The effects of manual airing strategies and architectural factors on the indoor air quality in college classrooms: A case study

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Abstract

In China, natural ventilation is a common way of improving indoor air quality (IAQ) in college classrooms. However, until now, the effects of both manual airing strategies and architectural factors on IAQ in classrooms have not been well explored. The present work aimed to investigate the effect of manual airing strategies, such as opening doors and opening exterior or interior windows, on the concentrations of both carbon dioxide (CO_2) and fine particulate matter ($PM_{2.5}$) in classrooms using field measurements. Through simulation, the effects of floor level, room orientation and the height of interior windows on CO_2 concentration were also analysed. The results of this study revealed that 1) simultaneously opening doors and exterior windows or opening the doors alone could effectively reduce the indoor CO_2 concentration, but the same effect could not be achieved by opening interior windows only; 2) the indoor $PM_{2.5}$ concentration was primarily affected by the level of outdoor $PM_{2.5}$, and it may exceed the recommended limit by 33% when the outdoor pollution level is high, even with closed doors and windows; and 3) in winter, both floor level and classroom orientation exerted a significant influence on the indoor CO_2 concentration, but the height of interior windows had no effect.

Keywords

Indoor air quality; classrooms; manual airing strategies; natural ventilation; influential factors

1. Introduction

Indoor air quality (IAQ) in college classrooms has been recognized as a major factor that affects student health (Aziz et al. 2015; Cichowicz et al. 2015; Stabile et al. 2017) and academic performance (Brink et al. ; Twardella et al. 2012). The IAQ is primarily indicated by indoor carbon dioxide (CO_2) and particulate matter (PM) concentrations (Chatzidiakou et al. 2015; Liang et al.). In buildings, CO_2 concentration is closely linked with occupants' physiological responses (Allen et al. 2016; Zhang et al. 2016), and high CO_2 concentration greatly reduce both cognitive performance and learning efficiency (Kenichi et al. 2018). PM from the outdoors can damage cell membranes and destroy antioxidant systems when it is inhaled into the human body, resulting in systemic inflammation and immune system disorders (Corsini et al. 2013; Davel et al. 2012; Deng et al. 2013).

Previous studies have suggested that the primary factors influencing the IAQ in buildings fall into three categories, namely, contextual factors, building-related factors and occupant-related factors (Sadat Korsavi et al. 2018). Contextual factors can be at either the macroscopic level (e.g., climatic conditions (Heebøll et al. 2018) and seasons (Canha et al. 2013; Gao et al. 2014; Turanjanin et al. 2014)) or the microscopic level (e.g., a regional airflow field (Santamouris et al. 2008)). Building-related factors include ventilation type and rate (Batterman et al. 2017), airtightness (Batterman et al. 2017; Luther et al. 2017), window design (Heebøll et al. 2018), CO_2 exhalation rate and room volume (Luther and Horan 2014). Occupant-related factors include occupant behaviour (Batterman et al. 2017; Coley and Beisteiner 2016), occupancy level (Dorizas et al. 2015; Luther et al. 2017), occupation time and the previous room's occupancy level (Turanjanin et al. 2014). Among these factors, building-related factors are much easier to control during the design and operation stages of building.

Natural ventilation is a common ventilation type for college classrooms that provides air exchange indoors to dilute CO_2 concentrations, which may go beyond the recommended limit due to the high student density (Dunnill 1962; Ling et al. 2017;

Selgrade et al. 2007). The effect of natural ventilation is influenced by various factors, including both manual airing strategies and architectural factors. For example, cross-ventilation during breaks has been suggested as an effective ventilation strategy for controlling CO_2 concentrations in classrooms (Heracleous and Michael 2019). During heating seasons, frequent and short periods of window opening have proven to be effective in reducing CO_2 concentrations and improving IAQ in classrooms (Schibuola et al. 2016). When students leave classrooms, there will be temporary door openings. Existing studies, however, often neglected the influence of this behaviour on the indoor environment, as shown in Table 1.

Table 1

Summary of previous relevant works.

No.	Building type	Indicators	Manual airing strategy	Architectural factor	Occupant number	Monitoring method	Ref.
1	School	CO_2, PM_s	Open the windows	n.c.	13-27	Continuous monitoring over a period	(Stabile et al. 2017)
2	School	CO_2, PM_s	n.c.	n.c.	15-26	Continuous monitoring over a period	(Rovelli et al. 2014)
3	School	CO_2	Open the windows	n.c.	24	24-hour continuous monitoring over a week	(Schibuola et al. 2016)
4	Office	$PM_{2.5}$	Open the windows	n.c.	1	Discontinuous monitoring over 9.5 months	(Pan et al. 2018)
5	School	CO_2, PM_s	Open the windows	n.c.	n.c.	Monitoring over a period	(Goyal and Khare 2011)
6	School	CO_2, SF_6	Open the door	n.c.	1-50	Monitoring during the class	(Bartlett et al. 2004)
7	School	Air change rate	Open the windows	The placement of openings	45-50	Simulated monitoring over a period	(Bughio et al. 2020)
8	Workshop	CO_2, PM_{10}	Open the door	n.c.	n.c.	An eight-hour sampling duration	(Kwong et al. 2018)
9	School	CO_2	Open the windows	n.c.	n.c.	Discontinuous monitoring	(Santamouris et al. 2008)
10	School	CO_2, CO	n.c.	n.c.	11-36	All measurements were collected once per minute during one school week.	(Otto Hänninen et al. 2017)

11	School	CO_2	n.c.	School orientation	0-47	Continuous monitoring during weekdays	(Asif et al. 2018)
12	School	CO_2	Open the windows	n.c.	23-25	Continuous monitoring over a period	(Heracleous and Michael 2019)
13	School	Thermal sensations	Open the windows	n.c.	30-40	Questionnaire survey	(Costa et al. 2019)

Note: n.c.= not concerned.

With the development of industrialization and the continuous consumption of fossil fuels, the concentration of outdoor PM has been rising rapidly in recent years (Fuzzi et al. 2015; Shiraiwa et al. 2017). To prevent ambient pollutants, such as $PM_{2.5}$ and PM_{10}, exterior windows in classrooms are often kept closed, which prevents the intake of fresh air (Chen et al. 2019). In this circumstance, the effect of natural ventilation on the IAQ in classrooms has become more complicated (Sakiyama et al. 2020). It has been reported that manual airing has a great impact on reducing indoor CO_2 concentrations by increasing the airing frequency. This strategy, however, also increases indoor fine particle concentrations introduced from the outdoors (Rovelli et al. 2014).

Previous studies have also considered the influence of architectural factors on the performance of indoor ventilation in classrooms. The adapted placement of openings, such as doors and windows, may help to enhance ventilation performance (Bughio et al. 2020). The impact of wind speed and apartment ventilation on both PM_{10} and $PM_{2.5}$ concentrations indoors in Kraków, Poland was investigated, and it was found that keeping windows open or closed had no statistically significant impact on indoor $PM_{2.5}$ concentration, regardless of weather type. For PM_{10}, however, window opening significantly increased indoor pollutant concentrations in different weather types (Cibor et al. 2020). Nevertheless, there have been limited studies analysing the details of opening placement, such as the height of windows. Room orientation has also been emphasized for maintaining thermal comfort during the building design stage (Asif et al. 2018).

In this study, the first aim was to analyse the effect of different manual airing strategies, including opening doors, opening exterior windows and opening interior windows, in terms of their impact on the concentrations of both CO_2 and $PM_{2.5}$ in college classrooms. This aim was achieved by field measurements carried out in four naturally ventilated college classrooms located in Tianjin, China. The second aim was to explore the effect of architectural factors, including both floor level, room orientation and interior window height, on CO_2 concentration, and this was accomplished with a modelling approach.

2. Methodologies

2.1. Field measurements

In this study, major indoor environmental parameters were measured in four identical college classrooms (as shown in Figure 1) in December 2017 and March 2018, all of which were naturally ventilated. These classrooms are all located at Tianjin University, China, and their main characteristics are shown in Table 2. During the field measurement process, indoor and outdoor CO_2 and $PM_{2.5}$ concentrations, as well as ventilation behaviours, were recorded.

Figure 1. One classroom chosen for this study.

Table 2

Primary characteristics of the monitored classrooms.

Classroom	Area (m^2)	Volume (m^3)	Capacity
A101	56	196	38
A103	56	196	38
A105	70	259	60
A206	68	238	60

In each classroom, there were five monitoring points arranged at a height of 1.1 m above the ground, as recommended by ISO 7726 (ISO 2001); their location in the room is shown in Figure 2. Indoor CO_2 and $PM_{2.5}$ concentrations were recorded every minute, and some major specifications of the measurement instruments are available in Table 3. Before measurement, all instruments were manufacture-calibrated and underwent zero checks. Additionally, the later data analysis was based on the average value of each parameter as recorded at all five locations.

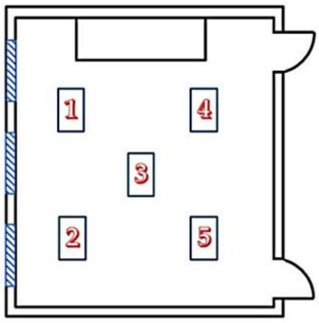

Figure 2. Location of the indoor monitoring points.

Table 3

Parameters of the measurement instruments.

Instrument	Parameter	Range	Precision
Temperature and humidity recorder L92-1+	Temperature	-40-70 °C	±0.5 °C
	Humidity	0-100%	±3%
TSI Q-Trak 7565	Wind speed	0-40 m/s	±0.02 m/s
CO_2 probe model MH-Z14A	CO_2 concentration	0-5000 ppm	±50 ppm
$PM_{2.5}$ probe model DSL-03	$PM_{2.5}$ concentration	0-999 μg/m^3	±10 μg/m^3

To reflect the actual IAQ in each classroom, measurements were conducted during lectures. The classrooms were used daily, and their usage schedules, including classes and breaks as well as the number of students in each class, were all recorded. There were two classes in the morning, from 8:30 to 10:05 and then from 10:25 to 12:00; there were two classes in the afternoon, from 13:30 to 15:05 and then from 15:25 to 17:00. The specific experimental plan is shown in Table 4. Ventilation behaviours, including opening and closing of doors, opening and closing of exterior windows and opening and closing of interior windows, were also recorded during the measurement.

Table 4

Measurement plan used in this study.

Case	Time	Classrooms	Parameters

1	Morning (01/12/2017)	A101, A103	CO_2, $PM_{2.5}$
2	Afternoon (26/12/2017)	A103, A206	CO_2, $PM_{2.5}$
3	Morning (29/12/2017)	A105, A206	CO_2, $PM_{2.5}$
4	Afternoon (09/03/2018)	A105, A206	CO_2, $PM_{2.5}$

2.2. Modelling approach

2.2.1. Model setup

To explore the effect of architectural factors on the CO_2 concentration in classrooms, the modelling approach was implemented using the CONTAM software, which can accurately predict pollutant concentration and ventilation performance in buildings (Moschetti and Carlucci 2017; Silva et al. 2016). This software is widely used in research related to ventilation, smoke control and the effect of chimneys in residential and commercial buildings (Man et al. 2019; Ng et al. 2012). A typical multizone model calculates the transmission of airflow and pollutants between different zones in a building or between the indoors and outdoors (Chen 2009). The air mass flow between different zones is calculated by Equation 1:

$$F_{j,i} = f(P_j - P_i) \tag{1}$$

where $F_{j,i}$ is the air mass flow from zone j to zone i in kg/s, P_j is the pressure of zone j in Pa, and P_i is the pressure of zone i in Pa.

According to the law of mass conservation, the pollutant mass concentration in the zone is calculated by Equation 2:

$$\frac{dm_{\alpha,i}}{d\tau} = -R_{\alpha,i}C_{\alpha,i} - \sum_j F_{i,j}C_{\alpha,i} + \sum_j F_{j,i}(1 - \eta_{\alpha,j,i})C_{\alpha,j} + m_i \sum_\beta K_{\alpha,\beta} + G_{\alpha,i} \tag{2}$$

where $m_{\alpha,i}$ is the mass of pollutant α in zone *i* in kg, τ is the time in s, $C_{\alpha,i}$ is the mass fraction of pollutant α in zone *i* in kg_α/kg_{air}, $F_{i,j}$ is the air mass flow from zone *i* to zone *j* in kg/s, $R_{\alpha,i}$ is the elimination coefficient of pollutant α, $G_{\alpha,i}$ is the generation rate of pollutant α in kg/s, $K_{\alpha,\beta}$ is the reaction coefficient of pollutants α and β and $\eta_{\alpha,j,i}$ is the filtering efficiency of pollutant α from zone *j* to zone *i*.

Figure 3a shows the actual building, and Figure 3b shows the virtual model used in the building simulation. There are a total of four floors in the building, and each floor has a height of 4.5 m. Figures 3c and 3d present the building's floor plans. The doors, exterior windows and interior windows are the primary openings in the building that facilitate airflow exchange between the room and its ambient environment.

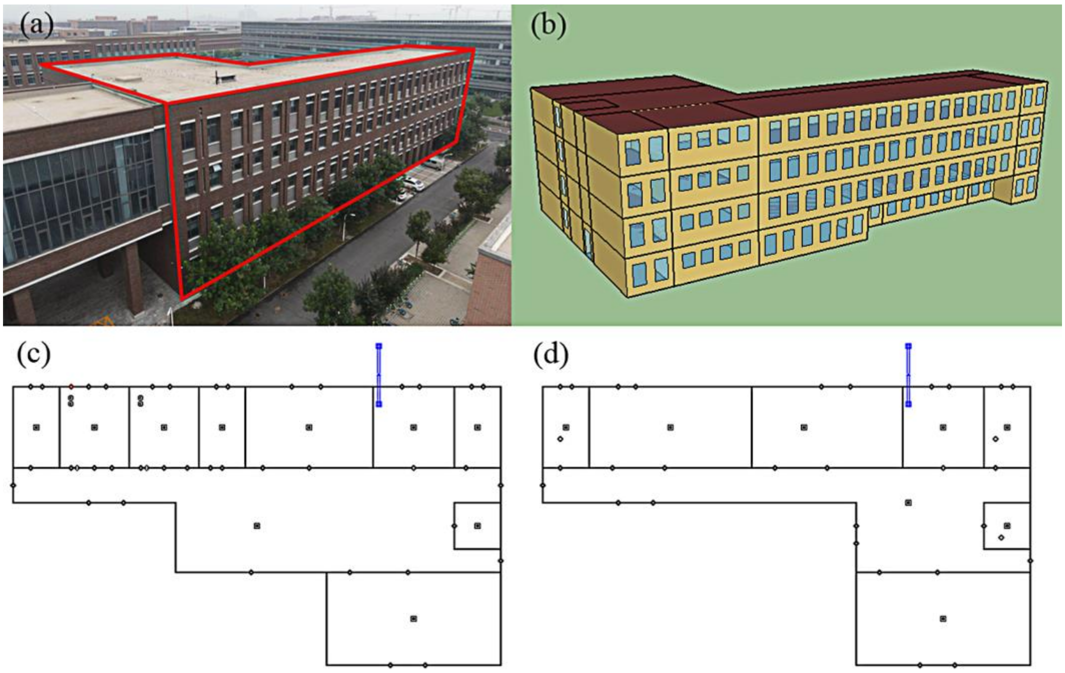

Figure 3. The layout of the model: (a) the actual building, (b) the simulation model, (c) the model's first- and second-floor plan, and (d) the model's third- and fourth-floor plan.

The natural ventilation performance in the classroom was generally simulated from 8:30 am to 12:00 am. The opening and closing conditions of the doors and the windows in each classroom were defined based on daily schedules, with doors only opened during breaks. CO_2 was used as the primary indicator of IAQ in the simulation, and its initial concentration was determined from the field measurement. The indoor CO_2 in the model was primarily generated by constant release from the room's occupants due to breathing. According to existing references (ASTM 2002; Bois and Bois 1989), the CO_2 generation rate of an individual equals V_{O2} multiplied by the respiratory quotient (RQ), as shown in Equations 3-5.

$$V_{CO2} = V_{O2} \times RQ \tag{3}$$

where V_{O2} is the rate of oxygen consumption and RQ is the respiratory quotient, which is equal to 0.83 for an average adult engaged in light or sedentary activity. (ASTM 2002)

$$V_{O2} = 0.00276 A_D M / (0.23 RQ + 0.77) \tag{4}$$

where A_D is the Dubois surface area in m^2 and M is the metabolic rate per unit of surface area, which varies under different states and is equal to 1 met when sitting or reading.

$$A_D = 0.202 W^{0.425} H^{0.725} \tag{5}$$

where W is body mass in kg and H is body height in m.

2.2.2. Model calibration

The simulation results were calibrated against the measured data on December 1st from classrooms A101 and A103. The measured data used for calibration are described in Table 5. The climatic parameters used in the simulation were dependent on the data provided by the China meteorological website (China Meteorological Website). According to the measured temperature, the temperature in the corridor, the elevator, and the hall were set to 16°C, while the temperature was set to 18°C in the other rooms. Other initial conditions, such as the indoor CO_2 concentration, occupancy changes and door and window states, were also based on actual measurements.

Table 5

Measured data used for model calibration.

Classrooms	CO_2 initial concentration (ppm)	Test period	Occupant number	Conditions of windows and doors		
				Exterior windows	Interior windows	Doors
A101	440	8:30-10:05	5	Closed	Closed	Closed
		10:05-10:25	Variation 1 [b)]	Closed	Closed	Open
		10:25-12:00	39	Closed	Closed	Closed
A103	550 [a)]	8:30-10:05	28	Closed	Closed	Closed

	10:05-10:25	Variation 2 c)	Closed	Closed	Open
	10:25-12:00	28	Closed	Closed	Closed

Notes: a) Students came in earlier, b) Students were gathering before class began, and c) students came in and out of the classroom during the break.

From the model calibration, there was good agreement between the simulated and measured indoor CO_2 concentrations, as shown in Figure 4, with mean relative errors of 5.0% and 4.5% for A101 and A103, respectively. Therefore, it is believed that the model developed for this study can be used for the following analysis.

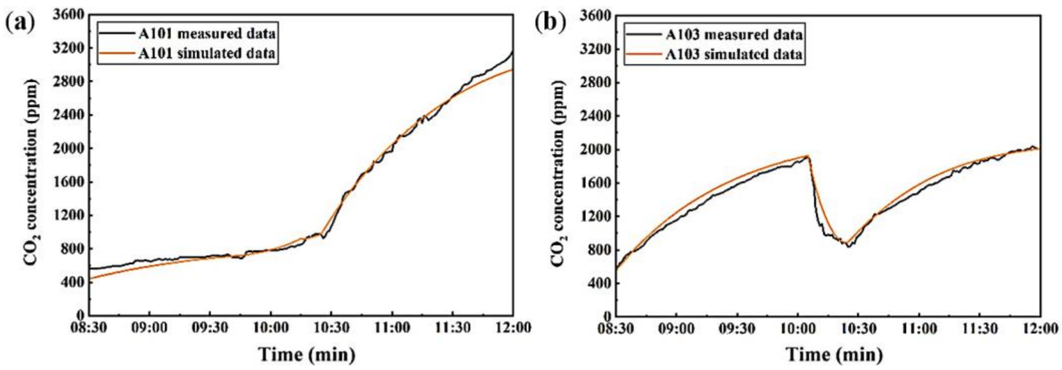

Figure 4. Comparison between measured data and simulated data of CO_2 concentration in (a) A101 and (b) A103.

3. Results and discussions

Figure 5 depicts the changes in both CO_2 and $PM_{2.5}$ levels in Classroom A103, measured in the morning on December 1st. The average indoor CO_2 level rose when the room was occupied and fell quickly during breaks due to opened doors, with the outdoor CO_2 concentration remaining stable at 440 ppm. On the other hand, there was an increase in the $PM_{2.5}$ concentration during the break, which was also due to opened doors; the $PM_{2.5}$ concentration also decreased when there was no purposeful ventilation. The change in indoor $PM_{2.5}$ level contrasted the change in the indoor CO_2 level, similar to what was observed by Chillon et al. (Chillon et al. 2021). One possible explanation for the reduction in indoor $PM_{2.5}$ concentration during the occupied period (everything closed) is that some PM was inhaled by students through breathing and some sedimented.

It is worth mentioning that both parameters showed similar trends in the multiple trials when the ventilation condition remained unchanged. Since this similarity always existed, the following analysis is based only on the average results of the field measurements.

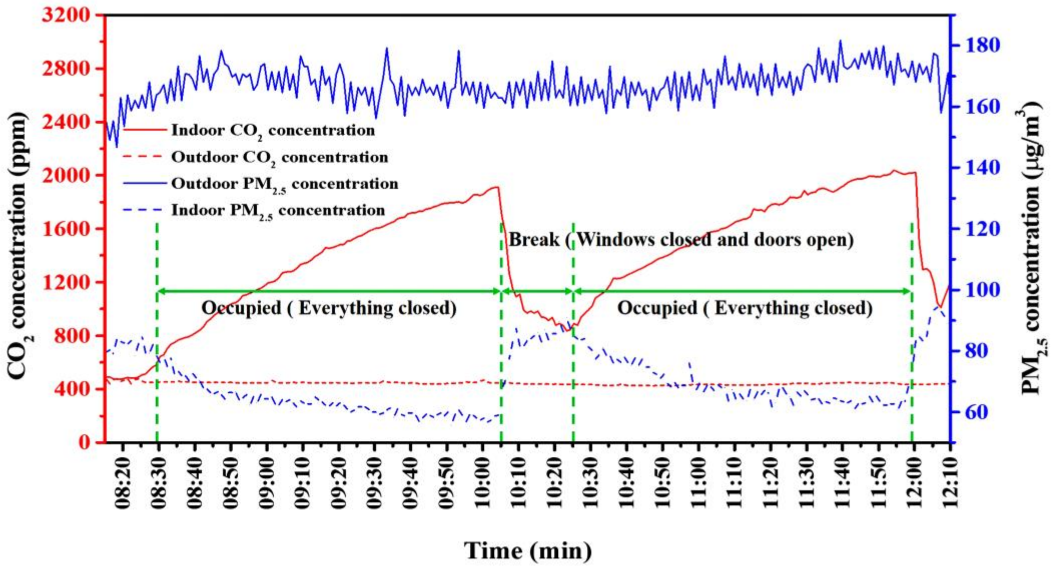

Figure 5. Trend of CO_2 and $PM_{2.5}$ levels in classroom A103 measured in the morning on December 1st.

3.1. The effects of manual airing strategies on CO_2 and $PM_{2.5}$ concentrations

According to the Guidelines from the World Health Organization (WHO 2006), the acceptable limits for indoor CO_2 and $PM_{2.5}$ levels are 1000 ppm and 75 μg/m³, respectively. The field measurements showed that the average level of indoor CO_2 generally exceeded the limit and needed to be reduced using manual airing strategies.

Figure 6a compares the situation in which both doors and exterior windows were closed with the situation in which the interior windows in A105 were open; the results demonstrate the effect of opening interior windows alone. The initial CO_2 concentration in this room was approximately 1519 ppm due to occupancy by students. During the measurement, the CO_2 concentration rose quickly at an average speed of 18.39 ppm/min when all doors and windows were closed. When the interior windows were left open, the average increase speed of the CO_2 concentration decreased to 8.94

ppm/min, 48.6% of the speed in the previous case.

Figure 6b compares the situation in A101, where the doors were open, with the situation in A103, where both the doors and windows were closed; this comparison demonstrates the effect of opening only the door. Since the two identical rooms had no courses before the test, the initial CO_2 concentrations in both rooms were similar to the outdoor level: 608 ppm in A101 and 582 ppm in A103. When the doors and windows were closed in both rooms in the first 50 minutes, the CO_2 concentration in both rooms increased, and the CO_2 concentration in A101 rose faster than that of A103, as A101 had more students. In A101, the CO_2 concentration decreased rapidly at an average speed of 29.06 ppm/min after opening the doors and remained at nearly the limit value after the 70th minute, which means that opening doors during the break may have significantly reduced the indoor CO_2 concentration.

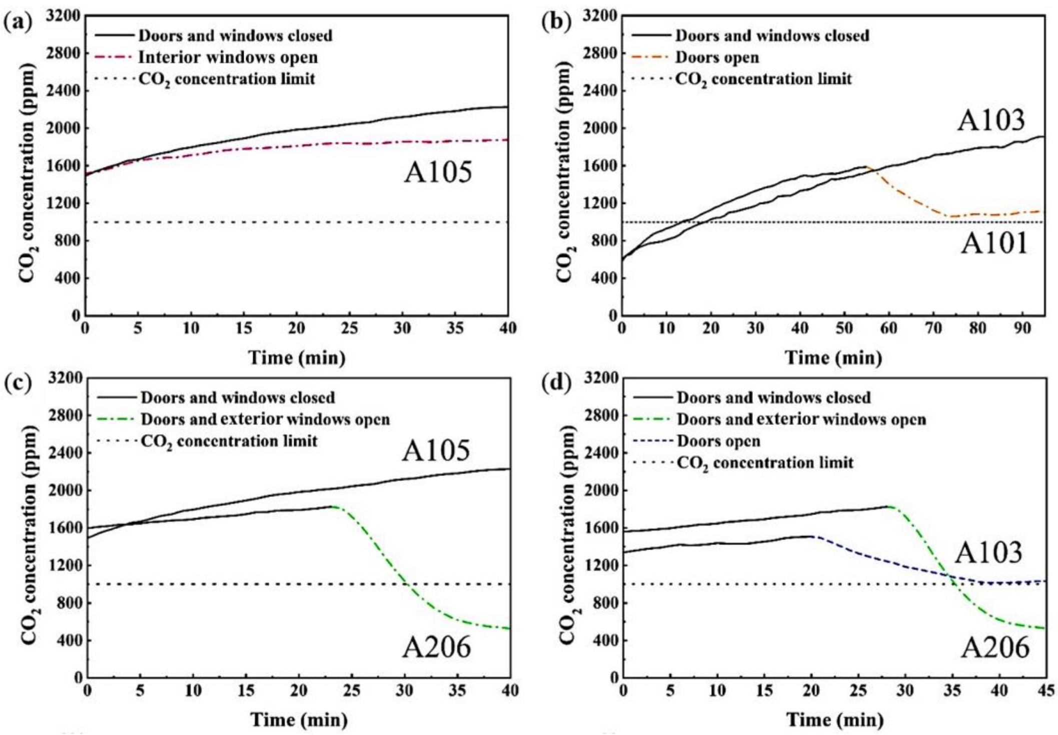

Figure 6. Comparison of CO_2 concentration trends under different manual airing strategies: (a) open interior windows alone, (b) open doors alone, (c) and (d) open both doors and exterior windows.

The effects of opening doors and exterior windows at the same time are shown in Figure

6c; the trend of CO_2 concentrations in A206, where the doors and exterior windows were open, and in A105, where doors and windows were closed, was compared. The initial concentrations were 1594 ppm in A206 and 1489 ppm in A105, as there were already students in the rooms. Since there were more students in A105, the rate of increase of the CO_2 concentration was higher when the doors and windows in both rooms were closed. After opening the doors and exterior windows for ventilation in A206, the CO_2 concentration rapidly dropped below the recommended limit at an average speed of 76.38 ppm/min.

Figure 6d compares the CO_2 concentrations in A103, where the doors were opened, and in A206, where the doors and exterior windows were opened. The growth rates of the CO_2 concentration were similar in A103 and A206 when both rooms closed the doors and windows; these rates were 8.4 ppm/min and 9.4 ppm/min, respectively. The initial concentrations were 1337 ppm in A103 and 1557 ppm in A206. The indoor CO_2 concentration declined instantly to below the recommended limit after opening the doors and exterior windows for eight minutes, while it could only be reduced to near the limit with the doors opened.

On the other hand, for $PM_{2.5}$ levels, there were limited relevant sources in the classrooms based on the observation record, and human activities, cleaning and chalkboard activities occurred during the break when the doors were open. Figure 7 presents the trends of indoor $PM_{2.5}$ concentrations under different outdoor conditions. The average outdoor $PM_{2.5}$ concentration was 208 μg/m³, while the indoor $PM_{2.5}$ concentration ranged from approximately 100 to 120 ppm μg/m³ in A105 during the occupied period; this level was higher than the ambient air quality standard value, as shown in Figure 7a. After opening the interior windows and doors at 10:05 am for ventilation, there was an upward trend in indoor $PM_{2.5}$ concentration, which intensified the indoor pollution; additionally, the speed of increase of the concentration was higher than when only the doors were open (refer to A103). This trend in $PM_{2.5}$ concentration was different from the discovery of (Rovelli et al. 2014), which stated that the frequent opening of windows did not significantly influence the indoor $PM_{2.5}$ concentration.

Moreover, as the next class started earlier, the indoor $PM_{2.5}$ concentration reached its peak value earlier than the planned time at 10:25.

In Figure 7b, the outdoor $PM_{2.5}$ concentration was between 6-20 μg/m³ and remained at a low level. There was a reduction in indoor $PM_{2.5}$ concentration when everything was closed, and the concentration remained nearly constant when the exterior windows and doors were open. The indoor $PM_{2.5}$ concentration varied from 4 μg/m³ to 6 μg/m³ when natural ventilation was carried out by opening the doors and exterior windows.

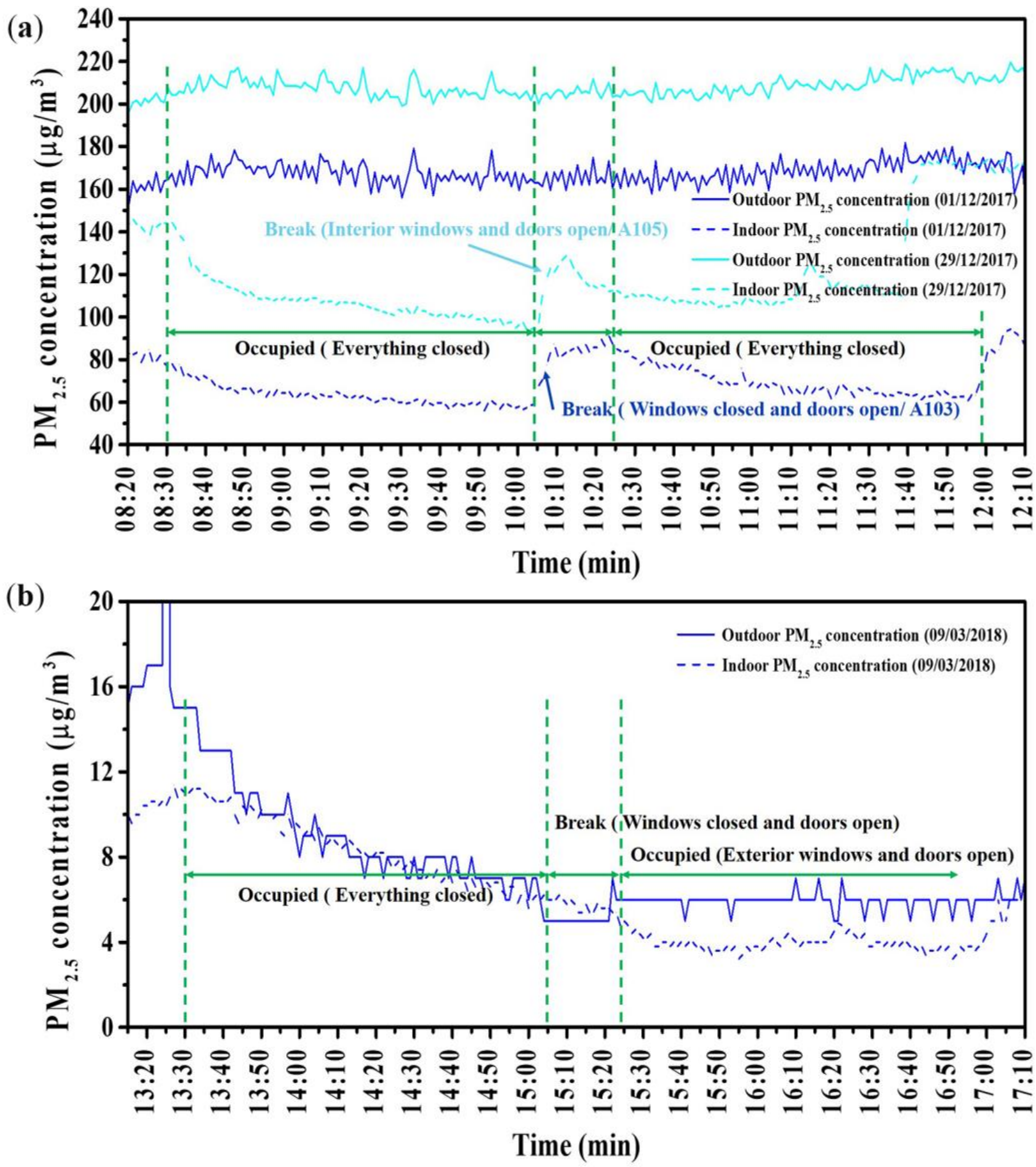

Figure 7. Trend in indoor $PM_{2.5}$ concentrations under different outdoor conditions: (a) polluted weather and (b) unpolluted weather.

The frequency distribution diagram of the outdoor $PM_{2.5}$ concentration in Tianjin is presented in Figure 8. Clearly, the cases studied represent the two extreme situations of both low and high outdoor $PM_{2.5}$ concentrations. The effect of manual airing strategies on indoor $PM_{2.5}$ concentration was also determined by the ambient climate. When the outdoor $PM_{2.5}$ concentration exceeded the recommended limit, opening the doors and exterior windows aggravated indoor pollution; in this case, installing an air purifier is recommended.

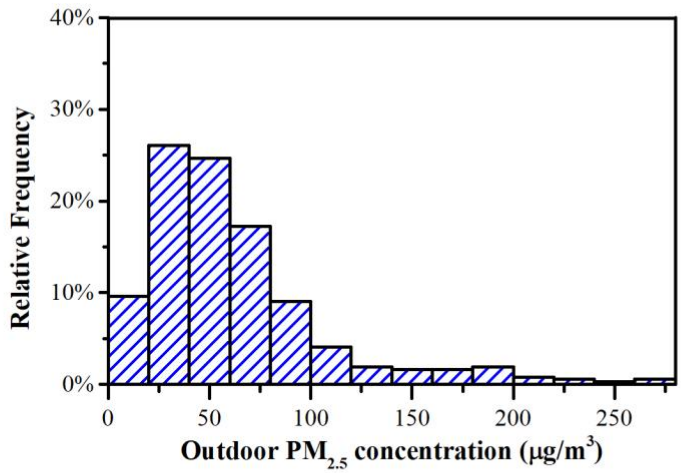

Figure 8. Frequency distribution of the outdoor $PM_{2.5}$ concentration.

3.2. The effects of architectural factors on the CO_2 concentration

To study the effect of the classroom floor on the natural ventilation performance, the CO_2 concentrations in A104 and A404, which share their size, number of students and orientation, were analysed. As shown in Figure 9a, the CO_2 concentrations at 12:00 am in A104 and A404 were 3362 ppm and 4072 ppm, respectively. The CO_2 concentration of A104 was 21.1% lower than that of A404. Therefore, the ventilation performance of the top floor is worse than that of the first floor with a more serious accumulation of CO_2.

The actual height of the interior window, 3.1 m, and the simulated height, 2 m, were compared; this comparison accounted for the fact that the actual height of the interior windows should not be very low. As shown in Figure 9b, the height of the interior windows had no obvious effect on natural ventilation in the classroom, as there was no difference in the trends of indoor CO_2 concentrations in either case.

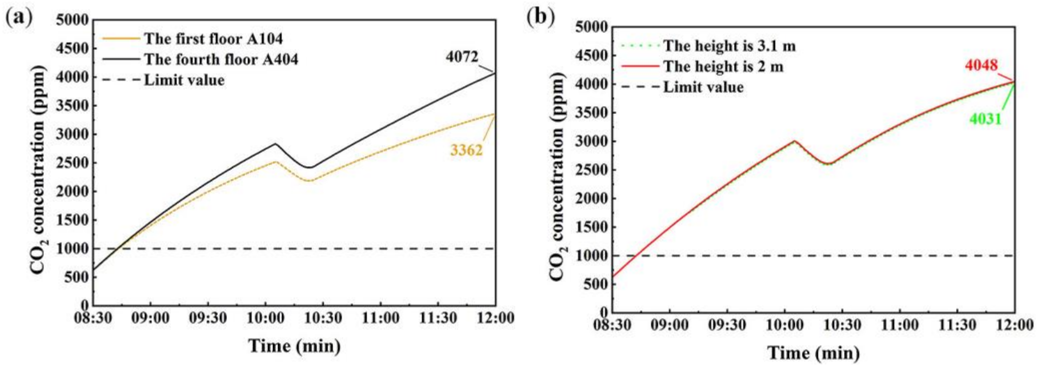

Figure 9. The effects of (a) the floor number and (b) the height of interior windows on the indoor CO_2 concentration.

To evaluate the effect of the building orientation on the natural ventilation performance, classrooms A302 and A303, which are on the same floor and have the same size but different orientations, were selected. Figure 10 shows the relative positions of the two classrooms and the wind rose diagram in Tianjin.

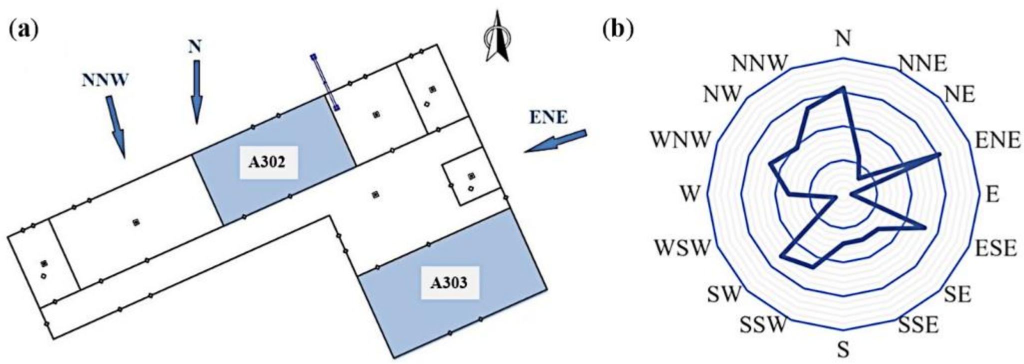

Figure 10. (a) Positions of A302 and A303 and (b) wind rose diagram in Tianjin.

As shown in Figure 11a, for the north wind, A302 was on the windward side, and A303 was on the leeward side. The CO_2 concentration in A302 reached 3517 ppm after class, which was 23.2% lower than that of A303. As shown in Figure 11b, with the NNW wind, the maximum CO_2 concentration in A302 was 3482 ppm, which was 26.4% lower than that of A303. Compared with the north wind, the NNW wind was more vertical to A302's facade, and the natural ventilation performance was better. As shown in Figure

11c, with ENE wind, the wind blew from approximately the side of the building. A303 was more sensitive because there were no other classrooms around it, and the maximum CO_2 concentration there was 3735 ppm, which was 13.2% lower than that of A302. When the wind blows vertically on the facade where the exterior windows are located, the natural ventilation performance in the windward classroom can be enhanced, while that of the leeward classroom becomes worse. Generally, in the case that the same manual airing strategy is used, the effect of the floor and orientation of the classroom on the indoor CO_2 concentration can be distinguished.

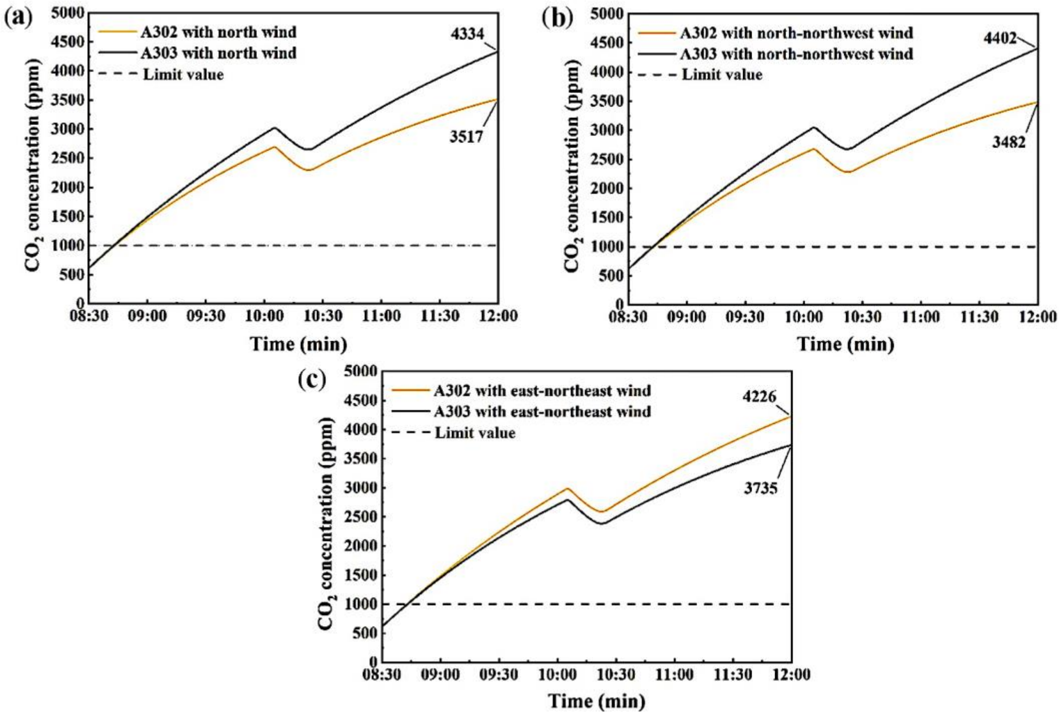

Figure 11. Comparison of CO_2 concentrations with different wind directions: (a) north wind, (b) NNW wind and (c) ENE wind.

4. Conclusions

The use of natural ventilation in college classrooms is regarded as an effective means to reduce pollutant concentrations and improve the IAQ. This study aimed to explore the effects of different manual airing strategies and architectural factors on the IAQ of naturally ventilated classrooms by both field measurements and simulations. Based on this aim, the IAQ was evaluated in different classrooms in terms of both $PM_{2.5}$ and CO_2

concentrations and was assessed when no prescribed airing strategy was imposed on the classroom occupants. By analysing the results of both measurement and simulation, some conclusions were drawn as follows:

(1) Opening doors and exterior windows can quickly reduce indoor CO_2 concentrations in healthy environments, which is very effective for college classrooms designed for natural ventilation. Opening doors can reduce CO_2 concentrations and keep them stable around the limit proposed by the WHO. Opening interior windows can slow down an increasing rate of CO_2 concentration but cannot change the increasing trend, with a rate of increase of only 48.6% when compared to classrooms with both doors and windows closed.

(2) The field measurement results showed that the indoor $PM_{2.5}$ concentration was affected by the outdoor level, and it exceeded the recommended concentration limit by 33% when the ambient pollution was serious, even when the doors and windows were kept closed. Therefore, a simultaneous reduction in both pollutants cannot be achieved if reduction strategies rely solely on the building's air permeability and manual airing.

(3) The simulation results showed that the ventilation performance on the first floor was better than that on the top floor; the maximum CO_2 concentration was 21.1% lower on the first floor than that on the top floor. The ventilation performance of the windward classroom was better than that of the leeward classroom; the CO_2 concentration in the windward classroom was 26.4% lower at most. The more vertical the facade of the exterior windows was to the wind direction, the better the ventilation performance was. The height of the interior windows in the classroom had no obvious effect on the natural ventilation performance.

The authors hope that this study can elucidate the ventilation effect of different manual airing strategies and architectural factors in college classrooms and provide a reference for the practice of natural ventilation. However, because of the limited measurement conditions, more work should be done on the prescribed combination of different airing strategies, different air permeabilities and weather conditions.

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Data availability statements

The datasets generated during the current study are not publicly available due to the requirements of the supported foundation but are available from the corresponding author on reasonable request.

Declarations of 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.

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