any defined zone, in this instance the classroom.

4. Conclusion

In principle, in-situ measurement in an enclosed environment gives the most realistic information concerning airflow and air

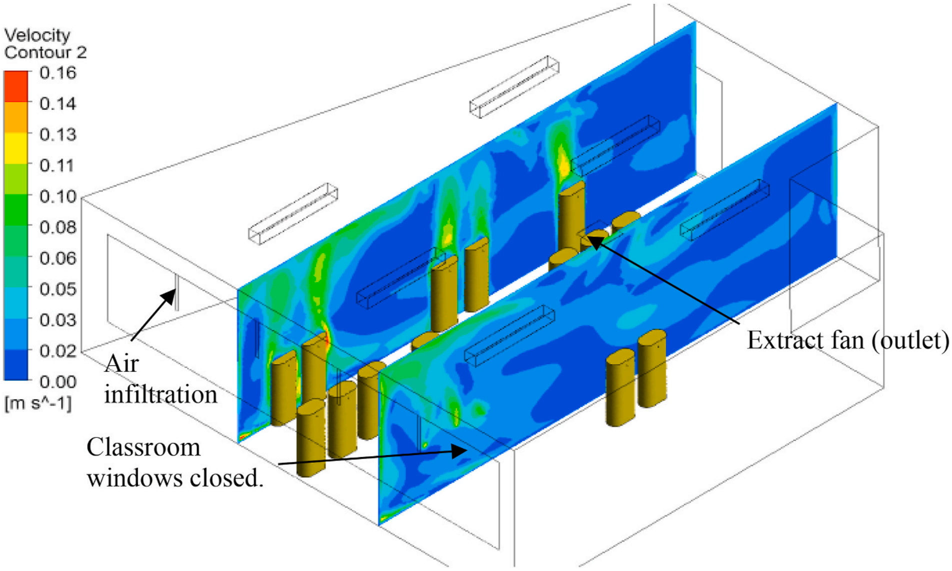

Fig. 12. The airflow pattern in classroom 111 for vertical planes x = 1.2 m and 3.2 m.

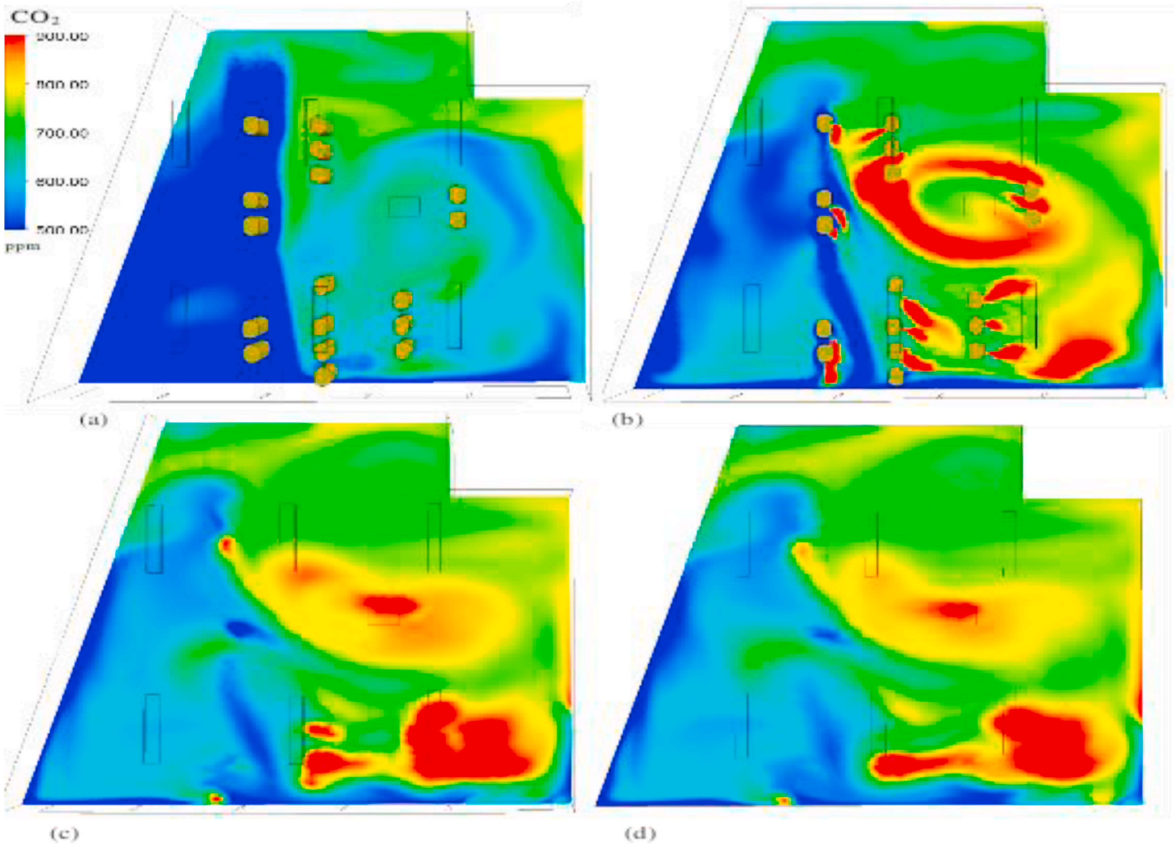

Fig. 13. The airflow pattern in classroom 111for horizontal planes of (a) y = 0.2 m, (b) y = 1.2 m, (c) y = 1.8 m and (d) y = 3.0 m (ceiling height).

distribution. However, because measurements must be made at many locations, direct measurements of the air and contaminant distribution can be very expensive and time consuming. Appropriate simulation of practical models is always representative less costly and less time consuming. Simulating the geometry of a nose and mouth (for exhalation) would be needed for studying the transport of exhaled air between occupants in a room. The significance of the breathing characteristics and other parameters such as body shape and posture, clothing insulation, etc. That may have an impact on the accuracy of the measurements also need to be studied systematically. While this investigation has presented analyses on the validation between measured and simulated results for each physical quantity, it also illustrates understanding of the similarities and differences in the transport and dispersion of different quantities along the spatial distributions investigated.

The performance of the CFD models depended on the boundary conditions specified which provided results with trends that aligned with that of the measurements. The simulated temperature and spatial distribution of CO_2 concentrations agreed with the experimental data in most cases, although significant differences between measured and predicted velocity field existed in others. The atmospheric boundary layer significantly affects flow velocities and surface pressures around the classroom, and the ventilation performance of the windcatcher is significantly affected by wind speed and direction. High velocity airflow on the windward side and high negative pressure on the leeward side are generated due to the effect of building shading.

Ventilation effectiveness, CO_2 concentration distribution, and temperature distribution in the classroom are closely related to the external flow field conditions, heat sources in the classroom and its layout. Knowledge of the spatial distribution of CO_2 concentration was essential in determining the best sampling locations. The type of ventilation strategies used, affected the spatial distribution of mean CO_2 concentrations. This study showed that; the use of only one sensor to monitor CO_2 concentrations in a room may lead to inaccurate estimations of the average CO_2 levels. Understanding the effect of air movement in a room is very significant when choosing the sampling locations. The overall findings would also be of immense benefit to designers and building authority in enhancing classroom design guidelines for school buildings in the tropics.

CRediT authorship contribution statement

Norhayati Mahyuddin: Writing – review & editing, Writing – original draft, Data curation. **Emmanuel A. Essah:** Writing – review & editing, Writing – original draft, Software, Data curation.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

References

[1] P.S. Hui, L.T. Wong, K.W. Mui, Feasibility study of an express assessment protocol for the indoor air quality of air-conditioned offices, Indoor Built Environ. 15 (4) (2006) 373–378.

[2] M. Oliveira, et al., Children environmental exposure to particulate matter and polycyclic aromatic hydrocarbons and biomonitoring in school environments: a review on indoor and outdoor exposure levels, major sources and health impacts, Environ. Int. 124 (2019) 180–204.

[3] A. Fox, et al., Increased levels of bacterial markers and CO2 in occupied school rooms, J. Environ. Monit. 5 (2) (2003) 246–252.

[4] L. Zhang, et al., Characteristics of air pollutants inside and outside a primary school classroom in Beijing and respiratory health impact on children, Environ. Pollut. 255 (2019) 113147.

[5] I. Rivas, et al., Outdoor infiltration and indoor contribution of UFP and BC, OC, secondary inorganic ions and metals in PM2.5 in schools, Atmos. Environ. 106 (2015) 129–138.

[6] D.A. Krawczyk, B. Wadolowska, Analysis of indoor air parameters in an education building, Energy Proc. 147 (2018) 96–103.

[7] A. Riham Jaber, M. Dejan, U. Marcella, The effect of indoor temperature and CO2 levels on cognitive performance of adult females in a university building in Saudi arabia, Energy Proc. 122 (2017) 451–456.

[8] J.M. Daisey, W.J. Angell, M.G. Apte, Indoor air quality, ventilation and health symptoms in schools: an analysis of existing information, Indoor Air 13 (1) (2003) 53–64.

[9] U.S. Environmental Protection AgencyE., Building Air Quality: A Guide for Building Owners and Facility Managers, U.S EPA and US Department of Health and Human Services, Washington, D.C, 1991.

[10] H.N. Knudsen, G. Clausen, P.O. Fanger, Sensory characterization emmissions from materials, Indoor Air 7 (1997) 107–115.

[11] R. Maddalena, et al., Effects of ventilation rate per person and per floor area on perceived air quality, sick building syndrome symptoms, and decision-making, Indoor Air 25 (4) (2015) 362–370.

[12] O.A. Seppanen, W.J. Fisk, M.J. Mendell, *Association of ventilation rates and CO_2 Concentrations with health and other responses in commercial and institutional buildings*, Indoor Air 9 (1999) 226–252.

[13] D.G. Shendell, et al., *Associations between classroom CO_2 concentrations and student attendance in Washington and Idaho*, Indoor Air 14 (5) (2004) 333–341.

[14] P. Wargocki, D.P. Wyon, P.O. Fanger, The perfomance and subjective responsesof call-center operators with new and used supply air filters at two outdoor air supply rates, Indoor Air 14 (8) (2004) 7–16.

[15] X. Zhang, P. Wargocki, Z. Lian, Human responses to carbon dioxide, a follow-up study at recommended exposure limits in non-industrial environments, Build. Environ. 100 (2016) 162–171.

[16] H. Maula, et al., The effect of slightly warm temperature on work performance and comfort in open-plan offices – a laboratory study, Indoor Air 26 (2) (2016) 286–297.

[17] J.G. Allen, et al., Associations of cognitive function scores with carbon dioxide, ventilation, and volatile organic compound exposures in office workers: a controlled exposure study of green and conventional office environments, Environ. Health Perspect. 124 (6) (2016) 805–812.

[18] T. Lu, et al., A novel methodology for estimating space air change rates and occupant CO2 generation rates from measurements in mechanically-ventilated buildings, Build. Environ. 45 (5) (2010) 1161–1172.

[19] M.J. Mendell, G.A. Heath, Do indoor pollutants and thermal conditions in schools influence student performance? A critical review of the literature, Indoor Air 15 (1) (2005) 27–52.

[20] W.J. Fisk, The ventilation problem in schools: literature review, Indoor Air 27 (6) (2017) 1039–1051.

[21] ASHRAE, *ANSI/ASHRAE Standard 62.1-2016: Ventilation For Acceptable Indoor Air Quality*, I. American Society of Heating Refrigeration and Air-Conditioning Engineers, Atlanta Editor, 2016.
[22] T. Leephakpreeda, et al., Occupancy-based control of indoor air ventilation: a theoretical and experimental study, Sci. Asia: J. Sci. Soc. Thail. 27 (4) (2001) 279–284, 2001.
[23] M.P. Kozar, J.D. Laman, A. Fox, Muramic acid is not generally present in the human spleen as determined by gas chromatography-tandem mass spectrometry, Infect. Immun. 70 (2) (2002) 741–748.
[24] L.J.S. Liu, et al., Investigation of the concentration of bacteria and their cell envelope components in indoor air in two elementary schools, J. Air Waste Manag. Assoc. 50 (11) (2000) 1957–1967.
[25] S.N. Rudnick, D.K. Milton, Risk of indoor airborne infection transmission estimated from carbon dioxide concentration, Indoor Air 13 (2003) 237–245.
[26] E. Bjorn, P.V. Nielsen, Dispersal of exhaled air and personal exposure in displacement ventilated rooms, Indoor Air 12 (3) (2002) 147–164.
[27] R. Howden, et al., The effects of breathing 5% CO2 on human cardiovascular responses and tolerance to orthostatic stress, Exp. Physiol. 89 (4) (2004) 465–471.
[28] S.C. Lee, et al., Inter-comparison of air pollutant concentrations in different indoor environments in Hong Kong, Atmos. Environ. 36 (12) (2002) 1929–1940.
[29] M.J. Mendell, et al., Association of classroom ventilation with reduced illness absence: a prospective study in California elementary schools, Indoor Air 23 (6) (2013) 515–528.
[30] J. Bennett, et al., Sources of indoor air pollution at a New Zealand urban primary school; a case study, Atmos. Pollut. Res. 10 (2) (2019) 435–444.
[31] D. Teli, et al., Thermal performance evaluation of school buildings using a children-based adaptive comfort model, Procedia Environmental Sciences 38 (2017) 844–851.
[32] ASTM D6245-07, Standard guide for using indoor carbon dioxide to evaluate indoor air quality and ventilation, Reapproved (October 2007).
[33] W.J. Fisk, Estimates of potential nationwide productivity and health benefits from better indoor environments: an update, in: J. Spengler, J.M. Samet, J. F. McCarthy (Eds.), Indoor Air Quality Handbook (2001). New York: MCGraw Hill).
[34] I.T.S. Yu, et al., Evidence of airborne transmission of the severe acute respiratory syndrome virus, N. Engl. J. Med. 350 (17) (2004) 1731–1739.
[35] Sung and Kato, Method to evaluate UV dose of upper-room UVGI system using the concept of ventilation efficiency, Build. Environ. 45 (2010) 1626–1631, 2010.
[36] C.Y. Chao, M.P. Wan, A.K. Law, Ventilation performance measurements using constant concentration dosing strategy, Build. Environ. 39 (2004) 1277–1288.
[37] P.D. Gaspar, F.R. Barroca, R.A. Pitarma, Performance evaluation of CFD codes in building energy and environmental analysis, in: International Building Simulation Conference (IBSA), 2003, pp. 276–291. Eindhoven-Netherlands.
[38] P.J. Jones, G.E. Whittle, Computational Fluid Dynamics for building air flow prediction-current status and capacities, Build. Environ. 27 (3) (1992) 321–338.
[39] Q. Chen, Computer simulations and experimental measurement of air distribution in buildings, HVAC R Res. 13 (6) (2007) 849–851.
[40] Y. Cho, H.B. Awbi, A study of the effect of heat source location in a ventilated room using multiple regression analysis, Build. Environ. 42 (5) (2007) 2072–2082.
[41] Z.T. Ai, C.M. Mak, Modelling of coupled urban wind flow and indoor air flow on a high-density near-wall mesh: sensitivity analyses and case study for single-sided ventilation, Environ. Model. Software 60 (2014) 57–68.
[42] I.T.S. Yu, et al., Evidence of airborne transmission of the severe acute respiratory syndrome virus, N. Engl. J. Med. 350 (17) (2004) 1731–1739.
[43] Y. Li, et al., Multi-zone modeling of probable SARS virus transmission by airflow between flats in Block E, Amoy Gardens, Indoor Air 15 (2) (2005) 96–111.
[44] D.K. Milton, P.M. Glencross, W.M. D, Risk of sick leave associated with outdoor air supply rate, humidification, and occupant complaints, Indoor Air 10 (2000) 212–221.
[45] P.V. Nielsen, Flow in Air-Conditioned Rooms, Technical University of Denmark, Copenhagen, 1974.
[46] S. Zhu, P. Demokritou, J. Spengler, Experimental and numerical investigation of micro-environmental conditions in public transportation buses, Build. Environ. 45 (10) (2010) 2077–2088.
[47] A.K. Persily, W.S. Dols, in: M.H. Sherman (Ed.), *The Relation Of CO_2 Concentration To Office Building Ventilation, ASTM STP 1067*, American Society for Testing and Materials, Philadelphia, 1990, pp. 77–92.
[48] N. Mahyuddin, H.B. Awbi, M. Alshitawi, The spatial distribution of carbon dioxide in rooms with particular application to classrooms, Indoor Built Environ. 23 (3) (2013) 433–448.
[49] N. Mahyuddin, H. Awbi, The spatial distribution of carbon dioxide in an environmental test chamber, Build. Environ. 45 (9) (2010) 1993–2001.
[50] N. Mahyuddin, H.B. Awbi, E.A. Essah, Computational fluid dynamics modelling of the air movement in an environmental test chamber with a respiring manikin, Journal of Building Performance Simulation 8 (5) (2015) 359–374.
[51] H.B. Awbi, Ventilation of Buildings, second ed., E & FN Spon, London, 2003.
[52] S. Somarathne, Dynamic thermal modelling using CFD, in: Department of Mechanical Engineering, Brunel University, 2003, p. 13.
[53] Q. Chen, W. Xu, A zero-equation turbulence model for indoor airflow simulation, Energy Build. 28 (2) (1998) 137–144.
[54] B.E. Launder, D.B. Spalding, The numerical computation of turbulent flows, Comput. Methods Appl. Mech. Eng. 3 (1974) 269–289.
[55] L. Zhang, et al., Validation of CFD model for research into displacement ventilation, Architect. Sci. Rev. 48 (4) (2005) 305–316.
[56] F.R. Menter, M. Kuntz, R. Langtry, Ten years of experience with the SST turbulence model, in: K. Hanjalic, Y. Nagano, M. Tummers (Eds.), Turbulence, Heat and Mass Transfer, Begell House Inc, 2003. Redding, CT.
[57] A. Jouvray, P.G. Tucker, Computation of the flow in a ventilated room using non-linear RANS, LES and hybrid RAN/LES, Int. J. Numer. Methods Fluid. 48 (1) (2005) 99–106.
[58] P.J. Richards, A.D. Quinn, S. Parker, A 6 m cube in an atmospheric boundary layer flow Part 2 Computational solutions, Wind Struct. 5 (2–4) (2002) 177–192.
[59] S.T. Taylor, *LEED and standard 62.1.* American society of heating, refrigerating and air-conditioning engineers, ASHRAE J. 47 (9) (2005).
[60] T. Schneider, Measuring strategies and monitoring of the indoor environment, J. Environ. Monit. 1 (1999) 427–434.
[61] E.A.B. Maldonado, J.E. Woods, A method to select locations for indoor air quality sampling, Build. Environ. 18 (4) (1983) 171–180.
[62] S. Weichenthal, et al., Characterizing and predicting ultrafine particle counts in Canadian classrooms during the winter months: model development and evaluation, Environ. Res. 106 (3) (2008) 349–360.
[63] W. Chan, et al., Indoor air quality in new hotels' guest rooms of the major world factory region, Int. J. Hospit. Manag. 28 (1) (2009) 26–32.
[64] E.Z.E. Conceição, M.M.J.R. Lúcio, Air quality inside a school building: air exchange monitoring, evolution of carbon dioxide and assessment of ventilation strategies, Int. J. Vent. 5 (2) (2006). Paper 8.
[65] L. Guo, J.O. Lewis, Carbon dioxide concentration and its application on estimating the air change rate in typical Irish houses, Int. J. Vent. 6 (3) (2007).
[66] W. Yang, et al., Indoor air quality investigation according to age of the school buildings in Korea, J. Environ. Manag. 90 (1) (2009) 348–354.
[67] Y.C. Chien, C.P. Chang, C.P. Lo, Assessment of air change rates in chemical laboratories, Indoor Built Environ. 18 (2009) 162–167.
[68] S.L. Miller, et al., An assessment of indoor air quality in recent Mexican immigrant housing in Commerce City, Colorado, Atmos. Environ. 43 (35) (2009) 5661–5667.
[69] A.K. Persily, Evaluating building IAQ and ventilation with indoor carbon dioxide, Build. Eng. 103 (2) (1997) 103–204.
[70] P.S. Hui, L.T. Wong, K.W. Mui, Evaluation of professional choice of sampling locations for indoor air quality assessment, Build. Environ. (2006) 1–8 (article in press).
[71] G. Bertoni, C. Ciuchini, R. Tappa, Measurement of long-term average carbon dioxide concentrations using passive diffusion sampling, Atmos. Environ. 38 (11) (2004) 1625–1630.
[72] P. Nejat, J. John Kaiser Calautit, Y. Fekri, M. Sheikhshahrokhdehkordi, H. Alsaad, C. Voelker, Influence of terrain and atmospheric boundary layer on the ventilation and thermal comfort performance of windcatchers, J. Build. Eng. 73 (2023).
[73] N.J. Potter, Effect of fluctuating wind pressures on natural ventilation, Build. Eng. 85 (1979) 445–457.