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# Ventilation and Indoor Thermal Environment in Air-Conditioned Rooms with Open Windows in Winter

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## ABSTRACT

*Under the influence of biological hazards including COVID-19, it is required sufficient ventilation to decrease the infection risk in the indoor area. In particular, the natural ventilation with window opening is recommended in rooms with inadequate ventilation. However, the ventilation rate, energy loss, and indoor thermal environment with window opening in air-conditioned room varies hourly with given environment. In addition, opening windows in winter causes serious problems such as deterioration of the indoor thermal environment and reduction of absolute humidity. The purpose of this study is to evaluate the changes of ventilation rate, energy loss, and indoor thermal environment with window opening. To achieve this purpose, actual measurements in a residential house during the winter were performed. In the actual measurement, fluctuations in ventilation rate, indoor temperature and humidity distribution, and electric power usage of air-conditioner with the window opening area were measured. In addition, the effect of opening windows on the human body was examined using a thermal manikin. As a result, when a window with a height of 2 m was opened 0.02 m, a ventilation rate of 56.6 $m^3/h$ was obtained. In addition, the opening of the windows caused cold draft and deterioration of the indoor thermal environment.*

## 1 INTRODUCTION

In the midst of the COVID-19 epidemic, it is effective to ensure proper ventiration in order to reduce the risk of infection in the indoor area (ASHRAE, 2020). Guidelines have been created as preventive measures against infectious diseases in various countries around the world (REHVA, 2020, ISHRAE, 2020). In order to maintain a healthy indoor space, it is recommended to open the windows to ensure ventilation rate in rooms that do not have sufficient ventilation capacity. If there is a difference between the indoor and outdoor temperatures such as during the heating and cooling period, it is possible to increase the indoor ventilation rate by leakage from opening windows. In particular, there is a large temperature difference between indoors and outdoors during the heating period. Therefore, increasing the ventilation rate in the room may cause an excessive increase in heating load and deterioration of the indoor environment, so proper window control is required. However, it remains unclear how much windows should be opened to ensure ventilation rate and the impact of increased ventilation rate on the indoor thermal environment. Also, there are very few research cases related to it. The authors examined the ventilation rate by opening windows in summer (Lee et al., 2020). The purpose of this study is to evaluate the changes of ventilation rate, energy loss, and indoor thermal environment with window opening. To achieve this goal, the ventilation rate and temperature distribution in the room and the electric power consumption of the air conditioner according to the width of the window opening were measured in actual house. In addition, the effect of opening windows on the human body using a thermal manikin was investigated. This paper describes the actual measurement results in winter season.

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## 2 METHODS

The measurement target is a mobile home located in Nagano City (latitude: 138.14, longitude: 36.41, GMT+9), Japan, which is used as an emergency temporary housing. Figure 1-(a) shows the exterior of the target building, (b) shows the 3D model of the interior, and (c) shows the details and measurement points of the equipment installed. The target building has a floor area of 35.5 $m^2$ and a volume of 78.1 $m^3$, and the bedroom and living room are one room without partition walls. In addition, the airtightness performance is 1.7 $cm^2/m^2$, and heat transmission coefficient of exterior wall was measured by Infrared camera method (Lee et al., 2013) as 0.8 $W/(m^2{\cdot}K)$. A window with a height of 2 m and a width of 1.6 m is installed in the living room (maximum opening width: 0.68 m). A ventilation fan is installed as an exhaust ventilation system in the living room and it was measured as 32.2 $m^3/h$ by tracer gas decay method. Actual measurement was conducted from 0:00~6:00 in March 2021 to clarify changes in ventilation rate and the indoor thermal environment by opening the window. Measurement items are the ventilation rate, thermal environment, and electric power consumption. The ventilation rate is measured by the constant concentration method using sulfur hexafluoride ($SF_6$) as a tracer gas. In addition, a thermal manikin was installed and the surface temperature was measured in order to understand the effects of the deterioration of the indoor thermal environment and cold draft on the human body. The thermal manikin was seated on the floor in front of the window. During the actual measurement, an air conditioner with a heating capacity of 3.6 kW was used and operated at a set temperature of 20 ºC. The cases examined in the actual measurement are a total of 3 patterns when the window opening width is 0.02 m, 0.10 m, 0.68 m (fully opened).

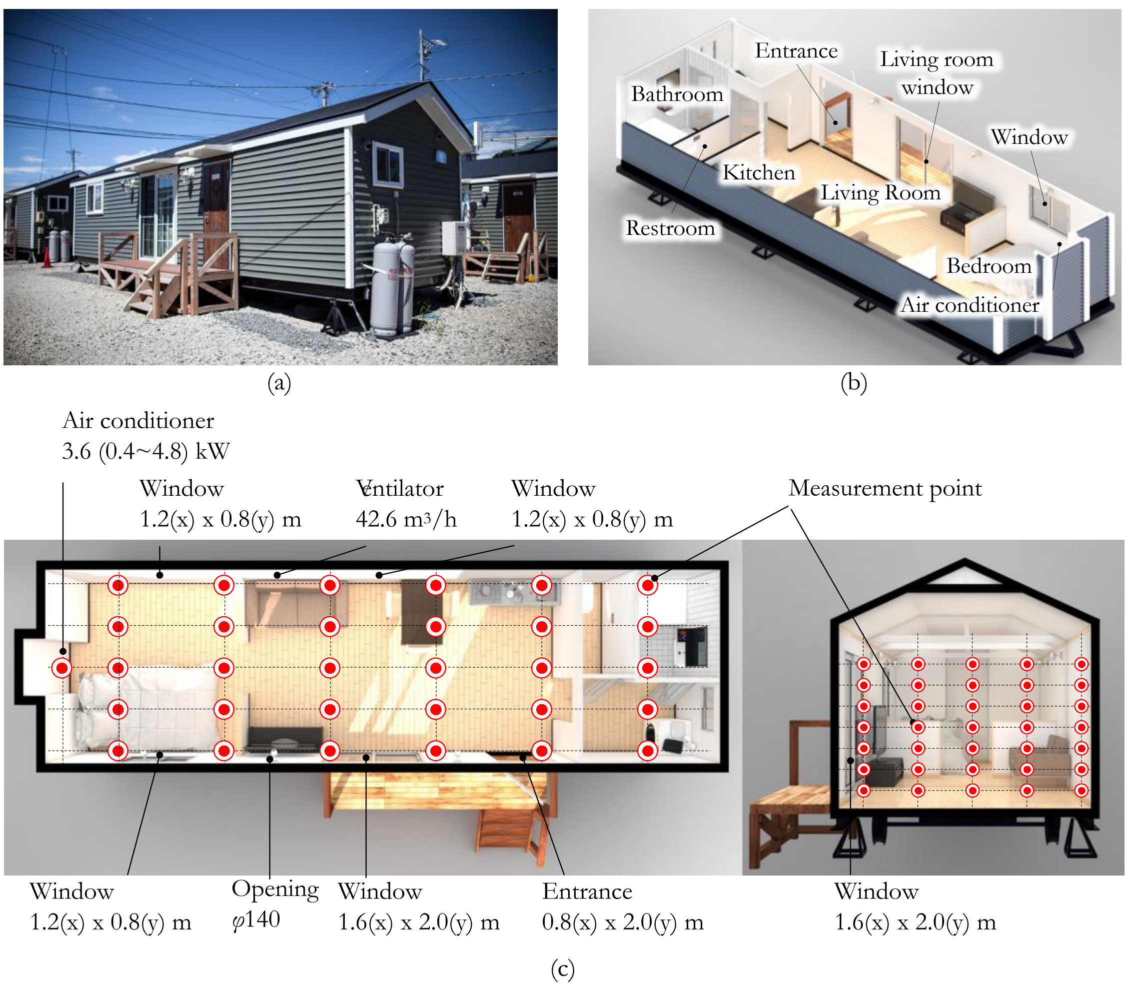


**Figure 1** Outline of the target building: (a) Photograph of the target building, (b) 3D modeling, (c) Equipment details and measurement points.

## 3 RESULTS

### 3.1 Indoor thermal environment

Figure 2 shows the horizontal and vertical temperature distribution in the room at 3:00 for each pattern. When the window was opened 0.02 m, the horizontal temperature distribution was maintained between 18 ºC and 22 ºC. By increasing the opening width of the window, the room temperature was lowered, and it was maintained at 17~20 ºC for 0.10 m and 14 ºC~18 ºC for 0.68 m. It is considered that this is because the ventilation rate increased due to the opening of the windows and the heating capacity of the air conditioner became insufficient, so that the indoor thermal environment deteriorated. On the other hand, the room temperature changes greatly depending on the height. When the window was opened 0.02 m, the temperature near the floor was about 16 ºC, which was about 3 ºC lower than the upper part. When the opening width of the window was increased, the temperature near the floor dropped significantly, and when it was opened 0.10 m, it dropped to about 10 ºC. When opened 0.68m, the temperature was the lowest and dropped to about 4 ºC, and the temperature difference from the upper part of the room was about 12 ºC. It is probable that this was because the outside cold air entered the room due to the opening of the windows and cold draft occured. Natural ventilation due to the opening of windows in winter causes a serious deterioration of the indoor thermal environment.

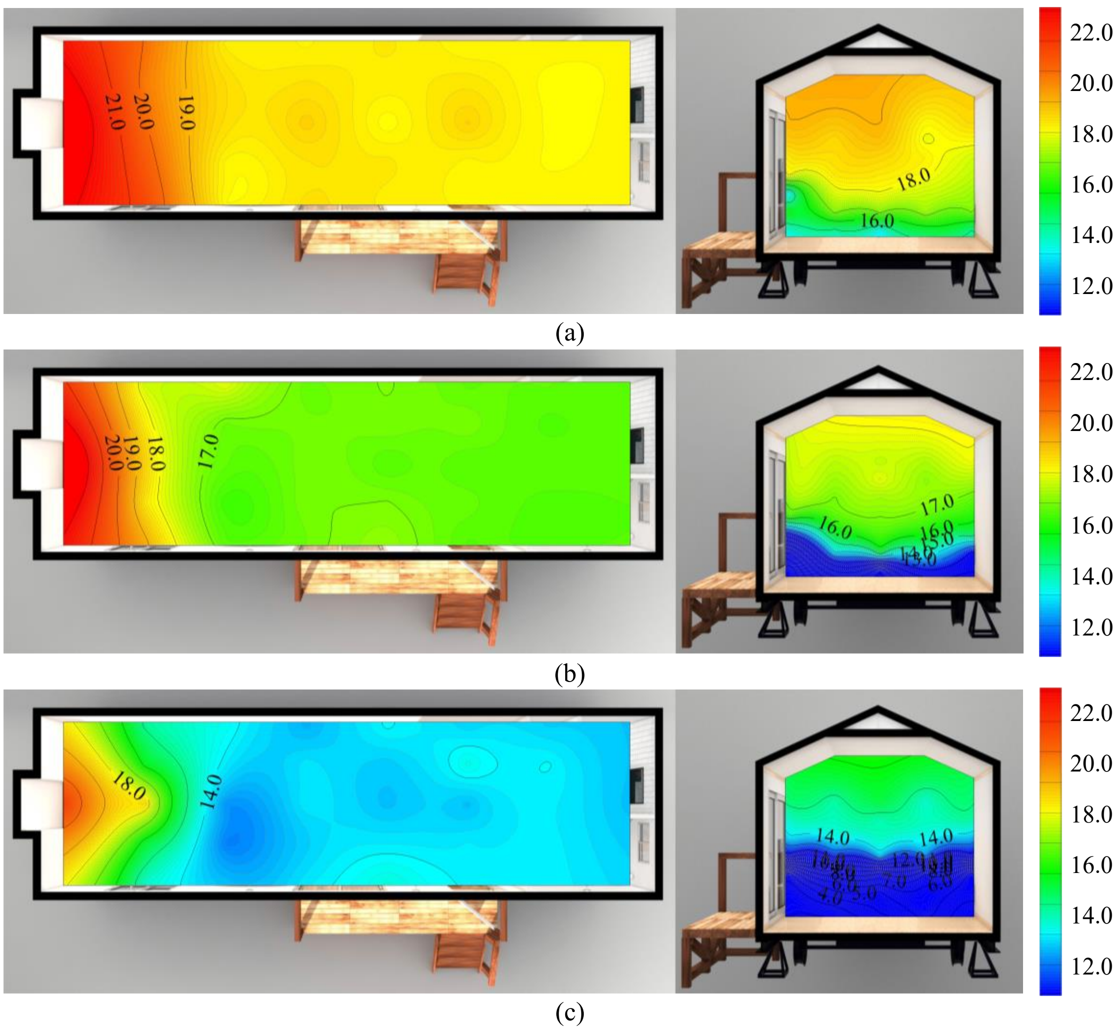


**Figure 2** Measurement results of horizontal and vertical temperature distribution in the room at 3:00: (a) Window opening width 0.02 m, (b) Window opening width 0.10 m, (c) Window opening width 0.68 m.

## 3.2 Thermal manikin

Figure 3 shows the infrared thermal image of the thermal manikin at 3:00, and Figure 4 shows the surface temperature of the thermal manikin. As a result, the surface temperature of the manikin was lowered by increasing the opening width of the window. The average surface temperature was 31.6 ºC when the window was opened 0.02 m, 29.6 ºC when the window was opened 0.10 m, and 22.2 ºC when the window was opened 0.68 m. In this actual measurement, the thermal manikin was seated on the floor, so it was greatly affected by the cold draft.

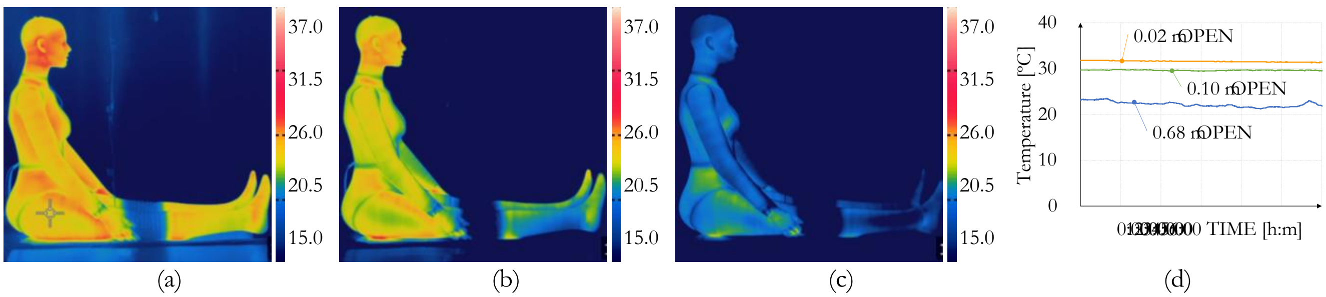


**Figure 3** Infrared thermal images of thermal manikin at 3:00 and average skin surface temperature of thermal manikin: (a) Window opening width 0.02 m, (b) Window opening width 0.10 m, (c) Window opening width 0.68 m,(d) average skin surface temperature of thermal manikin.

## 3.3 Ventilation rate

Figure 4 shows the measurement results of the ventilation rate of each pattern, the value calculated by Eq. (1), and the calculated value when the room temperature is maintained at 20 ºC. Equation 1 has been proposed by Pham and Oliver (1983) and it shows an equation for calculating the infiltration rate due to natural convection at a single opening.

$$Q = 0.226A(gH)^{0.5}\left[\frac{\rho_i-\rho_o}{\rho_i}\right]^{0.5}\left[\frac{2}{1+(\rho_o/\rho_i)^{0.333}}\right]^{1.5} \quad (1)$$

where, $A$ [m$^2$] is opening area, $g$ [m/s$^2$] is the gravitational acceleration, $H$ [m] is the opening height, $\rho_i$ [kg/m$^3$] is the indoor air density, $\rho_o$ [kg/m$^3$] is the outdoor air density.

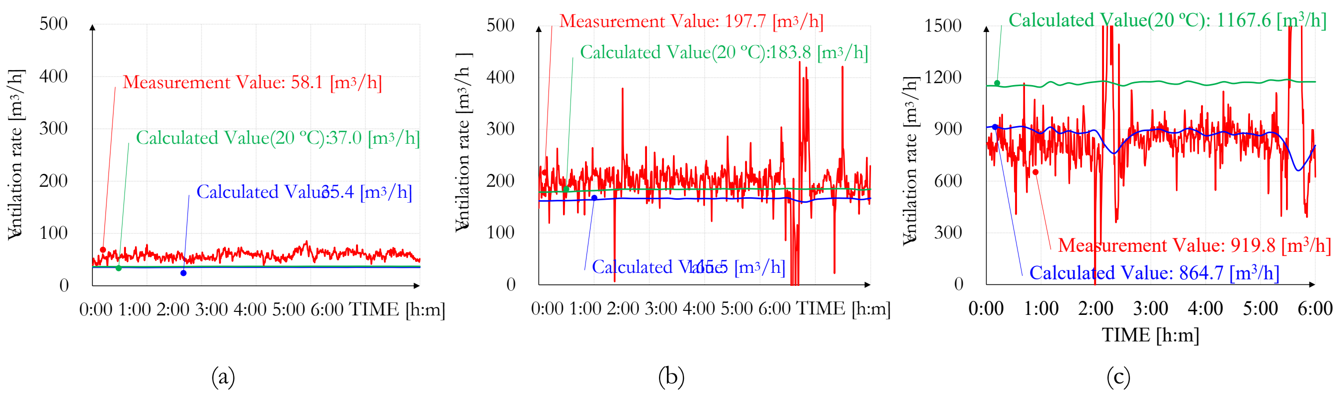


**Figure 4** Measurement results of the ventilation rate of each pattern and the value calculated by equation proposed by Pham and Oliver: (a) Window opening width 0.02 m, (b) Window opening width 0.10 m, (c) Window opening width 0.68 m.

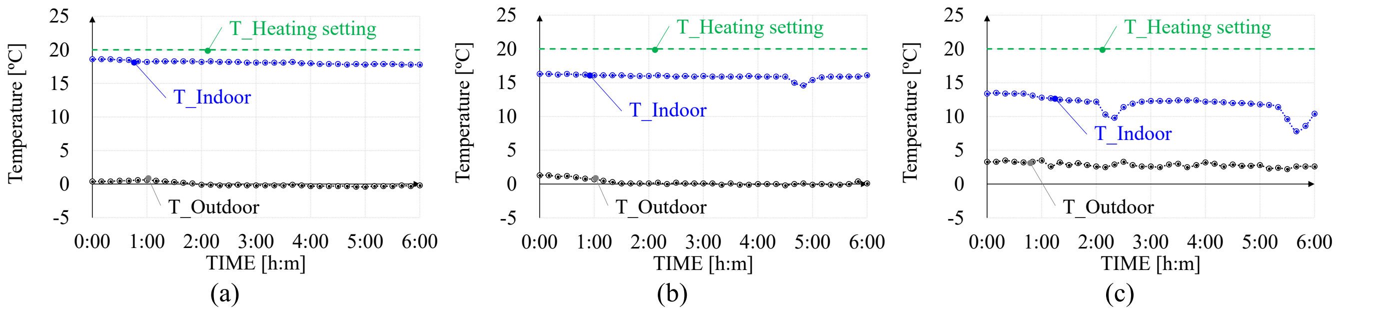


**Figure 5** Measurement results of the outdoor and indoor temperature of each pattern: (a) Window opening width 0.02 m, (b) Window opening width 0.10 m, (c) Window opening width 0.68 m.

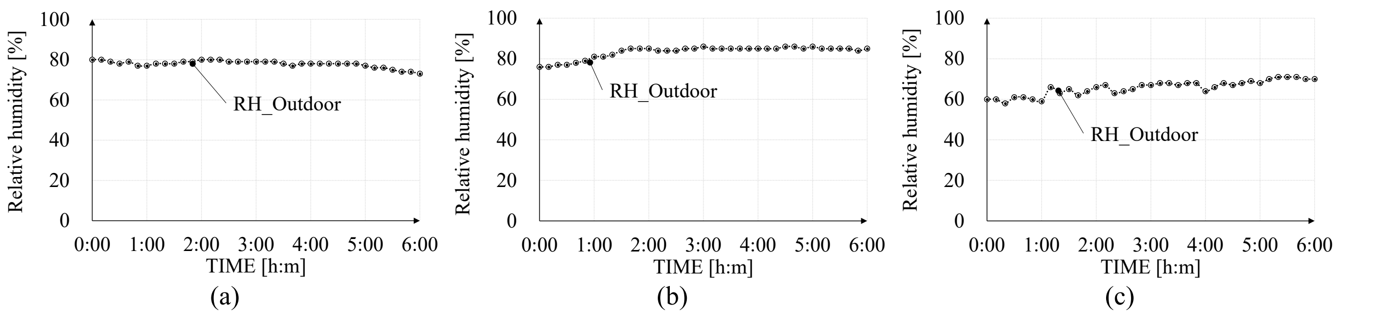


**Figure 6** Measurement results of the outdoor and indoor temperature of each pattern: (a) Window opening width 0.02 m, (b) Window opening width 0.10 m, (c) Window opening width 0.68 m.

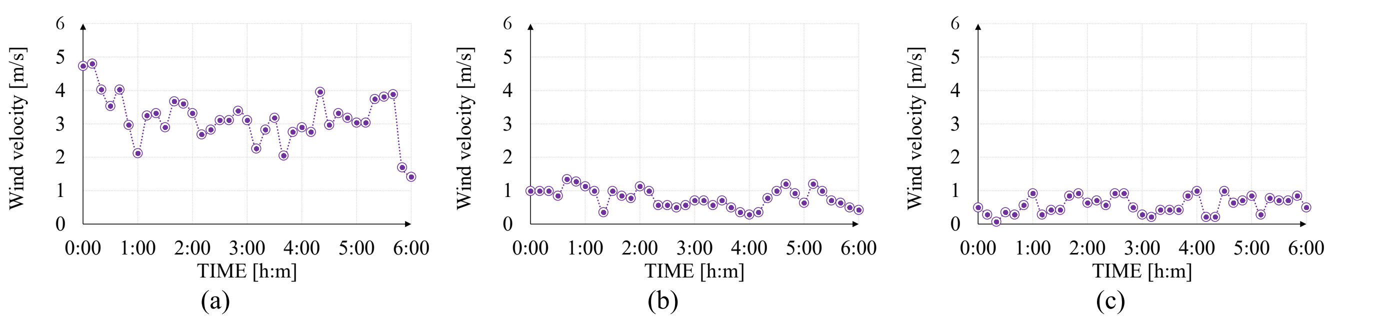


**Figure 7** The wind velocity during measurement of each pattern: (a) Window opening width 0.02 m, (b) Window opening width 0.10 m, (c) Window opening width 0.68 m.

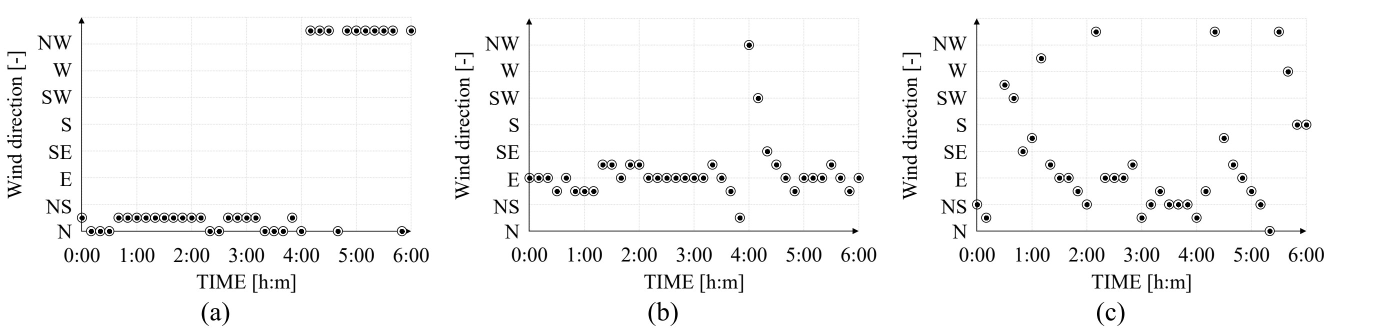


**Figure 8** The wind direction during measurement of each pattern: (a) Window opening width 0.02 m, (b) Window opening width 0.10 m, (c) Window opening width 0.68 m.

Figure 5 shows the indoor and outdoor air temperature during each pattern measurement. The outdoor air temperature was maintained at 0 to 3 ºC during the measurement period. The temperature difference between indoor and outdoor was about 15 ºC, but when the window was opened 0.68m, it was about 10 ºC. Figure 6 shows the relative humidity of the outside air. Relative humidity maintained 60 to 80 % during the measurement period. Ambient humidity does not significantly affect natural ventilation, but ventilation reduces the absolute humidity in the room. When the window was opened 0.02 m, the measured ventilation rate was stable and the average value was 58.1 $m^3$/h. This is a value that can cover the ventilation rate required per person, 30 $m^3$/h. Since the temperature difference between indoors and outdoors becomes large in winter, a sufficient ventilation rate can be ensured even if the opening width of the window is small. Increasing the opening width of the window increased the natural ventilation rate, which was 197.7 $m^3$/h when the opening width was 0.10 m and 919.9 $m^3$/h when the opening width was 0.68 m. The measurement results of ventilation rate were larger than the value calculated by Eq. (1) for any pattern. It is considered that this is because the measured value became large due to the influence of external wind pressure and disturbance. Figure 7 shows the wind velocity at the time of each pattern measurement and the wind direction at the time of each pattern measurement as shown in Figure 8. The target building was a low-rise house, and the measured wind velocity was less than 5 m/s at all times. In addition, the wind often blows from the east or north side, and the effect of the wind direction on the ventilation rate was small. Therefore, the driving force of natural ventilation is dominated by the temperature difference between indoors and outdoors (Awbi, H. B., 1991). When the window was opened 0.02 m, the calculated value assuming that the indoor temperature was maintained at 20 ºC by heating was 37.0 $m^3$/h and almost the same as the value calculated by the measured value of the indoor and outdoor temperature difference. This is because when the opening width is small, the room temperature is maintained at about 20 ºC by heating. On the other hand, when the window was opened 0.68 m, the calculated value assuming that the room temperature was maintained at 20 ºC by heating was 1,167.6 $m^3$/h and about 300 $m^3$/h larger than the value calculated using measurement results. It is considered that this is because the temperature difference between the indoor and outdoor areas became smaller due to the decrease in the indoor temperature, and the ventilation rate decreased. As a result, it can be seen that opening windows in winter can lead to increased ventilation rate and a lack of heating capacity in the building. In order to predict or control the ventilation rate based on the opening width of the window, it is necessary to consider the deterioration of the indoor thermal environment depending on the increase in ventilation rate.

## 3.4 Electric power consumption

Figure 9 shows the electric power consumption of the air conditioner in each pattern. All patterns operated from 0:00 to 6:00 with a power consumption of 0.8 to 1.0 kW. As a result, it can be seen that the air conditioner was operating at maximum during the actual measurement. This result suggests that opening windows in winter increases the ventilation load and causes significant energy loss. In addition, since defrosting operation is performed, electric power consumption will be reduced intermittently. Therefore, if the windows are opened for ventilation, the room air temperature will drop sharply during the defrosting operation.

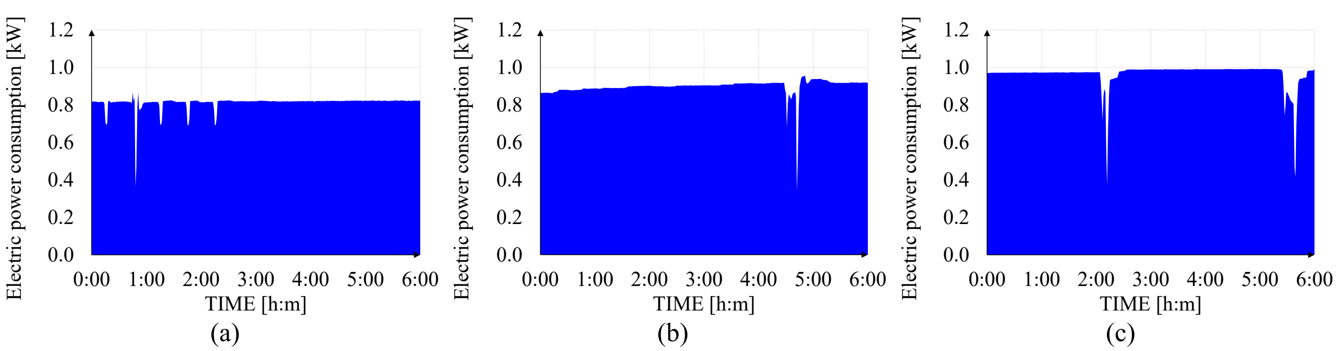


**Figure 9** Electric power consumption of each pettern: (a) Window opening width 0.02 m, (b) Window opening width 0.10 m, (c) Window opening width 0.68 m.

## 4 CONCLUSIONS

In this paper, in order to examine the effect of opening windows on the ventilation rate and the indoor thermal environment, actual measurements were made on actual buildings in winter. In the actual measurement, the fluctuation of the ventilation rate, the indoor temperature distribution, the surface temperature of the thermal manikin, and the electric power consumption of the air conditioner were measured by changing the opening width of the window. The following conclusions can be drawn from the results of the study:

(1) In winter, the ventilation rate of 58.1 $m^3$/h was obtained by opening a window with a height of 2 m by 0.02 m, and the required ventilation rate per person was 30 $m^3$/h. In winter, the temperature difference between indoors and outdoors is large, and a sufficient ventilation rate can be secured by opening the windows slightly.

(2) When the window was opened 0.68 m, the calculated value assuming that the room temperature was maintained at 20 ºC by heating was about 300 $m^3$/h larger than the value calculated using measurement results. It is considered that this is because the temperature difference between the indoor and outdoor areas became smaller due to the decrease in the indoor temperature, and the ventilation rate decreased.

(3) By opening the window, the room temperature became low. When the window was opened 0.02 m, the horizontal temperature distribution was maintained between 18 ºC and 22 ºC. By increasing the opening width of the window, the room temperature was lowered, and it was maintained at 17~20 ºC for 0.10 m and 14 ºC~18 ºC for 0.68 m.

(4) the room temperature changes greatly depending on the height. When the window was opened 0.02 m, the temperature near the floor was about 16 ºC, which was about 3 ºC lower than the upper part. When the opening width of the window was increased, the temperature near the floor dropped significantly, and when it was opened 0.10 m, it dropped to about 10 ºC. When opened 0.68m, the temperature was the lowest and dropped to about 4 ºC, and the temperature difference from the upper part of the room was about 12 ºC. Cold drafts occurred due to the opening of the windows, and the indoor thermal environment deteriorated.

(5) the surface temperature of the manikin was lowered by increasing the opening width of the window. The average surface temperature was 31.6 ºC when the window was opened 0.02 m, 29.6 ºC when the window was opened 0.10 m, and 22.2 ºC when the window was opened 0.68 m. The human body is greatly affected by the cold draft generated by opening the windows.

(6) The electric power consumption of the air conditioner was 0.8 to 1.0 kW in all patterns, and it can be seen that the maximum operation was performed during the actual measurement. Opening windows in winter can cause a significant increase in heating load. In addition, if the windows are opened for ventilation, the room air temperature will drop sharply during the defrosting operation.

(7) In order to predict or control the ventilation rate based on the opening width of the window, it is necessary to consider the deterioration of the indoor thermal environment depending on the increase in ventilation rate.

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