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Effects of Outdoor Air Pollutants on Indoor Environment Due to Natural Ventilation

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Abstract: This study measured ventilation volumes and particle concentrations in indoor environments with open windows and doors. In addition, the effect of the airflow mode of the air conditioner on the ventilation volume and indoor particle concentration variations was also measured. The ventilation fan could only provide approximately 43% of the ventilation volume during the design phase. The amount of ventilation differed depending on the opening area in windows and doors. The ventilation volume was increased by opening multiple windows or doors, even when the area of the opening was the same. No significant change in the ventilation rate was observed, although the air conditioner was expected to promote the ventilation rate in the room when set on blow mode. It was confirmed that both 0.3 and 1 μm particles could enter through the gaps around the windows and doors. Although most of the 5 μm particles were from the outdoor air, when the air conditioner was operated in airflow mode, the removal of 5 μm particles was performed by the air conditioner filter. The use of medium-performance or HEPA filters is expected to remove smaller particulates.

Keywords: pollutants; natural ventilation; indoor environment; particles

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1. Introduction

In recent years, natural ventilation, an energy conservation technique, has been incorporated in various buildings [1,2]. In Japan, "The 6th Strategic Energy Plan" [3] approved by the Cabinet in October 2021 clearly states the goal to ensure energy-saving performance at the level of the zero-energy house (ZEH) and zero energy building (ZEB) standard in houses and buildings by 2050. These standards are necessary to achieve energy conservation without compromising the health of occupants. For this reason, natural ventilation is commonly used to achieve energy savings in buildings. A new coronavirus, SARS-CoV2, was identified in December 2019 [4], and the World Health Organization named the viral disease COVID-19 [5]. COVID-19 has had a significant impact on social activities [6]. In particular, natural ventilation is required to prevent infection indoors. It is natural ventilation with a different meaning from conventional natural ventilation.

According to building management law in Japan, the concentration of carbon dioxide in offices is 1000 ppm or less. Educational facilities are regulated at 1500 ppm as a standard. In addition, the ventilation rate of the house is 0.5 times/h. On the other hand, the Japanese government has been affected by the new corona and recommended the following measures. Japan's Ministry of Health, Labor, and Welfare has announced new lifestyle guidelines to prevent coronavirus infection, including avoiding three levels of crowd density (dense, close, and enclosed) [7], increasing the frequency of hand washing, and using proper cough etiquette [8]. Additionally, they published a ventilation method to improve poorly ventilated enclosed spaces, recommending that the indoor carbon dioxide concentration should be less than 1000 ppm and that the ventilation frequency should be at least two times per hour [9]. Following these recommendations, restaurants, offices, and educational facilities are required to open windows for natural ventilation, even when air conditioners are in use [10].

Although the risk of transmission of novel coronaviruses can be reduced by improving ventilation, there is a concern that natural ventilation through window openings may result in an inflow of contaminants from the outdoor air. Pollutants originating from outdoor air include yellow dust, particulate matter under 2.5 μm in size (PM2.5), pollen, and microorganisms [11–13]. Yellow dust is approximately 4 μm in diameter and may absorb ammonium, sulfate, and nitrate ions from the atmosphere [14]. The human health effects of DSS include allergic, respiratory, and circulatory diseases [15]. PM2.5 is fine particulate matter suspended in the atmosphere [16], some of which is emitted directly from the combustion of materials [17]. In addition, gaseous air pollutants, including sulfur oxides (SOx), nitrogen oxides (NOx), and volatile organic compounds (VOCs), may enter via natural ventilation [18–20]. Fine particulate matter can easily penetrate deep into the lungs, affecting the circulatory and respiratory systems [21–23]. In Japan, it is reported that there are more than 60 types of pollen allergies caused by plants [24]. Typical pollens include cedar, cypress, birch, grass, and Asteraceae [25,26]. Adverse effects observed in humans include sneezing, runny or stuffy nose, itchy, watery, or bloodshot eyes, itchy throat, itchy skin, diarrhea, and fever [27,28]. As mentioned above, indoor ventilation by opening windows is now required as a countermeasure against new coronavirus infections, but existing studies on the measurement of ventilation volume by window opening methods and indoor contamination by outdoor air pollutants are insufficient.

In this study, the effect of outdoor air pollutants on the indoor environment was evaluated along with the amount of natural ventilation created by the window-opening method of the building.

2. Methods

2.1. Overview of the Measurement Room

Table 1 shows an overview of the measurements of the room, and Figure 1 shows the floor plan and cross-sectional views. Measurements were performed in a laboratory on the second floor of the main building at the Tokiwa Campus of the Faculty of Engineering of Y University, Yamaguchi, Japan. The subject building was located on the southwest side of the campus. The site area was 144,281 m^2, and the total floor space was 5898 m^2. The building was a reinforced concrete structure with four floors above the ground. The study room was a laboratory facing southwest on the second floor of the main building. The study room was 8×7.2 m in size, 2.6 m high, and had a volume of 149 m^3. The mechanical ventilation system consisted of one 300 mm (Diameter) ventilation fan installed above window A on the south. For the air conditioning system, two ceiling cassette-type multi-mode indoor units were installed. The reason why we chose the student laboratory for this research was that this university was conducting lectures online to prevent corona infections. However, the student laboratory limited the number of users, and it was possible to use this laboratory. In addition, the size of the laboratory is the standard size in this university, so it was selected as a measurement target. Two carbon dioxide meters and one particle counter were installed indoors, while an additional particle counter was installed outdoors. The indoor instruments were installed near the center of the room, while the outdoor instruments were on the balcony, as shown in Figure 2. The indoor and outdoor measurements are shown in Figure 2. Assuming that the person in the room is sitting at a desk, the measurement equipment was installed at a height of about 1.2 m, which is the breathing area.

Table 1. Outline of the study room.

Building	Y University, Faculty of Engineering Main Building 2F Laboratory Room 202	
Floor area	57.6 m^2	
Volume	149 m^3	
Ceiling height	2.6 m	
Ventilating facilities	ventilation fan (300φ) × 1 (300 m^3/h)	
Air conditioner	Equipment specification: YZCP71MM Yanmar Holdings Co., Ltd., Osaka, Japan, Multi-type indoor unit × 2 Ceiling cassette type (four-direction ejection)	
	Air filter: Antifungal antibacterial resin net (long life) Gravimetric method: 60–90%	
	Air flow: Mode 1: 20.0 m^3/min Mode 2: 16.0 m^3/min Mode 3: 12.5 m^3/min	

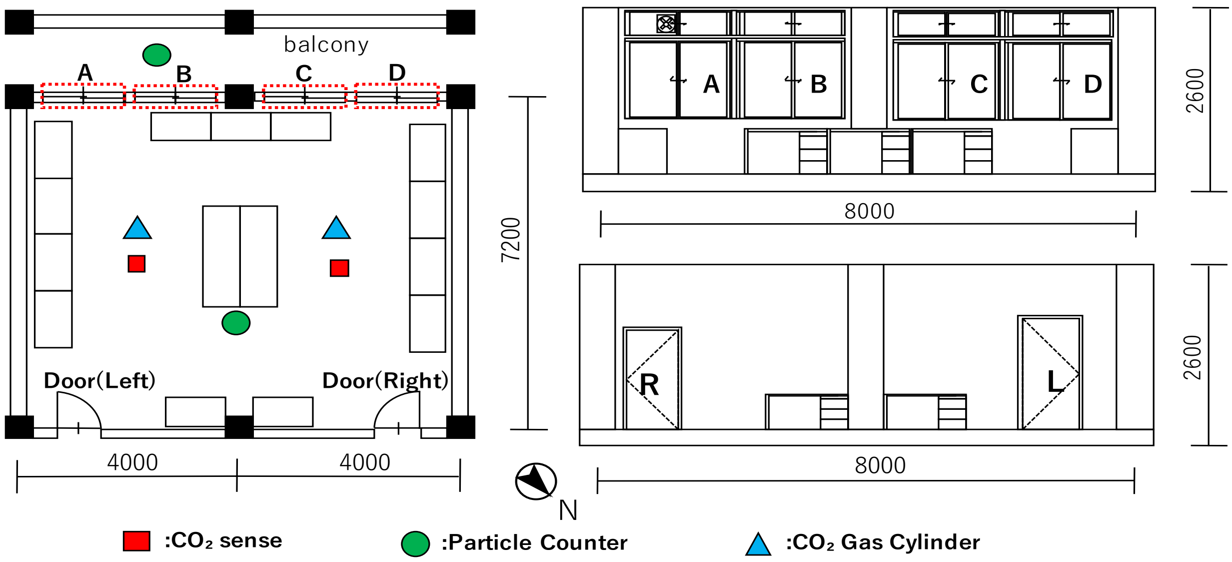

Figure 1. Floor plan and cross-section of the study room.

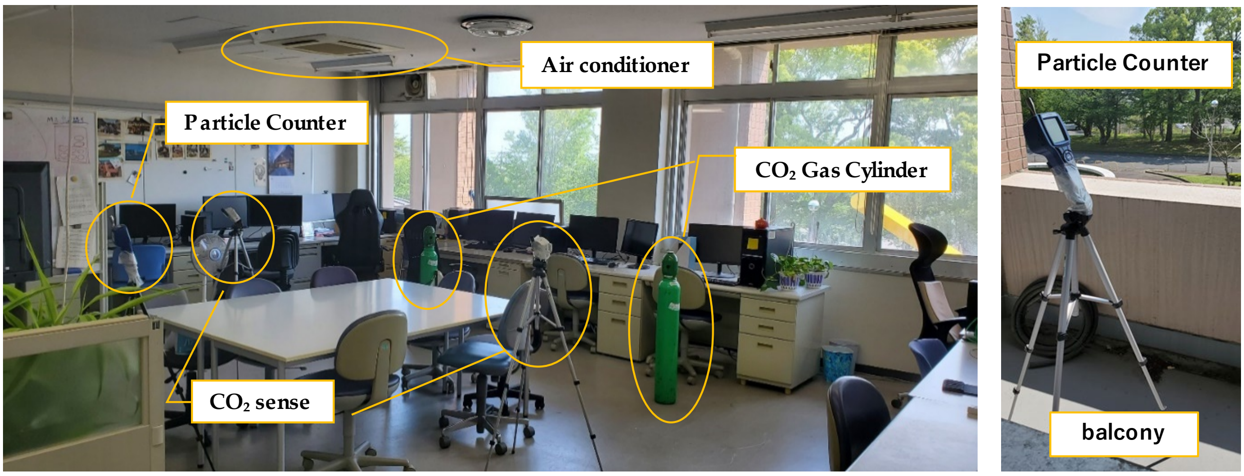

Figure 2. Indoor and outdoor measuring instruments.

2.2. Data Collection

The carbon dioxide concentrations and outdoor and indoor particulate concentrations were measured. Measurements were taken from March to May 2022. This season was selected as the measurement period because it is the season with the highest pollen concentration in the outside air in Japan. Carbon dioxide gas cylinders were opened for approximately 5 min to allow carbon dioxide to fill the room and stabilize at a concentration of approximately 6000–7000 ppm; the gas flow was then stopped, and the windows and doors were opened depending on the experimental conditions. The measurements were completed once the carbon dioxide concentration in the room had decayed to approximately 700 ppm. A summary of the instruments used to measure carbon dioxide and particulate concentrations is shown in Table 2. The measuring instrument used in this study was assumed to be Japanese Industrial Standard and was calibrated before the measurement.

Table 2. Overview of equipment.

CO_2	Measuring Device	USB CO_2 Logger (TR-76Ui; T&D)
	Range	0–9999 ppm
	Recording Interval	1 min
Particle	Measuring Device	AeroTrak Handheld Particle Counter 9303 (TSI)
	Range of Measurement	0.3–10 μm
	Particle Size Division	0.3,·1.0,·5.0 μm
	Recording Interval	1 min

(1) Ventilation volume

The ventilation volume and frequency for carbon dioxide concentration were determined using the decay method, and the equation used to determine the ventilation volume and frequency from the CO_2 concentration decay is shown below. Two electric fans were used to agitate the indoor air so that the concentration of CO_2 at the measurement location was uniform. Moreover, it confirmed that the difference in the CO_2 concentration measured from the two CO_2 sensors was less than 100 ppm and started the measurement of ventilation volume.

$$p - p_0 = \left(p^1 - p^0\right)e^{\frac{-Qt}{V}}$$

Q: ventilation volume [m^3/h]
V: chamber volume [m^3]
p: indoor pollutant concentration [ppm/m^3]
p^0: outdoor air pollutant concentration [ppm/m^3]
p^1: initial indoor contaminant concentrations [ppm/m^3]
t: time [h]

(2) Experimental conditions

The measurement conditions are listed in Table 3. Eight conditions were measured covering a combination of ventilation methods with and without ventilation fan operations, natural ventilation from open windows and doors, or an air conditioner operating in the room. In conditions 1 and 2, no windows or doors were open, and the air conditioning units were off; observations were made with and without a ventilation fan. In conditions 3–5, the ventilation fan was on, and the air conditioning units were off; observations were made under various natural ventilation scenarios: one window and one door in condition 3, three windows and one door in condition 4, and three windows and two doors in condition 5. Under these conditions, the windows and doors were set to have the same opening area. In conditions 6–8, the ventilation fan and air conditioning units were on, and various window and door configurations were observed: in condition 6, one window and one door were open; in condition 7, three windows and one door were open; and in condition 8, three windows and two doors were open. Under these conditions, the windows and doors were set to have the same opening area. However, the condition of fully opening all windows and doors was not included in the measurement conditions of this time because it was predicted that the ventilation volume would be large.

Table 3. Measurement conditions.

<table>
<tr><th rowspan="2">Condition</th><th colspan="4">Window</th><th colspan="2">Door</th><th rowspan="2">Ventilation Fan</th><th rowspan="2">Air Conditioner</th></tr>
<tr><th>A</th><th>B</th><th>C</th><th>D</th><th>R</th><th>L</th></tr>
<tr><td>1</td><td colspan="4" rowspan="2">closed</td><td colspan="2" rowspan="2">closed</td><td>OFF</td><td rowspan="5">OFF</td></tr>
<tr><td>2</td><td rowspan="7">ON</td></tr>
<tr><td>3</td><td>30 cm</td><td colspan="3">closed</td><td rowspan="2">10 cm</td><td rowspan="2">closed</td></tr>
<tr><td>4</td><td rowspan="2">10 cm</td><td rowspan="2">closed</td><td rowspan="2">10 cm</td><td rowspan="2">10 cm</td></tr>
<tr><td>5</td><td>5 cm</td><td>5 cm</td></tr>
<tr><td>6</td><td>30 cm</td><td colspan="3">closed</td><td rowspan="2">10 cm</td><td rowspan="2">closed</td><td rowspan="3">ON</td></tr>
<tr><td>7</td><td rowspan="2">10 cm</td><td rowspan="2">closed</td><td rowspan="2">10 cm</td><td rowspan="2">10 cm</td></tr>
<tr><td>8</td><td>5 cm</td><td>5 cm</td></tr>
</table>

3. Results

3.1. Ventilation Volume

(1) Ventilation fan (Condition 1: Off; Condition 2: On)

Condition 1 measured the amount of ventilation without opening any windows or doors to verify the performance of the ventilation fans installed in the laboratory. Condition 2 measured the amount of ventilation when only the ventilation fan was in operation. Figure 3 shows the measurement results for conditions 1 and 2. For condition 1, the carbon dioxide concentration was 6669 ppm at the start of the experiment and decayed to 701 ppm after 15 h. The ventilation rate of this laboratory was 28 m^3/h, and the ventilation frequency was 0.19 times/h. It is likely that the air was ventilated through gaps, such as those around windows and doors. For condition 2, the carbon dioxide concentration was 6546 ppm at the start of the experiment and decayed to 682 ppm approximately 4 h later. The ventilation rate was 130 m^3/h, and the ventilation frequency was 0.87 times/h. The ventilation fan installed in the laboratory had an airflow rate of 300 m^3/h, but based on these results, only met approximately 43% of its potential. The reason for this could be that the ventilation fan was installed in the upper left corner of the window and that window had poor airtightness, resulting in a high ventilation rate through the gaps around the ventilation fan.

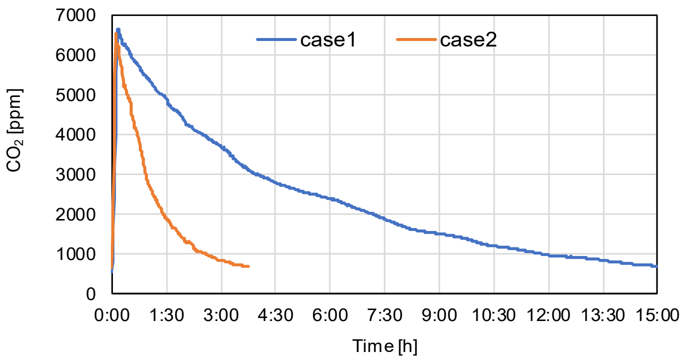

Figure 3. Carbon dioxide concentrations with and without a ventilation fan (conditions 1 and 2).

(2) The effects of ventilation fans and natural ventilation (Conditions 3–5)

The results for conditions 3–5 are shown in Figure 4. Conditions 3–5 compared various window and door opening combinations when the ventilation fan was in operation.

Condition 3 included a 30 cm opening in one of the windows and a 10 cm opening in one of the doors. The carbon dioxide concentration at the start of the experiment in condition 3 was 6544 ppm and decayed to 665 ppm approximately 1 h later. The ventilation rate was 444 m^3/h, and the ventilation frequency was 3.0 times/h. Condition 4 included a 10 cm opening in three of the windows and a 10 cm opening in one of the doors. The carbon dioxide concentration at the start of the experiment for condition 4 was 6719 ppm and decayed to 700 ppm approximately 1 h and 19 min later. The ventilation rate was 377 m^3/h, and the ventilation frequency was 2.5 times/h. This result was not obviously different from that obtained under condition 3. Condition 5 included a 10 cm opening in three of the windows and a 5 cm opening in two of the doors. The carbon dioxide concentration at the start of the experiment in condition 5 was 7137 ppm, which decayed to 475 ppm after 1 h and 17 min. The ventilation rate was 670 m^3/h, and the ventilation frequency was 4.5 times/h. These results showed that the ventilation rate for condition 5 was the highest. From the above, it can be concluded that to increase the efficiency of natural ventilation, it is more effective to increase the number of openings, even if the opening area is the same, rather than to increase the degree to which fewer windows and doors are opened.

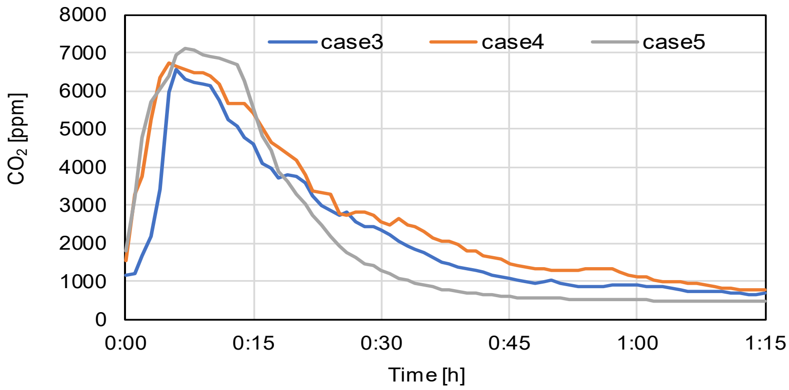

Figure 4. Carbon dioxide concentrations with a ventilation fan and natural ventilation (conditions 3–5).

(3) The effects of air conditioner blast mode (conditions 6–8)

The results for conditions 6–8 are shown in Figure 5. Conditions 6, 7, and 8 measured the ventilation volume when the indoor air conditioner was operated in airflow mode with the same window and door opening as conditions 3, 4 and 5. The cooling and heating functions of the air conditioners were not used. The carbon dioxide concentration at the start of the experiment under condition 6 was 7678 ppm and decayed to 623 ppm after 1 h and 13 min. The ventilation rate was 524 m^3/h, and the ventilation frequency was 3.5 times/h. The ventilation rate under condition 6 was 0.5 times/h higher than that under condition 3. The carbon dioxide concentration at the start of the measurement under condition 7 was 6666 ppm, which decayed to 533 ppm after approximately 1 h and 16 min. The ventilation rate was 545 m^3/h, and the ventilation frequency was 3.6 times/h. Condition 7 was measured 1.1 times/h more than the ventilation frequency of condition 4. The carbon dioxide concentration at the start of the experiment under condition 8 was 6929 ppm and decayed to 501 ppm after approximately 1 h and 16 min. The ventilation rate was 661 m^3/h, and the ventilation frequency was 4.4 times/h. Condition 8 was found to have 0.1 times/h less ventilation frequency than that under condition 6. From the above measurements, it was determined that the ventilation rate did not change significantly owing to the operation of the air conditioner in the room.

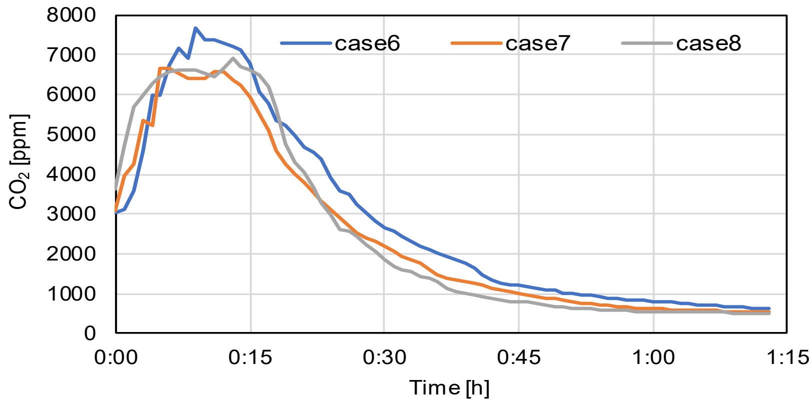

Figure 5. Carbon dioxide concentrations with use of a ventilation fan, natural ventilation, and an air conditioner (conditions 6–8).

3.2. Changes in Particulate Concentration

The results for conditions 1 and 2 are presented in Figure 6. The results for conditions 3–5 are shown in Figure 7. The particulate I/O ratio results for conditions 6–8 are shown in Figure 8. The mean, median and standard deviation by particle size in each condition is shown in Table 4.

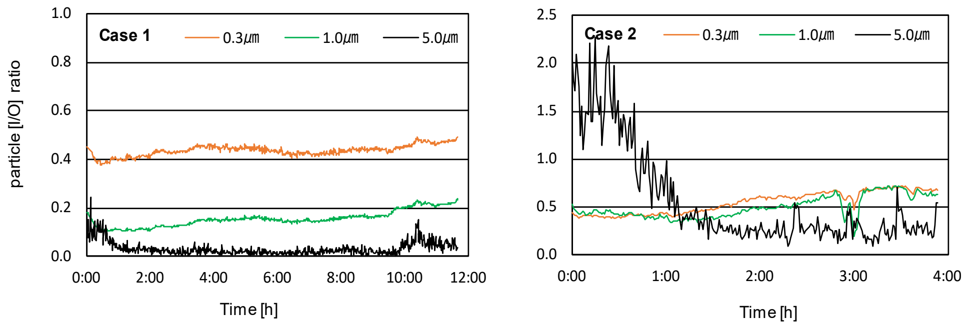

Figure 6. Particulate I/O ratio with and without ventilation fan (conditions 1 and 2).

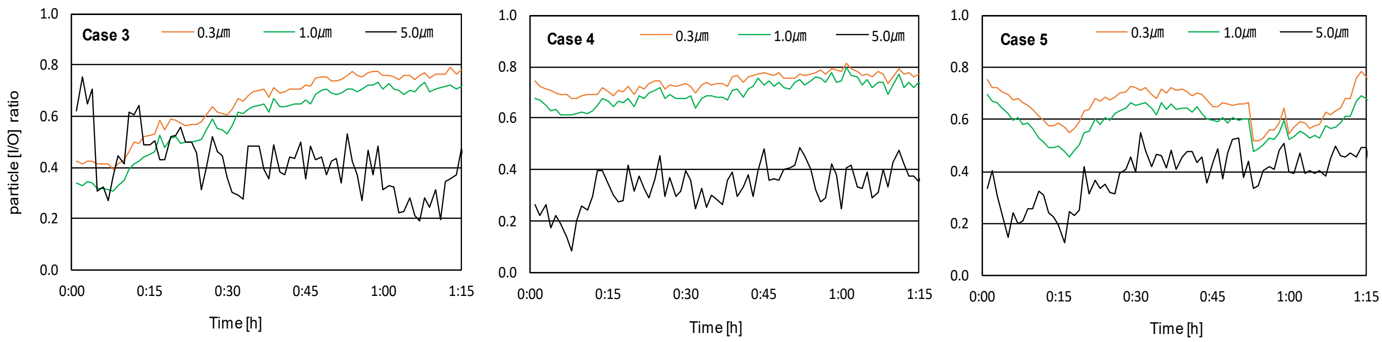

Figure 7. Particulate I/O ratio with a ventilation fan and natural ventilation (conditions 3–5).

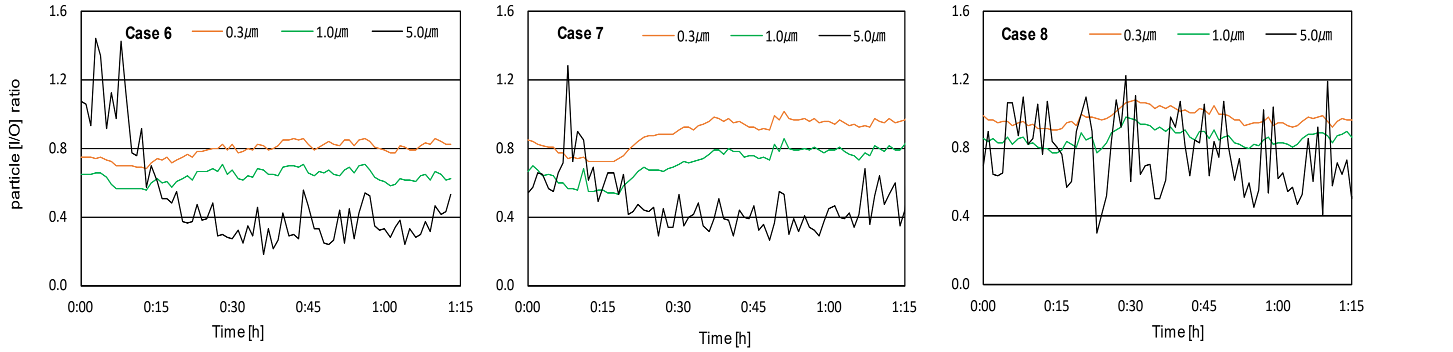

Figure 8. Particulate I/O ratios with a ventilation fan, natural ventilation, and an air conditioner (conditions 6–8).

Table 4. The mean, median and standard deviation by particle size in each condition.

Condition	Particle Size	Average	Median	Standard Deviation
case 1	0.3 µm	0.44	0.44	0.02
	1.0 µm	0.16	0.15	0.03
	5.0 µm	0.03	0.02	0.03
case 2	0.3 µm	0.54	0.57	0.11
	1.0 µm	0.49	0.47	0.11
	5.0 µm	0.57	0.32	0.52
case 3	0.3 µm	0.65	0.70	0.12
	1.0 µm	0.58	0.64	0.13
	5.0 µm	0.42	0.43	0.12
case 4	0.3 µm	0.74	0.74	0.03
	1.0 µm	0.70	0.70	0.05
	5.0 µm	0.33	0.33	0.08
case 5	0.3 µm	0.65	0.66	0.06
	1.0 µm	0.59	0.60	0.06
	5.0 µm	0.38	0.40	0.10
case 6	0.3 µm	0.79	0.80	0.05
	1.0 µm	0.64	0.64	0.04
	5.0 µm	0.50	0.38	0.30
case 7	0.3 µm	0.89	0.93	0.09
	1.0 µm	0.72	0.75	0.09
	5.0 µm	0.49	0.44	0.18
case 8	0.3 µm	0.98	0.97	0.04
	1.0 µm	0.86	0.86	0.05
	5.0 µm	0.76	0.74	0.22

(1) Ventilation fan (Condition 1: Off, Condition 2: On)

The results are expressed as an indoor/outdoor (I/O) ratio to determine whether the particles present in the room were generated indoors or outdoors. The measured particle sizes were 0.3 µm, 1 µm, and 5 µm. For condition 1, the particulate I/O ratios for the particle size of 0.3 µm ranged from 0.45 to 0.78. The particulate I/O ratios for the particle size of 1 µm ranged from 0.18 to 0.73. Finally, the particulate I/O ratios for the particle size of 5 μm ranged from 0.08 to 0.42. The results show a gradual increase in the particle sizes of 0.3 and 1 μm. However, the 5 μm particle size leveled off with no significant fluctuations. For condition 2, the particulate I/O ratios for the 0.3 μm particle size ranged from 0.44 to 0.48 and those for the 1 μm particle size ranged from 0.52 to 0.63. At the beginning of the experiment, the particulate I/O ratio for the 5 μm particle size was 2.04 but was less than 1.0 after 1 h. The particulate I/O ratio for 5 μm grain size was 2.04 at the start of the measurement but dropped below 1.0 after 1 h. Thereafter, it fluctuated within the range of 0.1 to 0.7, potentially due to the influence of outdoor air.

(2) The effects of ventilation fans and natural ventilation (Conditions 3–5)

The particulate I/O ratios for condition 3 ranged from 0.42 to 0.78 for the 0.3 μm particle size and increased gradually from the beginning of the experiment. The I/O ratios for the 1 μm particle size ranged from 0.34 to 0.78 and showed the same trend as that of the 0.3 μm grain size throughout the experiment. The particulate I/O ratios for the 5 μm particle size ranged from 0.63 to 0.19, with both increases and decreases during the experimental period. The particulate I/O ratios for condition 4 ranged from 0.75 to 0.77 for the 0.3 μm particle size, but no significant fluctuations were observed over the experimental period. The particulate I/O ratios for the 1 μm particle size ranged from 0.68 to 0.74 and showed the same trend over the experimental period as that of the 0.3 μm particle size. The particulate I/O ratios for the 5 μm particle size ranged from 0.26 to 0.35, with a slight increase in I/O ratios during the experimental period. The I/O ratios for condition 5 ranged from 0.75 to 0.76 for the 0.3 μm particle size, and the lowest I/O ratio during the experiment was about 0.50. The particulate I/O ratios for the 1 μm particle size ranged from 0.70 to 0.68 and showed the same trend as that of the 0.3 μm particle size. The particulate I/O ratios for the 5 μm particle size ranged from 0.33 to 0.49, and the ratios increased and decreased repeatedly during the experimental period. Conditions 3–5 did not involve the operation of computers or other equipment to prevent particle generation in the room. In addition, measurements were always taken while there were no occupants in the room. In condition 1, the particulate I/O ratios of the 0.3 and 1 μm particle size increased with time, indicating that the particles may have entered through gaps around windows and doors. For the 5 μm particle size, the particulate I/O ratios changed significantly with the use of a ventilation fan, indicating the influence of outdoor air.

(3) The effect of air conditioner (conditions 6–8)

For condition 6, the maximum I/O ratio for the 0.3 μm particle size ranged from 0.75 to 0.86 and increased gradually from the beginning of the experiment. The particulate I/O ratios for the 1 μm particle size ranged from 0.59 to 0.71 and showed no significant change over the experimental period. The maximum value of the I/O ratio for a particle size of 5 μm was 1.44, but it decreased to 0.18 after approximately 30 min. Thereafter, the particulate I/O ratio increased and decreased repeatedly during the experimental period. For condition 7, the particulate I/O ratios for the 0.3 μm particle size ranged from 0.73 to 1.02 and from 0.54 to 0.86 for the 1 μm particle size. The maximum I/O ratio for the 5 μm grain size was 1.29 but decreased to 0.27 after approximately 30 min. Thereafter, the I/O ratio fluctuated between 0.29 and 0.68. For condition 8, the I/O ratios for the 0.3 μm particle size ranged from 0.99 to 1.11. The maximum I/O ratio for a particle size of 1 μm was 1.11 and the minimum was 0.74. The particulate I/O ratios for the 5 μm particle size ranged from 0.29 to 1.29, with a high amount of variation. Based on the above results, it is likely that particle sizes of 0.3 and 1 μm are less affected by the air conditioner filter than the 5 μm particles. The particulate I/O ratios for conditions 6 and 7 exceeded 1.0 but decreased over the experimental period. However, the 0.3 and 1 μm particle sizes did not vary significantly during the experimental period.

4. Discussion

This study was conducted in a university laboratory to measure the effects of natural ventilation by opening windows and doors and operating air conditioners. In addition, the inflow of contaminants from the outdoor air caused by natural ventilation was investigated. In this experiment, ventilation through gaps was observed even when all windows and doors were closed. It was also found that the installed ventilation fan could only provide approximately 43% of the ventilation volume. Therefore, it was difficult to secure the required ventilation volume using only a ventilation fan. It was found that opening windows and doors could provide a larger amount of ventilation than operating only the ventilation fan. It was also found that while it is important to increase the opening area, opening multiple windows and doors is more efficient in ventilating the entire room. Natural ventilation is known to be significantly affected by indoor temperature and outdoor wind speed, although window and door openings are also important [29]. While outdoor wind speeds were not measured during this experiment, according to information from the Japan Meteorological Agency, the outdoor wind speeds for conditions 3–5 ranged between 1–3 m/s blowing to the southeast toward the windows. For conditions 6–8, the outdoor wind speeds were 3–4 m/s blowing to the west, which was not directly against a window. In the future, it will be necessary to consider not only the wind speed but also the temperature difference between indoors and outdoors in order to obtain the natural ventilation rate.

Changes in the concentration of particulates in the room owing to natural ventilation and air conditioner operation (airflow mode) were also measured. The I/O ratios showed different trends for each particle size. Under condition 1, wherein no ventilation was used, there was a gradual increase in the I/O ratio for particles 0.3 and 1 μm in diameter. This is thought to be due to the inflow of particles originating from the outdoor air through the gaps around the windows and doors. Nazaroff and others investigated particle penetration through windows and reported that of the particles 0.2–3 μm in diameter, more than 80% passed through window gaps [30]. They also reported low penetration rates for particles smaller than this size and for particles larger than 3 μm. This past study was consistent with the present experiment. We also observed a higher penetration of 5 μm particles when the ventilation fan was running, and the windows and doors were open. Therefore, contamination by natural ventilation should be considered for particles larger than 5 μm in diameter. In Japan, various pollens are dispersed in the air depending on the season [31]. In particular, natural ventilation is required during non-cooling and non-heating periods to reduce building energy consumption. However, because cedar and other pollens are distributed in large quantities from March to June in Japan, adverse health effects on the building occupants due to pollen are possible. In a study on ventilation and indoor pollen contamination, Menzel et al. reported that pollen I/O ratios were highest in rooms with fully open windows and additional mechanical ventilation, second highest in rooms with fully open windows, and lowest in rooms with short window openings [32]. They also reported that the hourly I/O ratio varied with the weather and was influenced by the outdoor temperature and wind speed.

In this study, we measured the changes in ventilation rate and particle concentration owing to the operation of the indoor air conditioner in airflow mode. It was expected that placing the indoor air conditioner in airflow mode would agitate the air and affect the ventilation rate, but it did not have a significant effect on the ventilation rate. However, changes in the particle concentrations in the room were observed. In particular, the initial I/O ratio of the 5 μm particle size was high but decreased over time. In this study, air conditioners were equipped with an anti-mold and anti-bacterial resin net, which were capable of removing PM2.5. We observed that particles with diameters of 0.3 and 1 μm were not removed. The use of medium-performance or HEPA filters may be considered for the removal of PM2.5.

Recently, natural ventilation has been mandated to save energy in buildings and reduce the indoor infection rate of COVID-19. However, natural ventilation may be difficult depending on the local climate and outdoor air environment. In Japan, the climate is hot and humid during the summer months, and natural ventilation adversely affects the indoor thermal environment depending on the season [33]. Natural ventilation is effective in preventing the indoor infection rate of COVID-19; however, it is believed that an appropriate amount of ventilation should be ensured by opening windows and doors.

5. Conclusions

In this study, the ventilation rates and particle concentrations were measured with and without a ventilation fan and with varying window and door configurations. The effect of the blower mode of the air conditioner on the ventilation volume and indoor particle concentration was also measured. The marketed airflow rate of the ventilation fan was found to differ from the ventilation rate observed when the fan was in use. In addition, the ventilation volume differed depending on the openings in windows and doors. Even though the opening areas were the same, the amount of ventilation in the room was greater when several doors or windows were opened. We expected that natural ventilation and an air conditioner in blast mode would increase the amount of ventilation in the room, but no significant changes were observed. It was confirmed that 0.3 and 1 μm particles could enter through the gaps around the windows and doors, even without ventilation. The results of this study suggested that the 5 μm particles were mostly derived from outdoor air. When the air conditioner was operated in airflow mode, it was observed that 5 μm particles could be removed by the air conditioner filter. The use of a medium-performance or HEPA filter may remove smaller particles from the air. As a future study, it is considered necessary to study the annual ventilation volume and pollutants derived from the outside air using simulations.

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