Thermal Performance Evaluation of a Dynamic Insulation Technology Applied to a Timber Framework House in a Real Environment

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Abstract

This paper presents the thermal performance evaluation of a dynamic insulation technology applied to the building envelope of a timber framework house. The concept of dynamic insulation technologies is to draw outside air in through insulation materials in a wall to recover conduction heat loss from inside the building. The authors applied dynamic insulation technology to the walls and ceiling of a timber framework house to allow outside air to pass through permeable insulation materials within the walls and ceiling. The experiment was conducted at a building in Sapporo, Hokkaido to evaluate the thermal performance of a building envelope with dynamic insulation technology in a real environment. The results showed that the dynamic insulation technology can significantly reduce heat loss through the building envelope.

Keywords: Dynamic Insulation; Thermal Performance

1. Introduction

Considering the current global environmental problems and demands for net zero energy buildings/houses (Chung, 2013), various energy saving methods should be developed. In this study, the authors applied a dynamic insulation (DI) technology to a timber framework house to reduce the energy consumption and to improve the indoor air quality. The concept of DI technologies is to draw outside air inward through insulation materials to recover conduction heat loss from inside the building. Research on DI technologies has been conducted for heavyweight structures such as masonry walls (Baily, 1987; Qiu, 2007; Gan, 2000; Imbabi 2013). However, few studies have applied DI technologies to a timber framework house. The authors conducted an experiment by simply applying DI envelopes to a timber framework house in a cold region. Compared to a conventional timber framework house, which prevents interstitial condensation with an airtight sheet, DI technology has the advantage of both improving the thermal performance and preventing interstitial condensation without an airtight sheet by introducing dry air in the building envelope (Note). This paper presents the results of the thermal performance evaluation.

2. Experimental Building

2.1 Details of the Experimental Building

The experimental building was constructed in Sapporo, Hokkaido using the timber framework method. The experimental building comprised a single room with dimensions of 1820 mm width × 2730 mm length × 2200 mm height. Fig.1 shows the floor plan and cross section plan of the experimental building. Wood fiber insulation (thermal conductivity of 0.038 W/mK) was installed in the ceiling, walls, and floor. The building included a window of triple-glazed low-E glass with Ar gas (u-value of 0.75 W/m²K) and door of double-glazed low-e glass (U-value of 1.23 W/m²K). A sirocco fan acted as an exhaust ventilation system.

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The sirocco fan had an inverter and damper to control the air flow rate and pressure difference between the inside and outside of the room. The specifications of the experimental building are given in Table 1. With DI, the ventilation inlet was sealed, and the outside air flowed inward through the ventilation holes in the walls. Without DI, the ventilation holes were sealed; therefore, the outside air flowed inward through the ventilation inlet. The area of the opening was adjusted to be equal to the total area of the ventilation holes in the case with DI.

2.2 Concept of the DI Technology Applied to an Experimental Building

The working principle of DI technologies is to draw outside air into the building envelope through porous materials to recover conductive heat loss. In this study, the authors applied a DI technology to the walls and ceiling of the experimental building. A ventilating layer was provided by siding materials outside the walls, and ventilation holes were opened within the walls from the inside to allow outside air to pass through the permeable insulation materials of the walls into the room. The outside air recovered conduction heat loss from inside the building when it passed through the walls. Fig.1. shows the areas with DI in red. Fig.2. shows a cross section of the DI-applied wall and outside air inflow route. Table 2. presents the details of the ventilation holes in the walls. The ratio of the area of ventilation holes to the total area of the DI-applied walls was approximately 0.03%.

2.3 Air Tightness Performance

The air tightness test was conducted in the experimental building. To maximize the effect of DI technology, a high level of air tightness is required in areas other than the DI-applied areas to pass a sufficient volume of outside air through the DI-applied walls. The equivalent leakage area was calculated by measuring the air flow rate and pressure difference between the inside and outside of the room. Fig.3. shows the air leakage graph. When no openings are established, the ventilation inlet and ventilation holes are sealed, and the equivalent leakage area is small. The equivalent leakage area of 0.26 indicates that the experimental building had a high level of air tightness. To calibrate the equivalent leakage area of the different cases, the air tightness test was performed for each case. For the case with DI, the authors measured the equivalent leakage area including the ventilation holes. For the case without DI, the ventilation holes were sealed, and the opening area of the ventilation inlet was adjusted to ensure the equivalent leakage area was equal to that of the case with DI. The results are shown in Table 3.

2.4 P–Q Characteristics of the Sirocco Fan

The air flow rate during the experiment was calculated by using the P–Q characteristics of a sirocco fan; these were obtained by measuring the differential pressure of the front and rear of the sirocco fan and the air flow rate. The output of the sirocco fan inverter was set to 48.8 Hz in all cases. The air flow rate during the experiment was calculated by the regression line of the P–Q characteristics. Fig.4. shows the graph of the P–Q characteristics of the sirocco fan.
3. Results
3.1 Experimental Condition
An experiment was conducted to evaluate the thermal performance on November 6–12, 2012. The thermal performance of the experimental building was evaluated according to the coefficient of heat loss from the entire building envelope; the results with and without DI were compared. This is because evaluating the thermal performance of each wall was difficult because the air flow rate of each wall could be different. With DI, the ventilation holes in the walls and ceiling were used as an air supply inlet, whereas the ventilation inlet was used as the air supply inlet in the case without DI. The experiment was conducted without DI on November 8–10 and with DI on November 10–12.

The inverter output of the sirocco fan was set to the identical frequency of 48.8 Hz in each case to equalize the electric consumption from the sirocco fan. The pressure difference between the inside and outside of the room was set to 20 Pa, and the air flow rate was set to 28 m$^3$/h. These values were determined by assuming that the DI technology was applied to one side of a room with 2.7 m width, 3.6 m length and 2.2 m height at 0.5 ACH. In this case, the ventilation rate is approximately 10.7 m$^3$/h (2.7 m x 3.6 m x 2.2 m x 0.5 ACH). Supposing that one wall in the room with 2.7 m width and 2.2 m height was used for the DI wall, the velocity at the wall was 1.8 m/h (10.7 m$^3$/h ÷ (2.7 m x 2.2 m)). When the velocity was applied to the DI wall in the experiment (area: 13.8 m$^2$), the required air flow rate was 24.8 m$^3$/h (1.8 m/h x 13.8 m$^2$). An air flow rate of 28 m$^3$/h was set to ensure that the air flow was more than required. The pressure difference between the inside and outside of the room was set to 20 Pa to reduce the influence of fluctuations in wind velocity. A radiant heater provided heat constantly to the room at an output of 400 W, and two electric fans stirred the air in the room. A fluorescent light was on throughout the experiment. Note that the pressure differences in this table indicate those between the outdoors and indoors. This difference is distinct from the sirocco fan pressure in Fig.4.

3.2 Results of Thermal Performance
3.2.1 Thermal Image
A thermal image of the case with DI was taken at the south wall of the experimental building at 19:40, 3 h after sunset. Fig.5. shows the thermal image and picture of the experimental building taken from the south. The right side of the south wall, shown in red in the picture, is the DI-applied wall. In a comparison of the right and left sides of the south wall, the outer surface temperature of the former was lower than that of the latter. This image qualitatively shows the effect of the DI system; the system decreases the temperature of the outdoor wall surface. This reduction originates from inside the building. The qualitative evaluation is presented in the next section.

3.2.2 Thermal Performance
To evaluate the thermal performance of the building envelope, the authors introduced the following formula to simply calculate $Q'$[W], which is the heat loss from the building envelope divided by the environmental temperature difference.

$$Q' = \frac{H - L - VP}{\theta_i - \theta_o}$$

$$L = \rho C_p V (\theta_{ea} - \theta_{out})$$

where $H$ [W] is the internal heat generation, $L$ [W] is the heat load because of ventilation, $V$ [m$^3$/s] is the air flow rate, $P$ [Pa] is the kinetic pressure in the exhaust air, $\theta_i$ and $\theta_o$ [°C] are the indoor and outdoor environmental temperatures, respectively, $\rho$ [kg/m$^3$] is the air density, $C_p$ [J/(kg K)] is the specific heat

Table 3. Equivalent Leakage Area

| Case          | Regression Line | Equivalent Leakage Area [cm$^2$/m$^2$] |
|---------------|-----------------|----------------------------------------|
| No Opening    | $\log P' = \log 0.11 + \frac{1}{0.93} \log \Delta P$ | 0.26                                   |
| Without DI    | $\log P' = \log 6.53 + \frac{1}{1.98} \log \Delta P$ | 2.94                                   |
| With DI       | $\log P' = \log 5.02 + \frac{1}{1.76} \log \Delta P$ | 2.63                                   |

Table 4. Experimental Conditions

| Case          | Air Supply Inlet | Pressure Difference | Air Flow Rate (Measured Value) | Indoor Load Condition |
|---------------|------------------|---------------------|-------------------------------|-----------------------|
| Without DI    | Ventilation inlet 20 Pa | 28 m$^3$/h (28.6 m$^3$/h) | Radiant heater 400 W Electric fans 40 W Flourescent light 35 W Sirocco fan 5 W |
| With DI       | Ventilation holes 20 Pa | 28 m$^3$/h (27.3 m$^3$/h) | | |

Fig.4. P–Q Characteristics of the Sirocco Fan
capacity of air, and $\theta_{ea}$ and $\theta_{out}$ [°C] are the exhaust and outdoor air temperatures, respectively.

The heat loss from the building envelope was obtained by subtracting the sum of the ventilation load and kinetic energy of the ventilation from the rate of internal heat generation and dividing this value by the environmental temperature difference between the indoors and outdoors. The rate of internal heat generation is given by adding the measured energy consumption to the assumed energy consumption from the fluorescent light (35 W) and sirocco fan (5 W). In this experiment, the indoor environmental temperature was provided by the global temperature located at the center of the room, and the outdoor environmental temperature was provided by the sol-air temperature (SAT) for a horizontal surface at the site (Hattori, 2008).

Fig.6. shows the variation in heat loss during the experiment. Fig.7. shows the measured heat loss for each weather condition. The hourly averaged data from 17:00 to 6:00 was used to exclude the influence of solar radiation. Fig.7. shows that the heat loss in the case with DI was reduced compared to the case without DI under the identical weather conditions of cloudy and rainy. A statistically significant difference was recognized in the heat loss of each case ($p < 0.05$). This suggests that the thermal performance improved by using the DI technology. Although the data were only obtained for the case with DI, the rate of heat loss decreased in clear weather, which implies a dependence on the weather. The reference outdoor environmental temperature was lower than the actual temperature in clear weather because the outdoor environmental temperature was taken from the SAT for a horizontal surface at the site.

![Fig.5. Thermal Image and Picture of the Experimental Building](image-url)

![Fig.6. Variation in Heat Loss during the Experiment](image-url)
The Q value was used to evaluate the effect of applying DI technology. Table 5. shows the Q value and details of the heat loss from each element. The Q value of the experimental building was calculated to be 2.30 W/m²K based on the specifications. The actual Q value was calculated to be 2.26 W/m²K based on the measured heat loss from the entire building envelope in the case without DI. Assuming that the difference between the theoretical and actual Q values was because of a construction error, the difference was distributed at the area ratio to the heat loss from the walls. To account for the heat loss from the DI-applied area, the heat loss difference between the cases with and without DI was assumed to be because of the effect of the DI technology. The heat loss per unit temperature at the DI-applied area was 3.19 W/K without DI and 1.83 W/K with DI. This indicates that applying DI technology reduced the heat loss by 42.6%.

4. Conclusion
The authors applied DI technology to the walls and ceiling of a timber framework house and evaluated the thermal performance through actual measurements. The heat loss through the building envelope was significantly reduced with DI technology. The heat loss was reduced by 42.6% for the DI-applied wall.

This study mainly focused on the thermal performance. The application of DI technology, however, has a risk of decreasing the thermal comfort because of the decrease in the inner wall surface temperature. Conversely, the application can also contribute to an increase in thermal comfort because of a rise in temperature resulting from outdoor air intake. These phenomena have been analyzed in continuous studies (Yaegashi, 2014).

Note
Whereas the air-conditioning system is on in the summer, the air flow should be reversed to prevent condensation in the wall by introducing cooled and dried indoor air into the wall. The indoor wall surface temperature approaches the indoor air temperature and the heat flow from indoors to the indoor wall surface decreases. Concurrently, the outdoor wall surface temperature approaches the indoor air temperature resulting in the increase in the heat flow from the outdoor wall surface to the outdoors. The increased heat flow, however, can be replaced by the heat flow between the exhaust air and outdoor environment. Thus, this flow does not result in an increase in the heat loss through the wall when the heat loss is discussed for the entire building system. In winter, the heat loss because of exhaust air can be recovered by heat pump systems, whereas the recovery is difficult in summer. In this sense, the application of the DI system has an advantage in winter.

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Symbols
\[ C_p \]: specific heat capacity of air [J/(kg K)]
\[ H \]: internal heat generation [W]
\[ L \]: heat load because of ventilation [W]
\[ P \]: kinetic pressure in the exhaust air [Pa]
\[ Q \]: heat loss from the building envelope divided by the environmental temperature difference [W]
\[ V \]: air flow rate [m³/s]
\[ V' \]: air flow rate [m³/h]
\[ \Delta p \]: pressure difference [Pa]
θ_i: indoor environmental temperature [°C]
θ_o: outdoor environmental temperatures [°C]
θ_ea: exhaust air temperatures [°C]
θ_out: outdoor air temperatures [°C]
ρ: air density [kg/m³]