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# Evaluating Indoor Carbon Dioxide Concentration and Ventilation Rate of Research Student Offices in Chinese Universities: A Case Study

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**Abstract:** This work provides a case study on the indoor environment and ventilation rate of naturally ventilated research student rooms in Chinese universities. In the measured room, air temperature, relative humidity and carbon dioxide ($CO_2$) concentration were monitored during the heating period for 4 weeks. The number of indoor occupants, occupied time of the room and window/door-opening cases were simultaneously recorded. Results showed the research student room was occupied for an average of 12.0 h each day. Due to a large indoor and outdoor temperature difference during the heating season, and occupants' adaption to indoor environment, indoor occupants seldom open windows/doors for ventilation. Air exchange of the room only by air infiltration cannot meet the ventilation requirement. As a result, an average of 77.6% of measured $CO_2$ data each day exceeded 1000 ppm during occupied time. In fact, according to $CO_2$ data, it was observed that window/door opening could effectively decrease indoor $CO_2$ concentration. Therefore, intermittent window/door opening or $CO_2$-based demand-controlled ventilation facilities were suggested for improving indoor air quality of such rooms. Additionally, special attention should be paid to other possible outdoor pollution.

**Keywords:** indoor air quality; high occupancy rate; natural ventilation; university building

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## 1. Introduction

Since entering the new century, China's higher education has achieved a leapfrog in development. According to China's statistics yearbook 2021 released by the National Bureau of Statistics of China [1], in 2020 there were about 36 million students in colleges or universities, and the student population was the largest in the world. For these students, almost all of their time was spent in university buildings, including classrooms, dormitories and other possible rooms (e.g., laboratory, library and lecture hall). Indoor air quality (IAQ) inside these rooms is one of the key issues for a pleasant stay for students. However, these rooms usually present a high occupancy rate; as a result, ventilation of these rooms is generally insufficient. A few published studies have confirmed this point. Regarding classrooms, Sarbu et al. measured indoor carbon dioxide ($CO_2$) levels in two air conditioned classrooms at a university in the west of Romania during both cooling and heating seasons [2]. Results indicated that indoor $CO_2$ concentration could reach a value of 2400 ppm in the case of inadequate ventilation. In addition, the $CO_2$ concentration could decrease significantly to 1500 ppm by manually opening the windows. Chang et al. evaluated IAQ in two computer classrooms and one general classroom in a southern Taiwan college, and indicated that low ventilation rates were likely responsible for the very high indoor $CO_2$ concentration [3]. By measuring and comparing IAQ in 15 classrooms in Brazilian universities, Jurado et al. found that the $CO_2$ level in the air-conditioned rooms was significantly higher than that in naturally ventilated rooms [4]. Asif et al. investigated the IAQ and thermal comfort in classrooms of four buildings of an educational institute and found that indoor $CO_2$ concentration in naturally ventilated classrooms exceeded safe levels at higher frequency [5]. Argunhan and Avci measured indoor temperature, relative humidity (RH) and IAQ of the classrooms in universities in Turkey and found that average indoor $CO_2$ level is higher than the ASHRAE standards, due to closed doors and windows in winters [6]. With regard to college student dormitories, Li et al. tested indoor $CO_2$ concentration in naturally ventilated student dormitories in a college in Beijing, China and showed that indoor $CO_2$ concentration most of the time exceeded the referenced guideline of 1000 ppm provided by IAQ standard [7], due to the low ventilation rate of the dormitories by air infiltration. However, through single-sided natural ventilation, sufficient outdoor air could be provided to dilute the indoor $CO_2$. Zhang et al. monitored indoor $CO_2$ concentration in three selected rooms of university dormitory buildings in winter in Shanghai, China and found that the occupants tended to close the windows to maintain an indoor thermal environment in winter, thereby resulting in elevated $CO_2$ concentrations during sleeping hours [8]. The above literature review indicated that ventilation in these university rooms was insufficient, even in developed countries. Furthermore, IAQ of other rooms such as libraries [9], lecture rooms [10,11], and research laboratories [12,13] in university buildings was also studied by some researchers.

As a matter of fact, in university buildings, there is also another type of room, namely the research student room. A research student room is often the place where postgraduate students carry out scientific research and administrative work in universities. Figure 1 shows indoor views of several typical research student offices in some universities of China. In recent years, due to a sharp increase in the number of postgraduate students in China, these rooms present a much higher occupancy rate than other offices in general office buildings. Additionally, these rooms usually have no fresh air unit in Chinese universities. For these rooms, the most effective ways to provide necessary outdoor fresh air are usually natural ventilation, which refers to air change through the intentional openings of building envelopes (windows/doors); and air infiltration, which refers to the air change through unintentional leakage areas of building envelopes when the doors and windows are closed [14]. In fact, in China most research student rooms in universities are not originally designed for high occupancy rates. Instead, with a rapidly increasing population of postgraduates in universities, some unoccupied rooms in universities have to be used as research student rooms. This inconsistency between design and utilization of the room is bound to bring about poor IAQ.

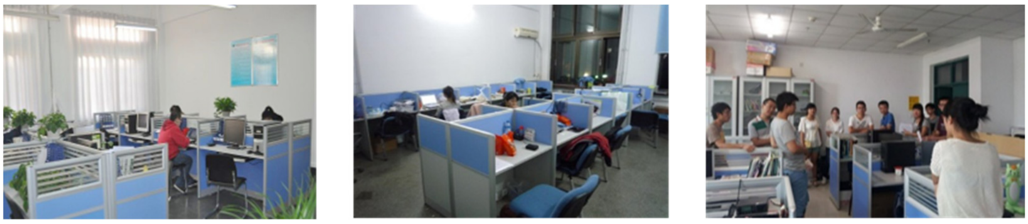

**Figure 1.** Indoor views of typical research student offices in some universities of China.

To date, however, indoor environment, ventilation rate and occupancy characteristics of such rooms in Chinese universities are rarely investigated. How about the indoor environment in such rooms? Can natural ventilation meet the requirements of postgraduate students? How to improve the ventilation rate of such rooms?

With these questions, a case study on naturally ventilated research student rooms in Chinese university is provided in the present paper. We selected a representative research student room with a high occupancy density in a university of China as the measured room and monitored indoor environmental parameters (including temperature, relative humidity and $CO_2$ concentration) for four weeks during the heating period. At the same time, occupied and unoccupied profiles of the room and open/closed cases of the windows/doors were recorded. Based on $CO_2$ measurement data and occupancy profile of the room, indoor environment and ventilation rate of the room were assessed. The results would be instructive to improve Chinese research students' studying environment and to improve the ventilation rate of such rooms.

## 2. Materials and Methods

### 2.1. Description of the Measured Room

In this study, a representative research student room in a university of Beijing (latitude: 39°54′ N, longitude: 116°23′ E) was selected as the measured room. The room is on the second floor of a five–story university building, as shown in Figure 2. The five-story university building was built in the 1980s and is close to the urban main road. The layout of the measured room is given in Figure 3. The room has a height of 2.8 m and a floor area of 23 $m^2$. In addition, the room has a door, which is set into the corridor. The fully opened door has an area of 1.8 $m^2$. There are two in-swinging casement windows, which are located at a height of 0.9 m above the floor. Each window comprises two window sashes. Each fully opened window sash has an area of 0.55 $m^2$, as shown in Figure 4. There is no air supply system in the room. Beijing is located in the cold region; in winter, there are three months during which the monthly mean temperature is below 0 °C. Due to low outdoor air temperature, building heating is imperative for occupants' thermal comfort in winter. Accordingly, central heating system is used in this room in winter. In general, seven postgraduate students work in this room. During monitoring period, however, one of the postgraduates was not staying in the room. Thus, the room was generally occupied with six postgraduate students during measuring period. The details of the occupancy characteristics of the room are described in the Results, Section 3.3.

**Figure 2.** Aerial view (**a**) and outdoor view (**b**) of the measured room.

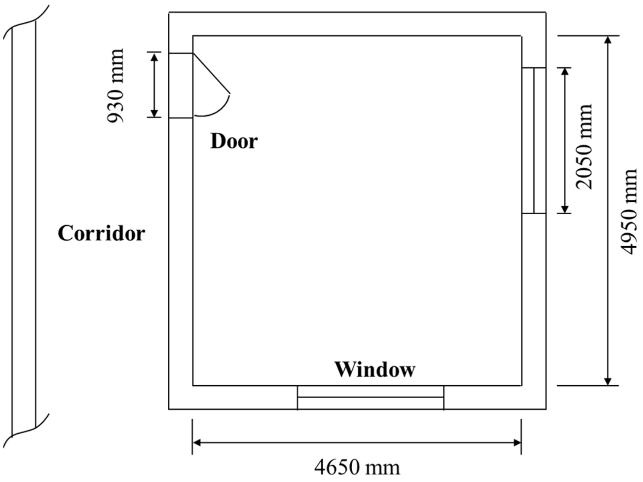

**Figure 3.** Layout of the measured room.

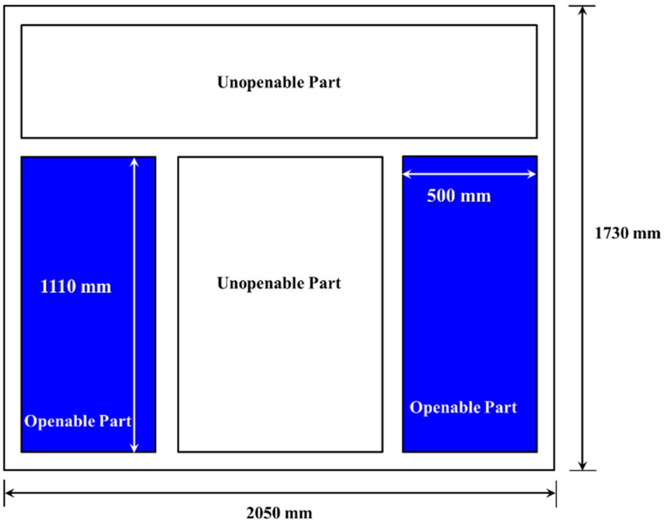

**Figure 4.** Layout of the window.

### 2.2. Measuring Process

The measurement was conducted in the research student room for 4 weeks during the typical heating period. Measured parameters included air temperature, RH and $CO_2$ concentration. Considering probably inadequate full mixing of indoor air, two sets of equipment were placed in the room. The data loggers (Testo 175H1, shown in Figure 5) with temperature and humidity sensors were used to monitor indoor air temperature and RH. Outdoor meteorological data were recorded by a small-sized automatic weather station. Indoor and outdoor $CO_2$ concentration were monitored using data loggers with $CO_2$ sensor (MCH–383SD, shown in Figure 5). The $CO_2$ data loggers were installed on the convenient position to avoid the influence of the occupants' exhalation. The locations of all used instruments were at the height of 1.3 m (the breathing zone of a seated postgraduate) above the floor level, away from the windows and door. These instruments recorded data at an interval of 5 min. Table 1 summarizes the test range and accuracy of the instruments used in the current study. Furthermore, the postgraduates were asked to complete a Room Occupation Log Sheet so that the number of occupants, occupied and unoccupied periods of the room and open/closed cases of the windows/door were clarified.

**Figure 5.** Recording instruments for temperature and RH (Testo 175H1) and $CO_2$ (MCH-383SD).

**Table 1.** Summary of instrument range and accuracy.

| Parameters | Range | Accuracy |
|---|---|---|
| $CO_2$ concentration | 0–4000 ppm | ±40 ppm (below 1000 ppm)<br>±5% rdg (1001~3000 ppm)<br>±250 ppm (above 3000 ppm) |
| Indoor temperature | −20–55 °C | ±0.4 °C |
| Indoor RH | 0–100% | ±2% |

### 2.3. Calculation of Ventilation Rate

There are many studies using exhaled $CO_2$ as a tracer gas to evaluate the ventilation rate [15,16]. In this study, a 24-hour day is split into occupied period when postgraduate is present during daylight and unoccupied period when postgraduate is absent during nighttime. Postgraduates can generate $CO_2$ into the room when they are present. During unoccupied period, there is no indoor source of $CO_2$, so air exchange rate (AER) of the room by air infiltration can be evaluated using $CO_2$ decay method. The tracer-gas method is based on the principle of mass balance in a designated room and the assumption of uniform distribution of indoor air. The tracer-gas mass-balance equation can be expressed as [7]:

$$V\frac{d(C_{in}(t))}{dt} = Q(C_{out}(t) - C_{in}(t)) \tag{1}$$

where $V$ is room volume ($m^3$), $t$ is the time (h), $C_{in}(t)$ is indoor $CO_2$ concentration at time $t$ ($m^3/m^3$), $Q$ is volumetric airflow rate into (and out of) the space ($m^3/h$), $C_{out}(t)$ is outdoor $CO_2$ concentration ($m^3/m^3$).

If $Q$ is assumed, and $C_{out}(t)$ is constant, Equation (1) can be integrated to obtain the following equation for $C_{in}(t)$:

$$C_{in}(t) = C_{out}(t) + [C_{in}(0) - C_{out}(t)]e^{-Nt} \tag{2}$$

where $C_{in}(0)$ is the indoor $CO_2$ concentration at time $t$ = 0, $N=Q/V$ is AER.

If air exchange rate (i.e., $N$) is given a value (adjustable variable parameter) and outdoor $CO_2$ concentration (i.e., $C_{out}(t)$) is given a constant parameter, a series of theoretical concentrations $C_{in}(t)$, can be calculated at the end of each time interval by Equation (2). Then, the difference between the measured and theoretical values is calculated by the least-squares method:

$$Error = \sum_{1}^{n}[C_{in,t}(n) - C_{in,m}(n)]^2 \tag{3}$$

where $n$ is the number of measured concentrations, $C_{in,t}(n)$ and $C_{in,m}(n)$ is the computed concentration and measured concentration at the end of the $n$th time interval, respectively. Finally, air exchange rate is fitted out by obtaining theoretical concentration close to the measured concentration.

### 2.4. Model for Human $CO_2$ Generation Rate

To analyze the association among $CO_2$ concentration, occupancy rate and air change rate, $CO_2$ generation rate from human respiration needs to be calculated. According to ASHRAE Handbook Fundamentals [17], an empirical formula to calculate $CO_2$ generation rate can be expressed as follows:

$$V_{CO_2} = RQ\cdot\frac{0.55887W^{0.425}H^{0.725}M}{0.23RQ + 0.77} \tag{4}$$

where $RQ$ is the respiratory quotient, volumetric ratio of $CO_2$ produced to oxygen ($O_2$) consumed, dimensionless; a good estimate for the average adult is $RQ$ = 0.83 for light or sedentary activities ($M$ < 1.5 met), 1met = 58.1 $W/m^2$. $M$ is the metabolic rate, $W/m^2$, depending on the level of physical activity, $M$=1.2 for occupant working in research student room; $W$ is the body weight (kg); $H$ is the body height (m).

## 3. Results

### *3.1. Long-Term Monitoring $CO_2$ Concentration*

We firstly compared the $CO_2$ data from indoor two monitoring points and found that the maximum nonuniformity coefficient of indoor $CO_2$ distribution is 5.68%, less than 10% required by ASTM E741. Thus, this study considered indoor air to be uniformly distributed and reported an average $CO_2$ value of two measuring points as indoor $CO_2$ concentration. Figure 6 shows indoor and outdoor $CO_2$ concentrations during the monitoring period of four weeks. During the period, indoor $CO_2$ concentration in the room ranged from 442 to 3491 ppm, with an average of 1161 ppm, while outdoor $CO_2$ value varied very little, with an average of 458 ppm. Obviously, indoor $CO_2$ concentration variations appeared with peaks and valleys. The reason is that the room was generally occupied in the daytime and unoccupied in the evening.

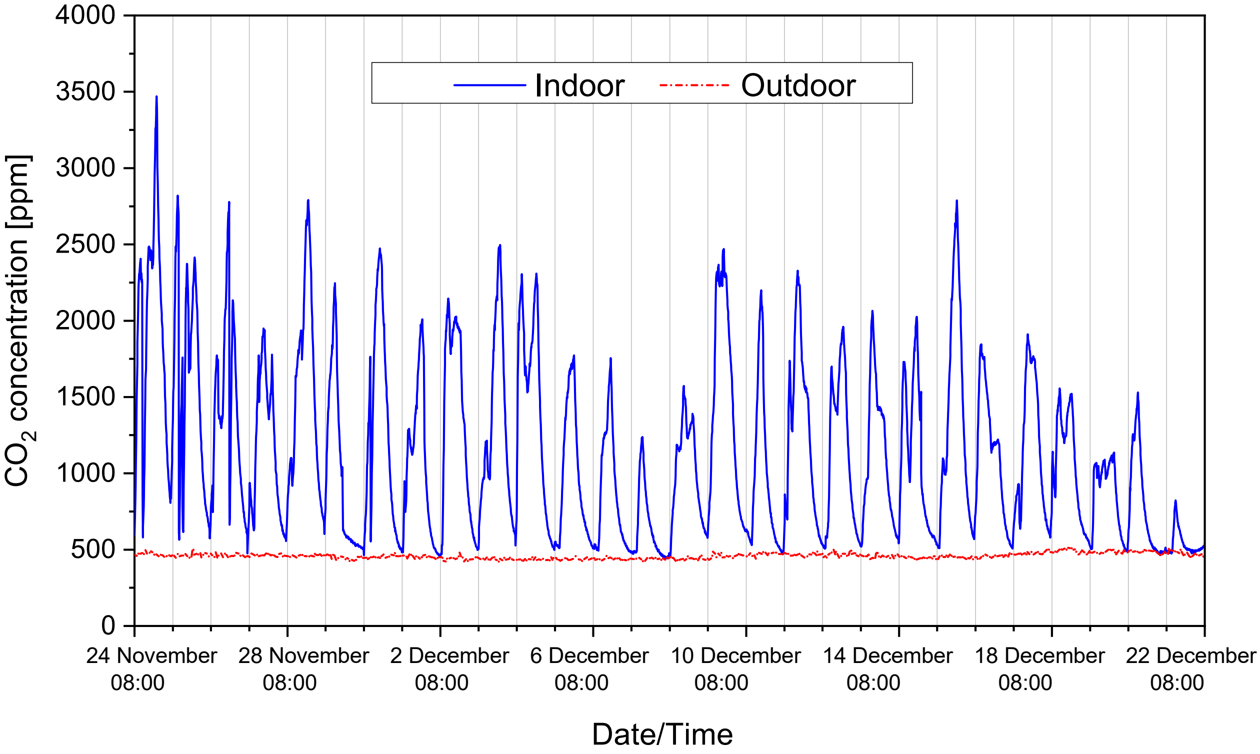

**Figure 6.** Indoor and outdoor $CO_2$ concentration during monitoring period.

According to ASHRAE Standard 62.1 [18] and the Chinese indoor air quality standard GB/T 18883 [19], indoor $CO_2$ concentration should be kept below the commonly referenced guideline of 1000 ppm (8–h average). However, based on the measured data, there was a large chunk of time when indoor $CO_2$ concentration exceeded the guideline each day. Figure 7 shows the cumulative frequency of indoor $CO_2$ concentration during the measuring period. Over 50% of the measured data were more than 1000 ppm. A total of 27.8% of the measured data were more than 1500 ppm and 1.7% of the measured data exceeded 2500 ppm.

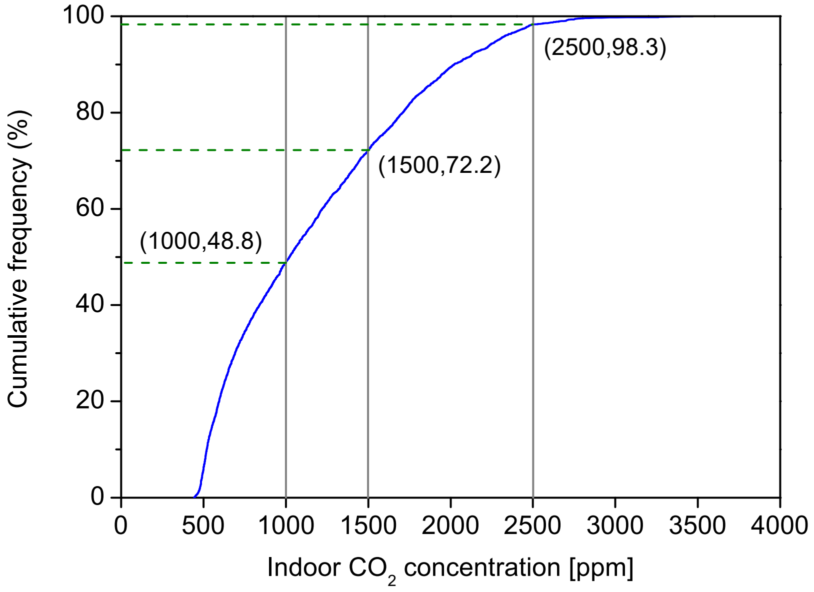

**Figure 7.** Cumulative frequency of indoor $CO_2$ concentration during monitoring period.

Figure 8 summarizes the time of indoor $CO_2$ level over 1000 ppm each day. As a whole, indoor $CO_2$ concentration exceed 1000 ppm during nearly all monitoring days. During the occupied time each day, the period when indoor $CO_2$ concentration exceeded 1000 ppm ranged from 2.0 to 18.8 h, with an average value of 10.2 h. The percentage of occupied times with a $CO_2$ concentration higher than 1000 ppm ranged from 58.3% to 96.2%, with an average value of 77.6% each day. These results indicate that indoor air quality in the research student room was poor during heating season.

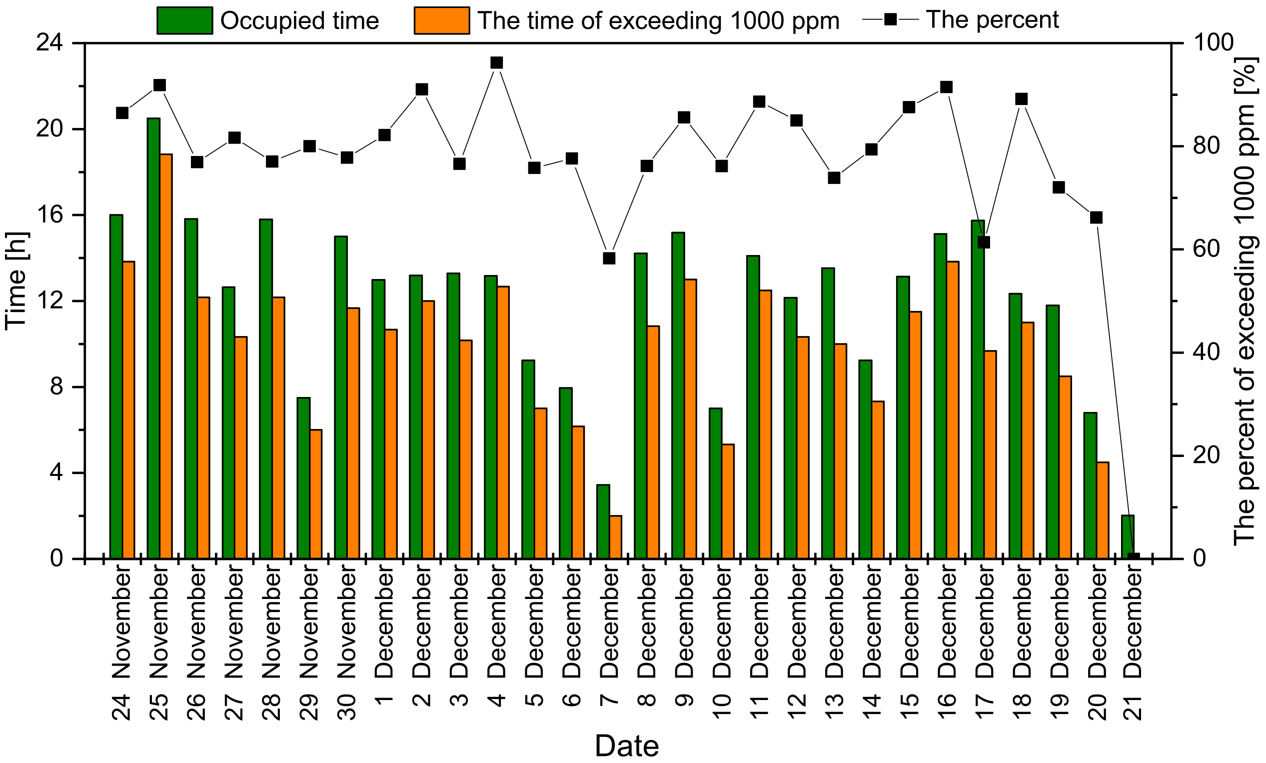

**Figure 8.** Summary of duration for indoor $CO_2$ level over 1000 ppm each day during monitoring period.

### *3.2. Air Exchange Rate of the Room by Infiltration*

Air exchange rate (AER) of the room by air infiltration can be evaluated using the $CO_2$ decay method. As a general requirement, during the unoccupied period, the $CO_2$ steady decay period when the initial $CO_2$ level exceeds 1000 ppm is selected to calculate the air exchange rate of the room. Outdoor $CO_2$ concentration is given as a constant 458 ppm (average value during monitoring period). Table 2 summarizes the AERs of the room calculated using the $CO_2$ decay method during the unoccupied period each day (Adj. $R^2 > 0.99$). There were two days when indoor $CO_2$ concentration could not meet the above requirement. During the decay periods for calculation, the difference between indoor and outdoor temperature ranged from 18.7 to 26.3 °C, with an average of 22.3 ± 3.6 °C. Differences between indoor and outdoor temperature can cause different air infiltration, thereby generating different AERs. From Table 2, calculated AERs have a range of 0.247–0.409 $h^{-1}$, and an average value of 0.313 $h^{-1}$; that is, 0.9 L/ (s·person) when all postgraduate students are in the room, which is significantly lower than the minimum ventilation rates of 2.5 L/ (s·person) in breathing zone for office space.

**Table 2.** Summary of AER calculated by using $CO_2$ decay method during unoccupied period.

| Date | Decay Period | Initial $CO_2$ Level [ppm] | Final $CO_2$ Level [ppm] | AER [$h^{-1}$] | Adj. $R^2$ |
|---|---|---|---|---|---|
| 24 November | - | - | - | - | |
| 25 November | 03:10–06:20 | 1500 | 828 | 0.332 | 0.9987 |
| 26 November | 00:00–07:00 | 1777 | 643 | 0.303 | 0.9975 |
| 27 November | 00:00–06:20 | 1506 | 615 | 0.291 | 0.9986 |
| 27 November | 23:00–06:00 | 1474 | 586 | 0.317 | 0.9968 |
| 28 November | 23:10–06:30 | 2135 | 702 | 0.271 | 0.9980 |
| 29 November | 15:00–18:00 | 1771 | 983 | 0.316 | 0.9928 |
| 30 November | 23:00–08:00 | 1373 | 484 | 0.373 | 0.9991 |
| 1 December | 22:10–07:30 | 1171 | 475 | 0.409 | 0.9989 |
| 2 December | 23:30–06:30 | 1253 | 521 | 0.343 | 0.9975 |
| 3 December | 23:10–06:00 | 1945 | 642 | 0.317 | 0.9996 |
| 4 December | 21:30–06:00 | 1924 | 538 | 0.351 | 0.9996 |
| 5 December | 20:30–05:00 | 1544 | 584 | 0.285 | 0.9961 |
| 6 December | 20:00–03:00 | 1360 | 559 | 0.320 | 0.9974 |
| 7 December | 15:30–22:30 | 1132 | 550 | 0.293 | 0.9929 |
| 8 December | 23:50–07:00 | 1150 | 597 | 0.247 | 0.9905 |
| 9 December | 23:30–07:00 | 1494 | 635 | 0.280 | 0.9911 |
| 10 December | 19:30–02:00 | 1361 | 586 | 0.306 | 0.9968 |
| 11 December | 23:10–05:30 | 1427 | 607 | 0.296 | 0.9991 |
| 12 December | 23:00–07:00 | 1459 | 550 | 0.301 | 0.9995 |
| 13 December | 23:00–06:00 | 1282 | 598 | 0.255 | 0.9954 |
| 14 December | - | - | - | - | |
| 15 December | 23:00–06:00 | 1898 | 607 | 0.325 | 0.9995 |
| 16 December | 23:10–06:10 | 1148 | 527 | 0.341 | 0.9969 |
| 17 December | 23:20–06:20 | 1449 | 605 | 0.301 | 0.9946 |
| 18 December | 21:40–05:00 | 1248 | 596 | 0.277 | 0.9914 |
| 19 December | 23:20–06:00 | 1067 | 506 | 0.376 | 0.9990 |
| 20 December | 15:00–23:50 | 1278 | 507 | 0.310 | 0.9992 |

### *3.3. Indoor Occupancy Characteristics*

Indoor occupants are an important component of the built environment, since both occupancy rate and occupant activities have an effect on the requirement of ventilation. Figure 9 shows indoor occupancy cases of the research student room in a representative week. From Figure 9, in a day, the first occupant normally entered the room at 7:00–8:00, and the last occupant left the room at 23:00–24:00, while at mealtimes the room was sometimes unoccupied. The peak occupancy rate of the room each day mainly occurred at 10:00 in the morning and 16:00 in the afternoon. In addition, sometimes there were visitors entering the room, so the peak occupancy rate of the room was more than six. When the room was occupied with six persons, the per-capita area was 3.8 $m^2/p$. There is no specific definition of high-occupancy density in offices in any building design standard of China. According to the Building Area Index for Regular Institutions of Higher Education [20] released by Ministry of Education of the People's Republic of China, the subsidy building area per person for graduate student learning was 6 $m^2/p$ for Master's degree candidates and 8 $m^2/p$ for PhD degree candidates. Obviously, the measured research student room was crowded. In terms of occupied time, the occupied time of the research student room each day overall varied from 3.4 to 20.5 h, with an average value of 12.0 h. Compared with other rooms in university buildings, the occupied time of the research student room was longer. In general, both the occupied time and occupancy rate of the research student room on weekdays were more than that on weekends, because most postgraduate students tended to have a rest on weekends. In this measurement, the average occupied time on weekdays and weekends was 13.5 h and 8.2 h, respectively. Postgraduate students in the room were commonly at the activity level of typing or reading.

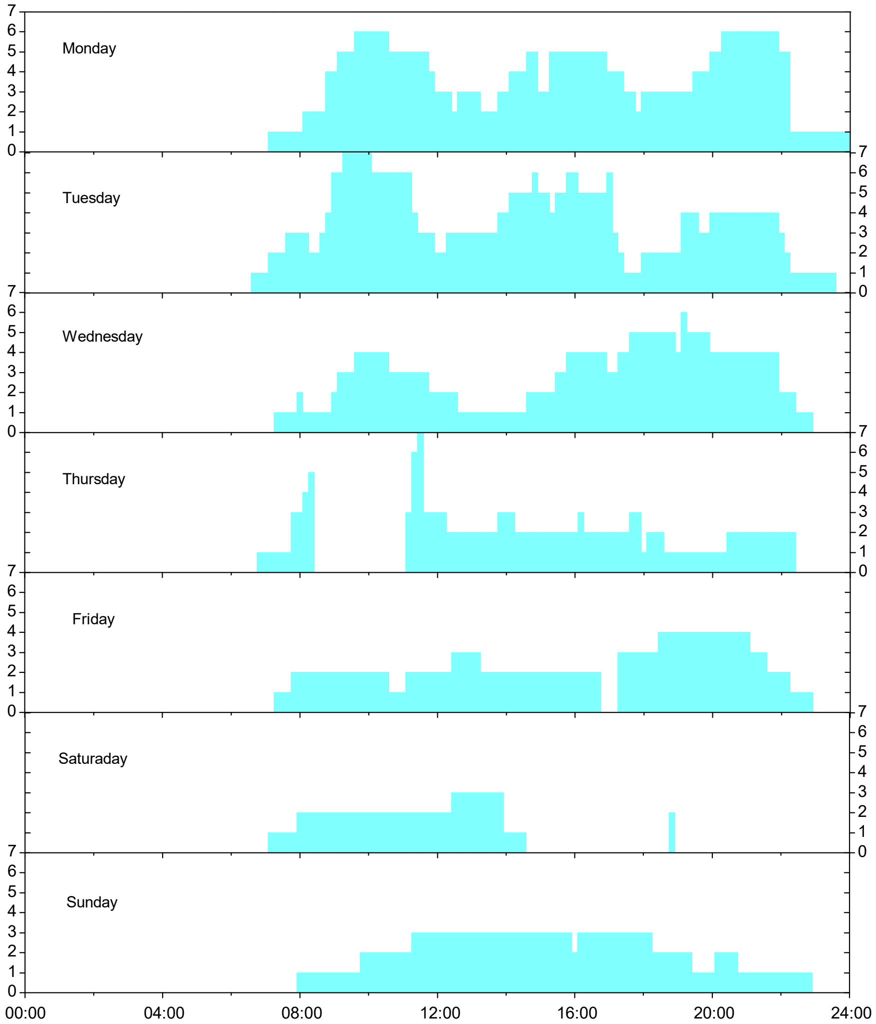

**Figure 9.** Indoor occupancy case of the research student room in a representative week.

### 3.4. Window/Door-Opening Behaviors of Postgraduate Students

Table 3 summarizes the window/door-opening behaviors of postgraduate students. During the monitoring days, there were only five days when postgraduate students actively opened windows/doors during the occupied period. We also find that, when window/door-opening behavior occurred, indoor $CO_2$ concentrations were always at a high level. In addition, when both the window and door were open, the duration was relatively short (12 min and 8 min). The reason might be that when both the window and door are open, cross-ventilation is produced through the room. Cross-ventilation for a long time might reduce indoor thermal comfort due to a great indoor and outdoor temperature difference. When only the door was open, because the temperature in the corridor was not as low as outdoors, the duration was relatively long (16 min, 22 min and 31 min, respectively). Interestingly, it was observed that window/door-opening behaviors generally occurred when postgraduate students just went from outside into the room. A possible explanation for this case was that when occupants just went from outside into the room, they had completely adapted to outdoor fresh air, so that they could not bear indoor high $CO_2$ concentration and bioeffluents. Consequently, they opened the window/door of the room for ventilation and let outdoor fresh air in. This indicated that occupants tended to adapt to high $CO_2$ concentrations and bioeffluents, and had less control over window/door opening for ventilation requirement, when staying in the environment for a long time. In addition, during four weeks of continuous monitoring, as a general rule, the first occupant going into the room in the morning customarily opened the window/door to have proper ventilation for 5–10 min, although indoor $CO_2$ concentration was not high. This might be greatly ascribed by the inadaption induced by going into the room from outside. The standard of ASTM D6245 [21] also pointed out that for adapted persons (i.e., indoor occupants), the ventilation rate per person to provide the same acceptance was approximately one-third of the value for unadapted persons (i.e., visitors), and the corresponding $CO_2$ concentrations that outdoors-adapted occupants could accept were three times higher than those for unadapted persons. Although adapted occupants were able to accept high $CO_2$ concentrations caused by such a reduction in the ventilation rate, the effect of exposure to high $CO_2$ concentration on occupants' health and productivity was not negligible. In addition, a reduction in the ventilation rate might give rise to high concentration of other contaminants. Thus, the method where the occupants control window/door opening for ventilation in such rooms by perceived air quality was inadvisable.

**Table 3.** Summary of opening window/door operation during occupied time.

| Days | Windows | Door | Window/Door-Opening Duration (min) | Indoor $CO_2$ Level When Occupants Open Windows/Door (ppm) |
|---|---|---|---|---|
| 1 | x | o | 16 | 2254 |
| 2 | o | o | 12 | 2694 |
| 3 | x | o | 31 | 1759 |
| 4 | x | o | 22 | 2776 |
| 5 | o | o | 8 | 1746 |

Notes: x is closed; o is opened.

## 4. Discussion

### 4.1. Occupancy Rate Affects Indoor $CO_2$ Level

Figure 10 shows indoor $CO_2$ concentration and occupancy rate at typical weekdays and weekends, when the door/windows are closed. It was observed that the variation in indoor $CO_2$ concentration was sensitive to the indoor occupancy rate. Indoor $CO_2$ concentration usually decreased to outdoor levels during the unoccupied period (i.e., nighttime). In general, indoor $CO_2$ concentration increased with occupancy time. The variation in $CO_2$ concentration began to grow relatively fast, and then gradually became slower. However, when $CO_2$ concentration reached a certain level, indoor $CO_2$ concentration also decreased with time, although the room was still occupied. The reason was that indoor $CO_2$ generation was not enough to offset the $CO_2$ decrement induced by indoor and outdoor air exchange. Moreover, when indoor $CO_2$ generation was equal to the $CO_2$ decrement induced by indoor and outdoor air exchange, indoor $CO_2$ generation tended to stabilize. On the whole, due to high occupancy rates and long occupancy time on weekdays, the duration times of indoor $CO_2$ concentration above the reference level (dashed line in Figure 10) were longer than that on weekends. Therefore, in such kinds of room, it was recommended to reduce the number of students to ensure a low carbon dioxide concentration in the room.

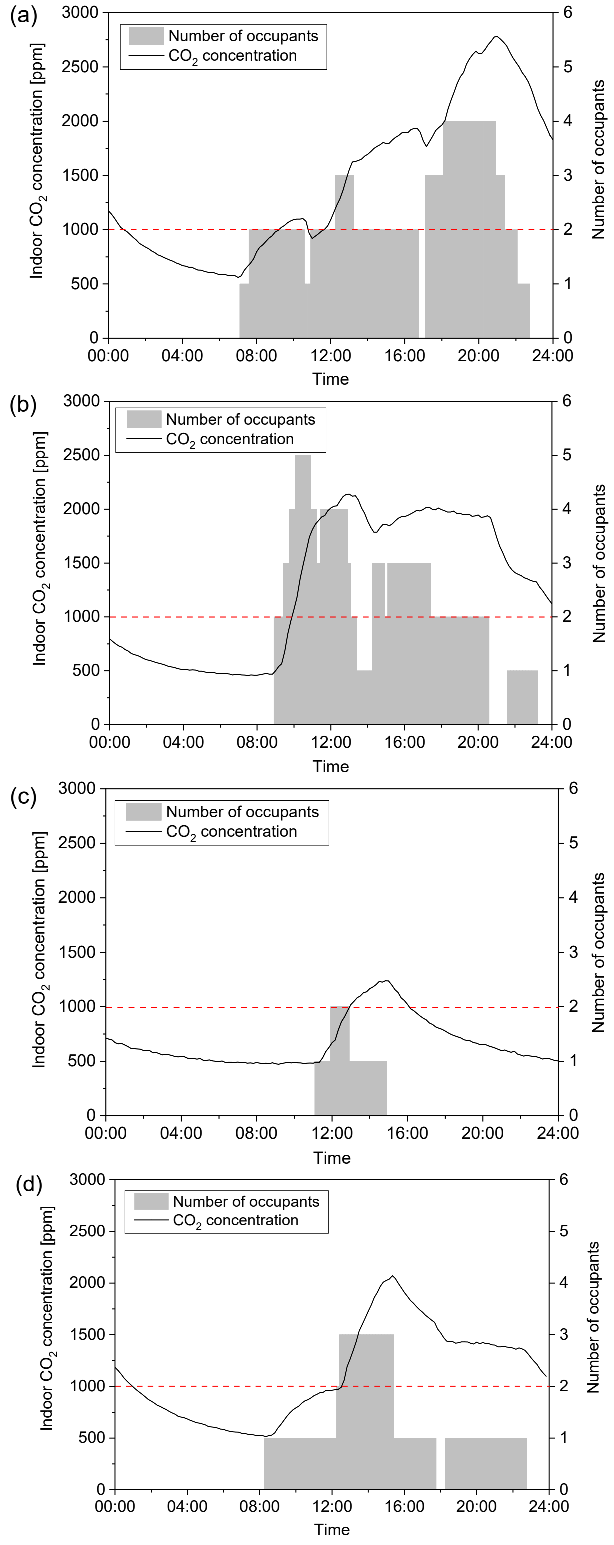

**Figure 10.** Indoor $CO_2$ concentration and occupancy rate (door/window closed): (**a**,**b**) at weekday; (**c**,**d**) at weekend.

### *4.2. Opening Door/Windows Decreases Indoor $CO_2$ Concentration*

As aforementioned in the Section Result, the average air exchange rate of the measured room by air infiltration was 0.313 $h^{-1}$. In fact, this air infiltration rate could not meet indoor ventilation requirements, due to a high occupancy rate. This point was also verified by the monitoring data of indoor $CO_2$ concentration. From Figure 11, it is seen that opening windows/doors could give rise to a considerable AER, a few dozen times higher than the air infiltration rate. Thereby, the shorter duration of opening windows/doors could significantly decrease indoor $CO_2$ concentration close to outdoor level. Therefore, for such research student rooms with high occupancy rates, intermittent window/door opening might be an effective way to avoid continuous indoor high $CO_2$ concentration. However, due to the great indoor and outdoor temperature difference during the heating season, postgraduate students tended to close windows/doors for a long time. When staying in the environment for a long time, postgraduate students had adapted to high $CO_2$ concentrations and had less control over opening windows/doors for indoor ventilation.

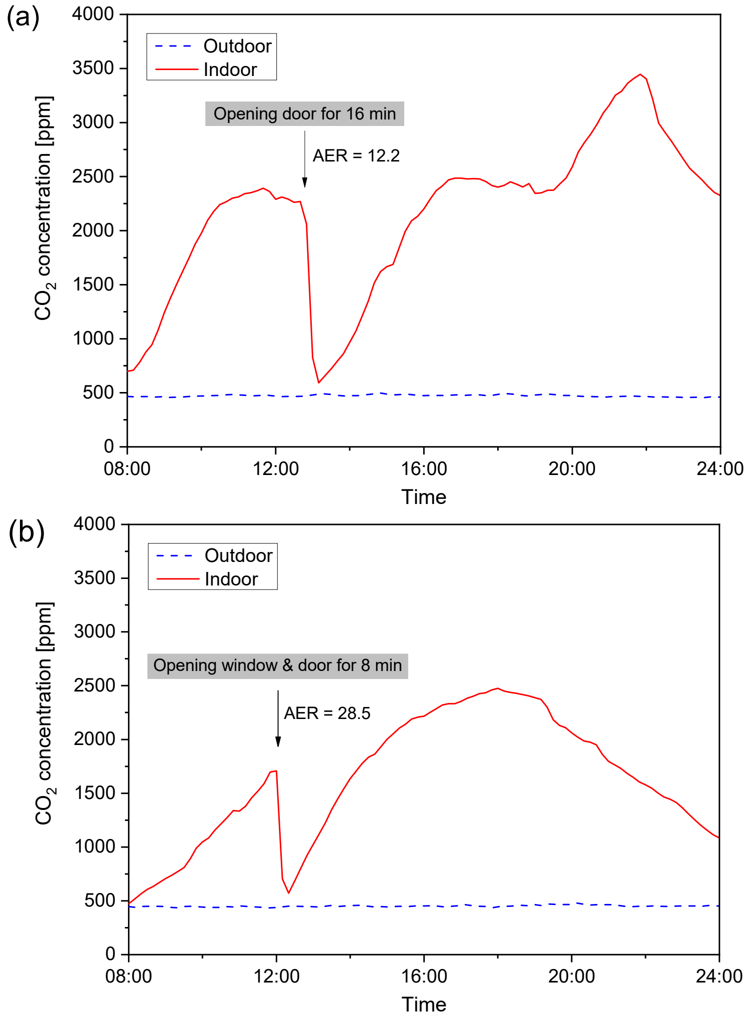

**Figure 11.** Indoor $CO_2$ concentration and door/window opening: (**a**) 24 November; (**b**) 30 November.

### *4.3. Suggestion for Ventilation in Such Rooms*

Based on the aforementioned discussion, the high occupancy rate and low air exchange rate of the room are the principal determinants of high indoor $CO_2$ concentration of the naturally ventilated room. If any of these two parameters are adjusted, indoor air quality can be improved. However, with a rapidly increasing population of graduate students in universities, it seems to be difficult to decrease the occupancy rate of such rooms; instead, the occupancy rate may even increase. For this situation, adjusting ventilation rate of the room may be an effective way to maintain good IAQ. A basic way to enlarge the ventilation rate is for indoor occupants (graduate students) to open windows/doors. In particular, indoor occupants may need to be reminded to implement the action of opening windows/doors. For example, we can install a $CO_2$ monitor with a warning device in such rooms. When indoor $CO_2$ level exceeds a preset level, the device can remind indoor occupants to open window or doors.

In fact, indoor $CO_2$ concentration can be roughly estimated based on indoor occupancy characteristics and ventilation rate. For a single-zone room, when the only indoor source of $CO_2$ comes from occupants in the room, the indoor $CO_2$ concentration mass balance equation can be expressed as:

$$V\,\frac{d(C_{in}(t))}{dt} = Q(C_{out}(t) - C_{in}(t)) + G(t) \tag{5}$$

where $V$ is room volume (m$^3$); $t$ is the time (h); $C_{in}(t)$ is indoor $CO_2$ concentration at time $t$ (m$^3$/m$^3$); $Q$ is volumetric airflow rate into (and out of) the space (m$^3$/h); $C_{out}(t)$ is outdoor $CO_2$ concentration (m$^3$/m$^3$), and the value varied very little; $G(t)$ is $CO_2$ generation rate in the room at time $t$ (m$^3$/h).

If $Q$ is assumed, and $C_{out}(t)$ and $G(t)$ are constant, Equation (5) can be integrated to obtain the following equation for $C_{in}(t)$:

$$C_{in}(t) = C_{out}(t) + \frac{G(t)}{Q} + \left[C_{in}(0) - C_{out}(t) - \frac{G(t)}{Q}\right]e^{-Nt} \tag{6}$$

where $C_{in}(0)$ is the indoor $CO_2$ concentration at time $t$ = 0; $N$ is AER, $Q/V$.

For Equation (6), if outdoor $CO_2$ concentration—$C_{out}(t)$, indoor initial $CO_2$ concentration—$C_{in}(0)$, and room volume—$V$ are known, there will be close associations among indoor $CO_2$ concentration—$C_{in}(t)$, AER—$N$, and indoor $CO_2$ generation rate—$G(t)$. Once two parameters of them are known, the remaining one will be obtained. Based on the aforesaid model for human $CO_2$ generation rate in the "Materials and Methods" section, The $CO_2$ generation rate corresponding to an average-sized adult (BSA = 1.8 m$^2$) engaged in office work (1.2 m) is about 18720 mL/h. The number of indoor occupants in the room hypothetically is $m$; Equation (6) can be converted into the following equation:

$$C_{in}(t) = C_{out} + \frac{m\cdot 18720}{N\cdot V} + \left[C_{in}(0) - C_{out} - \frac{m\cdot 18720}{N\cdot V}\right]e^{-N\cdot t} \tag{7}$$

The duration of $CO_2$ concentration from indoor initial level to the referenced guideline (1000 ppm) is obtained as:

$$t = \frac{1}{N}\{\ln[m\cdot 18720 - (C_{in}(0) - C_{out})\cdot N\cdot V] - \ln[m\cdot 18720 - (1000 - C_{out})\cdot N\cdot V]\} \tag{8}$$

If indoor initial $CO_2$ concentration $C_{in}(0)$ is equal to outdoor $CO_2$ concentration, Equation (8) can be converted into the following equation:

$$t = \frac{1}{N}\{\ln(m\cdot 18720) - \ln[m\cdot 18720 - (1000 - C_{out})\cdot N\cdot V]\} \tag{9}$$

Generally speaking, outdoor $CO_2$ concentration $C_{out}$ varies very little in an area. Therefore, from Equation (9), the main factors of the duration of indoor $CO_2$ concentration increasing from the outdoor level to 1000 ppm are the number of indoor occupants, room volume and AER. If the three factors are known, the duration will be clear. Taking a room with four persons, a volume of 100 m$^3$ and an AER of 0.5 h$^{-1}$ as an example, the duration of indoor $CO_2$ concentration increasing from the initial level to 1000 ppm in the room can be calculated as 0.9 h. This duration can also be considered as the reference of the interval of opening windows/doors for ventilation. Of course, for some economically viable universities, $CO_2$-based demand-controlled ventilation facilities were also proposed to be installed in such rooms. An appropriate way to control the ventilation facilities is to directly measure the indoor $CO_2$ level and activate the facilities if the level exceeds a preset level. Considering the serious outdoor air pollution due to particulate matter in winter in some regions of China, such as the Beijing–Tianjin–Hebei region, the simple idea to provide more outdoor air to dilute indoor $CO_2$ concentration may even worsen indoor air quality. In this case, ventilation facilities with air-filter apparatus should be required. This is also the requirement for mechanical ventilation equipment stipulated by the current building ventilation standards in China. At the same time, it is recommended that monitoring devices for environmental pollution parameters (e.g., $PM_{2.5}$, $PM_{10}$, $O_3$, $NO_2$, $SO_2$, CO) should be installed indoors to achieve real-time evaluation of indoor air quality [22,23]. When the concentration of indoor pollutants exceeds the threshold, indoor air-purification devices are also recommended to ensure good indoor air quality and the health of indoor occupants.

### *4.4. Limitations*

There are several limitations for this study. A first obvious limitation was that this study only took one room as a case study, which might affect the representativeness and universality of the results. Another limitation is the accuracy of the measuring device. Compared with some instruments with high precision, the error of the instrument used in this study may affect the accuracy of measuring data, but it does not seem to make much influence on our conclusion.

## 5. Conclusions

In Chinese universities, postgraduate students usually carry out scientific research in a research student room in university buildings. This paper selected a naturally ventilated research student room in Chinese universities to conduct continuous field measurements of indoor $CO_2$ level, air temperature and RH during the heating period, and then evaluated indoor environment and ventilation rate of the measured room based on measured $CO_2$ concentration. Results showed that the research student room was crowed, and occupied time of the research student room each day varied from 3.4 to 17.5 h, with an average of 12.0 h, which was longer than general offices. During the occupied time, 58.3% to 96.2% (average 77.6%) of measured $CO_2$ data each day exceeded 1000 ppm. Indoor high $CO_2$ concentration was attributed to the high occupancy rate and low air infiltration rate of the room. Therefore, in such kind of rooms, it was recommended to reduce the number of students. Furthermore, it was found that opening windows/doors for several minutes could significantly decrease the indoor $CO_2$ level close to the outdoor level. However, due to the great indoor and outdoor temperature difference during the heating season, and occupants' adaption to indoor environment, indoor occupants (postgraduate students) generally have less control over window/door opening for ventilation requirements in such rooms. Therefore, intermittent window/door opening reminded by warning devices or estimated by indoor occupancy and air infiltration volume were suggested in such rooms. For economically viable universities, $CO_2$-based demand-controlled ventilation facilities were also advocated for improving indoor air quality of such rooms. These results would be helpful to improve Chinese research students' studying environment.

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## Abbreviations

| | |
|---|---|
| IAQ | Indoor Air Quality |
| $CO_2$ | Carbon Dioxide |
| RH | Relative Humidity |
| RQ | Respiratory Quotient |
| ASHRAE | American Society of Heating, Refrigerating and Air-Conditioning Engineers |

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