Pergamon

PII: S0038–092X(01)00022–6

Solar Energy Vol. 71, No. 2, pp. 135–145, 2001

0038-092X/01/$ - see front matter

www.elsevier.com/locate/solener

A SOLAR COOLING PROJECT FOR HOT AND HUMID CLIMATES

JIANG HE*,†, AKIO OKUMURA**, AKIRA HOYANO*** and KOHICHI ASANO***
*OM Solar Association, 158-1 Nagatsuru-cho, Hamamatsu City 435-0031, Japan
**OM Institute, 3-8-6 Mejiro, Toshima-ku, Tokyo 171-0031, Japan
***Tokyo Institute of Technology, 4259 Nagatsuta-cho, Midori-ku, Yokohama City 226-8502, Japan

Received 6 July 2000; revised version accepted 11 December 2000

Communicated by ANDREAS ATHIENITIS

Abstract—This paper presents a solar house built in a southern city of China where the summer is long, hot and humid. The house was designed appropriately for the climate and was constructed with local building materials where possible. A multifunctional solar system was used and a method for indoor ventilation was proposed. The design included double walls and a triple roof in order to remove heat by ventilation of the building envelope. The external walls were clad with unglazed bricks to allow evaporative cooling. The house has been monitored since completion and more than one year of data is available. Analysis of the monitored data shows that the solar techniques proposed in this design are effective in a hot and humid climate. Effective ventilation strategies for the improvement of thermal comfort are also discussed.

1. INTRODUCTION

In recent years, the number of households in the southern cities of the Peoples Republic of China that are able to afford home air-conditioning has increased significantly and the air-conditioner is regarded as an indispensable household appliance in modern life. Many newly constructed buildings are orientated solely toward air-conditioning and neglect sustainable design. This will have a large impact on the domestic energy consumption in the near future. Therefore, it is important to quickly establish viable technology for houses with minimal energy consumption. In order to demonstrate the technologies needed in sustainable house design for hot and humid climates, we have carried out a case study project in a southern city (Nanning) of China.

As pointed out by many researchers (Cook, 1989; Givoni, 1976, 1991, 1992; Yannas, 1997; Machado and La Roche, 1999; Anink *et al*., 1996), the main design guidelines for hot and humid climates are the reduction of heat gains through the building's envelope and the generation of air movement. Nevertheless, a climate-orientated solar design is important not only to reduce heat gains to a minimum level but also to allow passive systems to function adequately. From meteorological data, the locality is known to have an extremely hot and humid climate. Therefore, passive strategies and active cooling techniques are necessary in order to guarantee comfortable thermal conditions. The integration of passive techniques and active solar systems has been demonstrated in previous studies (Melody, 1999; Leboeuf and Christensen, 1999). Melody's research involved the development of a radiant barrier system to reduce heat gains into the building. A layer of aluminum foil material installed into the air space of a building envelope acts as a radiation barrier which blocks radiant heat transfer across building cavities. In order to increase the ability of natural ventilation to cool the structure, the design included a wing wall.

As appropriate to the local climate and the nature of the building materials, the design in the present study incorporated double walls so as to provide natural ventilation cooling in the exterior walls. Brick is one of the most popular building materials in the local area and was used to finish the external walls and floor of the house in order to utilize locally available materials. In contrast to the studies of Melody (1999) and Leboeuf and Christensen (1999), the active solar system employed in the house in this study is a multi-functional solar system that is used widely in Japan. The solar system is able to collect solar heat for space heating in winter, and cool the building in summer. In addition, the solar system

†Author to whom correspondence should be addressed. Tel.: +81-53-4605-112; fax: +81-53-4605-110; e-mail: kako@omsolar.co.jp

provides hot water and photovoltaic (PV) electricity.

The main focus of this paper is to describe the solar design strategies employed and clarify the effect of thermal improvement and the potential for solar energy utilization. For this purpose, the systems in the house have been monitored since construction was completed in April 1998. Data for a period of more than one year is available and described in this paper.

2. SOLAR DESIGN STRATEGIES

Nanning is located just south of the tropic of Cancer (N22°49′, L108°21′), where the summer season occurs between April and November and the highest daily air temperature exceeds 30°C, as shown in Fig. 1. The rainy season occurs between May and August, at which time the relative humidity averages over 80%. The monthly mean wind velocity is around 1 m/s throughout the year. Therefore a lack of wind is another characteristic. Heating is required for only 2 months, December and January. The climate of Nanning can be summarized as follows: winter is very short at 2 months and the summer is long, hot and humid without any breeze. According to such a climate, the following design principles are considered:

- prevent the house from becoming hot
- vent heat out by creating air movement
- exploit the coolness of night air
- utilize solar energy efficiently

The first design strategy under consideration is the prevention of heat entering the building where possible. A triple roof design is used. Forced and passive ventilation to exhaust heat from the roof is employed. Double walls passively allow heat to vent, and exterior surfaces are finished with unglazed hollow bricks, which enables natural ventilation and evaporative cooling for the external walls. As a result, heat transfer through the walls into the building is greatly reduced.

Because the local area lacks strong winds in summer, a method to enhance heat-removing ventilation was proposed. An exhaust stack was incorporated into the design. Hot air from the roof flows through the stack during a summer day, which causes the upper part of the stack to get hot, thus creating a chimney effect. The air movement in the stack draws indoor air from the building. In addition, in order to increase the area of moisture-absorbing surfaces, the interior walls are finished with lime plaster and the floor is covered with unglazed brick tiles.

The active solar system used in this house is an air-heating collecting system that has multiple functions. The heated air in the roof is utilized for floor and space heating in winter, as well as for the hot water supply in seasons that do not require heating. Cool and dehumidified night air is drawn into the rooms for cooling in summer. Further utilization of solar energy is with a PV integrated roof system that is linked to the local electricity grid, which allows surplus power to be supplied to the local area.

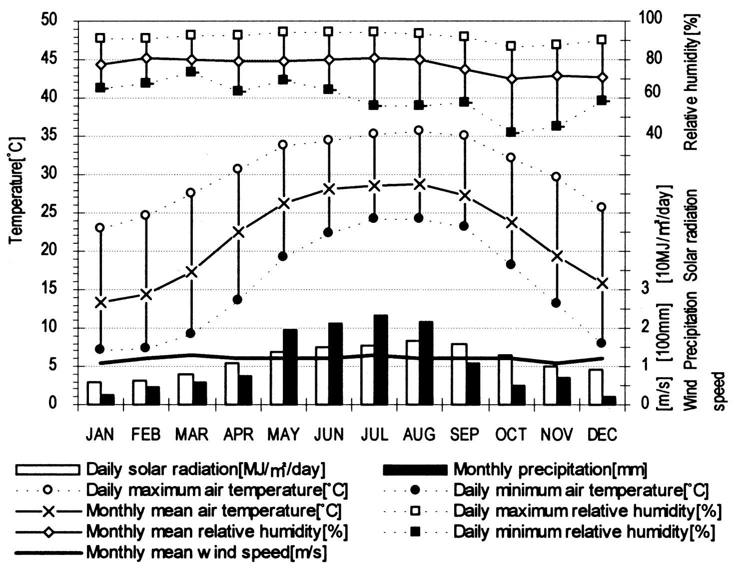

Fig. 1. Nanning annual meteorological data.

Fig. 2. Southeastern view of experimental house.

3. BUILDING DESCRIPTION

The experimental house as designed consists of two buildings (Fig. 2). The eastern structure is a two-story residence with an open ceiling and local standard floor area (ground floor area is 60 m^2, first floor is 29 m^2). On the ground floor is a kitchen, a dining room, a shower bathroom and a bedroom, and there are two bedrooms on the first floor (Fig. 3). The western structure is a single-story building that includes a large meeting room, a traditional Japanese tea ceremony room, a bathroom with a bath unit (hot water is supplied by the solar system) and an instrument room for data recorders and other equipment. The roofs are covered with metal (blackened stainless steel). The building fabric and internal walls are made of ferroconcrete. The exterior surfaces of the walls are clad with unglazed hollow bricks with a polystyrene foam backing (Fig. 4). The bricks have two vertical ridges on the inside face that create a continuous vertical air space allowing air to flow freely. The air inlets are in the lowest row of bricks and the outlets are at the top of the wall or below window frames.

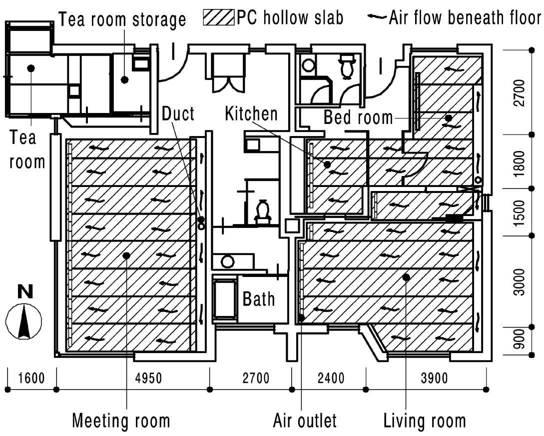

Fig. 3. Plan of ground floor.

4. OPERATING MODES OF THE SOLAR SYSTEM

The solar system has two seasonal modes that are adjusted manually for each season. Day and night operations differ and are changed automatically for each seasonal mode. The system specifications are given in Table 1 and details of the system operation are described below.

4.1. Heat collection in winter daytime

The surface of the south-facing roof is used for solar heat collection and is finished with blackened stainless steel. The upper part of the roof collector is made of glass under which there is a layer of air. As illustrated in Fig. 5, ambient air from inlets in eave edges is drawn by a fan installed in the air-handling box (air router) into

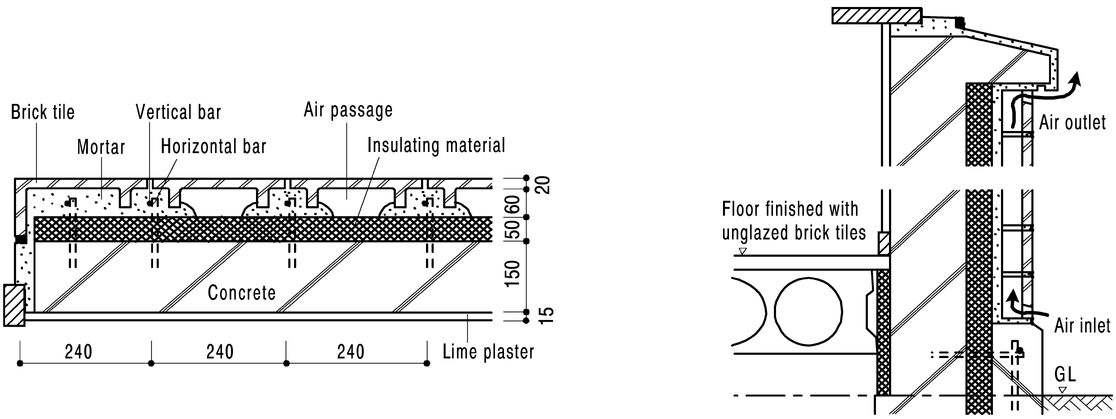

Fig. 4. Plan and cross-section of wall.

Table 1. Building and system specifications

- Construction: concrete fabric and brick wall
- Floor area = 166 m^2 (east = 88 m^2, south = 78 m^2)
- Roof insulation = rock wool (100 mm)
- Wall insulation = polystyrene foam (50 mm)
- Floor insulation = polystyrene foam (50 mm)
- Solar roof collectors
  - area = 70 m^2 (eastern house)
  - area = 58 m^2 (western house)
- Under-floor storage
  - area = 33 m^2 (eastern house)
  - area = 24 m^2 (western house)
- PV roof area = 39 m^2 (33 sheets, 2 kW)
- Heating/cooling and ventilation
  - volume of fresh air supply = 660 m^3/h (maximum)
- Hot water tank = 300 l

the roof air chamber through the space under the blackened steel. The outside air is heated by passing beneath the sun-absorbing metal roof during the day. The temperature of the heated air increases as it passes through the space under the glass. After passing through the roof air chamber, the airflow can follow two different channels as controlled by dampers, depending on the seasonal mode of the system controller.

In winter, hot air is introduced into the air space beneath the floor through the vertical air duct, and then escapes to the rooms from floor outlets. As the hot air passes under the floor, heat is conducted into the floor slabs. During operation, the rooms are ventilated, but fresh air can also be introduced. The fan stops automatically when solar heat is no longer available. Meanwhile, the inlet damper at the front of the air-handling box shuts down and the airflow from the roof air chamber to the rooms is cut off. At night, heat is released into the rooms from the floor, thus reducing the drop in room temperature.

4.2. Heat exhausting in summer daytime

In summer daytime, the hot air that is gathered in the roof air chamber is exhausted through the exhaust duct that is connected with the exhaust stack. This reduces heat transfer from the roof into the rooms. Below the air heat-collecting space is an insulating layer under which there is another air space that provides natural ventilation. Under the northern metal roof there is an air passage for natural ventilation. Air can pass from north to south, and this air passage is also connected to the exhaust stack, as are the vents in each room. The exhausted hot air heats the upper part of the stack and creates a rising air current, which draws air from the rooms to the stack through the vents. This method can increase ventilation in the rooms even when the outdoor wind velocity is insufficient.

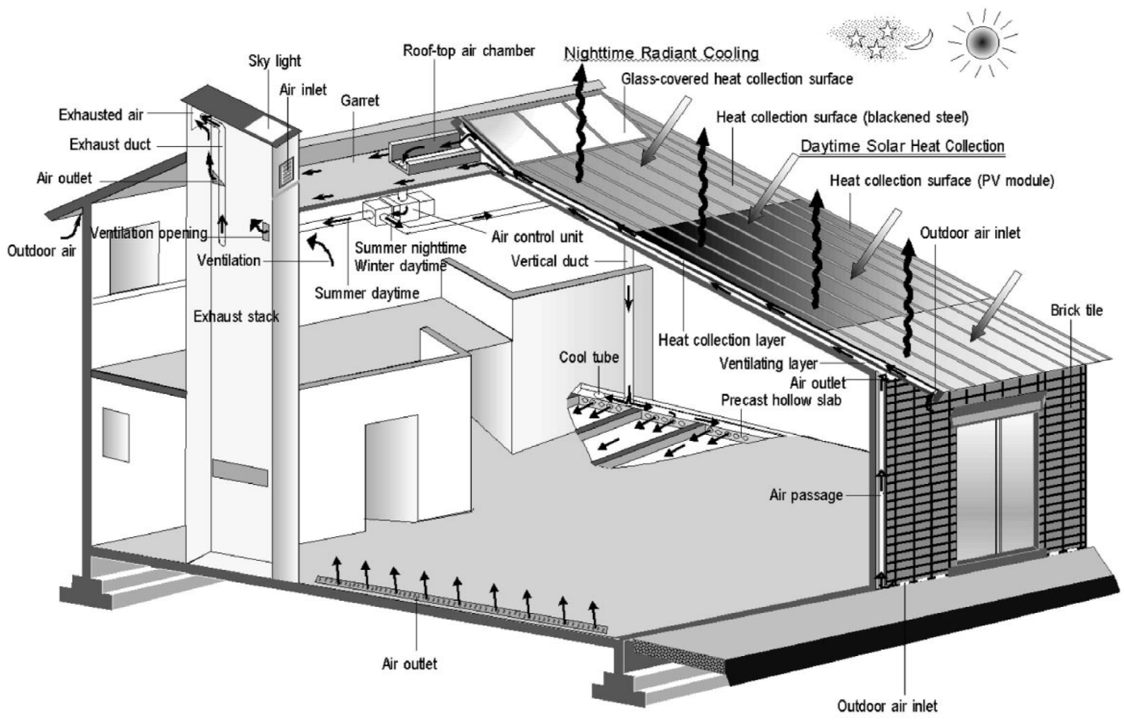

Fig. 5. Schematic diagram of solar system.

4.3. Cooling in summer nighttime

At night, outdoor air is allowed in and condensation may occur when the temperature of the metal roof becomes lower than the dew point temperature of the ambient air due to radiant cooling. The cool dry air is channeled down to the air space beneath the floor in the same way as in winter daytime. All of the rooms are ventilated and the air quality is improved overnight. Water may condense on the lower surface of the metal cladding overnight, however it evaporates quickly as soon as the heat-exhausting operation begins the next day.

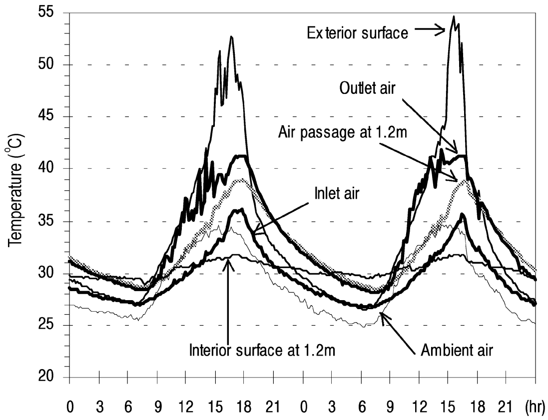

Fig. 7. Temperatures in western wall.

5. RESULTS AND DISCUSSIONS

5.1. Insulation of the wall

The surface temperature distribution of the eastern wall measured at 8:11 a.m. on a sunny summer day is shown in Fig. 6. The graph on the left of the figure shows the exterior surface temperature of an air passage. It is noted that the higher the surface temperature, the further the heat gradient climbs up the surface of the wall. This is representative of the fact that hot air rises in the air passage and is allowed to escape from the wall at the outlets.

Results for the western wall are shown in Fig. 7. The exterior surface temperature reaches more than 50°C in the afternoon. At that time, the air temperature at the outlet is 2–3°C higher than that at a height of 1.2 m above the ground, and about 5°C higher than that at the inlet. In other words, the temperature increases from the bottom of the air passage to the top. From this result, it can be said that the wall is capable of natural ventilation during the day, which allows a fraction of the solar heat absorbed on the outside surface of the wall to be dissipated. The interior surface temperature varies only slightly during the day, which is indicative of the high insulating properties of the wall.

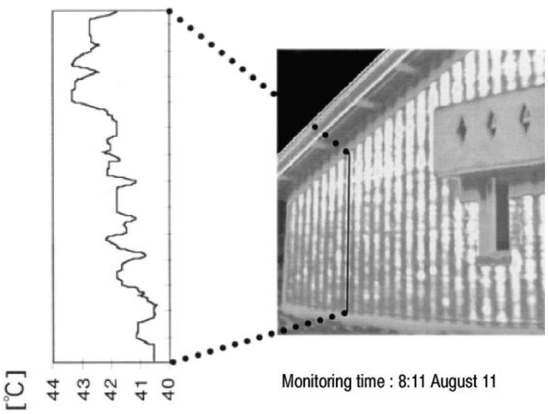

Fig. 6. Surface radiant temperature of eastern wall.

5.2. Indoor temperature

The temperature distribution from the roof to the floor is shown in Fig. 8, obtained from data recorded at 2-h intervals on a fine summer day (September 10). During measurement, the doors and windows were closed and there were no occupants in the house. Although the air temperature in the cavity immediately beneath the metal roof reaches 75°C at midday, the ceiling temperature varies only slightly within 2°C throughout the day. This is because the heat in the roof is almost entirely dissipated. Indoor air temperatures vary between 29°C and 31°C over the day. This result reveals that heat gains are extremely small. It was also found that temperatures beneath the floor are slightly lower than the indoor air temperature during the daytime. From this result, it can be deduced that the coolness stored beneath the floor may play a role in reducing rises in indoor temperature.

Another contribution to the reduction of indoor temperatures is considered to be water evaporation from the lime plaster and the floor. As seen from Fig. 10, water evaporation may occur during the day because indoor relative humidity is higher than outdoor relative humidity. In other words, evaporative cooling can be obtained. On the other hand, the indoor relative humidity becomes lower than the outdoor humidity at night. It can be said that indoor moisture is absorbed by the lime plaster and the floor during the night

Diurnal variations of indoor and outdoor air temperature and humidity are presented in Fig. 9. Maximum diurnal outdoor temperatures exceed

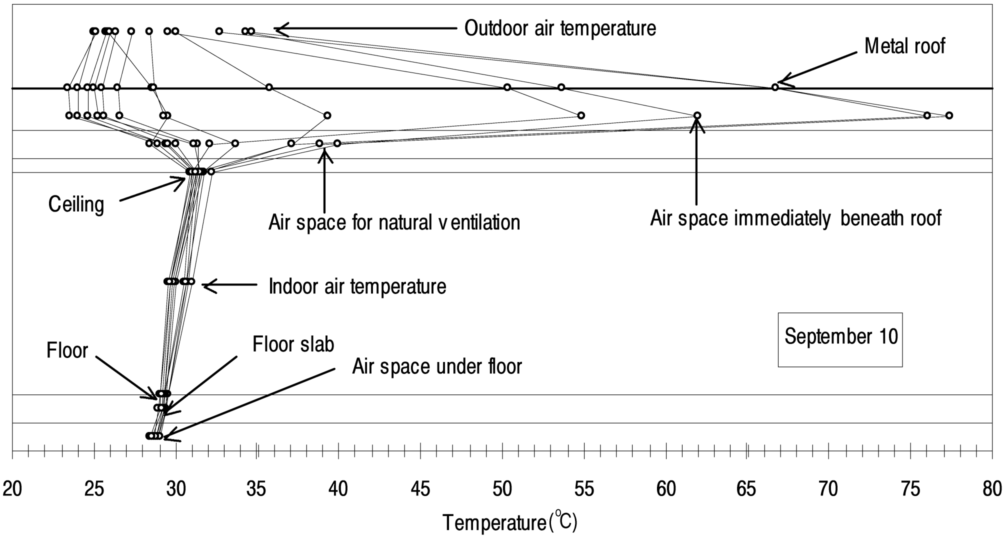

Fig. 8. Temperature distribution from roof to floor.

30°C from the middle of April to the end of October, and the minimum is over 25°C during the period June to August. The greatest variations in indoor temperature occur on days on which windows were open. This is because daytime ventilation allows warm air to enter which leads to a rise in indoor temperature during the day. As a result, heat gain is increased and the fabric becomes warm. This suggests that a deliberate ventilation strategy is useful for maintaining a comfortable environment (Blondeau *et al.*, 1997; Van der Maas and Roulet, 1997). The thermal performance of three ventilation strategies is examined in the following section.

5.3. Comfort-improving effect of ventilation strategy

The results of measurements over three summer days when the door and windows were opened all day (Case A) are shown in Fig. 10. The monitored site was the living room. Indoor air temperature can be seen to vary with outdoor air temperature yet consistently remains slightly lower than outdoor temperature during the day. At night, the

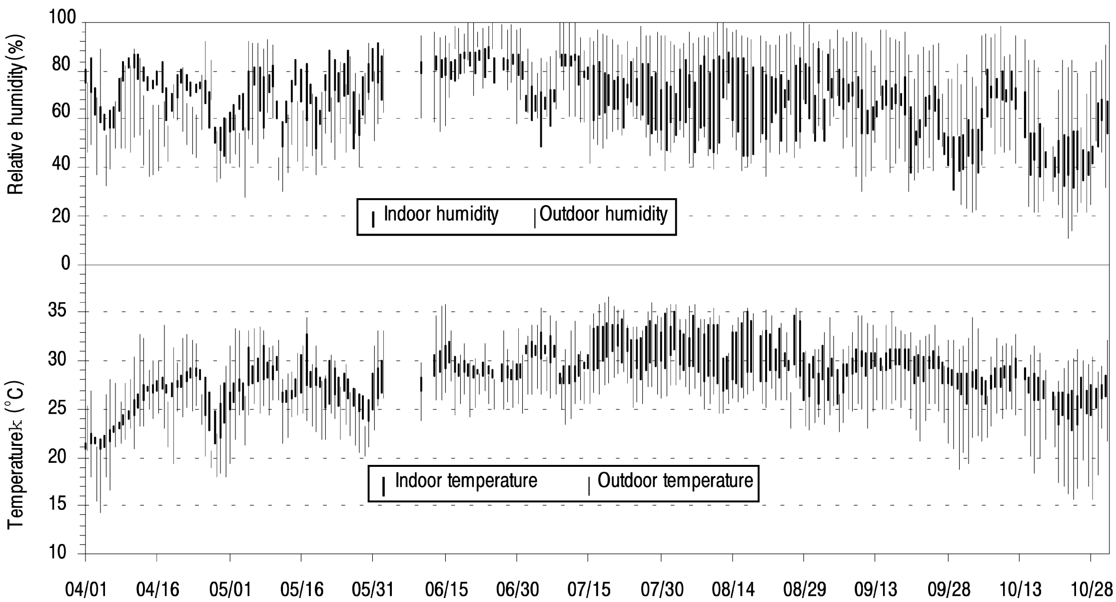

Fig. 9. Diurnal variations in indoor and outdoor air temperatures and relative humidity.

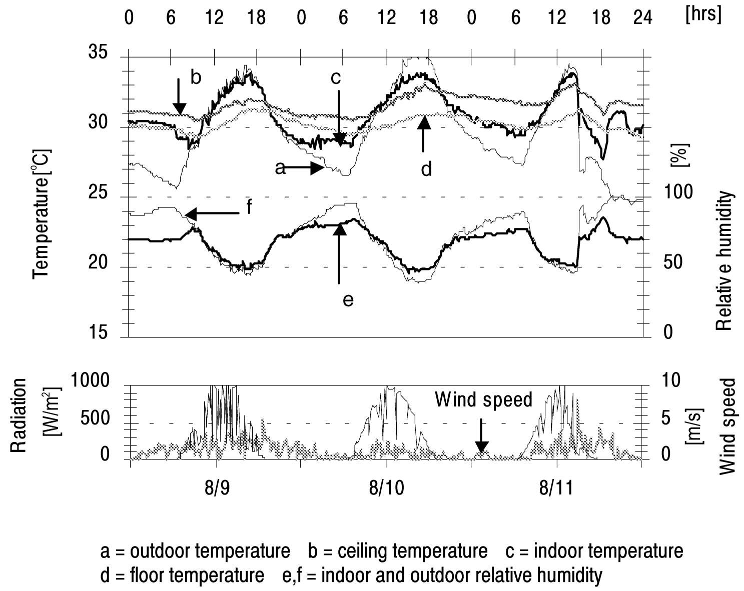

Fig. 10. Windows open all day (Case A).

indoor temperature drops and yet remains 2°C higher than the outdoor temperature. From morning to early evening, the surface temperature of the floor rises 2°C because warm outdoor air enters the house during the day.

On the other hand, when the door and windows were closed all day (Case B), the indoor temperature remains 3–4°C lower during the day and 5–6°C higher than the outdoor temperature at night, as shown in Fig. 11. This suggests that a better thermal environment may be achieved if the windows are closed during the day and opened at night. Measurements to confirm this suggestion were made and the results are shown in Fig. 12 (Case C).

In Case C, the doors and windows were closed manually at 7 a.m. and opened at 9 p.m. It can be seen that the indoor temperature is maintained at 4–5°C lower than the outdoor temperature during the day and is about 2°C higher at night. This indicates that Case C combines the merits of both Case A and Case B. When the windows are closed during the day, the cooler air indoors reduces the maximum indoor temperature and the influx of

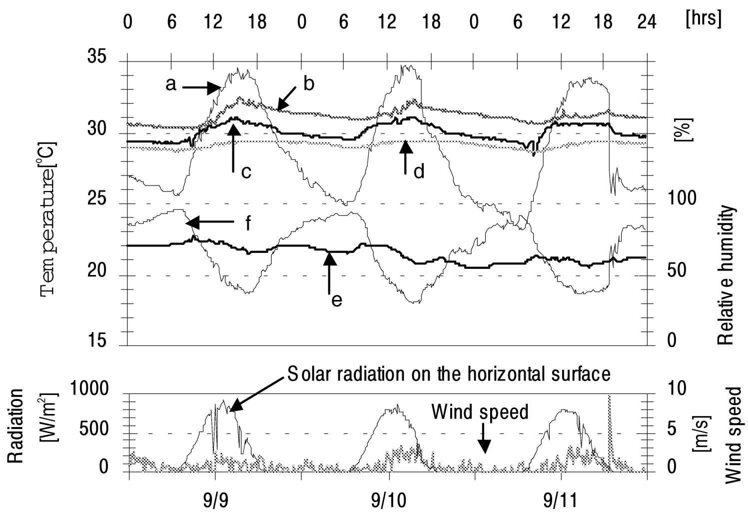

Fig. 11. Windows closed all day (Case B).

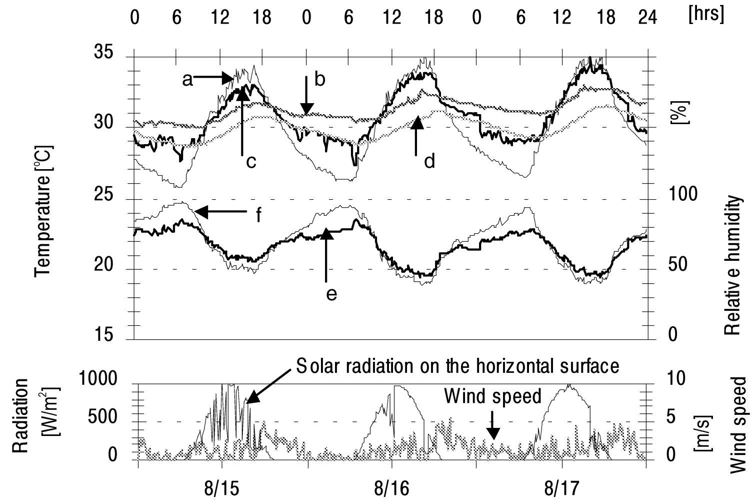

Fig. 12. Windows closed from 7 am to 9 pm (Case C).

warm air from outside can be controlled. When the windows are opened at night, ventilation cools the structural elements and dissipates heat inside.

In order to obtain a quantitative understanding of the comfort improvement of Case C, the differences between indoor and outdoor temperatures for the three cases were computed, as shown in Fig. 13. Positive values indicate that the indoor temperature is higher than the outdoor temperature and negative values indicate the reverse. As seen from the figure, during the day, indoor temperatures for each case are lower than the outdoor temperature and the smallest temperature difference is −1°C, −4°C and −5°C for Case A, B and C, respectively. On the other hand, during the night, indoor temperatures for each case are higher than the outdoor temperature and the largest temperature difference is 3°C, 6°C and 2°C for Case A, B and C, respectively. Therefore, it is clear that the indoor temperature is 1°C higher than outdoor temperatures due to heat storage when the windows are open during the day. Indoor temperatures remain 4°C lower during the day when the windows are kept closed.

5.4. Dehumidification

The dehumidification effect of the house can be investigated by comparing indoor humidity with that outdoors. Indoor relative humidity varies only a little over a day as is seen in Fig. 11. This suggests that the house has the same characteristics as a wooden house. The reason for this is that the interior surfaces are finished with lime plaster and brick tiles that absorb moisture when the indoor humidity is high, and release moisture when humidity is low. Even so, there should be a decrease in indoor humidity from evening to early morning. In this model, dry air from the roof is

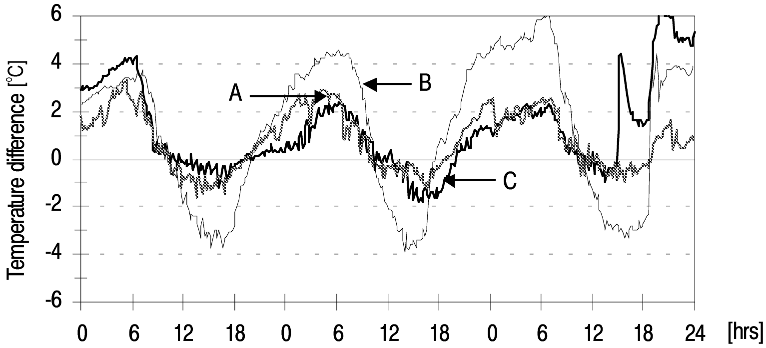

Fig. 13. Temperature difference for Case A, B, C.

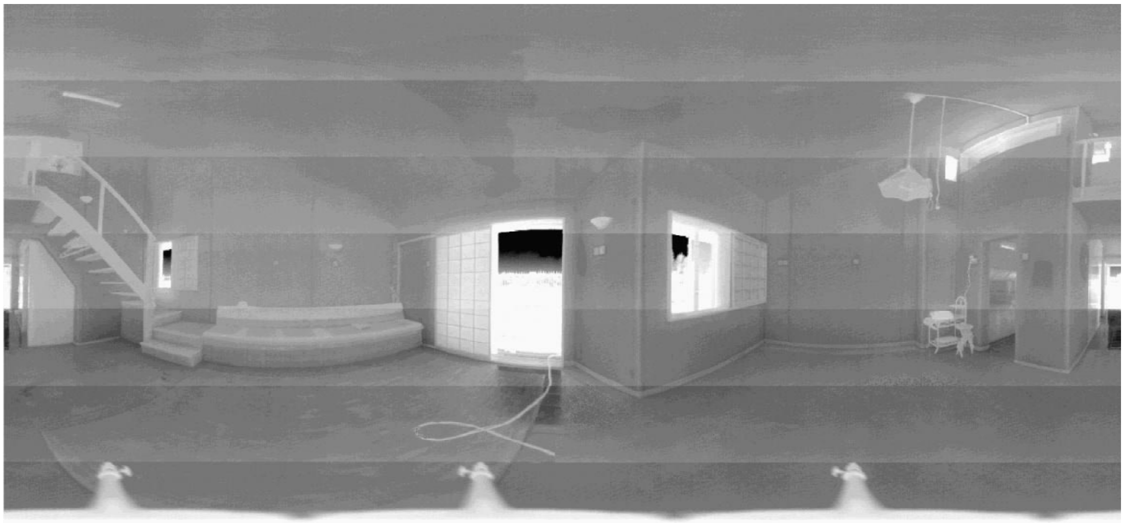

Fig. 14. Distribution of surface radiant temperature in living room, measured at 14:29 (Aug. 10, 1998).

channeled into the space under the floor and enters the rooms. As a result, the rooms are dehumidified during the night.

5.5. Analysis of indoor thermal comfort

Fig. 14 shows a spherical thermograph recorded in the living room at 14:29 on a clear summer day (August 10) when the doors and windows were kept open. As seen from the figure, the outdoor air temperature was 33.3°C and the radiant temperatures for all interior surfaces are lower. Average radiant temperatures in the morning, afternoon and evening are shown in Fig. 15. The radiant temperatures of each surface in the afternoon and evening are lower than 33°C (outdoor temperature). Therefore, it can be said that the building is well insulated and shaded. As shown in Fig. 16, the mean radiant temperatures (MRT) of the rooms in the afternoon and evening are lower than the outdoor temperatures measured at the same time. This may result in a more comfortable environment with radiative cooling for the occupants.

5.6. Performance of PV system and hot water supply

The middle part of the roof collector is a PV integrated solar module, under which the heat can be removed not only to improve the electrical efficiency of the PV module by lowering the temperature of the module but also to use the heated air. The wiring is installed in the air passages under the roof.

The array is three strings of 11 PV modules wired to an inverter that converts the DC supply

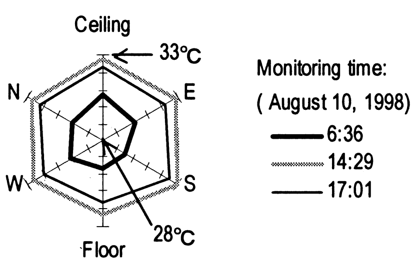

Fig. 15. Average surface radiant temperatures.

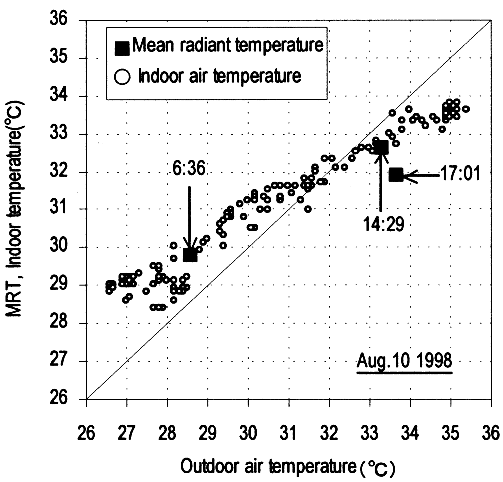

Fig. 16. MRT and indoor and outdoor temperature.

Table 2. Measurement results of PV roof system for a year

	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	Year
Monthly generation (kWh)	25.8	78.5	118.1	155.0	233.2	199.6	146.7	234.4	238.4	234.4	140.7	149.4	1954.2
Number of monitoring days	5	22	31	30	31	30	21	27	28	29	29	31	314
Daily average (kWh/day)	5.16	3.57	3.81	5.17	7.52	6.65	6.99	8.68	8.51	8.08	4.85	4.82	6.22
Daily average (kWh/day)	0.132	0.091	0.098	0.132	0.193	0.171	0.179	0.223	0.218	0.207	0.124	0.124	0.160

Table 3. Maximum temperature of hot water and time on representative clear days for each month

	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	Year
Maximum temperature (°C)	40.6	35.9	40.9	45.1	44.8	46.2	48.0	54.1	50.6	49.6	43.0	34.5	34.5–54.1
Time of occurrence	15:00	15:30	14:50	15:20	13:50	14:30	15:50	15:10	13:40	15:00	14:50	14:20	13:50–15:30

generated to AC current that is ready for domestic use. The PV system has a peak capacity of 2 kW and is connected in parallel to the main electricity supply. The inverter can supply any excess AC supply after use by household loads to the external power grid and any shortfall in output from the array can be met by external supply.

Monitored results of the performance of the PV roof for a year are listed in Table 2. Electricity production per year reaches more than 2000 kWh, which is sufficient to power an average household for a year.

The results of monitoring the performance of the hot water system are listed in Table 3. The highest temperature of the hot water and the time of occurrence on a representative clear day are listed for each month. The hot water temperature reaches a maximum during the period 13:50 to 15:30 on sunny days and the range of the maximum temperatures for the year is between 34.5°C and 54.1°C. The hot water tank of 300 l used in this house is sufficient for an average family for 1 day.

6. CONCLUSIONS

This paper described the solar cooling strategies employed in the experimental solar house built in a southern city (Nanning) of China, where the climate for most of the year is hot and humid. The results of monitoring the house for one year have shown that the proposed double wall and triple roof designs are effective for insulating and removing heat from the building's envelope. These heat-insulating and exhausting strategies can maintain the diurnal fluctuation of indoor air temperature to within 2°C on a typical mid-summer day.

Nighttime natural ventilation is an effective method for passive cooling in the hot and humid and breeze-less climate. In order to quantitatively clarify this cooling effect, three passive ventilation strategies were investigated experimentally. Measurements show that when the windows are closed during the day and opened at night, the rooms can be kept 4°C cooler than if the windows are opened all day.

From the monitoring results, it has been found that the house has an effect on the humidity of the environment due to use of moisture-absorbing materials in the interior finishing. Coolness stored under the floor creates radiative cooling and achieves a significant comfort improvement for the occupants.

In extremely hot and humid summers such as between July and August in Nanning, passive cooling techniques alone may not guarantee comfortable conditions and mechanical cooling may still be necessary. The energy for mechanical cooling systems can be supplied by the PV system that is integrated in the roof of the house. In addition, 300 liters of hot water at temperatures of 35–54°C can be obtained on any sunny day throughout the year, and most of the hot water can be supplied by the integrated solar system.

Acknowledgements—This is a joint research project carried out by OM Solar Association and the Institute of Applied Physics of Guangxi, and has been funded by the Guangxi Science Technology Board (No. 9456013), Guangxi Science Academy (No. 19961011), Guangxi Bureau of Foreign Experts. The authors would like to take this opportunity to thank Bei Yaowu, Du Hui, Wang Mingzhen, Guo Bing and Hu Dongnan of the Institute of Applied Physics of Guangxi for their help.

REFERENCES

Anink D., Boonstra C. and Mak J. (1996) *Handbook of Sustainable Building*, James & James, UK.

Blondeau P., Sperandio M. and Allaed F. (1997) Night ventilation for building cooling in summer. *Solar Energy* **61**(5), 327–335.

Cook J. (1989) *Passive Cooling*, MIT Press, Cambridge, Massachusetts.

Givoni B. (1976) *Man, Climate and Architecture*, 2nd ed., Applied Science Publishers, London.

Givoni B. (1991) Performance and applicability of passive and low-energy cooling systems. *Energy and Buildings* **17**, 177–199.

Givoni B. (1992) Comfort, climate analysis and building design guidelines. *Energy and Buildings* **18**, 11–23.

Leboeuf C. and Christensen C. (1999) The minimum energy house. *Solar Today* **January–February**, 15–19.

Machado M. V. and La Roche P. M. (1999) Materials and appropriate design strategies for buildings in hot climates. *Proceedings of the 16th International PLEA (Passive and Low Energy Architecture) Conference, Brisbane, Australia* **vol. 1**, 357–362.

Melody I. (1999) Solar cooling research for hot, humid climates. *Solar Today* **January–February**, 23–24.

Yannas S. (1997) Architecture, sustainability and environmental design. *Proceedings of the 14th International PLEA (Passive and Low Energy Architecture) Conference, Kushiro, Japan* **vol. 1**, 21–23.

Van Der Maas J. and Roulet C. A. (1997) Night-time ventilation by stack effect. *ASHRAE Transactions* **97**, 1.