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Shading effects on the winter thermal performance of the Trombe wall air gap: An experimental study in Dalian

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Abstract

There has been little research on the application of shading devices in the air gap of the Trombe wall in China. Experiments on the thermal performance of an advanced Trombe wall with shading in the air gap was conducted in a passive solar house in Dalian. The thermal performance was investigated with regard to the simultaneous temperatures, heat gain and their acquisition of the Trombe wall. By analyzing experimental data, an investigation was carried out on the heat preservation effect by the shading device on a winter night. The theoretical optimum fixed location of the shading in the air gap for minimizing the heat loss was also discussed. Finally, the influence of shading on improving indoor thermal comfort was discussed using the concept of the building envelope response factor (BER) presented earlier by Lukic [The transient house heating condition—the building envelope response factor (BER). Renewable Energy 2003;28(4):523–32].

Keywords: Passive solar house; Trombe wall; Shading device; Night insulation; Energy efficiency

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1. Introduction

To enhance the thermal storage effect of a Trombe wall, various techniques have been developed and used, such as installing an absorber plate in the air gap and using a black surface of the heat storage wall. For the sake of reducing heat loss of the Trombe wall at

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Nomenclature

λ_e	equivalent thermal conductivity, W/(m^2 °C)
λ	thermal conductivity, W/(m^2 °C)
Gr_δ	Grashoff number, $\mathrm{Gr}_\delta = gl^3\alpha\Delta T/\nu^2$
Pr	Prandtl number, $\mathrm{Pr} = \nu/a$
ε_c	dimensionless convective coefficient, which is a function of $\mathrm{Gr}_\delta\, Pr$,
T_{wo}	external surface temperature of the Trombe wall, °C
T_w	core temperature of the Trombe wall, °C
T_{wi}	inner surface temperature of the Trombe wall, °C
T_a	air temperature of the air gap, °C
T_s	shading temperature, °C
T_g	inner surface temperature of the glazing, °C
T_m	characteristic temperature of the air in the gap, °C
T_o	outdoor temperature, °C
ΔT_{wg}	temperature difference between the inner surface of the glazing and external surface of the massive wall, °C
ΔT_{sg}	temperature difference between the inner surface of the glazing and the shading, °C
SR	solar radiation, MJ
BER	building envelope response factor, kW °C h^2
DH	degree–hour number, °C h

Subscripts

e	east side (no shading)
w	west side (shading)

night in a cold climate, insulated layers are installed outside the massive walls. But the outside insulated layer also greatly weakens its heat storage capacity. In order to improve heat accumulation of the massive wall at daytime and reduce its heat loss at nighttime, a shading device is installed in the air gap in a passive solar house in Dalian, China. In winter, the shading device can be opened at daytime to allow the black massive wall to absorb solar heat directly and shut down at night to minimize heat loss of the wall. In summer, the shading device can be closed at daytime to decrease the direct heat gain from solar radiation and prevent overheating.

An experiment was carried out in the passive solar house to investigate thermal performance of the Trombe wall with a shading device in the air gap during a winter period at night from February 12 to 16, 2004.

2. Experiments

2.1. Test cell

One test room and one reference room are included in our experiment (see Fig. 1). The two rooms are partitioned by a 100 mm thick styrofoam panel. The volumes of both rooms

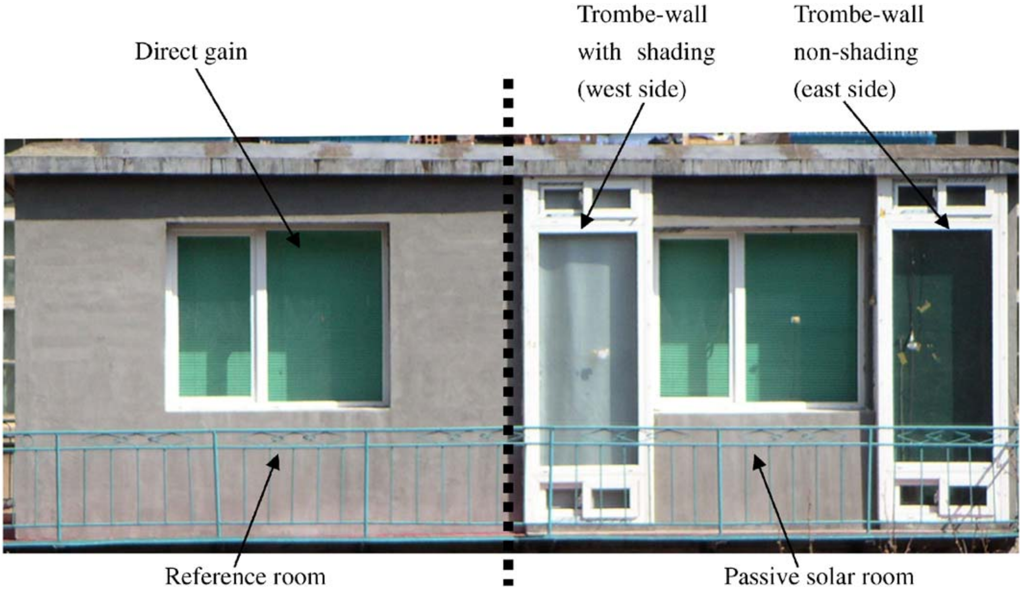


Fig. 1. South facade view of the test room (right) and the reference room (left).

are 3.9 (long) × 3.9 (wide) × 2.7 (high) m^3. In our Trombe wall system, a south-facing concrete wall is located behind the double glazing to form a narrow air gap. The massive wall is constructed of 300 mm thick concrete. A shading device with a low emissivity is introduced in the air gap to avoid overheating in summer and improve insulation in winter. Two pairs of rectangular vents, each of size 0.17 m × 0.15 m, were located at the bottom and top of the massive wall. Except for the south wall of the test room, the other components of both the rooms are constructed to be the same. The external walls are made of 300 mm thick cinder block and 100 mm thick styrofoam panels. The ceiling is made of 80 mm thick concrete and 100 mm thick styrofoam panels. The structure of the Trombe wall and temperature probe locations are shown in Fig. 2.

2.2. Measurement

This experiment was carried out from February 12 to 16, 2004. Measured parameters include solar radiation SR, outdoor air temperature T_o, air temperature in the gap T_a, temperature of the massive wall T_w, inner surface temperature of glazing T_g and inner/external surface temperatures of the massive wall T_{wi} and T_{wo}, respectively. Data were recorded every 10 min and saved by a computerized data-logger. Climate data (temperature, relative humidity, wind speed and direction) were also recorded every 10 min by a WMR968 cable-free weather station driven by a solar cell, and hourly solar radiation accumulative value was measured by a PC-2 Pyranometer.

To study the effect of the shading device on insulation performance of the massive wall, a comparative experiment is designed. The shading device on the east side was opened throughout the day and that on the west side was controlled depending on the weather, which was opened during sunshine periods and closed at cloudy weather or at night. The

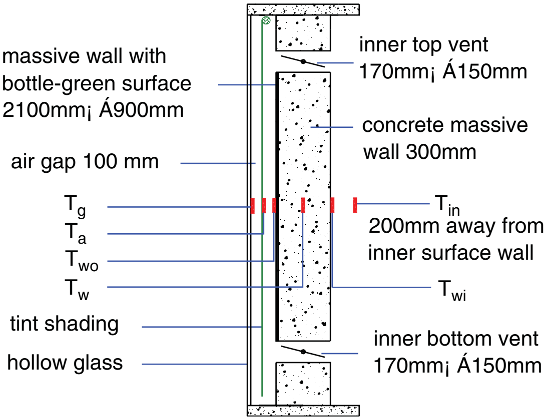


Fig. 2. Schematic diagram of the structure and locations of temperature probes of the Trombe wall.

Table 1
Shading operation of the west side and weather conditions

Date	Weather	Ambient temperature (°C)		Open/close time of the shading of the west side	
		Highest	Lowest	Open	Close
February 12, 2004	Fine	10	0	8:45	17:05
February 13, 2004	Cloudy and rainy	8	−1	11:00	16:30
February 14, 2004	Fine	7	0	8:45	17:22
February 15, 2004	Cloudy	9	−2	9:00	17:10
February 16, 2004	Cloudy	4	−2	8:35	17:05

shading operations of the west side and the weather conditions during the experimental period are summarized in Table 1. During the experimental period, the ambient temperature ranged between −2 and 10 °C.

3. Experimental results and discussion

3.1. Preservation effect of the shading

Fig. 3 shows the temperature of each probe in the air gap during the experimental period. It is observed that T_a and T_{wo} of the east side are both about 2 °C lower than those of the west side at night. On the contrary, T_g of the west side is about 1–3 °C higher than that of the east. This result is consistent with the insulation effect of the shading device at night. The use of the shading device makes the wall less influenced by the outdoor environment and the wall temperature is increased by minimizing the heat loss. But the glazing temperature dropped along with a lower heat gain from the wall. So the temperature difference between the two vertical surfaces (the external surface of the massive wall and the inner surface of the glass panel) of the east side (ΔT_{wge}) is about 5 °C

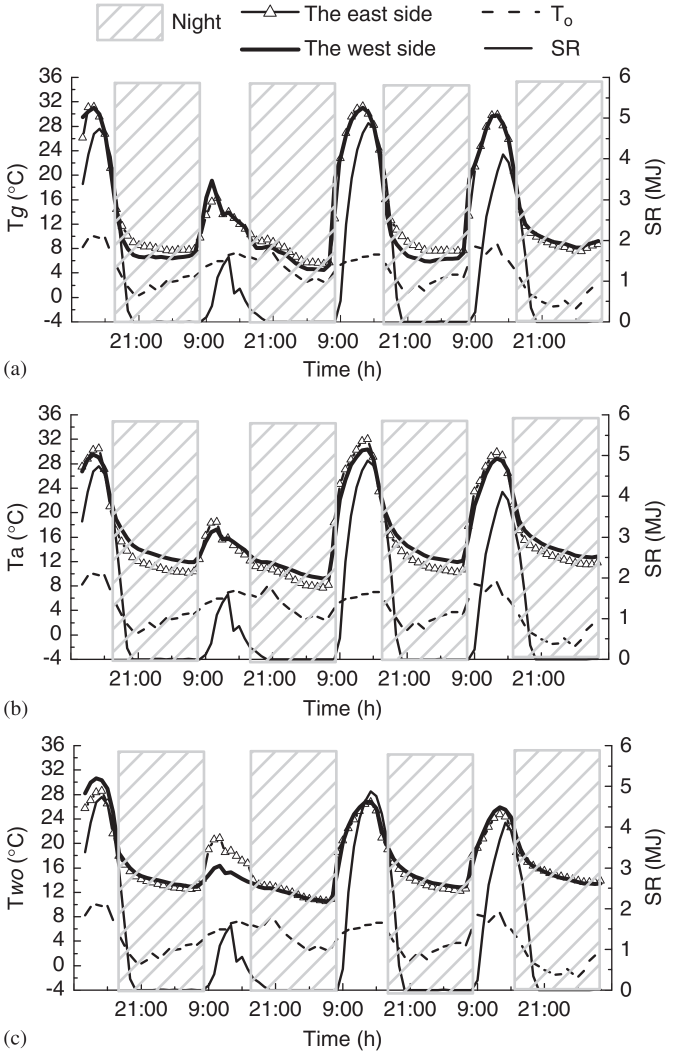
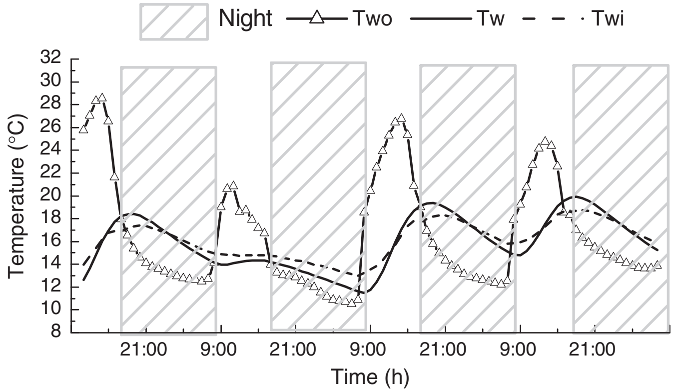


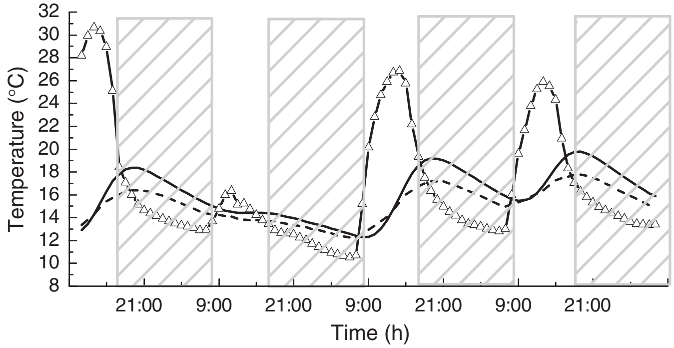
Fig. 3. Hourly temperature variations of probes in the air gap.

lower than that of the west side (ΔT_{wgw}) and this temperature difference has a direct effect on conductive and radiative heat transfer which is discussed in the following section.

Fig. 4 shows the temperature profile of the massive wall. On the west side, both inner and external surface temperatures of the wall are lower than the core temperature of the wall ($T_{\mathrm{wow}} < T_{\mathrm{wiw}} < T_{\mathrm{ww}}$) at night. The temperature difference between the core and the external surface is larger than that between the core and inner surface. Thus, the heat loss to the air gap is more than the heat loss to the room on the west side [1]. It should meliorate the shading design (material or fixed location) to improve its insulation performance. But on the east side, T_{wie} is sometimes higher than T_{we} at night. It means that the indoor environment loses more heat to the outdoor without shading than with shading.



(a) The east side



(b) The west side

Fig. 4. Hourly temperature variations of probes in the Trombe wall.

3.2. Analysis of heat transmission

When investigating the thermal performance of a traditional wall in winter, its heat transfer process can be approximately regarded as a steady state because mean temperature difference between indoor and outdoor is much larger than the oscillating value of the outdoor temperature [2]. But for the special structure of the Trombe wall, the heat transfer process becomes rather complex. Due to the fact that the periodic solar radiation and ambient temperature have a large integrative influence on the air temperature in the air gap, the wall heat transfer process becomes unsteady according to the studies in [3,4]. The mathematical model for the narrow air gap should thereby be the unsteady state.

In order to evaluate the performance of the conduction and convection in the overall heat transfer process of the air gap, an equivalent conductivity λ_e [4] is introduced, which represents the proportion of conduction and convection in the heat transfer process:

$$\varepsilon_c = \lambda_e/\lambda. \tag{1}$$

For $1.0 \times 10^3 < \mathrm{Gr\,Pr} < 1.0 \times 10^9$ in the present study, the following equation is used to evaluate ε_c:

$$\varepsilon_c \approx 0.18(\mathrm{Gr}_\delta\,\mathrm{Pr})_m^{1/4}. \tag{2}$$

When $\varepsilon_c = 1.0$, it means only conduction exists in the air gap. If the ε_c value is much larger than 1.0, natural convection dominates in the whole process and the conductive heat transfer can be neglected. In this experiment, $\varepsilon_c = 4.1$ on the east side and $\varepsilon_c = 3.8$ on the west side, which are both larger than 1.0. But in order to clarify the thermal performance of the shading device more accurately, the conductive, radiative and convective heat transfer processes of the air gap are all considered.

3.2.1. Conductive heat transfer

The thickness of the shading is about 0.2 mm and its thermal conductivity is infinitesimal compared with that of the air in the gap. Thus, only the air conductive thermal resistance is taken into account in calculating conductive heat transfer between the wall and glazing. Fig. 5(a) shows the hourly heat loss of the air gap. It can be observed that conductive heat loss of the air gap with shading (about 297.0 kJ) is slightly larger than that without shading (about 240.0 kJ) at night, since ΔT_{wg} of the west side is slightly higher than that in the east and it has already been illustrated in Section 3.1. Although the conductive heat loss is increased a little using shading, its insulative performance is positive, because the contribution from heat conduction is the least one to the whole heat transfer process and it will be clarified further in the following section.

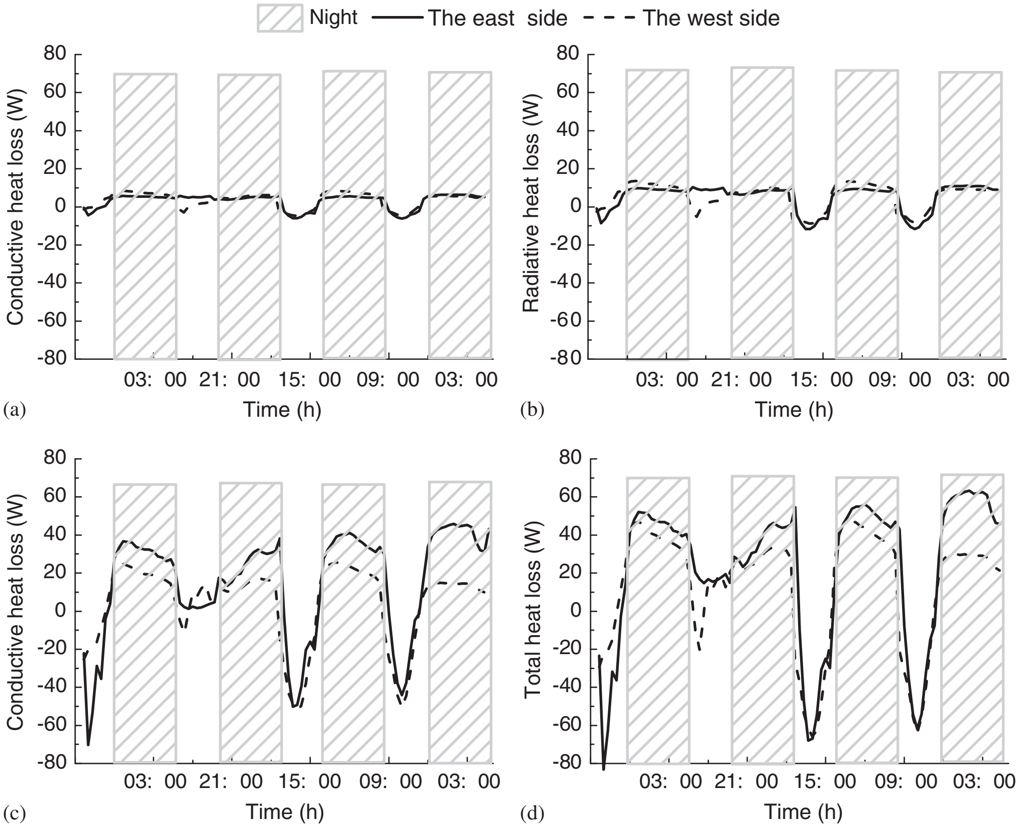


Fig. 5. Comparison of hourly heat loss in the air gap.

In this experiment, the conductive thermal resistance of the shading is so small that it can be ignored in the calculation. But changing its conductive resistance by way of changing shading material or increasing its thickness, the total thermal resistance of the air gap of the west side is increased and the conductive heat loss is correspondingly decreased. According to our simple estimation, the conductive heat loss in the west side drops less than that in the east side when the shading conductive coefficient is greater than 3.0 $\mathrm{m^2\,{}^\circ C/W}$. Normally, the thermal resistance should be as high as possible, but the feasibility of the installment should be also considered in practice.

3.2.2. Radiative heat transfer

It is well known that glazing can effectively prevent long-wave radiation to the sky, which is emitted from the external surface of the black–green wall at night. Therefore, the radiative heat transfer mainly occurs between the external surface of the massive wall and the inner surface of the glazing, and it is a function of the temperature difference between them. For the west side, T_a and T_s are almost close to T_{wo}. Thus, the radiative loss between the shading and the massive wall can be ignored and the radiative loss mainly occurs between the shading and glazing. Fig. 5(b) illustrates the hourly radiative loss in the gap of the east and west sides at night. It seems that the mean value of the radiative loss in the gap of the west side (about 543.0 kJ from the shading to the glazing) is a little more than that of the east side (about 510.0 kJ from the wall to the glazing), which is due to the relatively higher temperature difference ΔT_{sg}. However, the use of shading can prevent radiative loss from the wall to the glazing directly at night.

Furthermore, emissivity of the shading is a main factor that influences radiative heat transfer. Shading with a low emissivity and a high radiative resistance can further decrease the heat loss at night.

3.2.3. Convective heat transfer

According to the theory of natural convection in a narrow space [1], the thickness of the air gap has a great impact on the air flow pattern. So varying the thickness of the air gap is another way to reduce heat loss. In this experiment, the air gap thickness is 100 mm on the east side, while on the west side, the air gap is divided into two 50 mm spaces and the shading thickness is ignored. Because of the relative larger cross-section size of the air gap (2.7 m × 0.1 m), the relatively lower air temperature and current velocity, the air flow pattern is considered as laminar in the gap. The Nusselt number can be calculated by Eqs. (3) and (4):

$$\mathrm{Nu}_\delta = 0.197(\mathrm{Gr}_\delta\,\mathrm{Pr})^{1/4}\left(\frac{\delta}{h}\right)^{1/9} \quad 6000 < \mathrm{Gr}_\delta\,\mathrm{Pr} \leqslant 2.0\times10^5, \tag{3}$$

$$\mathrm{Nu}_\delta = 0.073(\mathrm{Gr}_\delta\,\mathrm{Pr})^{1/3}\left(\frac{\delta}{h}\right)^{1/9} \quad 2.0\times10^5 < \mathrm{Gr}_\delta\,\mathrm{Pr} < 1.1\times10^7. \tag{4}$$

Fig. 5(c) shows hourly variations of the convective heat loss of both sides. From calculation, the mean value of the convective heat loss of the east side at night is about 4412.5 kJ, while that of the west side is about 2200.0 kJ. It can be known that the convective heat loss is the absolutely major part of the whole heat losses, and using shading can decrease effectively the convective heat loss.

3.2.4. Total heat loss

Fig. 5(d) represents the total hourly heat loss of the east and west sides. According to the comparison, the total heat loss is reduced by 20–40% because of using shading at night.

In summary, although the rise of ΔT_{sg} and ΔT_{wg} and, ignoring the conductive coefficient of shading leads to an increase in radiative and conductive heat loss of the air gap, the shading can effectively decrease the convective heat loss and prevent the radiative heat loss from the wall to the glazing directly. Thus, installing shading results in an insulation effect which improves thermal performance of the massive wall.

4. Effect of the shading location

There are two important factors for determining the conductive and convective heat losses in the air gap, i.e. the shading material and fixed location, because different shading materials can lead to different thermal resistances and different fixed locations means different structures of the air gap which dominate the air flow pattern. But when the air gap thickness is greater than 60 mm, the thermal resistance of the channel will tend to be stable with the gradual enhancement of convection [3].

From Fig. 5, it can be seen that the convective heat loss is dominant in the total heat loss. From this point of view, the key to the improvement of insulation performance of the Trombe wall is to decrease the convective heat transfer. If the size of the air gap is confirmed, changing the fixed location of the shading can alter the air flow pattern and decrease the convection heat loss in the air gap. At the same time, varying the thickness of the air gap can also affect the conductive heat loss. So there must be a reasonable location of the shading that results in the least convective and conductive heat loss. It is assumed that the optimum distance between the shading and glazing is δ.

According to [5,6], δ can be calculated using the following equation:

$$\delta = 2 \times 2.93\,\mathrm{Pr}^{-1/2}(0.952 + \mathrm{Pr})^{-1/4}\,\mathrm{Gr}^{-1/4}\,\mathrm{h}. \tag{5}$$

In this experiment, the optimum distance between the shading and glazing δ as confirmed by Eq. (5) is 23 mm and the convective heat loss is reduced by about 20%. In the present experimental study, the facility has already been completed and the shading is hermetic in the gap. Thus it is not possible to validate the optimum location. The location of the shading is an important factor for improving the thermal performance of the Trombe wall and raise the indoor temperature in winter, so it will be further investigated in our subsequent study.

5. Analysis of indoor thermal comfort

Installing shading in the air gap of the Trombe wall can raise indoor temperature and improve thermal comfort owing to its insulative performance in winter. The influence of walls on thermal comfort is presented by the analysis of the building envelope response factor (BER) which was introduced by Lukic [7]. The greater the BER, the more the heat needed to reach the indoor comfort zone. In other words, the higher the value of BER, the greater the indoor air temperature deviated from the comfort zone. BER is defined in Eq. (6) as

$$\mathrm{BER} = \mathrm{DH}\sum(Q_{\mathrm{hc}}^{\mathrm{n}}\Delta t), \tag{6}$$

where BER is the building envelope response factor, kW °C h^2; $\sum(Q_{\mathrm{hc}}^{\mathrm{n}}\Delta t)$ is the total heating load during one heating day, W; and DH is the degree–hour number, °C h.

$$\mathrm{DH}=\sum(T_{\mathrm{tc}}-T_{\mathrm{in}}^{\mathrm{n}})\Delta t, \tag{7}$$

where T_{tc} is defined as the thermal comfort temperature and it is 18 °C in this experiment; $T_{\mathrm{in}}^{\mathrm{n}}$ is the indoor air temperature of the moment of calculation time, 200 mm from the wall, °C; and Δt is the time interval which is 10 min.

It should be noted that the $\sum(Q_{\mathrm{hc}}^{\mathrm{n}}\Delta t)$ value for calculating BER of the two experimental walls is identical because both walls are installed in the same passive solar room. Thus, the relationship between BER and DH becomes linear and thermal comfort can be analyzed by comparing DH values of the two massive walls only. Moreover, the indoor air temperature is influenced simultaneously by the two compared Trombe walls (the east and west sides) and the direct gain in this experiment. Thus, $T_{\mathrm{in}}^{\mathrm{n}}$ is represented by the air temperature 200 mm far from the massive wall for more objective analysis of the shading's insulative contribution. The result is shown in Fig. 6.

The DH difference between the two walls is not significant at daytime, but DH value of the east side is 10 °C h higher than that of the west at night. This illustrates that more heat should be consumed to meet thermal comfort requirements without shading at night. In this case, the installation of the shading device makes a positive effect on raising indoor temperature, thermal comfort and saving energy.

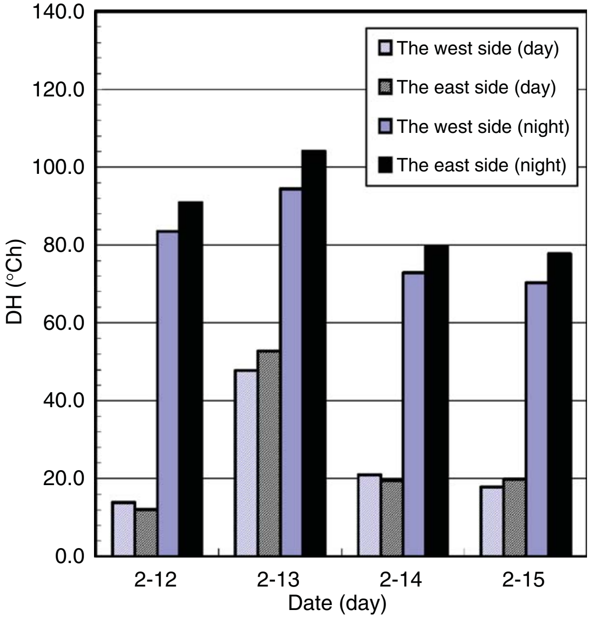


Fig. 6. Daily DH values of the Trombe wall.

6. Conclusions

The use of shading in the air gap is an effective way to improve thermal performance of the Trombe wall. The experimental data show that shading plays a significant role in optimizing the passive solar house design. Using shading can decrease convective heat loss of the air gap and prevent radiative heat transfer from the Trombe wall to the outside. Based on the calculation, it is found that the insulation can reduce about 20–40% heat loss in the air gap on a winter night and increase the external surface temperature of the Trombe wall. From analysis of the heat transfer process, convective heat loss is found to dominate in the total heat loss. Therefore, reducing convective heat loss is the key to improve thermal performance of the Trombe wall. Different shading fixed locations can change the thickness of the air gap, which has an important effect on the air flow pattern variation to decrease the convective heat loss. The relative optimized location of the shading in the gap calculated by Eq. (5) can reduce about 20% of the total convective heat loss. Referring to the thermal comfort, DH of the east side of the gap is about 10 °C h higher than that of the west side, so the shading has an obvious effect on improving indoor thermal comfort.

References

[1] Min ZX, Ren XP, Mei FM. Heat transmission, 3rd ed. Beijing: Architecture Publishing Company of China; 2000.

[2] Jin ZF, Zhu YX. Architecture environment. Beijing: Architecture Publishing Company of China; 2001.

[3] Jiang H, Hu HB, Wang ZQ, Sun ML. Influence of air-gap design on the preservative and energy saving wall thermal performance. Wall Innovat Build Energy Conserv 2002;1:35–8.

[4] Wang BX. Theory of heat and mass transfer in the project. Beijing: Beijing Science publishing Company; 1998.

[5] Hoffman JP. Heat transmission. People's Education Publishing Company; 1979.

[6] Shi YY, Liu H, Zhang JP. Optimized thermal design of passive solar house and massive wall. Ningxia Technol Inst J 1996;8(1):52–9.

[7] Lukic N. The transient house heating condition—the building envelope response factor (BER). Renew Energy 2003;28(4):523–32.