PERGAMON

Renewable Energy 18 (1999) 109–119

RENEWABLE ENERGY

Study of natural ventilation of houses by a metallic solar wall under tropical climate

J. Hirunlabh*, W. Kongduang, P. Namprakai, J. Khedari

Energy Technology Division, School of Energy and Materials, King Mongkut's University of Technology Thonburi, Toongkru, Bangkok, Thailand 10140

Received 18 June 1998; accepted 11 September 1998

Abstract

Heat removal from habitation was studied by using a metallic solar wall (MSW) at Bangkok. The MSW consists of a glass cover, air gap, black metallic plate and insulator made of micro-fiber and plywood. It was found that the MSW with 14.5 cm air gap and 2 m^2 of surface area ($H \times W$: 2×1 m) produced the highest air mass flow rate of about 0.01–0.02 kg s^{-1}. Room temperature during tests was near to ambient air, ensuring human comfort resulting from the ventilation produced by the MSW. Comparison between simulated and experimental results showed a good accord, therefore the numerical model is valid. Thus, it can be used to evaluate the long-term reduction of heat transfer into the habitation.

Nomenclature

- A surface area of MSW [m^2]
- A_0 surface area of free opening [m^2]
- C_d discharge coefficient
- C_{pa} specific heat of air [kJ kg^{-1} K^{-1}]
- g gravitational acceleration [m s^{-2}]
- Gr Grashof number
- h_{c1} convective heat transfer coefficient between cover or metallic surface and air in the gap [W m^{-2} K^{-1}]
- h_{c2} convective heat transfer coefficient between insulator and air in the room [W m^{-2} K^{-1}]
- h_{r2} radiative heat transfer coefficient between cover and metallic surface [W m^{-2} K^{-1}]

* Corresponding author

PII: S0960-1481(98)00783-6

h_{r3} radiative heat transfer coefficient between insulator and air in the room [W m^{-2} K^{-1}]
H height of MSW [m]
It solar radiation [W m^{-2}]
k_a air thermal conductivity [W m^{-1} K^{-1}]
k_{in} micro-fiber thermal conductivity [W m^{-1} K^{-1}]
k_m zinc thermal conductivity [W m^{-1} K^{-1}]
k_w plywood thermal conductivity [W m^{-1} K^{-1}]
m_f air mass flow rate [kg s^{-1}]
Nu Nusselt number
Pr Prandtl number
Q volumetric air flow rate [m^3 s^{-1}]
Ra Rayleigh number
T_a ambient temperature [K]
T_c cover temperature [K]
T_f air temperature in the gap [K]
T_m metallic plate temperature [K]
T_{out} outlet air temperature [K]
T_r room air temperature [K]
T_w room-side wall temperature [K]
U_b bottom loss heat transfer coefficient [W m^{-2} K^{-1}]
U_t top loss heat transfer coefficient [W m^{-2} K^{-1}]

Greek symbols
α thermal diffusivity [m^2 s^{-1}]
β volumetric thermal expansion coefficient [K^{-1}]
ε_W plywood surface emissivity
ε_m metallic surface emissivity
ε_C glass surface emissivity
ν kenematic viscosity [m^2 s^{-1}]
$\tau\alpha$ absorptance-transmittance product

1. Introduction

In Thailand, heat gain in summer is the main problem as it overheats the indoor environment of residential buildings. This forces the residents to utilize mechanical air conditioning systems to satisfy their comfort. Under today's economic crisis, energy conversation programs and acts for respect of environment are receiving more attention. As a contribution to such efforts and in order to overcome the heat gain in houses, we propose to utilize a passive system, namely, produced ventilation by a solar chimney.

There are a few researches on passive solar systems in Thailand. Recently, Pratinthong et al., Khedari et al., Wachirapuwadon and Khedari et al. [1–4] studied the feasibility of using roof and wall to induce ventilation. They showed a significant potential of passive solar ventilation of houses. A parametric study of Trombe walls for passive cooling of building was studied [5]. Sharma et al. [6] studied a modified form of Trombe wall. The experimental results indicate the potential applications of such a wall in solar passive building architecture for mixed climatic conditions. A common element in Iranian architecture [7] is the wind tower (or wind catcher) which harnesses the prevailing summer winds to cool the inside of a building. Wind towers resemble chimneys, with one end in the basement and the other end rising above the roof.

For heat removal by stack-effect ventilation, the greatest air flow is achieved by maximizing both the height of the stack and the temperature of air in the stack [8]. The air flow is determined by the inlet area and the square root of the height times the average temperature difference.

In this research a metallic solar wall (MSW) with room-side insulation was constructed to investigate heat removal of houses in Bangkok. Room air is removed by ventilation produced by the MSW through openings at the bottom and the top of MSW.

2. Materials and experimental method

A small model of a solar house with 2.68 m height and base area of 3.35×3.45 m was built as shown in Fig. 1. It had one window and one door with an air grille on the north side. The MSW was integrated to the south wall of the house. The other three sides of the house were made of plywood and gypsum plate. The roof was made of CPAC Monier concrete tiles ($33 \times 42 \times 1.5$ cm) in a dark red color. The floor was made of plywood supported by concrete beams. The MSW was 1 m wide and 2 m high. It consisted of zinc plate, micro-fiber and plywood with thickness of 0.7, 25.0 and 4.0 mm, respectively. Its outer surface was painted matt black and covered with commercial glass of 5 mm thickness. A pair of centered vents, 25×5 cm each was

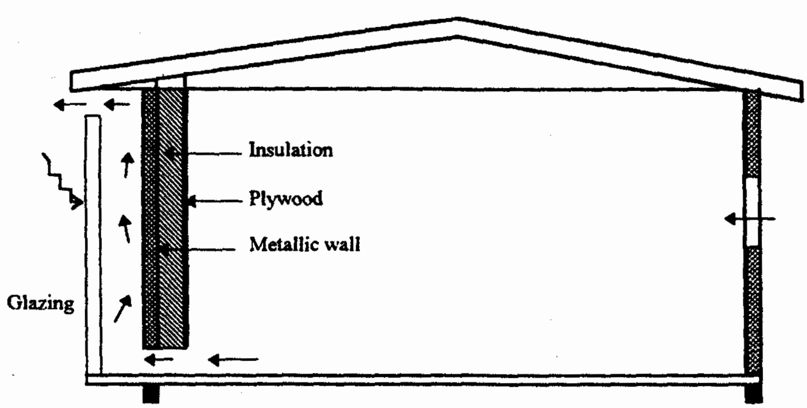

Fig. 1. Schematic representation of the passive solar house and natural ventilation by MSW.

located at the bottom of the metallic plate (room side) and another pair near the top of the cover (Fig. 2). Between the wall and cover there was an air gap. The cover was flush with the aluminium bar support. The design of MSW allows us to vary the height (1–2 m) and air gap (10–14.5 cm). A set of type-K thermocouples were used to measure the temperature at several points of the MSW as shown in Fig. 2 and at six

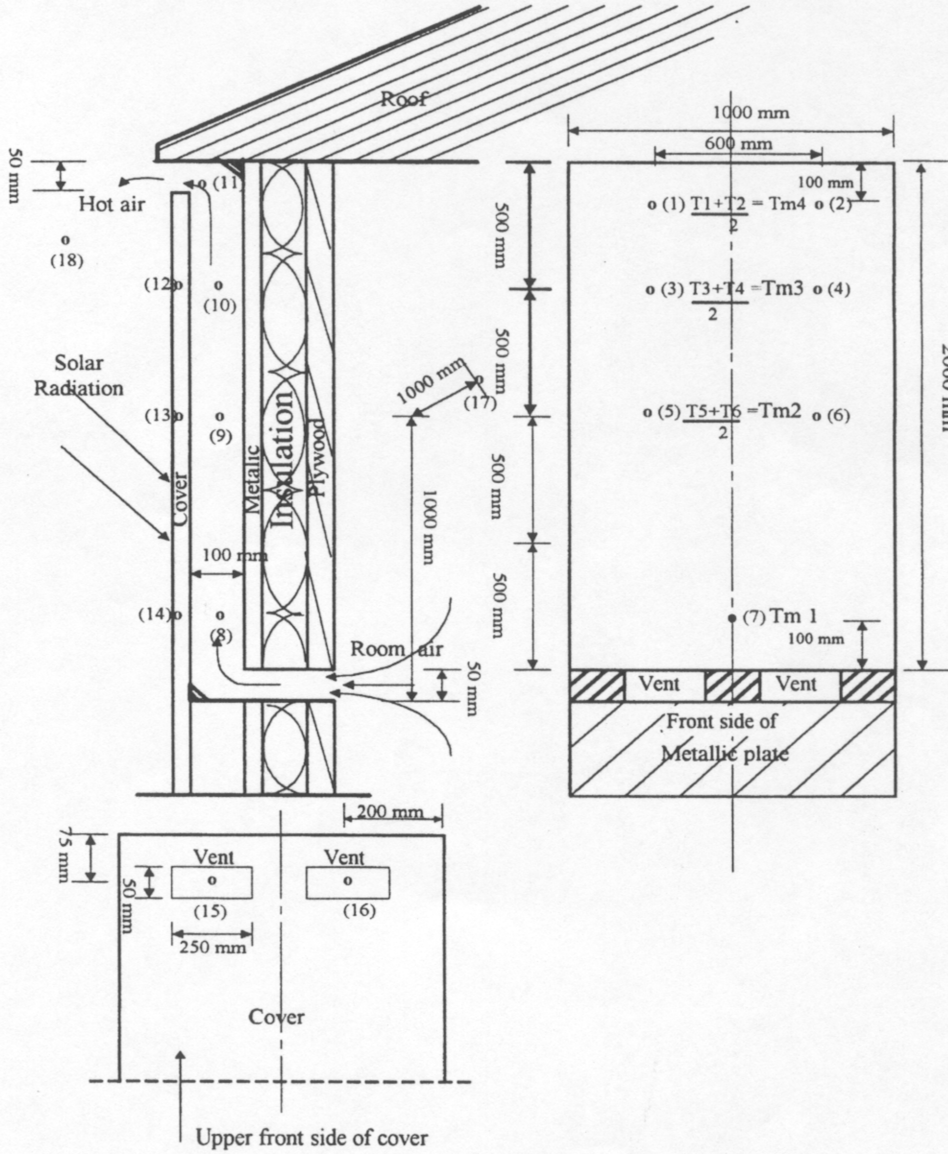

Fig. 2. Positions of thermocouple points on MSW and opening areas.

points inside the room elevated 1 m from the floor. A hot wire anemometer was used to measure the air velocity at the outlet and inlet vents at several points and an average was calculated. Campbell, portable hybrid and data logger recorder were used to record temperatures. A propeller type anemometer was used to measure the velocity and temperature of ambient air. Measurements were made from 08:00 to 17:00 h.

3. Mathematical model

Modeling of the MSW was developed based on the following assumptions:

(1) Steady state condition was assumed.
(2) Absorption of solar energy by cover was negligible.
(3) There would be one-dimensional heat flow through cover, MSW and then the room.
(4) The cover was opaque to infrared radiation.
(5) The sky could be considered as a blackbody for long-wavelength radiation at an equivalent sky temperature.
(6) Properties of solid materials were independent of temperature. Properties of air were functions of temperature.
(7) Room and ambient temperature were the same.
(8) The air in the gap was a non-radiation absorbing fluid.

Governing equations are as follows:
Cover:

$$U_t A(T_a - T_c) + h_{r2} A(T_m - T_c) + h_{c1} A(T_f - T_c) = 0 \quad (1)$$

Air gap:

$$h_{c1} A(T_c - T_f) + h_{c1} A(T_m - T_f) + m_f C_{pa}(T_{out} - T_a) = 0 \quad (2)$$

where mean air temperature T_f can be estimated, for simplicity, using a simple linear equation as follows:

$$0.75 T_{out} + 0.25 T_a - T_f = 0 \quad (3)$$

Metallic surface:

$$h_{c1} A(T_f - T_m) + h_{r2} A(T_c - T_m) + U_b A(T_w - T_m) + ItA(\tau\alpha) = 0 \quad (4)$$

Insulation:

$$h_{r3} A(T_a - T_w) + h_{c2} A(T_a - T_w) + U_b A(T_m - T_w) = 0 \quad (5)$$

Solar chimney equation can be used to estimate the volumetric air flow rate in the gap [8]:

$$Q - C_d A_0 \{gH(T_f - T_a)/T_a)\}^{1/2} = 0 \quad (6)$$

The preceding system of equations was solved [9] by using the well-known Newton–Raphson method. The calculation of coefficients of heat transfer was based on typical correlations in solar collector [10]. Natural convective heat transfer coefficient for air near the room-side vertical-wall surface was obtained from [11]:

$$h_{c2} = k_a Nu/H \quad (7)$$

with, for laminar flow ($Ra < 10^9$):

$$Nu = 0.68+(0.67Ra^{1/4})/[(1+(0.492/Pr)^{9/16}]^{4/9} \quad (8)$$

for turbulent flow ($10^9 < Ra$):

$$Nu = \{0.825+(0.387Ra^{1/6})/[(1+(0.492/Pr)^{9/16}]^{8/27}\}^2 \quad (9)$$

where $Ra = GrPr$, $Gr = g\beta(T_w - T_r)H^3/v^2$ and $Pr = v/\alpha$.

4. Results and discussions

4.1. Experimental results

To demonstrate that the MSW can induce natural ventilation, a preliminary experiment was made by closing the openings of the LSW. It was found that the air temperature at the top of the MSW (T_{out}) was 53°C on average and 60°C max when the mean solar intensity was about 425 W m^{-2}. Compared to the room air temperature of 34°C, the temperature was high enough to establish a density difference between air in the gap and room air and thus to create natural air circulation.

4.1.1. Effect of height and gap of MSW on temperature and mass flow rate

Under relatively similar ambient conditions, Figs 3 and 4 show the average temperatures of metallic plate, ambient air and air outgoing from the MSW for two

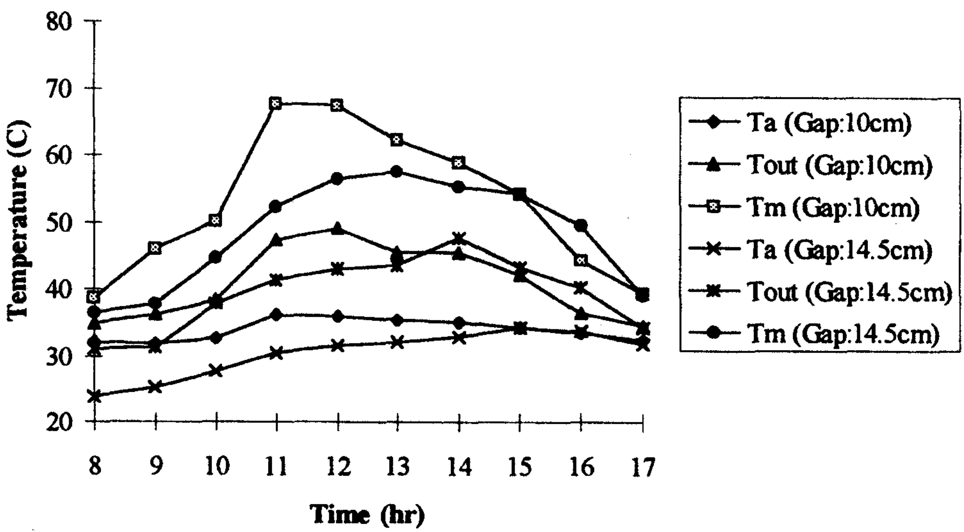

Fig. 3. Hourly variations of the average temperatures of metallic plate, ambient air and air outgoing from MSW with 1 m height for two different gaps: 10 cm (16 November 1996) and 14.5 cm (7 December 1996). Mean solar intensity is about 535 and 406 W m^{-2}, respectively.

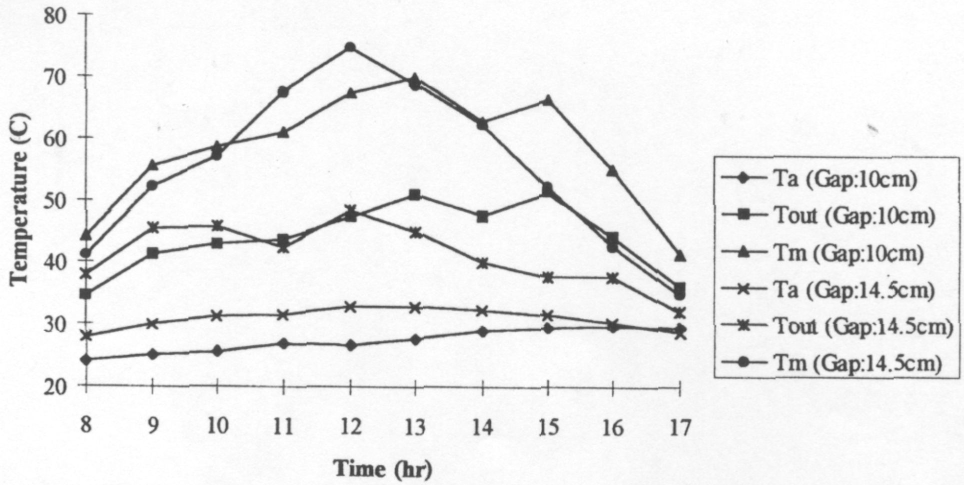

Fig. 4. Hourly variations of the average temperatures of metallic plate, ambient air and air outgoing from MSW with 2 m height for two different gaps: 10 cm (20 December 1996) and 14.5 cm (12 December 1996). Mean solar intensity is about 422 and 385 W m^{-2}, respectively.

heights: 1 and 2 m and two different gaps (10 and 14.5 cm). It was found that MSW temperatures increased with increased wall height and decreased gap, which is obvious as more radiation was absorbed by the MSW and a small volume of air had to be heated.

In addition, temperature along the metallic wall height is at a maximum at the middle of the MSW as shown in Fig. 5 and at a minimum near the openings due to

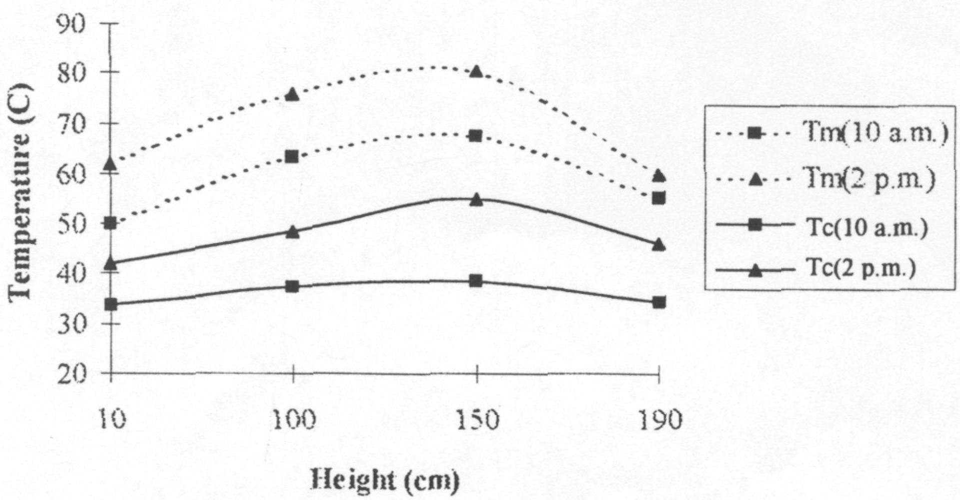

Fig. 5. Variation of the MSW temperatures and cover with wall height at different times (2 m height, 10 cm gap, 20 December 1996).

the incoming room air at the bottom of the MSW and to the contact with ambient air at the top.

Also, it was found that at a given height of the MSW, the two recorded temperatures of each component of the MSW (cover, air and metallic plate) were uniform.

Fig. 6 shows the hourly variations of the experimental air mass flow rate produced by the MSW for two heights and two different gaps. It can be seen that the mass flow rate increased with increased height and gap. The maximum average of air mass flow rate during the hot period (10:00–16:00 h) was about 0.015 kg s^{-1}.

4.1.2. Thermal comfort produced by MSW

Fig. 7 shows the average temperatures of room air, ambient air and air outgoing from the MSW at two heights: 1 and 2 m. It can be seen that room temperature is not very much higher than the ambient air when no ventilation is produced. This demonstrates that natural ventilation by MSW can ensure a certain feeling of thermal comfort within a house especially when the outdoor air temperature is lower than body surface temperature (32°C).

In the very hot season (April–May) when ventilation ceases generally to provide sufficient comfort except with a high number of air changes that could not be achieved with natural means, the main benefit of the MSW is its insulating effect that considerably reduces the rate of heat gain, i.e. the cooling load of the house.

4.2. Validation of mathematical model

To validate the developed mathematical model, the simulation program was run to predict the performance of the MSW under the ambient conditions on the day of the experiment. Relevant parameters used for the calculations were as follows:

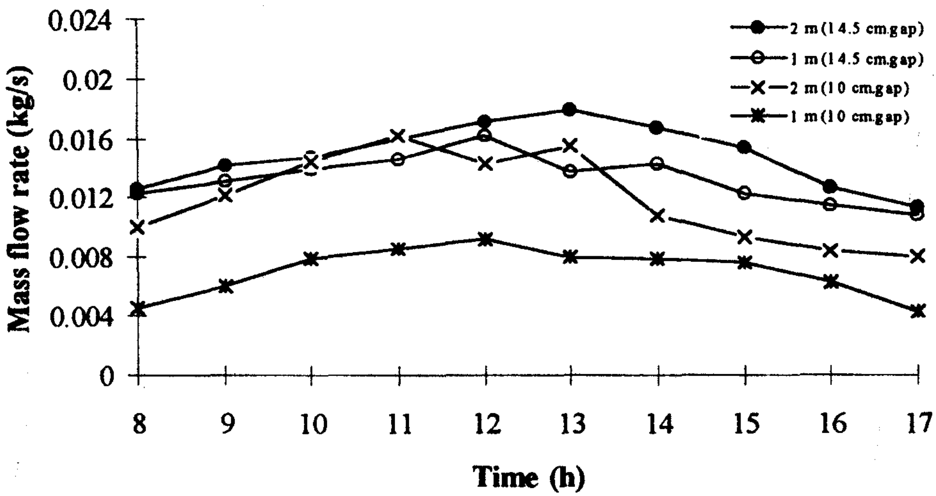

Fig. 6. Hourly variations of air mass flow rate in MSW with 2 m height and gaps: 10 cm (20 December 1996), 14.5 cm (12 December 1996); 1 m height and gaps: 10 cm (16 November 1996), 14.5 cm (7 December 1996).

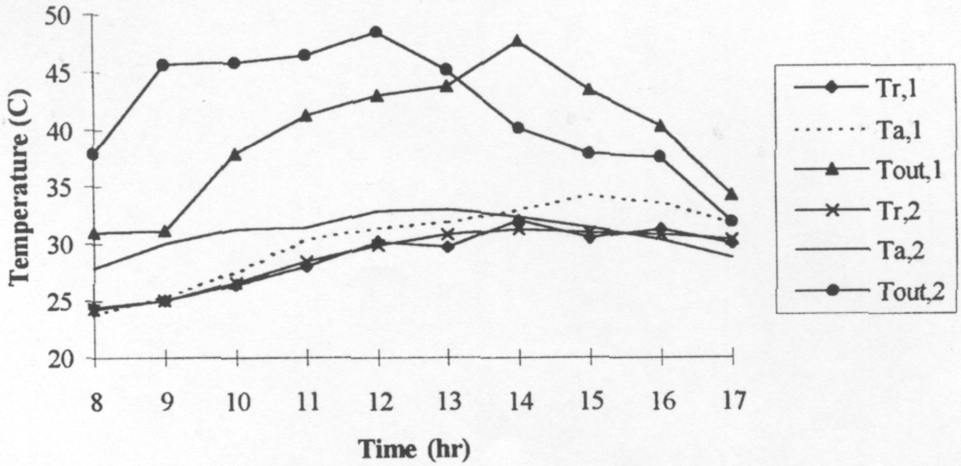

Fig. 7. Hourly variations of the average temperatures of room air, ambient air and air outgoing from MSW with 14.5 cm gap for two heights: 1 m (7 December 1996) and 2 m (12 December 1996). Mean solar intensity is about 406 and 385 W m^{-2}, respectively.

$\tau\alpha = 0.682$, $k_w = 0.138$ W m^{-1} K^{-1}, $k_{in} = 0.0324$ W m^{-1} K^{-1}, $k_m = 112.2$ W m^{-1} K^{-1}, $\varepsilon_W = 0.9$, $\varepsilon_m = 0.6$, $\varepsilon_C = 0.94$, $C_d = 0.8$.

4.2.1. Comparison between simulated and experimental temperature and air mass flow rate

Fig. 8 shows the simulated and average experimental temperatures of the metallic plate (average of $T_{m1}, \ldots, T_{m4}$, Fig. 2) and air in the gap (average of points 8–11, Fig. 2). Except for a little underestimation in the afternoon, the two profiles are similar. Fig. 9 shows the variations of average simulated and measured air mass flow rate produced by the MSW. The difference between the simulated and measured results is about 10%. The good agreement of the results validated the model. Therefore this simple technique could be used to assess the annual performance of MSW and its design.

5. Conclusions

Experimental investigations of the performance of the MSW showed that with 2 m height and 14.5 cm gap the MSW would produce optimum natural ventilation. The MSW can reduce significantly heat gain in the house by developing air circulation to improve the thermal comfort. The proposed system was economical due to little cost of materials used. Also the passive use of solar energy is energy efficient. The developed simulation program could save time in estimating the MSW's performance.

The described passive system presented here could also be used with reverse func-

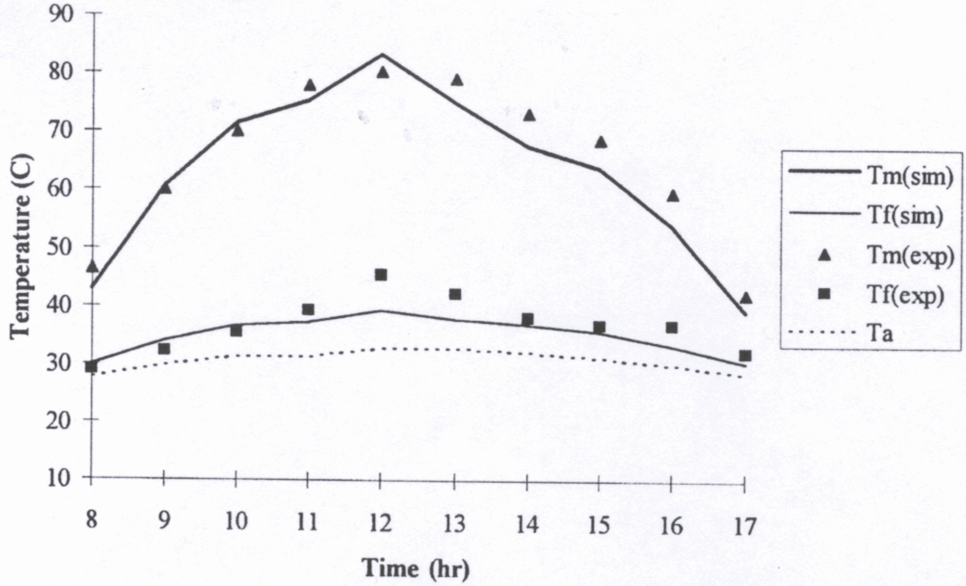

Fig. 8. Comparison between simulated and measured mean temperatures of metallic plate and air gap of MSW with 14.5 cm air gap and 2 m height (12 December 1996). Mean solar intensity is about 385 W m^{-2}.

tion, i.e. to admit ambient air and to inject hot air into the house in cooler regions to provide heating during winter.

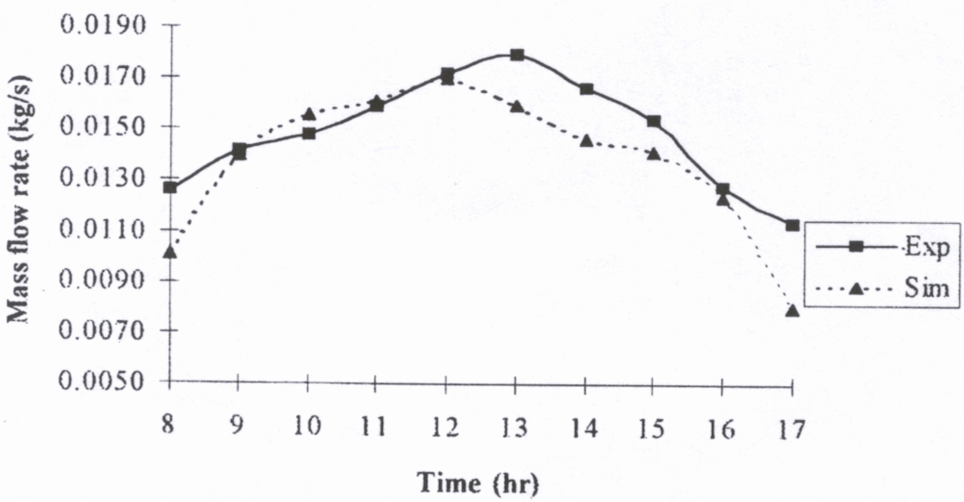

Fig. 9. Comparison between simulated and experimental air mass flow rate in MSW with 14.5 cm air gap and 2 m height (12 December 1996).

Acknowledgements

This research work is partially funded by the National Research Council of Thailand.

References

[1] Pratinthong N, Lertsatitthanakorn C, Hirunlabh J, Khedari J. Feasibility study of inducing natural ventilation and reducing heat transmitted into housing by using a modified Trombe wall. Proceedings of the Second ASEAN Renewable Energy Conference, Phuket, Thailand, 6–9 November 1997, p. 224–7.

[2] Khedari J, Chaima S, Hirunlabh J, Pratinthong N. Investigation of performance of roof solar collector. Proceedings of the Second ASEAN Renewable Energy Conference, Phuket, Thailand, 6–9 November 1997, p. 448–51.

[3] Wachirapuwadon S. An adapted model of passive roof solar collector for new houses with respect to traditional Thai style. M Sc. thesis Energy Technology Program, King Mongkut's University of Technology, Thonburi, 1996.

[4] Khedari J, Kaewruang S, Hirunlabh J, Pratinthong N. Natural ventilation of houses by Trombe wall. Proceedings of the Second ASEAN Renewable Energy Conference, Phuket, Thailand, 6–9 November 1997, p. 266–9.

[5] Gan G. A parametric study of Trombe walls for passive cooling of buildings. Energy and Buildings 1998;27:37–43.

[6] Sharma AK, Sodha NK, Gupta MS. Very-thermal wall for cooling/heating of building in a composite climate. Energy Research 1989;13(6):733–9.

[7] Sayigh AAM. Solar Energy Application in Buildings. New York: Academic Press, 1979.

[8] Bansal NK. Solar chimney for enhanced stack ventilation. Building and Environment 1993;28(3)373–7.

[9] Kongduang W. Study of the natural ventilation of habitation by using a metallic solar wall under tropical climate. M Eng. thesis Energy Technology Program, King Mongkut's University of Technology, Thornburi, 1997.

[10] Duffie JA, Deckman WA. Solar Engineering of Thermal Process. New York: John Wiley and Sons, 1980.

[11] Incropera FP, DeWitt DP. Fundamentals of Heat and Mass Transfer. New York: John Wiley and Sons, 1990.