IOP Conference Series: Earth and Environmental Science

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To cite this article: T Kubota and M A Zakaria 2019 *IOP Conf. Ser.: Earth Environ. Sci.* **294** 012089

IOP Conf. Series: Earth and Environmental Science **294** (2019) 012089 doi:10.1088/1755-1315/294/1/012089

Full-Scale Experiment on Energy-Saving Effects of Thermal Insulation for Urban Houses in Malaysia

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Abstract. This study investigates the energy-saving effects of thermal insulation for existing urban houses in Malaysia through the full-scale experiment. The experiment was conducted in two units of experimental houses located in the city of Johor Bahru, Malaysia from July to September 2017. The effects of external/internal insulation were examined under two different conditions, namely (1) naturally ventilated condition and (2) partial air-conditioning condition (where ACs were used only in master bedrooms), compared with the control unit. The results suggest that under the condition of night ventilation, external wall insulation is preferable for a high thermal mass building, whereas internal insulation prevents the effect of structural cooling during daytime. On the other hand, under the partial AC condition, internal insulation for the master bedroom is apparently a better option than external insulation. The cooling load of the room was reduced by up to 69.6% compared to the control room. It was also found that the modifications for other spaces were not effective in reducing the cooling load of the air-conditioned master bedroom.

1. Introduction

Energy consumption for space cooling in buildings has been increasing rapidly in developing countries particularly in the hot climates such as Southeast Asia. In fact, the ownership level of air-conditioner (AC) among households has increased in this region [1]. In Malaysia, for example, the total population has almost doubled over the last three decades and reached about 30 million people at present. The stable economic growth over the same period induced the rapid increase in nationwide energy demand by more than five times. Most of the urban houses in Malaysia are constructed of brick and concrete. The brick-walled houses account for approximately 91% of the urban houses [2]. These brick houses are becoming the norm across the cities in Southeast Asia. In the case of Malaysia, terraced houses are considered the most common housing type, which accounts for about 45% of all the urban houses [2].

Thermal insulation is a promising energy-saving strategy in the cold or moderate climates. However, it is rarely applied for residential buildings in the hot-humid developing countries. Despite the widespread of brick houses, it is still unsure whether thermal insulation is effective for those brick houses in the hot-humid climates. In 2015, we have constructed a full-scale experimental house in the main campus of *Universiti Teknologi Malaysia* (UTM), which is located in the city of Johor Bahru, Malaysia. This study investigates the energy-saving effects of thermal insulation for existing urban houses in Malaysia through the full-scale experiment using the UTM experimental house.

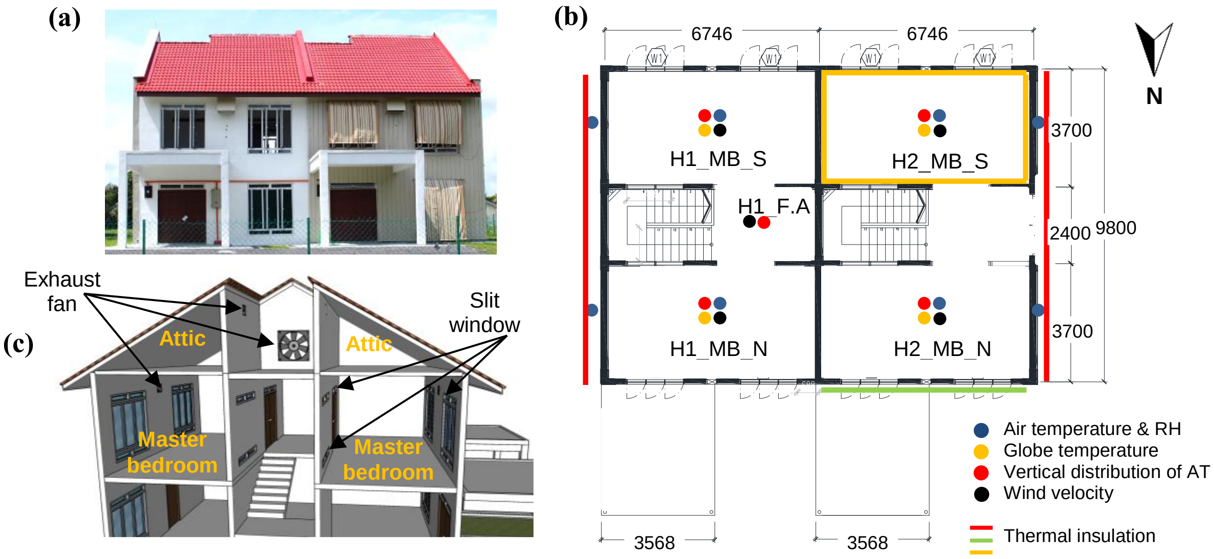

Figure 1. UTM experimental house. (a) Front view; (b) 1st floor plan and instrument setting; (c) additional passive cooling modifications.

Table 1. Experimental cases

	House 1: Control		House 2: Measurement	
	H1_MB_S	H1_MB_N	H2_MB_S	H2_MB_N
Naturally ventilated condition				
Case 1: Full-day ventilation	Control	Control	Internal insulation	External insulation
Case 2: Night ventilation	Control	Control	Internal insulation	External insulation
Partial air-conditioning condition				
Case 3: Daytime ventilation	Control	Control	Internal insulation	External insulation
Case 4: Night ventilation	Control	Control	Internal insulation	External insulation
Case 5: Night ventilation with window shading and whole house ventilation	Control	Control	Internal insulation	External insulation

2. Methodology

The full-scale experiment was conducted in two units of the UTM experimental house from July to September 2017 (1°29'N 103°44'E). The experimental house was designed to represent typical floor plans of existing terraced houses (Fig. 1). Each of the units measured approximately 6.7 m by 9.8 m with a total floor area of 127 m^2. As shown, the front façade of buildings is oriented towards north. It was constructed of brick and concrete, and has single glazing windows. In addition to the original plans, small slit windows were added onto the upper and lower parts of the main windows, partition walls, and doors (Fig. 1c). Moreover, exhaust fans were installed on the attic spaces, master bedrooms and staircase halls. Both end walls were insulated originally to eliminate the thermal influences from the outdoors.

In the experiment, one of the units (House 2) was equipped with thermal insulation (i.e. measurement unit), whereas the other unit (House 1) was remained unchanged as the control unit (Fig. 1). As shown, in House 2, the external insulation was adopted for one side of the unit (H2_MB_N), while the internal insulation (all walls, floor and ceiling) was applied for the master bedroom of another unit (H2_MB_S). The thermal resistance of the external and internal insulation of rock wool is 3 m^2·K/W and 1.5 m^2·K/W, respectively.

As summarized in Table 1, the effects of external/internal thermal insulation were examined under two different conditions, namely (1) naturally ventilated condition and (2) partial air-conditioning (AC) condition, in which ACs were operated only in master bedrooms, compared with the control unit. In both conditions, air temperature, RH, wind speed and globe temperature were measured at 1.1 m height above the floor (T&D TR-72WF; Vaisala HMP155-A; Kanomax 0965-03). Vertical distribution of air temperature was also measured at the centers of master bedrooms (Type T thermocouple and Graphtec GL-820). In addition, the detailed temperature gradients of the external walls of master bedrooms were measured by thermal couple wires. The outdoor weather data were recorded by a weather station (HOBO Pro V2 and U23-001) located in an open space approximately 40 m away from the experimental house.

The ACs used in the partial AC condition were non-inverter models (DAIKIN R410) with a cooling capacity of 3,517 W (COP: 3.18). Air temperature and RH were recorded at the inlet of AC, whereas air temperature, RH, air pressure and wind speed were measured at the outlet. Moreover, power consumption of each AC was recorded using a clamp meter during its operation (Graphtec CTT-CLS-CV250 and GL820). Sensible load and latent load from AC were calculated by the following formulas.

$$Q = Q_s + Q_l \quad (1)$$

$$Q_s = \rho U C_p \Delta T \quad (2)$$

$$Q_l = \rho U \lambda C_p \Delta X \quad (3)$$

Where Q_s is sensible load, Q_l is latent load, Q is cooling load, ρ is air density (kg/m^3), U is air flow rate of AC (m^3/s), C_p is air specific heat (kJ/kg℃), λ is latent heat of vaporization (kJ/kg), ΔT is difference

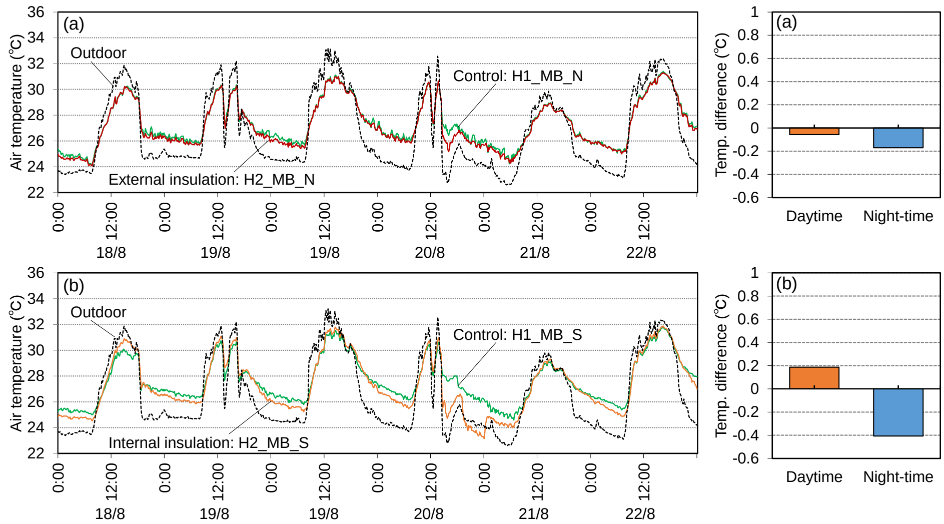

Figure 2. Indoor air temperature differences in the master bedroom in Case 1 (full-day ventilation). (a) External insulation (H2_MB_N); (b) internal insulation (H2_MB_S).

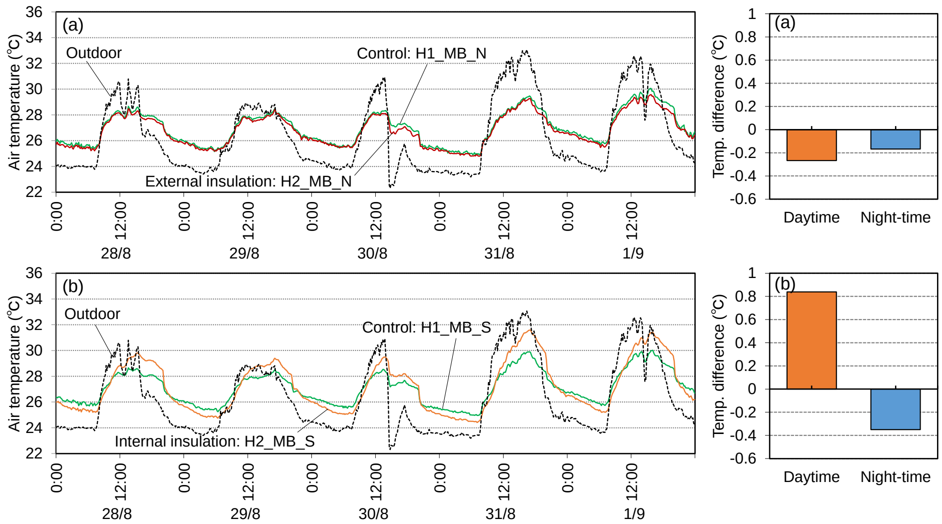

Figure 3. Indoor air temperature differences in the master bedroom in Case 2 (night ventilation). (a) External insulation (H2_MB_N); (b) internal insulation (H2_MB_S).

of air temperature between inlet and outlet (℃), and ΔX is difference of absolute humidity between inlet and outlet (kg/kg').

3. Results and Discussion

3.1. Naturally ventilated condition

Fig. 2 shows the temporal variations of measured air temperatures and the average air temperature differences in Case 1 that analyze the effects of external/internal insulation under the full-day ventilation condition. The outdoor air temperature during the measurement period ranges from 22.8-33.0°C. As shown, for both cases (external and internal insulation), there is almost no air temperature reduction (less than ±0.2°C) during the daytime due to the inflow of warm outdoor air into the rooms. Meanwhile, at night, the room with the internal insulation (H2_MB_S) shows a better reduction of about 0.4°C on average than that of external insulation (H2_MB_N). This is mainly because the internal insulation prevents the heat flow from entering the rooms from the warmed building structure.

Fig. 3 presents the results of Case 2 that analyzes the effects of both insulations under the night ventilation condition. In this case, during daytime, the master bedroom with external insulation

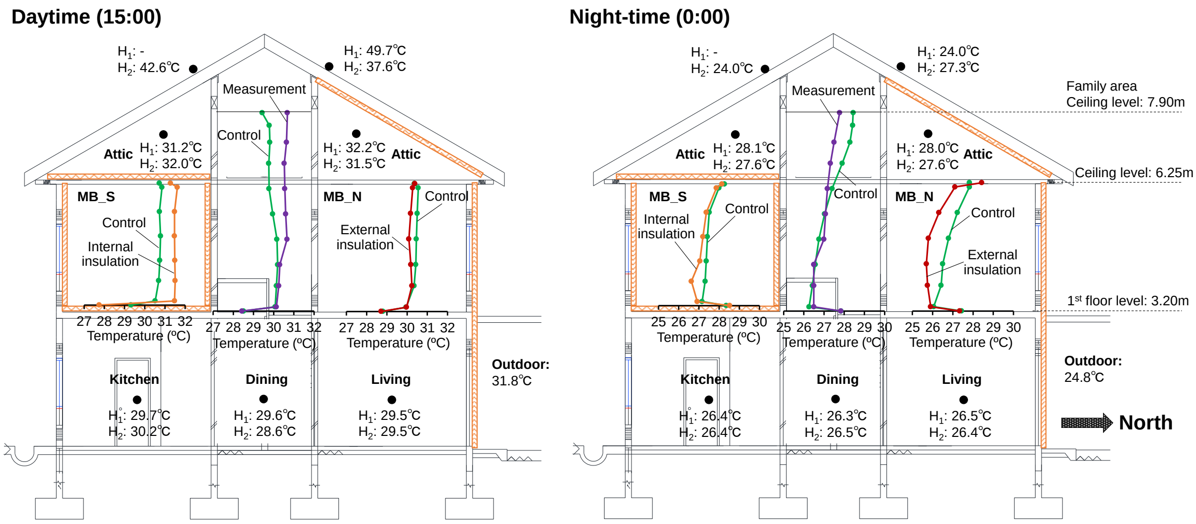

Figure 4. Vertical distribution of air temperature in the master bedrooms in Case 1 (full-day ventilation).

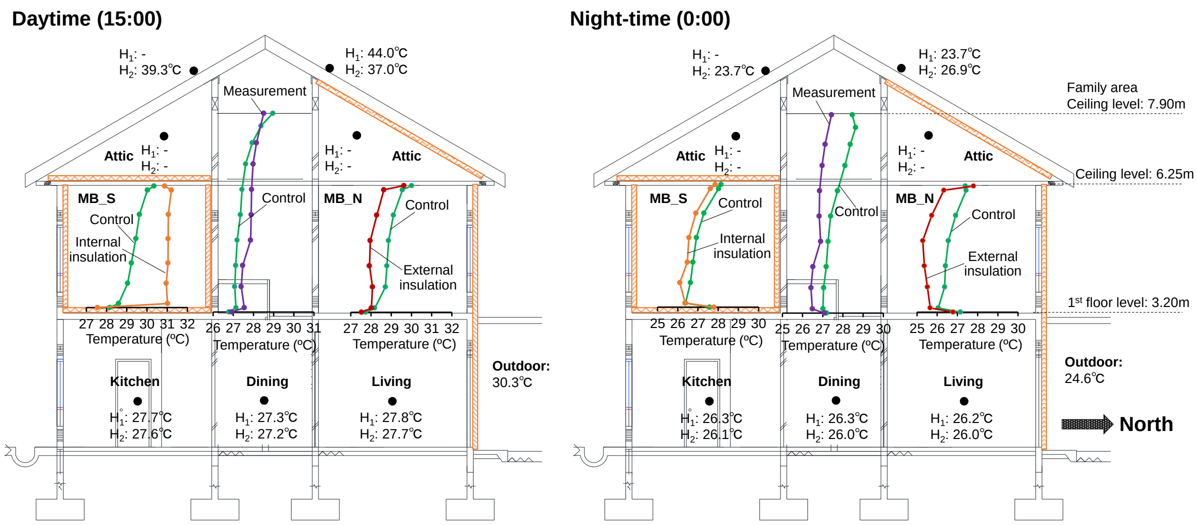

Figure 5. Vertical distribution of air temperature in the master bedrooms in Case 2 (night ventilation).

(H2_MB_N) obtain the temperature reduction of about 0.3°C on average due to the reinforced structural cooling effect. In contrast, the air temperature is increased with internal insulation (H2_MB_S) by about 0.8°C than that of control room. This is because the internal insulation diminishes the structural cooling effect. As before, at night, the room with internal insulation shows slightly better air temperature reduction compared to that of external insulation, which is about 0.4°C, compared to that of the control room.

Figs. 4 and 5 illustrate the vertical distribution of air temperature in the master bedrooms under the full-day ventilation and night ventilation, respectively. As shown, internal insulation is ineffective in lowering air temperature during daytime regardless of window-opening conditions. Under the internal insulated conditions, the daytime air temperatures can be as high as the corresponding outdoor temperatures. In contrast, clear temperature gradients can be seen during daytime in other rooms under closed-window conditions, showing the structural cooling effect, especially in the room with external insulation. Meanwhile, air temperatures are almost the same in ground floor rooms between control unit (H_1) and insulated measurement unit (H_2) throughout the day. This means that the effects of insulation installed at the roof/ceiling and first floor rooms do not reach the ground floor rooms.

3.2. Partial air-conditioning condition

In Cases 3-5, we analyze the effects of external/internal insulation under the partial air-conditioning conditions, given that air conditioners are used from 21:00 p.m. to 6:00 a.m. in each of the master bedrooms with a set point temperature of 23°C. Fig. 6 shows the resultant cooling load of the air conditioners under three experimental conditions (see Table 1).

As shown in Fig. 6a, overall, the cooling load in the room with external insulation is larger than that of control room in all cases. The cooling load is increased by about 22.7%, 17.0% and 24.2% in

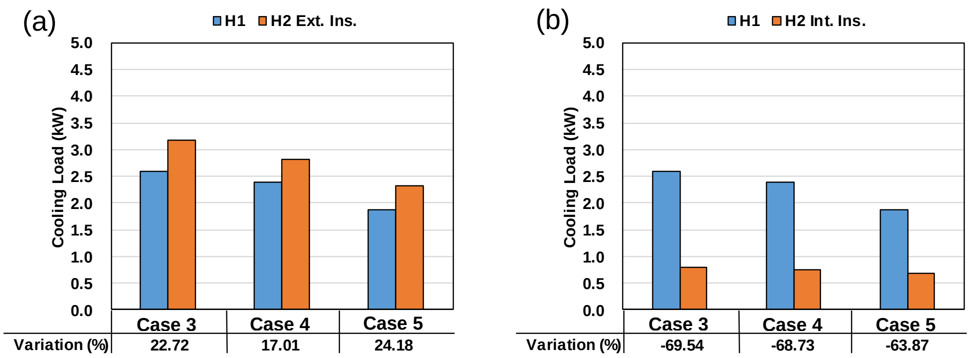

Figure 6. Cooling load of air conditioner in the master bedrooms under partial air-conditioning conditions in the cases of (a) external insulation (H2_MB_N) and (b) internal insulation (H2_MB_S).

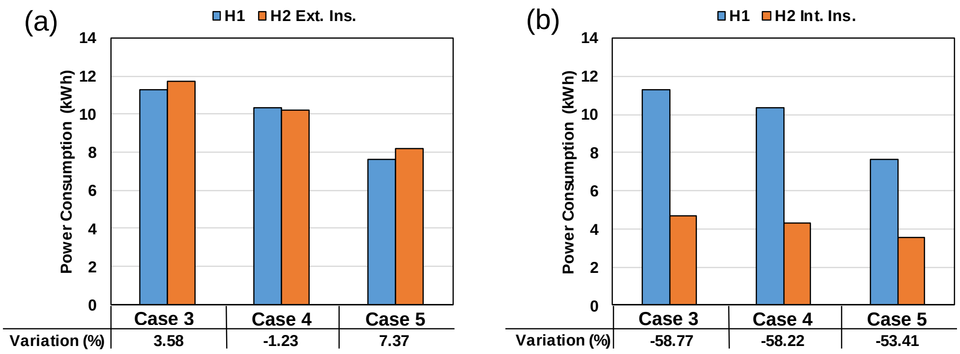

Figure 7. Power consumption of air conditioner in the master bedrooms under partial air-conditioning conditions in the cases of (a) external insulation (H2_MB_N) and (b) internal insulation (H2_MB_S).

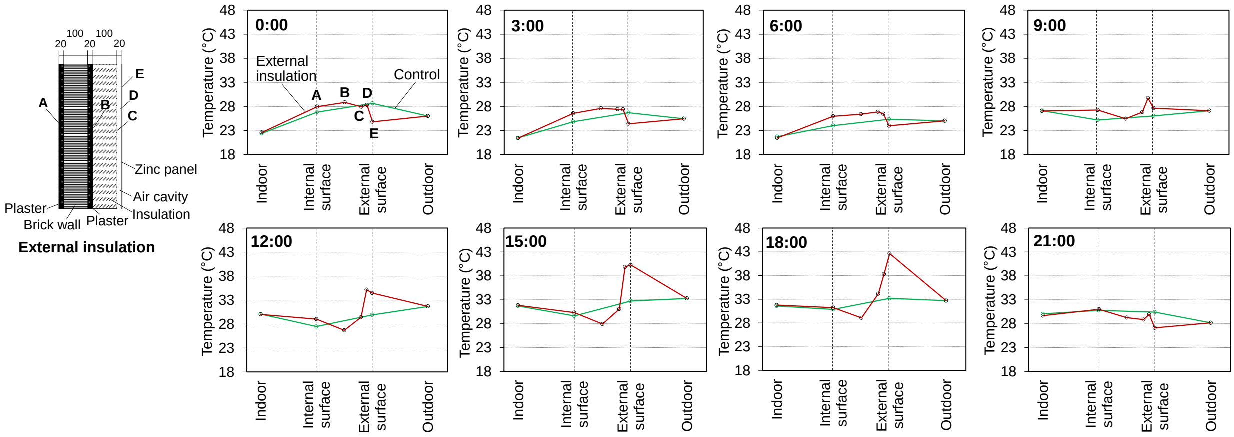

Figure 8. Temperature gradient of external walls with/without external insulation under partial air-conditioning condition in Case 3 (daytime ventilation).

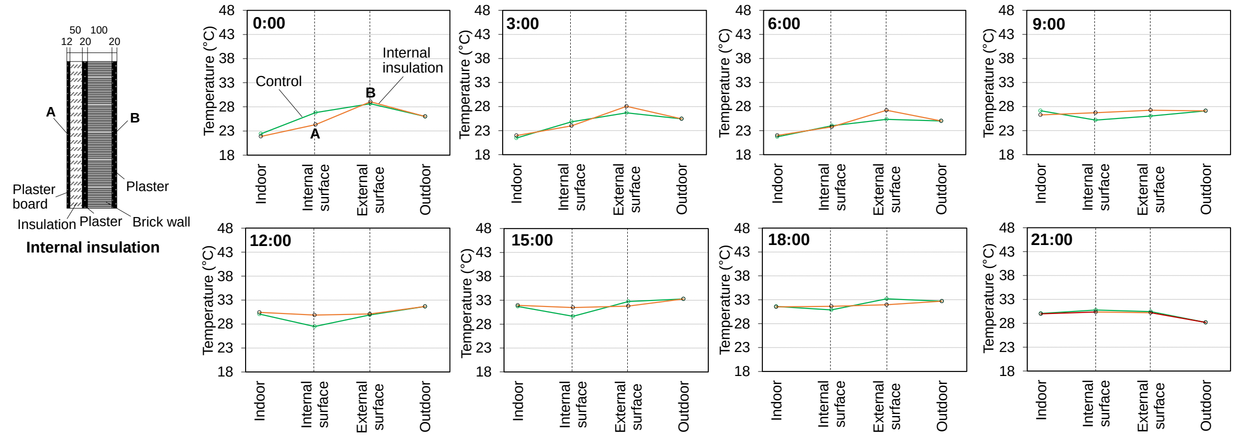

Figure 9. Temperature gradient of external walls with/without internal insulation under partial air-conditioning condition in Case 3 (daytime ventilation).

Cases 3-5 respectively. In contrast, the cooling load in the room with internal insulation is decreased efficiently by about 69.6%, 68.7% and 63.9% respectively (Fig. 6b). This indicates that the internal insulation is better able to provide lower cooling load in the master bedroom compared to that of the external insulation. Meanwhile, there is no significant difference of cooling load among the three cases. This means that modifications for the other spaces are not effective in reducing the cooling load of the master bedroom.

As indicated in Fig. 7, the resultant power consumptions show similar profiles with those of cooling loads. As shown, the external insulation slightly increased the power consumptions in Cases 3 and 5. Meanwhile, the power consumption in the room with internal insulation is reduced by approximately 58.8%, 58.2% and 53.4% respectively (Fig. 7b).

Fig. 8 depicts the detailed temperature gradient of external walls with/without external insulation under partial AC condition in Case 3 (daytime ventilation) for example. During night-time, the external insulation prevents the heat release to the outdoors. As a result, from 0:00 to 12:00 noon, the internal surface temperatures of external wall with external insulation are approximately 1.1-2.4℃ higher than those of control unit. This increased the cooling load of the room with external insulation compared with the control unit (see Fig. 6a). The surface temperature of zinc panel is increased up to 46.3℃ during the peak hours, but this does not affect the surface temperature of insulation form thanks to the naturally ventilated air cavity.

Fig. 9 shows the same temperature gradient with/without internal insulation in Case 3 for example. The effect of internal insulation is apparent during the period of AC operation (21:00 to 6:00). Especially during the early morning, the internal surface temperatures of external wall with internal insulation are up to 3.3℃ lower than those of control unit. This contributed to reduce its cooling load and thus power consumption significantly (see Figs. 6b and 7b). On the other hand, the said internal surface temperatures are approximately 1.3-2.4℃ higher than those of control unit during daytime. This is because the internal insulation diminished the structural cooling effect as seen in the previous section.

4. Conclusions

- Under the naturally ventilated condition, external wall insulation is probably preferable for high-thermal-mass buildings. Internal insulation may prevent the effect of structural cooling during daytime.
- Under the partial air-conditioning condition, internal insulation for the master bedroom is apparently a better option than external insulation. The cooling load of the room was reduced by up to 69.6% compared to the control room. It was also found that the modifications for other spaces were not effective in reducing the cooling load and power consumption of the air-conditioned master bedroom.

Acknowledgements
This research was supported by grants from Nichias Corporation and Asahi Glass Foundation.

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