Evaluation of an automatic opening window system to maintain adequate ventilation rates

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Abstract. Under the influence of COVID-19, it is recommended to ventilate to reduce the risk of infection in the room. In an air-conditioned room, opening windows increase the ventilation rate that caused by indoor and outdoor temperature differences. However, there is a concern that opening windows in the air-conditioned room will increase the heating and cooling loads due to air leakage. In addition, it is difficult to maintain the adequate ventilation rate. To solve this problem, we developed an automatic window opening system to control the natural ventilation rate. This system can be controlling the adequate ventilation rate for the room by adjusting the opening area of window automatically. The purpose of this study is to confirm the effectiveness of this system and to understand its performance. In this study, analysis was done to calculate the adequate opening width in Japan, and actual measurements were conducted to understand the operating performance of this system. As a result, it was confirmed that sensible heat load due to ventilation was reduced with this system, and the ventilation rate could be controlled by this system.

1 Introduction

It has been reported by ASHRAE [1] and others that securing adequate ventilation is effective to reduce the risk of infection such as COVID-19 in the room. Natural ventilation by opening windows and doors is the simplest method to increase the ventilation rate when there is an indoor and outdoor temperature differences. However, there are concerns that opening the window in the air-conditioned room may be affected by the outdoor air temperature, resulting in poor heating and cooling efficiency and deterioration of the indoor thermal environment. Also, excessive ventilation may increase the heating and cooling load and power consumption. In addition, it is difficult to maintain the adequate ventilation rate, because the outdoor air temperature changes from time to time. This indicates that it is not easy to maintain the proper ventilation rate by manually opening and closing the windows.

To solve this problem, we developed an automatic window opening system to control the natural ventilation rate. The purpose of this study is to confirm the effectiveness of this system and to understand its performance.

2 Analysis

In this study, analysis was done to calculate the adequate opening width in Japan. The ventilation rate changes at a single opening were calculated using CONTAM [2], a ventilation network simulation software. Table 1 shows the aperture conditions. Weather data from 47

Tab. 1. The aperture conditions.

Model Summary	
Type	Two-way flow
Formula	One-opening
Model Parameters	
Height	2 m
Width	10 mm – 100 mm
Discharge coefficient	0.6

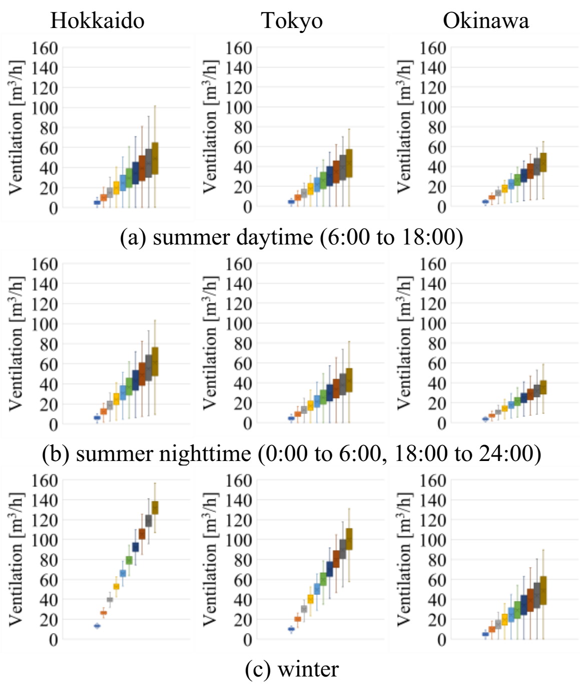

Fig. 1. The ventilation rate for each opening width.

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prefectures in Japan were used as external conditions. The weather data [3] were hourly data taken from the last 15 years (2007-2021). As internal conditions, the indoor temperature was fixed at 26 ºC in summer and 22 ºC in winter. The calculation period was three months from June to August for the summer cooling period and three months from December to February for the winter heating period.

2.1 Ventilation rate for each opening width

Figure 1 shows the results of the ventilation rate for each opening width. The ventilation rate increased as the opening width increased. There was a proportional relationship between opening width and ventilation rate. In summer, there was a difference between daytime and nighttime. However, in winter, there was little difference between daytime and nighttime. In Hokkaido, the outdoor temperature was sometimes lower than the indoor temperature in summer. Therefore, the indoor and outdoor temperature differences were sometimes larger than in other prefectures, resulting in a larger ventilation rate.

2.2 Adequate opening width by prefectures

Figure 2 shows the adequate opening width by 47 prefectures. The adequate ventilation rate was based on 30 m^3/h, which is the required ventilation rate per person [4],[5]. The adequate opening width was selected as the opening width that provides the adequate ventilation rate throughout the half-day period. In summer, during the daytime, the adequate opening width ranged from 60 mm to 80 mm. In most prefectures, the adequate opening width was 70 mm. During the nighttime, the adequate opening width ranged from 50 mm to 90 mm, with large differences depending on the region. In winter, there was no difference in the adequate opening width between daytime and nighttime. The adequate opening width was 20 mm in cold prefectures such as Hokkaido, 30 mm in most other prefectures, and 60 mm in Okinawa Prefecture only.

2.3 Heating and cooling load due to ventilation

To confirm the effectiveness of an automatic window opening system that controls adequate ventilation rates, the heating and cooling loads were calculated. The total heating and cooling load due to ventilation was calculated every three months in summer and winter. The results were compared between the case with the adequate opening width and the case with the automatic opening window system. Only sensible heat load was calculated using Equation (1).

Table 2 shows the total heating and cooling loads due to ventilation in summer and winter. In the case of the automatic window opening system, the total heating and cooling load due to ventilation tended to decrease compared to the case of the adequate opening width. In the case of adequate opening width, ventilation rate was sometimes excessive due to the indoor and outdoor temperature differences. Therefore, the heating and

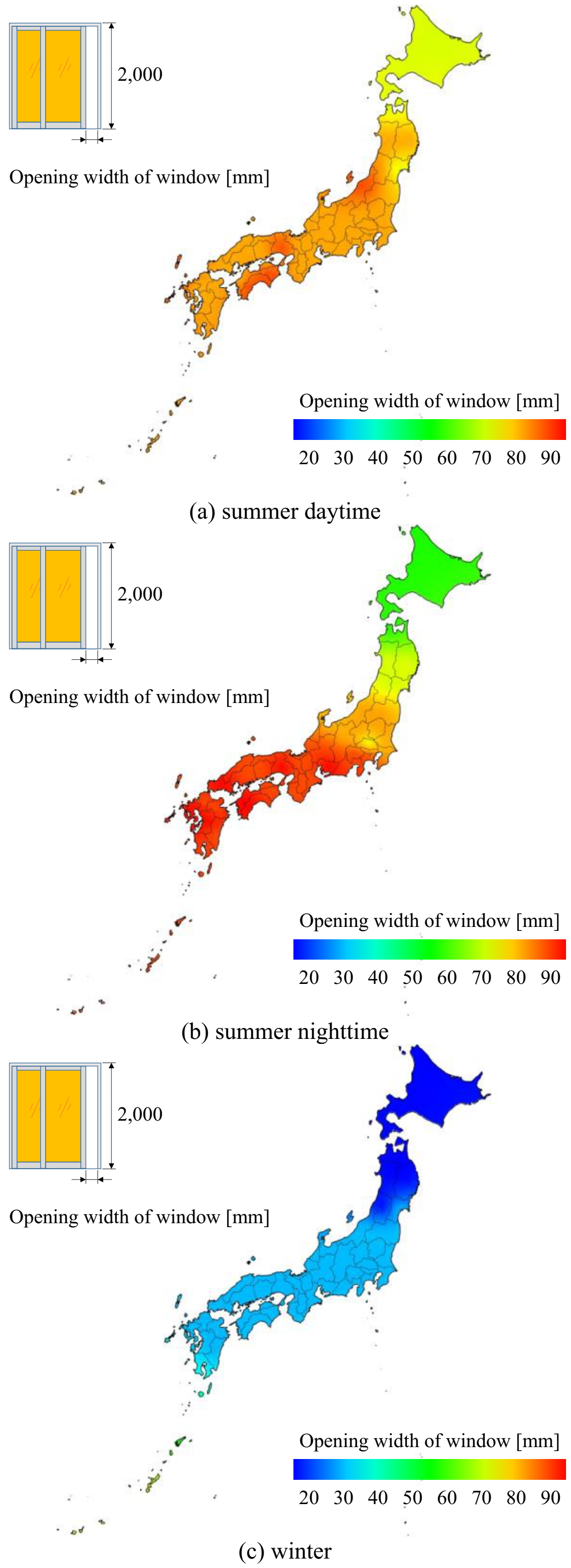

Fig. 2. The adequate opening width by 47 prefectures.

Eq. 1. Equation for load calculation

$$q_{os} = \rho \cdot C_p \cdot \Delta T \cdot V \qquad (1)$$

Where q_{os} is the sensible heat load due to ventilation [W], ρ is the fluid density of air [kg/m^3], C_p is the specific heat at constant pressure of air [J/(kg・K)], ΔT is the indoor and outdoor temperature differences [K], and V is the ventilation rate [m^3/s].

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cooling load due to ventilation is considered to have increased. In the case of Hokkaido, the heating load was large, and in the case of Okinawa, the cooling load was large. In addition, In the case of adequate opening width, the ventilation rate was sometimes less than the adequate ventilation rate depending on indoor and outdoor temperature differences. Therefore, it is considered effective to control the ventilation rate by using the automatic window opening system.

3 Automatic window opening system

Figure 3 shows an overview of the automatic window opening system we developed. This system can be controlling the adequate ventilation rate for the room by adjusting the opening area of the window automatically. In the case where indoor and outdoor temperature differences are large (a), the opening width is narrowed. In the case where indoor and outdoor temperature differences are small (b), the opening width is widened. In this way, the natural ventilation rate is maintained. From the equation of Brown (Equation (2)) [6], we calculated the opening width when the required ventilation rate per person is 30 m^3/h.

4 Actual measurement methods

In this study, actual measurements were conducted to understand the operating performance of the system. To confirm the indoor thermal environment, measurements were taken in summer. The measurement was conducted on September 11, 2021. Results were compared between the automatic window opened by this system and the ordinary window opened at 95 mm in width. The width of the automatic window opened by this system was adjusted every 30 seconds. Also, there are two types of window openings: constant opening and intermittent opening. In the case of intermittent opening, the concentration of pollutants in the room increases while the window is closed. So, the actual measurements were conducted with the window constantly open.

Fig. 4 shows the target experimental building in Takaoka city, Toyama, and Fig. 5 shows the temperature measurement points. Both rooms have a floor area of 6.25 m^2, a room volume of 15 m^3, and a window height of 2 m. All air conditioners in both rooms and the corridor were set at 22 ˚C. The ventilation rate using the constant concentration method, indoor temperature distribution, and power consumption were measured. In addition, to understand the external environment, the outdoor temperature, wind direction and speed, and solar radiation were measured.

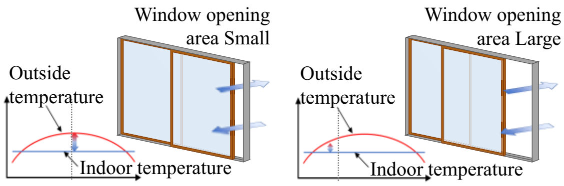
5 Actual measurement results

5.1 Ventilation rate

Fig. 6 shows the measured ventilation rate. According to the results, in the case of the automatic window opened by this system, the ventilation rate was generally maintained at 30 m^3/h throughout the day. The average

Tab. 2. The total heating and cooling loads.

Prefecture	Load with adequate opening width [kW]		Load with the system [kW]	
	summer	winter	summer	winter
Hokkaido	1.76	510.24	2.47	569.86
Tokyo	38.82	354.49	32.49	338.36
Okinawa	65.34	114.91	58.13	93.39



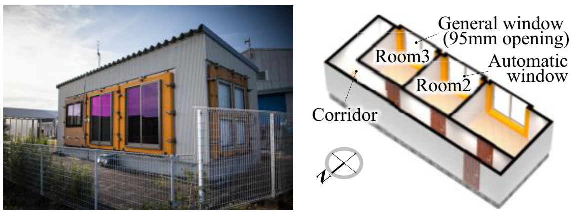
(a) ΔTemperature large (b) ΔTemperature small

Fig. 3. The automatic window opening system.

Eq. 2. The equation of Brown

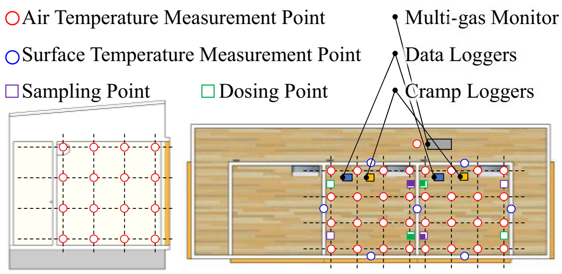
$$Q = \frac{\alpha A}{3}\sqrt{\frac{2\Delta P}{\rho}} \quad (2)$$

Where Q is the ventilation rate [m^3/s], α is the flow coefficient [-], A is the window opening area [m^2], ρ is the fluid density of air [kg/m^3], and ΔP is the pressure difference between indoor and outdoor [Pa].



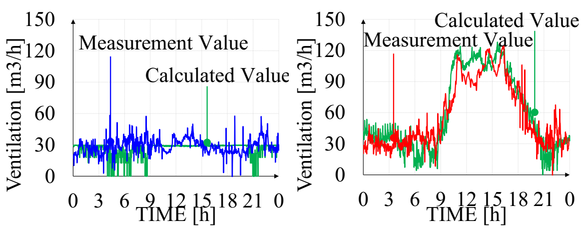
(a) External view (b) Interior view

Fig. 4. Overview of the experimental building.



Vertical section Horizontal section temperature

Fig. 5. Temperature measurement points.



(a) Automatic window (b) Ordinary window

Fig. 6. Ventilation rate in summer.

daily ventilation rate was measured to be about 28.9 m^3/h. On the other hand, in the case of the ordinary window opened at 95 mm in width, the average daily ventilation rate was measured to be about 50.0 m^3/h. As the outdoor air temperature increased, the ventilation rate increased, the maximum ventilation rate being 124.6 m^3/h. The system adjusted the opening width according to the indoor and outdoor temperature differences. It was confirmed that the ventilation rate could be controlled by using this system.

5.2 Indoor thermal environment

Fig. 7 shows the horizontal temperature distribution in the room at 10:00 and 13:00, and Fig 8 shows the vertical temperature distribution in the cross-section of the opening at 13:00. In both rooms, the indoor temperature was generally maintained at the set temperature of 22 ˚C. However, in the case of the ordinary window opened at 95 mm in width, the indoor temperature increased slightly due to the high outdoor temperature and increased air leakage. The maximum indoor and outdoor temperature differences were measured at 9.9 ˚C in the room with the automatic window opened by this system.

5.3 Power consumption

Fig. 9 shows the power consumption of the air conditioner in each room. There was no significant difference between the two rooms, and the air conditioner operated at about 0.1 kW to 0.15 kW during the daytime when power consumption was high. However, in the case of the ordinary window opened at 95 mm in width, it operated at about 0.18 kW from 13:00 to 14:00. Due to increased air leakage, the cooling load temporarily increased.

6 Conclusion

In this study, we developed an automatic window opening system to control the natural ventilation rate. The following findings were obtained from this study.

(1) In the case of the system, the total heating and cooling load due to ventilation tended to decrease compared to the case of the adequate opening width.
(2) The developed system was able to control the ventilation rate, and the daily average ventilation rate was about 28.9 m3/h throughout the day in summer.

In the future, it is planned to analyze the airflow distribution in the room and the annual heat load. Also, we will develop a system to control ventilation rates using casement windows.

Acknowledgement

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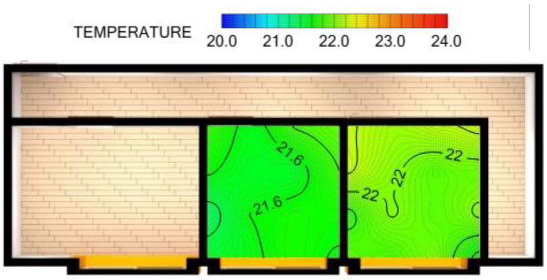
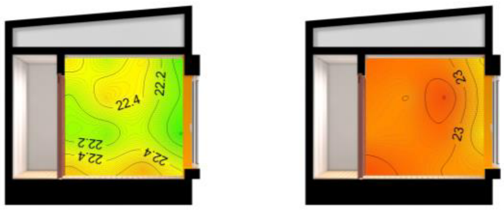


at 10:00 on September 11

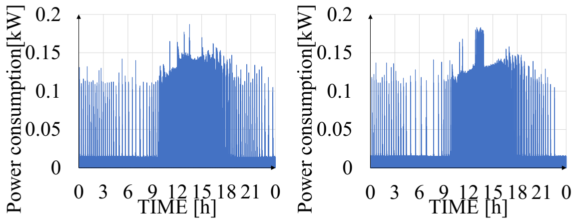
at 13:00 on September 11

Fig. 7. Horizontal temperature distribution in summer.



(a) Automatic window (b) Ordinary window

Fig. 8. Vertical temperature distribution in summer.



(a) Automatic window (b) Ordinary window

Fig. 9. Power consumption in summer.

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