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Energy 28 (2003) 1099–1114
ENERGY
www.elsevier.com/locate/energy

Field study of performance of solar chimney with air-conditioned building

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Received 14 October 2001

Abstract

The study examines the performance of a solar chimney (SC) within an air-conditioned building. To this end, a single-room house of 25 m^3 volume was used. Two configurations of SC were used: the roof solar collector (RSC) composed of CPAC monier concrete tile, 14 cm air gap and gypsum board, and the modified trombe wall (MTW) composed of a masonry wall, 14 cm air gap and gypsum board. To control the induced air flow rate, as excess incoming hot ambient air will increase air-conditioner (AC) load, the size of the SC inlet opening was used as a means of ventilation control and three opening sizes were considered per each SC configuration. Experiments were performed throughout a period of six months (March–September). A split type AC of 1 t nominal capacity was installed.

Comparisons between a common house and a solar chimney house (SCH) conducted using days with relatively similar ambient conditions demonstrated that a SCH could reduce the average daily electrical consumption of an AC by 10–20%, the ventilation fan saving must also be added. The appropriate size of inlet openings of a SC is 5×5 cm^2, which induces about 3–8 m^3/h/SC unit. The SC is very efficient for decreasing the AC load, namely when the AC is turned on at the beginning of afternoon (1 p.m.) as no heat is stored inside the room. In this operating mode the saving is much higher, about 30%.

Consequently, the SCH is highly suitable for a hot climate as it could be used for both an AC and a non-AC building. The design recommendations formulated here could be used to conduct a realistic design depending on the requirements of the house's owner.

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0360-5442/03/$ - see front matter © 2003 Elsevier Science Ltd. All rights reserved.
doi:10.1016/S0360-5442(03)00092-6

Nomenclature

Q	volume flow rate in the air gap (m^3/s)
C_D	discharge coefficient of the chimney
A_0	area of outside opening (m^2)
g	gravity acceleration (m/s^2)
L	length of SC (m)
θ	angle between SC and horizontal plane, in case of the wall $\theta = 75°$ is used
T_i	temperature of the air entering the SC (K)
T_0	temperature of the air exiting the SC (K)
T_b	average air temperature in the SC (K)
A_r	ratio of exit opening and entrance opening of SC

1. Introduction

Residential air-conditioning for human comfort must ensure not only appropriate temperature and humidity inside, but also a sufficient ventilation level. Insufficient ventilation will affect both human comfort and health.

In a hot and humid country like Thailand, people usually use air-conditioners to reduce indoor temperature and humidity and exhaust fans for ventiliation. As a result, electrical power consumption of air-conditioning is at a notably high level. However, with all-year sunny days, the solar chimney (SC) concept can be applied to reduce heat transfer through the walls and roof, thus easing air-conditioner's cooling load. SC also induces natural ventilation, so ventilation fan will be no longer necessary. However, since outdoor air has high temperature and high humidity, if the ventilation rate induced by the solar chimney is too great, it will bring heat inside. In this case, instead of reducing the cooling load, it will increase it and in consequence will increase electrical power consumption.

The solar chimney (SC) concept has been applied to buildings for several decades. By far the most populatr application is the well-known Trombe wall composed of glass, an air gap and concrete wall widely used for heating in winter. The literature is very rich and various numerical and experimental studies are available, including Arumi and Hourmanesh's [1] study on performance of energy walls and Moshfegh and Sandberg's paper on the flow and heat transfer characteristics of buoyancy-driven air convection in vertical panels [2]. Bansal et al. [3] developed a simple equation based on the stack pressure concept that can be used to estimate the induced ventilation rate.

$$Q = C_D.A_0\sqrt{\frac{2.g.L.\sin\theta\dfrac{(T_b - T_i)}{T_0}}{(1 + A_r^2)}} \tag{1}$$

All symbols are as listed in the Nomenclature.

In earlier studies, our center (BSRC) performed experiments in many modifications to the SC to serve requirements in Thailand. In addition to the trombe wall configuration, we designed and tested different configurations such as the roof solar collector (RSC), the partially glazed modified trombe wall and the bicolimatic roof. The last two units permit indirect daylight with noticeable ventilation rates. Performance was reported in a number of publications [4–8]. Although the literature is rich, to the best of our knowledge, there are no published data on the following remaining question: 'How would a SC perform and operate within an air-conditioned building?' This is the objective of the present research work. In fact, prediction could be made following common cooling load calculation methods [9–11] based on the thermal resistance of SCs and ventilation load. However, as no standard methods exist regarding this, experimental research would provide a more satisfactory understanding. The results from this study are therefore a guideline for sizing openings when designing residential buildings that use the SC concept for saving the electrical power consumption of air-conditioning and ventilation fans and also a guidline as to cost.

2. Experimental method and equipment used

Due to economic reasons and the simplicity of the construction and modification process, the RFC [4–5] and modified trombe wall [6] are selected for this investigation.

2.1. Description of the experimental house

The experiment and data collection were conducted using the center single-room house facility. The house is located on the 11th floor of the School of Energy and Materials building. The house has a surface area of 11.55 m^2 with an elevated concrete floor. The northern and southern walls each have a surface area of 6.9 m^2. The eastern and western walls are both 6.7m^2. The door is on the northern wall equipped with an air grille and nylon filters (37 lines per inch, 20×20 cm^2). The structure of the house was modified according to the experimental schedule as follows.

2.1.1. Structure 1 (common house)

- The roof gable, tilted at a 25°, is covered by CPAC monier concrete tiles. Tilt ceiling is made of gypsum with a 30 cm air gap.
- The north, east and west walls are made of commercial bricks of 5 cm thickness. The south wall is made of bricks of 10 cm thickness.

2.1.2. Structure 2 (SCH)

In this case, structure 1 was modified to act as SC as follows:

- The north roof has two units of RSC of the following dimensions: 1.5 m × 1 m × 30 cm. The south roof has two units of 1.5 m × 1 m × 14 cm RSC, (Fig. 1). The difference between the air gap is due to the existing metallic structure.
- All walls were modified to act as a modified trombe wall (MTW) configuration [3]. A gypsum board was installed at 14 cm from the inner brick side (Fig. 2).

An insect net is installed at the room-side opening of SCs. Figs. 1 and 2 indicate the positions where data were measured.

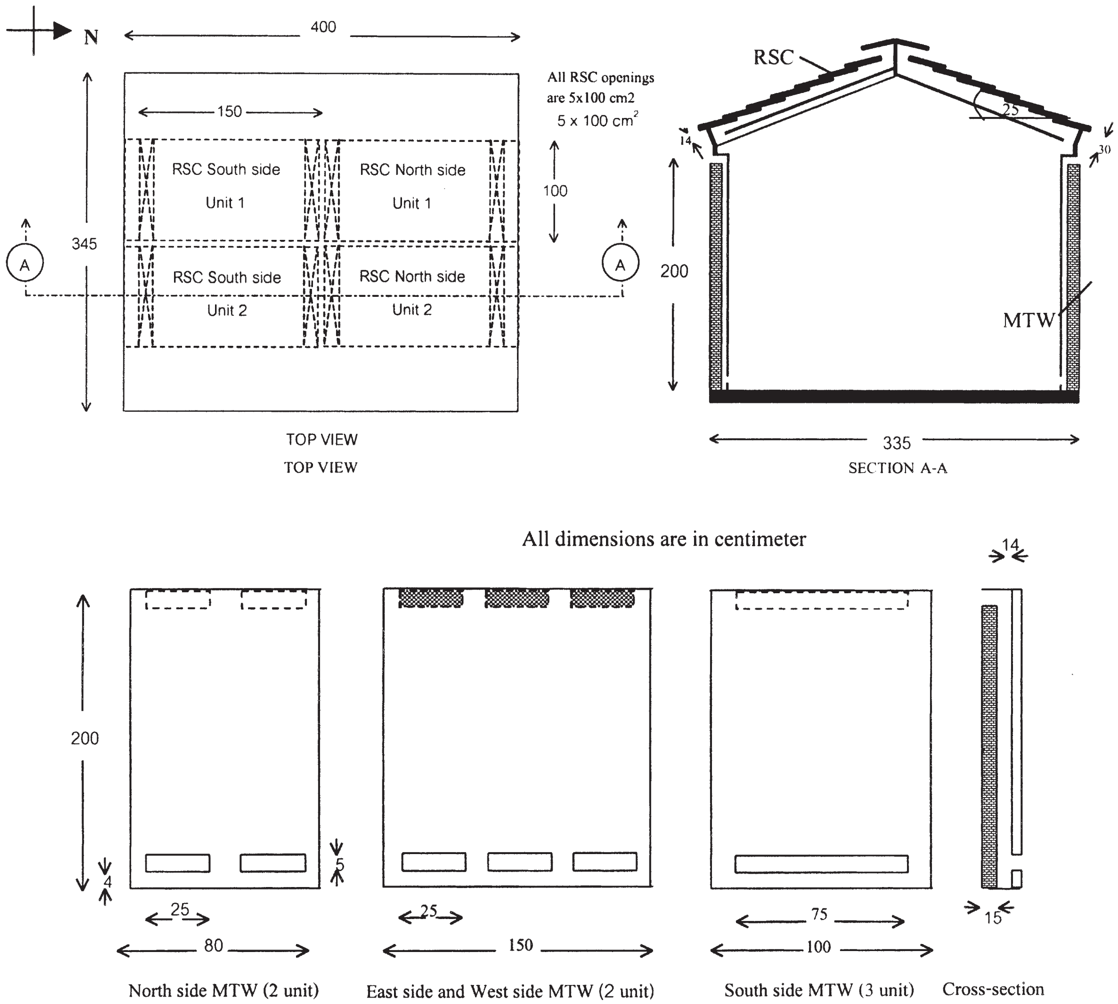

Fig. 1. Dimensions of roof solar collector and modified trombe wall (not to scale).

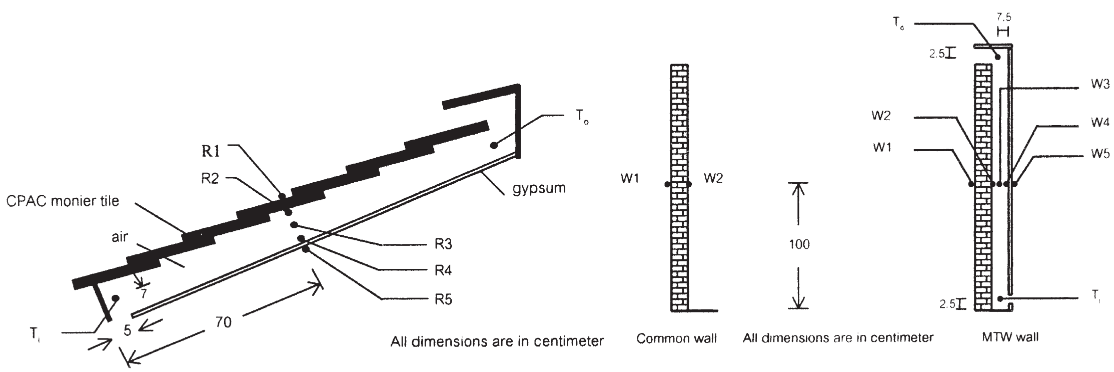

Fig. 2. Position of thermocouples setting in roof and walls (not to scale).

2.2. Instruments and equipment used

- A set of data logger campbell model SC 32A, storage module RS 232 and relay multiplexer AM 416 with thermocouples type K (range 0–1250 °C) was used to measure and record temperatures. The accuracy of the set is ±0.5 °C.
- A globe thermometer (Testo 950, range 0–120 °C, accuracy ±0.5 °C) was used to measure room globe temperature.
- A hot wire anemometer (TSI model 8388: 0–95% RH, 0.15–50 m/s, accuracy of ±3% RH and ±0.02 m/s) was used to measure indoor humidity and air velocity.
- A pyranometer, Kipp and Zonen B.V. model CM11 (accuracy ±10 W/m^2) was used to measure solar radiation.
- A humidity and temperature sensor, Testo model 175-2 : range −10–50 °C, 0–100% RH, accuracy ±0.5 °C, ±3% RH was used to measure outdoor humidity and temperature.
- A watt-hours meter, Mitsubishi 1000 kWh was used to measure electrical consumption.
- A split type AC manufactured by Saijo Denki company model SPU-13UP of 3927W cooling capacity with a COP of 3.48 was used for cooling the room.
- The ventilation fan used in the test was Sumon model SF 23092A. It can extract 56.88 m^3/h and consumes 13.2 W.

2.3. Experimental procedure

Data were collected every 15 min. Tests were divided into two series according to the house design.

2.3.1. Series 1: common house (structure 1)

- Turn on AC and exhaust ventilation fan (56.88 m^3/h) from 9 a.m. to 5 p.m.
- Turn on AC and ventilation fan from 1 p.m. to 5 p.m.

2.3.2. Series 2: SCH (structure 2)

- Close all SC openings. Turn on AC and ventilation fan from 9 a.m. to 5 p.m.
- Open the SC openings at various sizes on selected positions for ventilation. Turn on AC from 9 a.m. to 5 p.m.
- The same conditions as in the previous case but time period is changed to 1 to 5 p.m.

3. Results and discussion

Testing the performance of the SC within an air-conditioned building was performed during April–September. Data reported here were selected for days with relatively similar ambient temperatures that permit us to make a subjective comparison.

3.1. Effect of SC on wall and roof surface temperature and air gap

Fig. 3 shows the temperature variation at different parts of the roof when the AC is turned on between 9 a.m and 5 p.m. in the common house and SCH with closed and opened openings. As

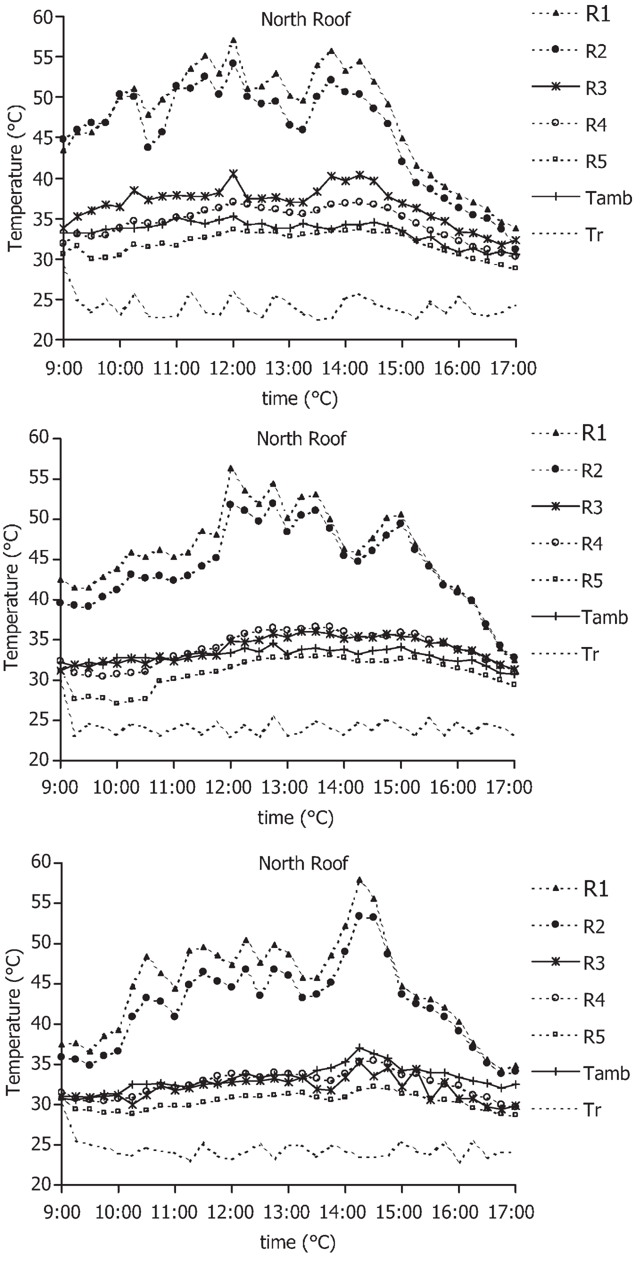

Fig. 3. Variation of temperatures at different positions of north roof. Top: common roof (average ambient condition: 492 W/m^2, 33.38 ºC; 6/5/00); middle: RSC with closed opening (average ambient condition: 462 W/m^2, 33.97 ºC; 14/6/00); bottom: RSC when opening (100 × 5 cm^2) are opened (average ambient condition: 469.85 W/m^2, 33.23 ºC; 15/6/00).

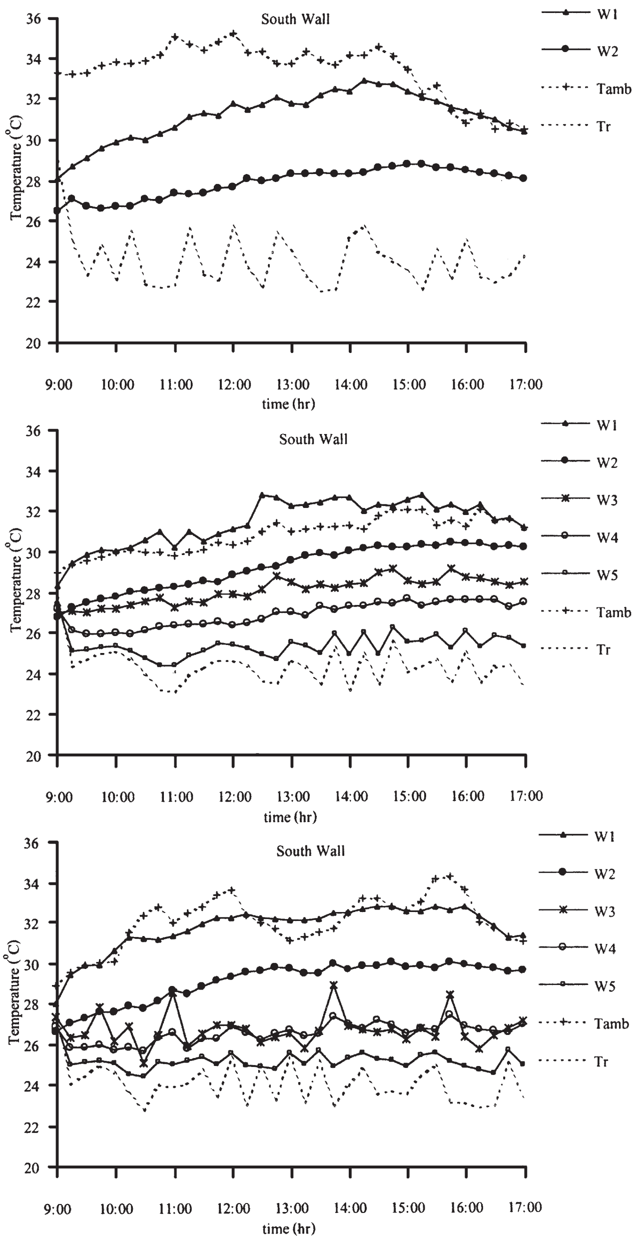

Fig. 4. Variation of temperatures at different positions of south wall. Top: common wall (average ambient condition: 492 W/m^2, 33.38 °C; 6/5/00); middle: MTW with closed opening (average ambient condition: 531 W/m^2, 30.82 °C; 18/7/00); bottom: MTW when opening (75×5 cm^2) are opened (average ambient condition: 411.94 W/m^2, 32.01 °C; 20/7/00).

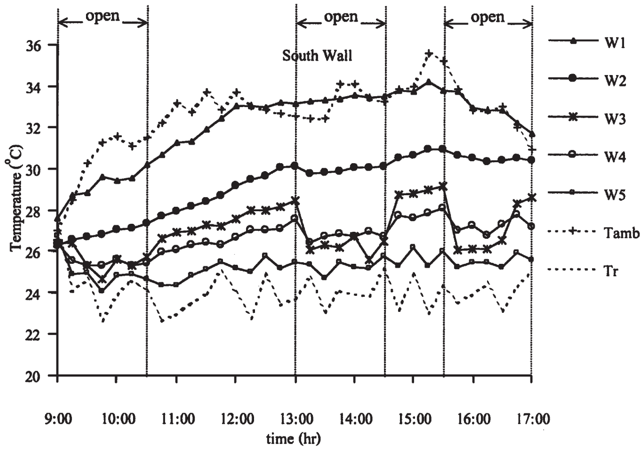

Fig. 5. Variation of temperatures of MTW when openings (surface area: 75×5 cm^2) are opened in intermittent mode: 9–10.30 a.m., 1–2.30 p.m. and 3.30–4.30 p.m. (19/8/00).

seen in the figure, the air gap temperature in the common roof (R3) is much higher than the surrounding temperature (T_{amb}) as heat is stored in the roof fabric and attic enclosure. In the case of the RSC, although the room-side opening is closed (Fig. 3, middle), the temperature of the air gap is lower because outdoor air is pulled into the air gap through CPAC tiles joints and some heat is lost to ambient at the top outlet opening of the RSC. When the room openings are opened (Fig. 3, bottom), the suction of the air inside the house into the roof makes the air gap temperature lower. This 'cool' air is not completely wasted as it is used for cooling the RSC resulting in lower heat transferred into the house. In addition, the room-side temperature of the ceiling gypsum board (R5) is lower compared to the other cases and more especially the common roof. This would

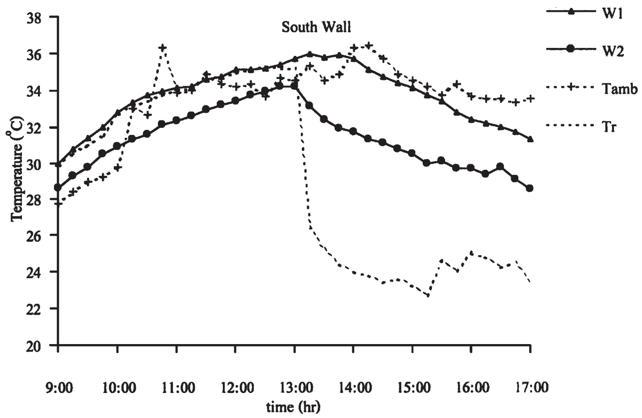

Fig. 6. Variation of temperatures of masonry wall of common house when the AC is turned on at 1 p.m. (average ambient condition: 539 W/m^2, 33.54 °C; 8/5/00).

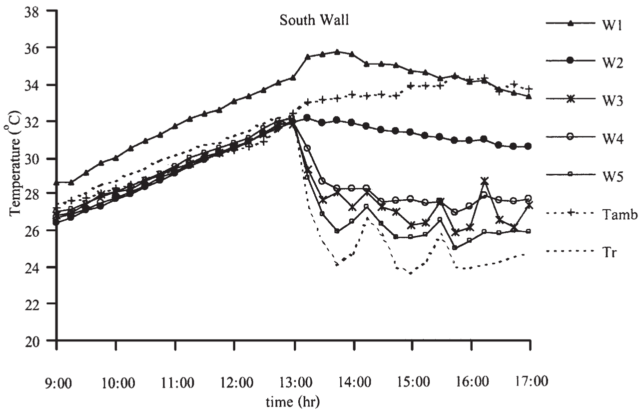

Fig. 7. Variation of temperatures of open MTW (25×5 cm^2) when the AC is turned on at 1 p.m. (average ambient condition: 530 W/m^2, 31.45 °C; 26/7/00).

improve the thermal indoor condition expressed in terms of globe temperature (to be discussed in section 3.2)

Fig. 4 shows the temperature variation on different parts of common brick wall and MTW with closed and opened openings. Here too, the AC was turned on between 9 a.m. and 5 p.m. Obviously, the room-side surface temperature of the MTW (W5) is lower than the common wall (W2). When the openings are opened, the 'cool' room air flows through the air gap causing lower temperature of the air in the gap. This will also reduce the temperature of the brick wall and gypsum wall.

In Fig. 5, the openings of the south MTW are opened intermittently (9 a.m.–10.30 p.m., 1–2.30 p.m. and 3.30–4.30 p.m.). It can be seen that during those periods, air gap and surface temperature of the brick wall and gypsum wall decreased due to the flow of room air. As a result, heat transferred through MTW into the house decreased too. This observation can be confirmed based on the temperature difference between the two side temperatures of the gypsum board

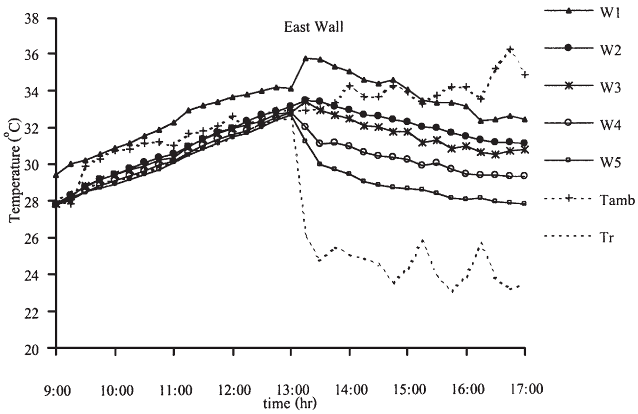

Fig. 8. Variations of temperatures of closed east-side MTW when the AC is turned on at 1 p.m. (average ambient condition: 465 W/m^2, 32.54 °C; 28/7/00).

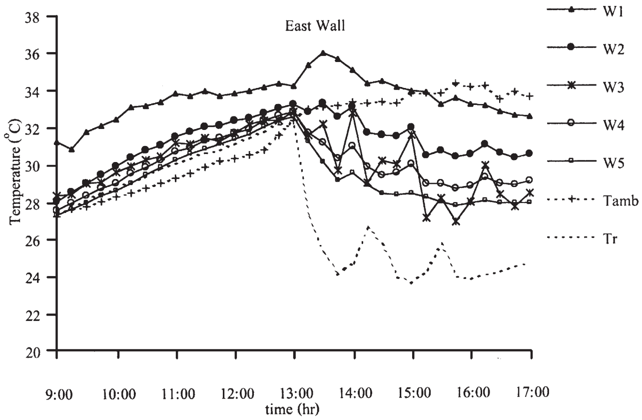

Fig. 9. Variation of temperature of open east-side MTW when the AC is turned on at 1 p.m. (average ambient condition: 530 W/m^2, 31.45 °C; 26/7/00)

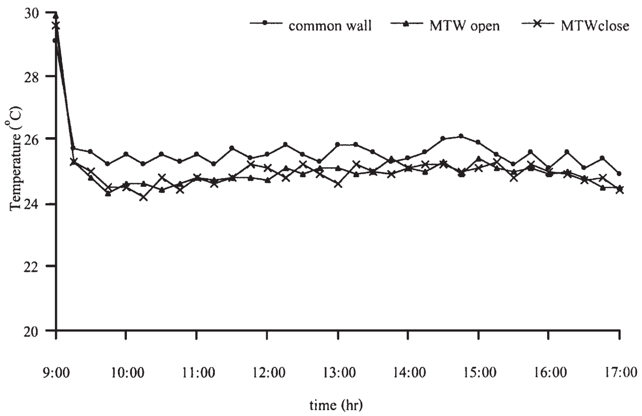

Fig. 10. Comparison of globe temperatures between common house (average 25.49 °C ,6/5/00), closed all RSC and MTW openings (average 24.89 °C, 14/6/00) and opened all SC (average 24.89 °C, 15/6/00).

(W4−W5). Therefore, the way the SC pulls outdoor air continuously into the house can ease the accumulated heat effectively.

To demonstrate the advantage of a SC as an efficient insulating material, we conducted the following test: we left the house to accumulate heat until 1 p.m., at which time we turned on the AC. Fig. 6 shows the temperature variation of different parts of the southern wall while Fig. 7 shows the temperature variation of the MTW at the same side of the house but with opened openings. Before the AC is turned on, the room and wall surface of the common house have a high temperature. On the other hand, those of the MTW house are lower and close to ambient as a result of the continuous induced natural ventilation. When the AC is on between 1 p.m. and 5 p.m., the inside surface temperature of the MTW house (W5) decreases quickly and is much lower than that of the surface of the common wall (W2).

Figs. 8 and 9 show comparison between closed and opened MTW. Between 9 a.m. and 1 p.m., air flows through the opened MTW and cools down the accumulated heat in the MTW. As a

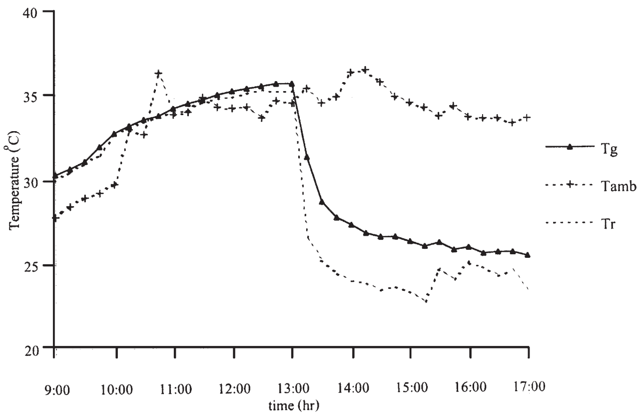

Fig. 11. Variation of globe temperature, ambient temperature and room temperature in common house when AC is turned on at 1 p.m. (average ambient condition: 539.40 W/m^2, 33.54 °C; 8/5/00).

result, the surface temperature of the wall (house side) is lower than when the MTW is closed. When the AC is on between 1 p.m. and 5 p.m., the air flowing through the MTW helps to decrease heat accumulation in the MTW (temperatures W2 and W4 follow that of W3).

3.2. Effect of SC on globe temperature

Mean radiation temperature, which has a significant effect on human comfort, can be assessed using a globe temperature sensor. Fig. 10 shows that the globe temperature in the common house is higher than in the SCH. This is due to the room surface temperature (walls and roof) which is higher than that of the SCH.

Figs. 11 and 12 show the results when the AC is operated in the afternoon (1–5 p.m.). It can be seen that globe temperature in the SCH decreases faster to a lower degree than that in the common house and remains practically constant.

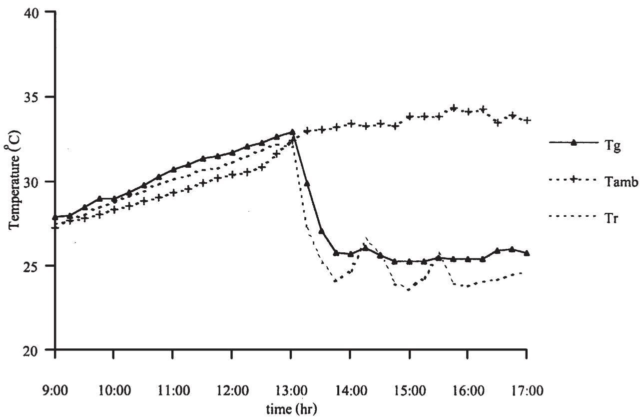

Fig. 12. Variation of globe temperature, ambient temperature and room temperature of SCH when AC is turned on at 1 p.m. with open all MTW (25 × 5 cm^2, average ambient condition : 530 W/m^2, 31.45 °C; 26/7/00).

3.3. Electrical consumption of the AC

We remind that tests were conducted using one room on different days. Thus, to reach a subjective conclusion, comparisons of electrical power consumption by air condition are made for a group of days with relatively similar climate conditions.

Fig. 13 presents the electrical consumption of the AC for different test conditions: common house, SCH with closed openings and SCH with opened openings. Although ambient conditions are not exactly the same, the figures demonstrate that the SCH reduces average electrical consumption by 10–20%.

Comparisons of electrical power consumption when air condition operated in the afternoon are given in Fig. 14. As discussed above, the SC can reduce heat accumulation in the morning. That is why within only 45 min the room is cooled. Whereas with the common house, the compressor of the AC works practically continuously for 2 h 15 min. The electricity saving in this case is much higher, about 30%, which is extremely important.

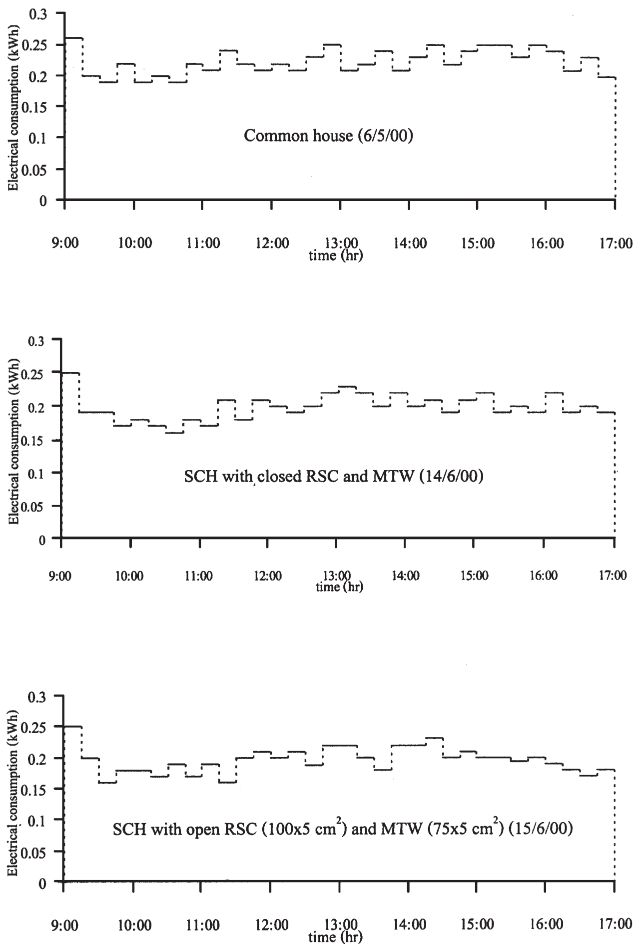

Fig. 13. Electrical consumption in 15 min intervals of AC for different test conditions.

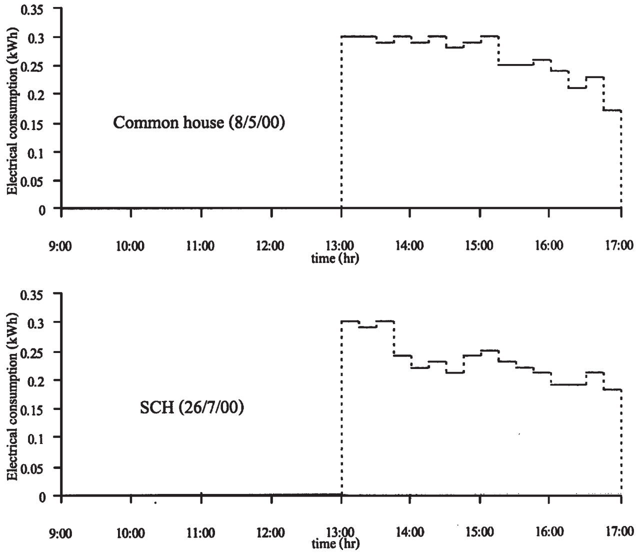

Fig. 14. Electrical consumption in 15 min intervals of of AC of common house and SCH turned on at 1 p.m. (26/7/00).

3.4. Ventilation performance

In this study, the size of the SC openings is used as a ventilation controller. Fig. 15 shows the induced ventilation rate of the south MTW with different sizes of opening. Obviously, the larger the size, the higher the ventilation rate.

In the SC system, the heat that passes the wall and roof structure into the house will be partly rejected to the outside air via the SC. The quantity of rejected air or induced flow depends mainly on the vertical distance between the SC openings and the temperature difference between chimney

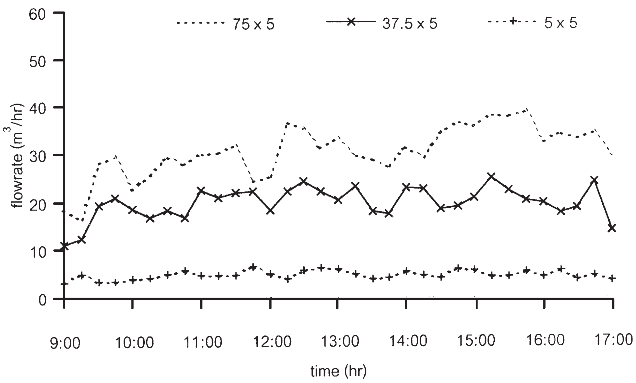

Fig. 15. Variation of air flow rate for different inlet openings of south MTW (75 × 5 cm², 20/7/00), (37.5 × 5 cm, 23/7/00) and (5 × 5 cm², 17/8/00).

and room. Fig. 16 shows the temperature at both inlet and outlet of the SC with different opening size of the southern MTW. It can be seen that the 5×5 cm^2 opening (Fig. 16 bottom) yields the largest temperature difference. Table 1 shows the volume air flow rate, heat removal rate and specific rate of heat removal per unit volume of air flow rate with different opening sizes of

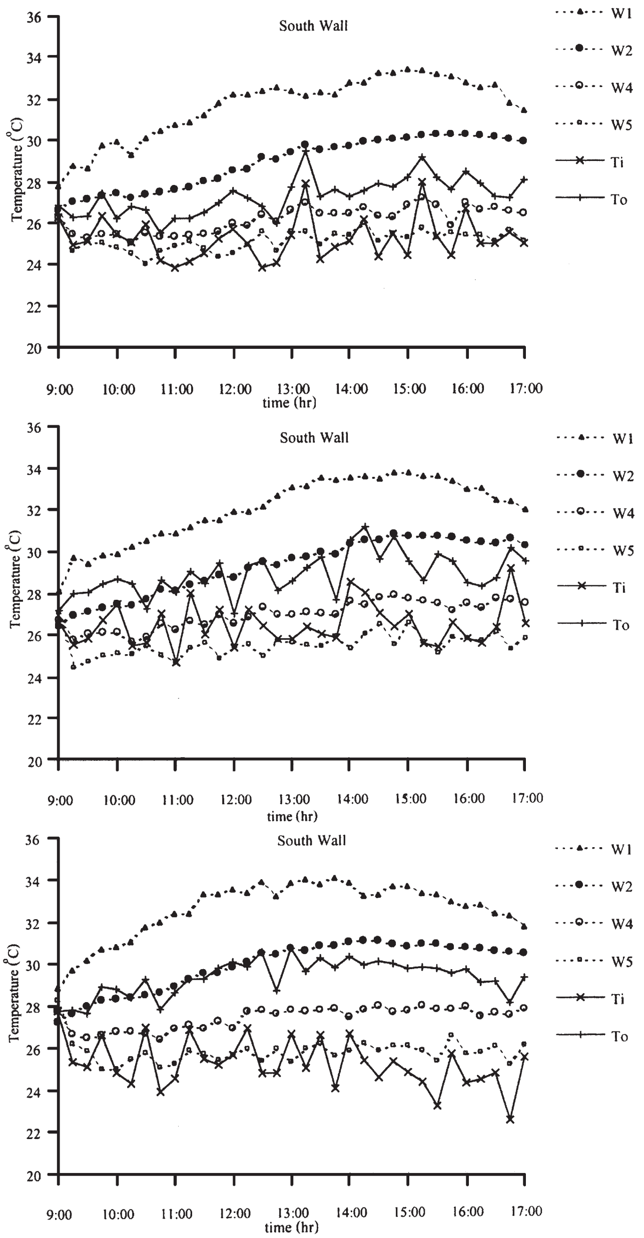

Fig. 16. Variation of temperatures at different positions of open south side MTW. Top: 75×5 cm^2 (average ambient condition: 512.48 W/m^2, 32.71 °C; 20/6/00); middle: 37.5×5 cm^2 (average ambient condition: 469.38 W/m^2, 32.39 °C; 23/7/00); bottom: 5×5 cm^2 (average ambient condition: 499.51 W/m^2, 32.07 °C; 17/8/00).

Table 1
Average daily volume air flow rate, heat removal rate and specific rate of heat removal per unit volume air flow rate for SC different openings of MTW

SC opening (cm^2)	Volume air flow rate (m^3/h)	Heat removal (W)	Specific of heat removal rate per unit volume air flow rate (Wh/m^3)
75×5 (20 June)	36.44	25.89	0.68
37.5×5 (23 July)	19.91	16.45	0.81
5×5 (17 August)	4.72	6.55	1.36

MTW. The 75×5 cm^2 opening induces the highest volume air flow and heat removal rates. However, considering the efficiency or specific rate of heat removal per unit volume of air flow rate, 5×5 cm^2 is the best. Therefore, when it comes to the matter of sufficient ventilation requirement in the case where the AC is to be turned on without increasing the cooling load, a 5×5 cm^2 opening is recommended.

4. Conclusion

Closed roof enclosures and simple brick walls which are the common structure of most residential houses in Thailand lead to excessive heat accumulation and thus costly high electrical power consumption of ACs. The SC's strong heat resistance and its induced natural ventilation are proved to be applied with air-conditioned buildings.

SC reduces the accumulated heat of the house continuously. The SCH consumes, depending on operating condition, 10–20% less electrical power compared with the common house. With the AC turned on in the afternoon, the AC in the SCH carries a lower heat load than that of the common house, by about 30%.

The size of openings of SCs inside the house was used to control the induced ventilation rate. Experimental comparison between various sizes of opening found that a 5×5 cm^2 opening is recommended for SC units when operated with an AC.

In conclusion, a SC is recommended for air-conditioned residential houses and buildings for both comfort and energy saving. The size of the SC can be adjusted according to the type of house and the intended use.

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