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A PASSIVE SOLAR SYSTEM FOR THERMAL COMFORT CONDITIONING OF BUILDINGS IN COMPOSITE CLIMATES

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Abstract—Passive solar heating is a well established concept in cold climates, but passive systems which provide heating, cooling and ventilation depending on the season are less common. Some of the known systems in this category are: Sky-Therm, earth-air tunnel, the Silvestrini Bell, and the Barra–Costantini System, which are applicable in composite climates. Large areas of Central and Northern India have a composite climate, which includes hot-dry, hot-humid and cold climatic conditions. The present paper describes the development of a solar passive system, which can provide thermal comfort throughout the year in composite climates. In the first phase, passive model 1 comprising two sets of solar chimneys was developed and monitored for its performance for 1 complete calendar year. Based on the feedback and experience, an improved version of model 2 was developed. In model 2 both the trombe wall and sack cloth cooling concepts were incorporated, in order to make it more effective and also to give it a more compact and aesthetic appearance. Detailed system descriptions along with year-round performance data are given in this paper.

1. INTRODUCTION

Passive solar heating is a well-established concept in cold climates. The techniques used for passive heating, (Passive Solar Design Handbook, 1984) such as direct gain, trombe wall, transparent insulation, etc. are more or less straightforward. However, passive cooling techniques are not as standardized as the passive heating techniques as they depend on judicious use of night ventilation, shading, evaporative cooling, etc. in hot and arid zones. Ancient methods of cooling in arid zones have been described in Bahadori (1978), and a summary of the state-of-art of passive cooling systems has been given in Givoni (1991), and The Residential Energy Audit Manual (1988). Passive systems, which provide heating, cooling and ventilation depending on the season, are also less common. Some of the known systems in this category are, Sky-Therm (Yellot and Hay, 1969), earth-air tunnel (Mihalakakou *et al*., 1995; Sodha *et al*., 1986), the Silvestrini Bell (Benedittini *et al*., 1981) and the Barra–Costantini system (Barra et al., 1980), which are applicable in composite climates. Simultaneous application of different natural cooling technologies has also been reported recently (Solaini *et al*., 1998; Hamdy and Firky, 1998).

Large areas of Central and Northern India, including New Delhi (28°35′ N latitude) have a composite climate with hot-dry, hot-humid and cold climatic conditions. Hay's sky-therm system was tried in New Delhi several years ago, but no systematic follow-up studies were made. Earth-air cooling had a limited success, but cannot be described as a completely passive system. In addition, it requires an underground tunnel, which may not always be feasible to construct. Other systems like the Barra house have not been studied in detail.

The present paper describes research and developmental efforts of a solar passive system, which can provide thermal comfort conditions inside the building throughout the year in composite climates.

2. BASIC CONCEPT OF THE SYSTEM

The passive model 1 system, shown in Fig. 1, consists of two solar air heaters with natural flow (solar chimneys or ventilators), one placed on the roof and the other placed on the ground. The roof air heater acts as an exhaust fan, sucking the room air and venting it out during sunshine hours. The bottom collector is used alternatively as a conven-

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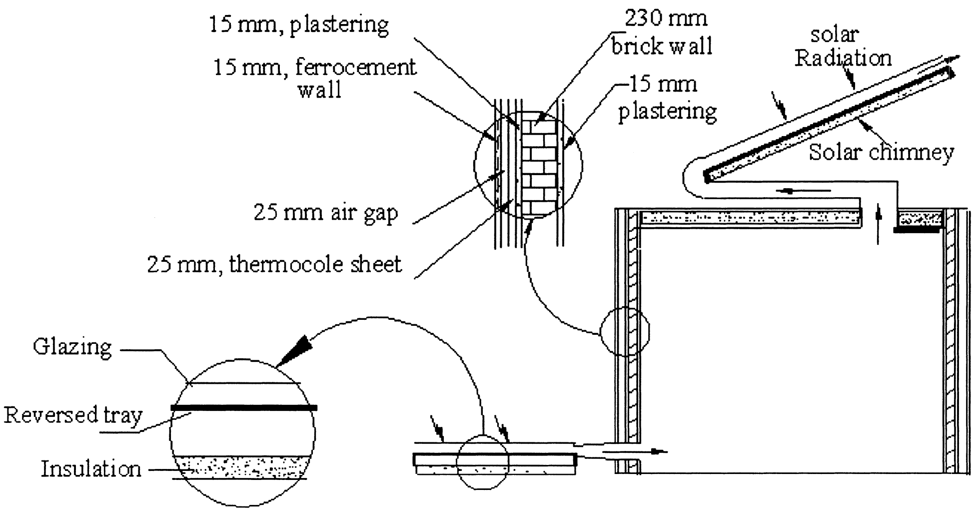
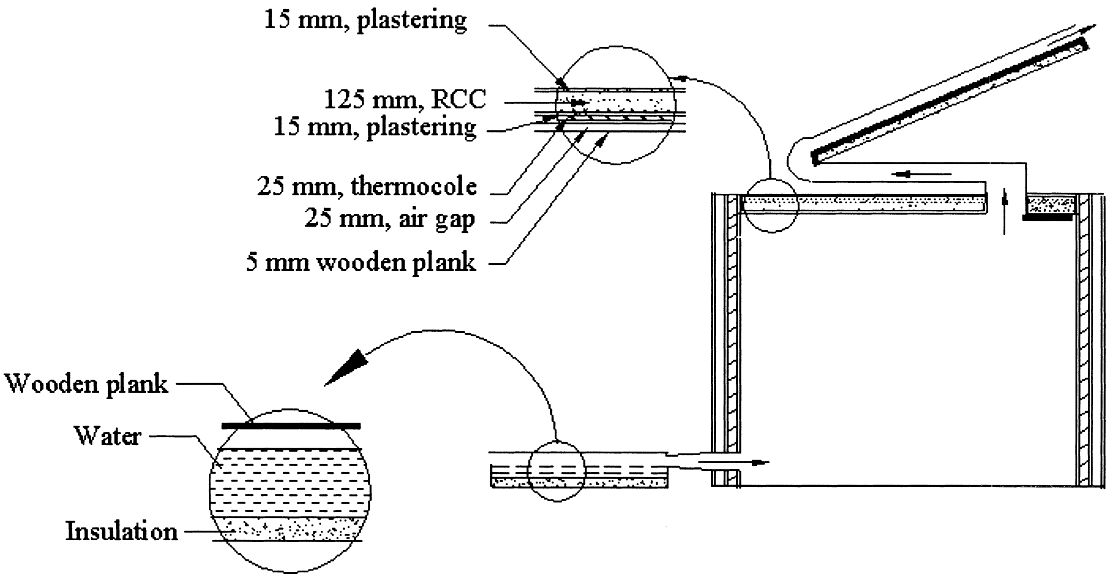


(a)



(b)

Fig. 1. (a) Schematic diagram of passive model 1 system for winter operation. (b) Schematic diagram of passive model 1 system for summer operation.

tional air heater during winter and as an evaporative cooler during summer, with some minor modifications. The bottom collector consists of a rectangular metal trough insulated at the bottom and sides. A metal duct of rectangular cross section is kept inside the trough. One end of the duct is connected to the room and the other end is open to the atmosphere. The top of the duct is painted black. During winter, the trough is emptied of water and is fitted with a glazing so that the unit acts like a solar air heater. During summer, the glazing is removed and a shadow is provided above the trough to prevent radiation absorption. Water is filled in the trough so that the metallic duct is completely immersed in it. The operation of the complete system for winter and for summer operation is shown in Fig. 1a and b, respectively. The connecting points between the collectors and the room are provided with wooden doors so that the room is completely insulated, as would be necessary for winter nights.

At an early stage of the work, it was decided to retrofit an existing single room structure so as to modify it to the solar passive system. Before proceeding with the incorporation of solar collectors, it was considered important to reduce the thermal conditioning load on the passive system, by proper insulation of the building. It was also necessary to develop a method of sizing the solar chimneys/collectors. These are discussed in the following sections.

3. BASIC DESIGN OF THE SYSTEM

3.1. Reduction of thermal conditioning load of the building

The existing single room is 5 m long, 4 m wide and 3 m high, with the longer side oriented along the east–west direction. It has masonry brick walls of 230 mm (9″) thickness, with an RCC slab of 100 mm (4″) thickness. A door (area 2 m^2) was fixed on the south facing wall and two windows (1 m^2 each) were provided on the east and west walls. A standard thermal network analysis was carried out to find out the thermal conditioning (heating/cooling) load of the building per unit volume for a design inside–outside temperature difference of 11°C, which worked out to be 2.904 W/m^3 K. In order to reduce the thermal conditioning load of the building, the following retrofitting measures were carried out.

- The windows were changed to double glazing panel with a curtain to reduce direct heating.
- The door was insulated by adding a plywood sheet and a 25-mm-thick thermocole sheet. An anteroom was also constructed so that the main entrance was shielded from direct wind.
- All the four walls were insulated from outside by providing a 25-mm-thick thermocole sheet and a 25-mm air gap. The air gap was created by constructing a ferrocement cladding all around the walls.
- Similarly the roof was insulated from inside with thermocole. However, a plywood sheet was used to create the air gap.

Applying the thermal network analysis again, the thermal load per unit volume of the modified structure was calculated to be 0.861 W/m^3 K. A comparison of thermal loads for the original and retrofitted structures is given in Table 1.

3.2. Modeling of solar chimney

The heart of the proposed thermal conditioning system is a solar chimney, which is nothing but a solar air heater operating in natural convection mode. The available literature on solar air heaters is mainly concerned with forced flow of air through solar collectors. As the solar chimney operates on natural convection mode all the parameters such as mass flow rate, rise in air temperature, pressure drop, etc. are interdependent and it becomes very difficult to predict its performance. For this purpose a computer model of the solar chimney was developed, to estimate the air mass flow rate. It can handle estimation of airflow under a given set of operating conditions, such as solar radiation intensity, ambient temperature, collector tilt angle, etc., which can help in evaluating its performance.

3.2.1. Analysis of the solar chimney. The schematic of the solar chimney considered for analysis is a collector of 1.2 m width and 2.5 m length. It has an aluminium absorber plate and a 3-mm-thick glass sheet as glazing material at a distance of 50 mm from the absorber plate. Glasswool insulation is provided at the bottom and sides. The south facing, open loop system, with a tilt of 45° from horizontal, has an air flow passage below the absorber plate with a gap of 50 mm between absorber plate and bottom insulation. The above configuration has been selected for simplicity, but the model developed here can

Table 1. Comparison of thermal load per unit volume for existing and modified building

Building component	Area (m^2)	Temperature difference	Unitary thermal conductance (W/m^2 K)		Heat load (W)	
		$(t_o - t_i)$ (K)	Existing	Modified	Existing	Modified
Floor	20	11	0.900	0.160	198.00	35.20
Roof	20	11	2.940	0.776	646.80	170.72
Walls	50	11	1.469	0.419	807.95	230.45
Windows	2	11	6.000	3.000	132.00	66.00
Door	2	11	6.000	3.000	132.00	66.00
Total thermal load (W)					1916.75	568.37
Thermal load per unit volume (W/m^3 K)					2.904	0.861

be extended to any other collector configurations and geometry.

In predicting the performance of a solar chimney, it is important to determine the amount of airflow rate it can handle under particular design and operating conditions. The driving force, which controls the airflow rate through the solar chimney, is the density difference of air at inlet and outlet of the solar chimney. This is created due to height and temperature difference and is a complex function of design and operating parameters such as solar radiation intensity, geometry, orientation, ambient temperature, etc. The higher the temperature difference, the higher is the draft created, causing a larger airflow through the collector. The larger airflow has a tendency to lower the air outlet temperature and results in higher frictional losses resulting in reduced net draft across the chimney. Thus, the balance of both these forces controls the air flow rate handled by the solar chimney under given operating conditions. Applying the energy balance equation to the solar chimney, one gets:

$$\frac{\rho_1 V_1^2}{2} + (\rho_1 - \rho_2) g L_c \sin\beta = \frac{\rho_2 V_2^2}{2} + \frac{f_{avg} 2 L_c \rho_{avg} V_{avg}^2}{D_H} + \frac{K_1 \rho_1 V_1^2}{2} + \frac{K_2 \rho_2 V_2^2}{2}. \tag{1}$$

Mass and heat balance equations give

$$m_{air} = \rho_1 A_1 V_1 = \rho_2 A_2 V_2 = \rho_{avg} A_f V_{avg} \tag{2}$$

$$m_{air} C_{p,air} (T_2 - T_1) = \eta_c A_c I. \tag{3}$$

Assuming air to be an ideal gas and keeping the flow area constant throughout the collector, the above set of equations leads to the following equation for mass flow rate

$$m_{air}^3 = \frac{2 g P_{atm}^2 M_{air}^2 L_c \sin\beta \eta_c A_c I}{C_{p,air} R^2 T_1 T_2 \left[\frac{f_{avg} 4 L_c T_{avg}}{D_H} + T_1 (K_1 - 1) + T_2 (K_2 + 1) \right]}. \tag{4}$$

Eq. (4) gives the air flow rate that can be handled by a solar chimney operating with a collector efficiency η and raising the temperature of air from T_1 to T_2. Collector efficiency η can be calculated from the following equation (Duffie and Beckman, 1980)

$$\eta_c = F' \left[(\tau\alpha)_c - \frac{U_L (T_{avg} - T_a)}{I} \right] \tag{5}$$

where F' is the collector efficiency factor, and U_L is the collector overall heat loss coefficient.

From the average mean plate temperature the top loss coefficient can be calculated for a given configuration of solar collector (Klein, 1975). Collector efficiency factor can be calculated by standard methods (Whillier, 1963; Sukhatme, 1984). In order to calculate F' and outlet air temperature T_2, an iterative method is used. First an initial guess of m_{air} and T_2 is made to evaluate F' and air properties. Then from Eqs. (4) and (5) the airflow rate handled by solar chimney and the efficiency at which it is operating is calculated. Then using Eq. (3) the new value of T_2 is calculated. The procedure is continued until the assumed and calculated values of T_2 and m_{air} match.

The mass flow rate handled by the solar chimney as a function of solar radiation intensity is given in Fig. 2 for different ambient temperatures. The chimney is, with solar air heating collectors, of length 2.5 m, width 1.2 m and air flow gap of 50 mm, inclined at 45° to the horizontal. These figures can be used for sizing solar chimneys for different applications.

As can be seen from Fig. 2, for given collector dimensions and ambient conditions, the airflow rate handled by the solar chimney increases with increasing solar radiation. For a given solar radiation, the mass flow rate is higher for higher ambient temperatures.

3.2.2. Sizing of the solar collectors. As mentioned in the earlier section the air flow rate through the roof collector acting as chimney can be calculated by applying mass and energy balance equations and by using appropriate pressure drop correlations for air carrying ducts. The air flow rates required to be handled by the solar chimney can be calculated from the heating load through the building structure, heat load from the occupants, infiltration, etc., and from the design inside and outside temperatures. The area of the top solar collectors needed to handle these flow rates can be calculated with the help of procedures given in the earlier section and with the help of curves shown in Fig. 2. For a design inside temperature of 27°C and design outside temperatures of 38°C in summer and 15°C in winter, the area of the top collector was estimated to be 6.4 m^2 for summer operation and 4.0 m^2 for winter operation. The larger of these areas can be selected, as the summer season was much longer than winter. Due to restrictions of space available on the roof, the total area had to be slightly

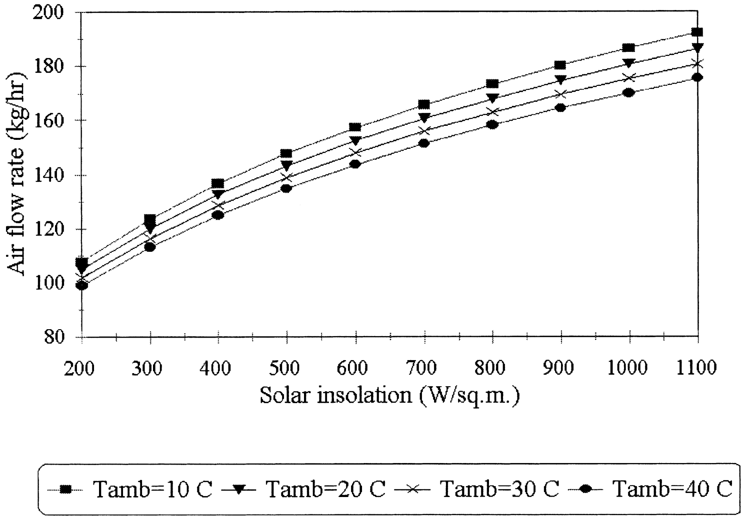


Fig. 2. Estimation of air flow rate handled by solar chimney.

reduced to 6.0 m^2. A similar size has been selected for bottom collectors also.

4. INSTALLATION AND TESTING OF PASSIVE MODEL 1

Two modules of solar collectors of size 2.5 m $\times$1.2 m with single glazing at the top and glass wool insulation at the bottom of an aluminium absorber plate were installed on the roof. An air gap of 50 mm was kept between the glazing and the absorber, and louvers were provided in that space to increase turbulence. The slope of the collectors was kept at 45° from the horizontal. The inlet of the roof collector was connected to the room through two rectangular (0.2 m$\times$0.9 m) metal ducts and through two rectangular openings (0.2 m$\times$0.6 m) made in the roof. The openings were made farthest from the south wall in order to reduce short circuiting of air flow. At each collector outlet, an umbrella type cover with its mouth pointing downwards was provided to act as a wind barrier.

The bottom collectors, two in number consisting of troughs, as described in Section 2 were kept on the ground just outside the south wall. The size of the collectors is identical to the roof collectors. The absorber ducts in the bottom collectors were kept at a lesser angle of about 5° from the horizontal, mainly for ease of conversion of the troughs into evaporative cooling ponds in summer. A single glazing was fixed on the trough and the duct was painted with a black paint for winter operation. The glazing was removed, the trough was filled with water and a plywood sheet was fixed 50 mm above the trough to facilitate evaporative and convective cooling, and to provide shading during daytime. As the air passed through cooled ducts, humidity was not added to the room, as is the case for conventional desert coolers.

4.1. Measurement of air exchange rate

In order to experimentally measure the ventilation (airflow) rate handled by the solar chimney through the passive building, a standard CO (carbon monoxide) decay method was used. A high CO concentration of about 50–60 ppm was built-up inside the room either by burning charcoal or by introducing producer gas (which has a high concentration of CO) from a gasifier. Oscillating wall mounted fans were kept on during the process of building up the CO concentration level inside the room in order to avoid any stratification, after which the source was withdrawn and fans were switched off. The decay of CO was observed by monitoring the variation of CO concentration as a function of time. The decay curves are generally exponential and the time constant can be calculated plotting ln[CO] against time and measuring the slope of the straight line thus obtained. A typical CO decay curve is shown in Fig. 3. For the solar insolation levels of about 500–700 W/m^2 typical air exchange rates obtained were in the range of 4.0–5.0 h^{-1} which corresponds to air circulation rates of 240–300 m^3/h. This means for a single collector the air circulation rates will be in the range of 120–150 m^3/h

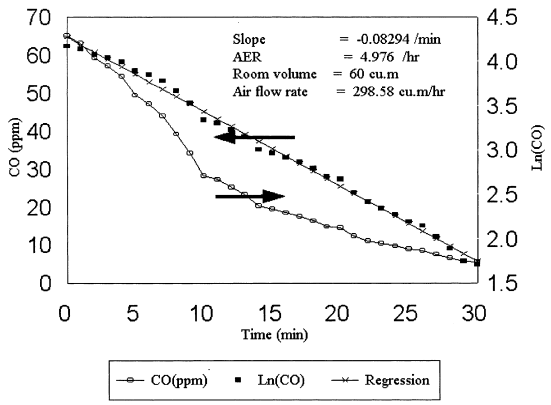


Fig. 3. Air exchange rate of the passive model 1.

which shows a reasonably good agreement between experimental and theoretical air flow rates as estimated in Fig. 2.

4.2. Performance of the passive model 1

A first floor room in an adjoining workshop was selected as a reference room. Battery operated thermo-hygrometers were used to record the temperature and humidity in the passive room and reference room. Ambient temperature data were taken from the Indian Meteorological Department for the nearest weather station. The performance of the system was monitored for 1 complete year from December to November.

Fig. 4a–c gives the various temperature variations for the periods December–March, April–July and August–November, respectively. It can be seen that for the winter period, the passive room maintained temperatures at about 4°C above the reference room. There was a cold wave period during the 2nd and 3rd week of January when the average ambient temperature dropped to about 11–12°C. During this time, the passive room remained at 19–20°C, which can be considered as comfortable for Delhi's winter.

During the hot-dry months of April–July, the bottom collectors were changed into evaporative cooling devices as described earlier. It can be seen from Fig. 4b that the passive room remained at about 2–3°C below the reference room. The trend continued in the hot-humid months of August–September. Though the room was more comfortable, especially in the hot afternoons, it cannot be said that the performance of the system was satisfactory. Subsequently the system was radically redesigned as described in the following sections.

5. INSTALLATION AND TESTING OF PASSIVE MODEL 2

A schematic diagram of passive model 2 building is shown in Fig. 5. A large portion of the south wall was painted black. A single glazing was fixed on the wall with wooden spacers. Two rectangular vents, with the width of 0.9 m and the height of 0.1 m each, were made both in the lower portion of the wall and at the top edge of the vertical collector. An air space was created above the roof slab by placing ferrocement plates over evenly spaced bricks and then joining all the plates by cement mortar. The false roof thus created was strong enough to be used as a terrace.

Air can enter the space between the ferrocement layer and the original roof slab from all four sides through suitable vents. The two rectangular openings (0.2 m$\times$0.6 m) present in the roof slab originally are left intact and wooden doors were fixed on these so that connection can be made from the room to the outside air gap.

During summer, the ferrocement layer was covered with gunny bags (sack cloth) stitched together and irrigated with water from an overhead tank connected to a drip irrigation network. Water flow by gravity was adjusted in such a way, that the sack cloth remained wet always. The door between the room and the outside air gap was kept open all the time so that ambient air entering the room passes through the air space and gets cooled. The top of the collector was left open. The south wall now acts like a chimney, drawing the room air from bottom and venting it out to the ambient. The cooler air layers at the top of the room move towards the bottom due to higher density. Thus a natural circulation is established. Hot ambient air passes through the cooler air space between the roof and ferrocement layer, enters the room and exits through the south wall collector. Use of a ceiling fan improves the circulation further. The summer operation is shown in Fig. 5a.

In winter, the openings in the roof were closed and the gunny bags were removed. The south wall collector was sealed at the top and the upper vents in the wall were opened as shown in Fig. 5b. The south wall now acts like a vented trombe wall. Both the vents in the wall were kept closed during the night to prevent heat losses.

5.1. Performance of the passive model 2

The temperatures of the passive building for typical summer and winter days are shown in Fig.

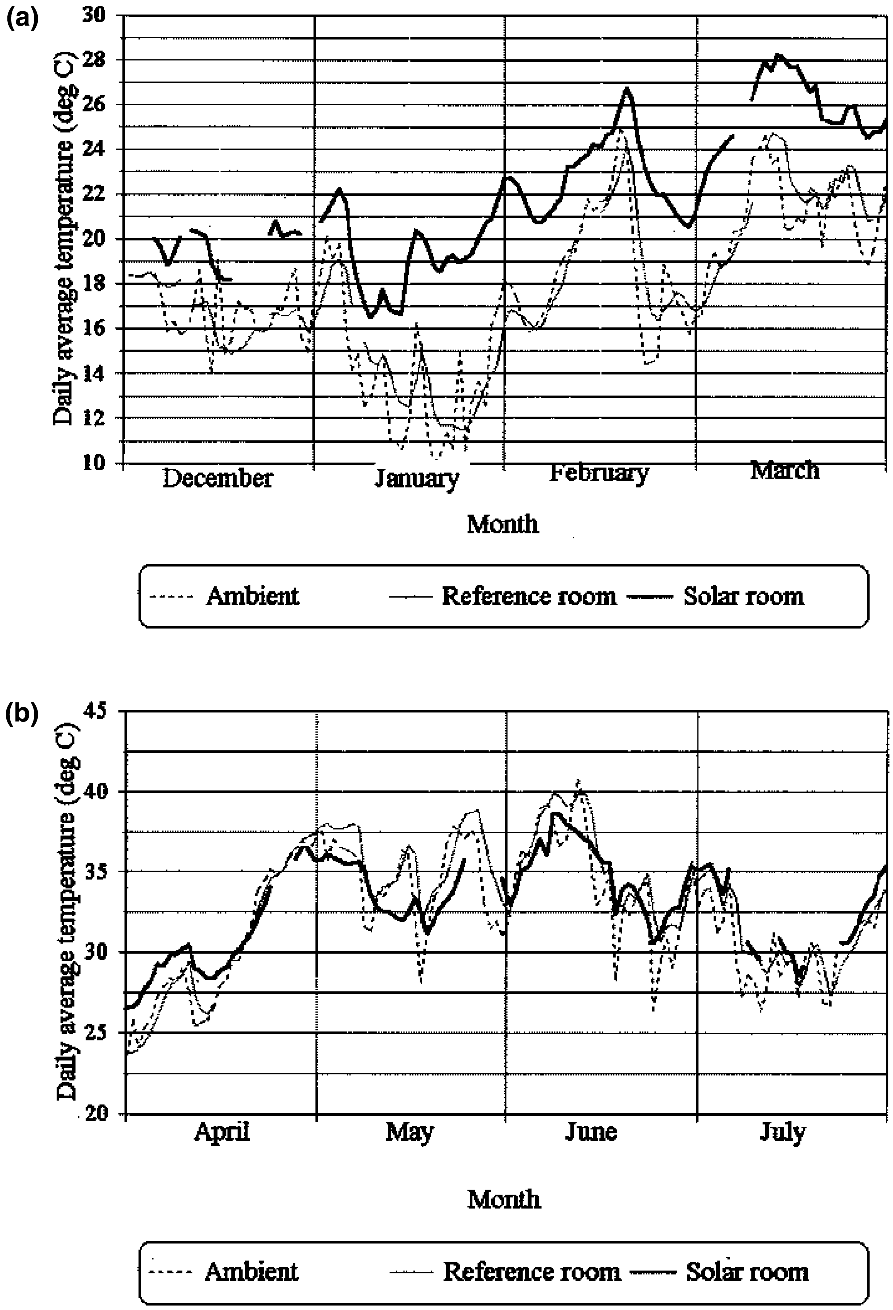


Fig. 4. (a) Passive model 1 system performance comparison curves for the period December to March (winter operation and transition to hot-dry season). (b) Passive model 1 system performance comparison curves for the period August to November (hot-humid summer season and transition to winter season). (c) Passive model 1 system performance comparison curves for the period August to November (hot-humid summer season and transition to winter season).

6a and b. It can be seen that the passive model 2 maintained a nearly constant room temperature of about 30°C when the ambient temperature went up to 42°C. Similarly, the passive model 2 room remained at around 16°C throughout the 24-h period when the ambient temperatures dropped to nearly 1°C in the winter nights. The temperature history of the passive model 2 for 1 year is shown in Fig. 7 along with the ambient temperature for the same period. Ambient temperature is expressed by using a thin line, while for expressing the trend of passive building room temperature, a

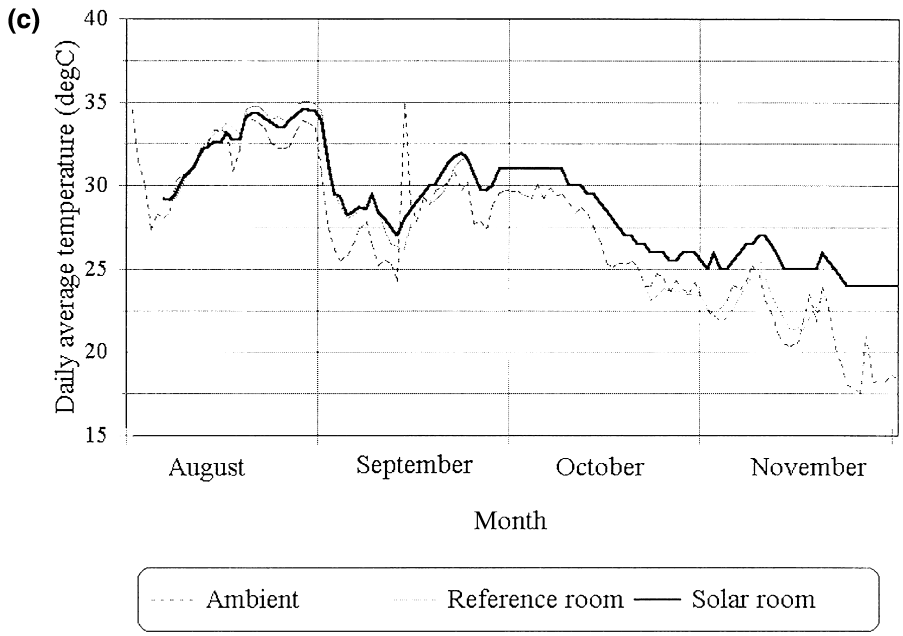


Fig. 4. (*continued*)

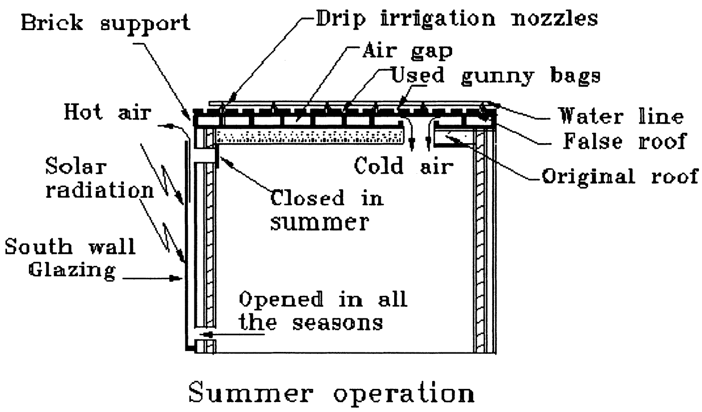
thick line is used to give a clear picture. Similarly comparison of humidity levels in the passive building is made to ambient humidity levels in Fig. 8. A photograph of the passive model 2 is shown in Fig. 9. It is apparent from Figs. 7 and 8 that both the temperature and humidity swings in the passive building are much lower compared to ambient conditions. The performance of the passive model 2 was much better than that of passive model 1. The room maintained a temperature of about 28°C during summer and about 17°C in winter, which can be considered as a very satisfactory performance for composite climates.

6. DISCUSSION

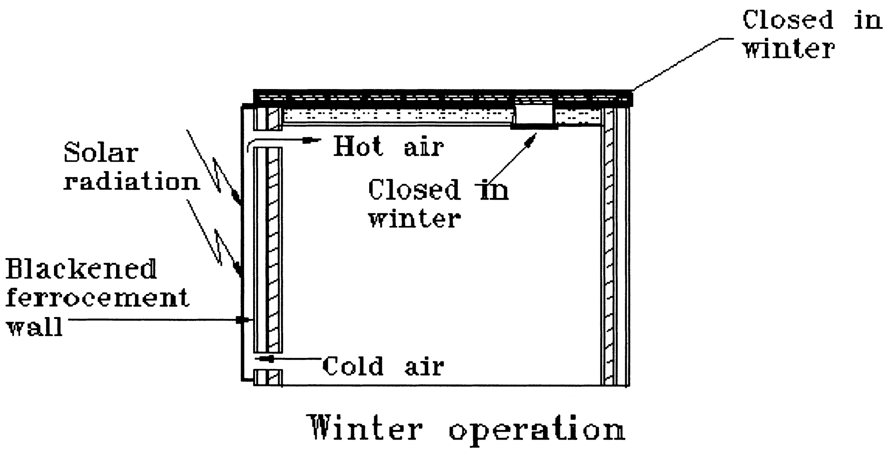
The passive model 2 system consisting of a south wall collector, a roof duct wetted on the top side by an evaporatively cooled surface, and insulated walls described in the paper seems to have a good potential of achieving thermal comfort in composite climates experienced over a large part of India. If adopted on a wide scale, the system also has the potential to reduce peak loads in summer due to extensive use of air conditioners. This system can be easily retrofitted to existing single floor houses. For two or three floor structures retrofitting may be difficult, but the passive features can be incorporated at the construction stage itself, with some modifications for distributing cool air from the roof duct.

Performance data of passive model 2 in this paper are for an empty room. Thermal loads due to appliances, metabolism etc. will, however, affect the performance of the passive house. In winters, loads originating from human activity will tend to increase the room temperatures and hence the comfort level will be better than that of an empty room. In summer, however, such loads will add to the cooling load and hence indoor temperatures achieved will be higher than those indicated by the empty room performance. But a real building will also have lesser direct and indirect solar gain than a single room exposed on all sides to solar variation. On the whole it should be expected that the comfort levels will be a little lower. Also, judicious use of night ventilation can add to the comfort as night cooling will be retained better by the additional insulation. Interest in the passive building has, however, come from some other applications such as silk worm rearing, hatcheries, poultry farms etc. where large temperature swings during a day or week are more detrimental than the absolute values.

Tentative cost estimates made for retrofitting indicate an average of about 20% increase over the conventional structures for a single room. The increase is lower for larger rooms and higher for smaller rooms. The additional cost will also be lesser for a complete house and will be lowest if the passive features are incorporated at the construction stage itself.



(a)



(b)

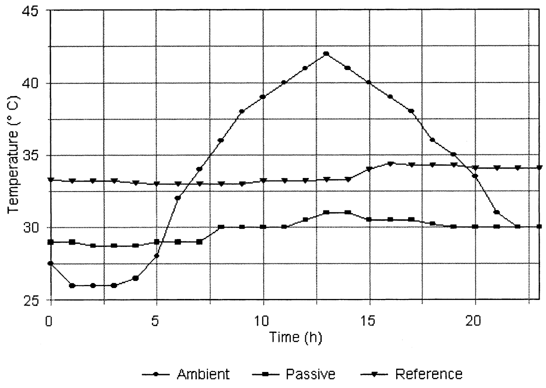
Fig. 5. (a) Schematic diagram of the passive model 2 system during summer operation. (b) Schematic diagram of the passive model 2 system during winter operation.

A proposal to construct passive houses for silk worm rearing, based on the current design, is under active consideration.

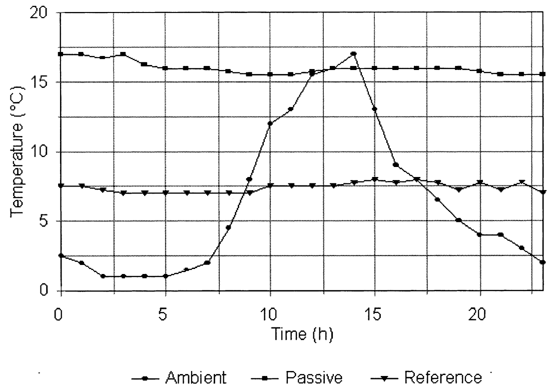
7. CONCLUSION

A passive solar house design based on the incorporation of solar chimneys for heating, cooling and ventilation in composite climates has been tested on a single room structure in Delhi. The air handling capacity of solar chimneys was predicted by computation and verified by measurements. The passive model 1 consisting of a set of two solar chimneys, an evaporative cooler (for summer) and added wall insulation, performed well for winter, but the summer cooling was not adequate. Consequently, a second passive model 2, which consisted of a south wall collection and a roof duct cooled from above by a sack cloth evaporative cooling system was constructed and monitored for 1 year. The thermal performance of passive model 2 was distinctly better than that of model 2.

The additional cost of providing passive components and wall insulation was estimated to be about 20% of the cost of a conventional room. Judging from the increasing costs of electricity and deteriorating power situation, the passive system described in the paper seems to have good potential. The system also seems to have a potential for application such as silk worm rearing where large temperature swings are detrimental to healthy growth of silk worms.



(a)



(b)

Fig. 6. (a) Temperature profile of the passive building for a typical summer day operation. (b) Temperature profile of the passive building for a typical winter day operation.

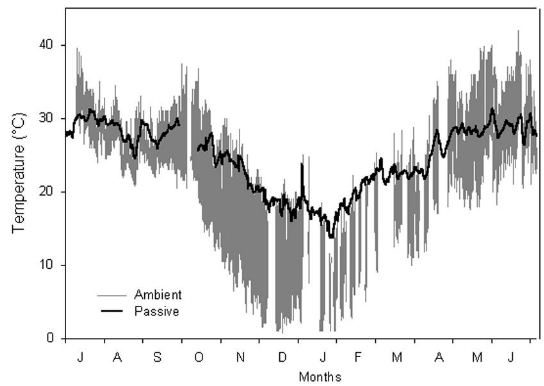


Fig. 7. Performance monitoring of passive model 2 system with regard to temperature.

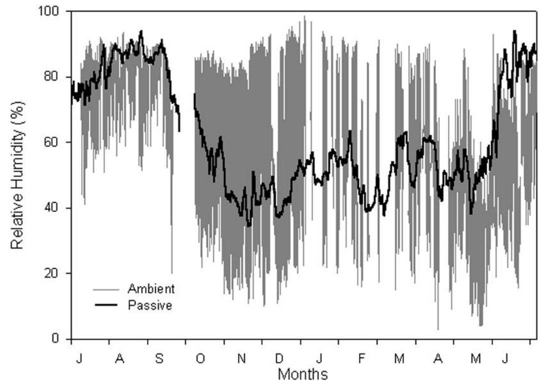


Fig. 8. Performance monitoring of passive model 2 system with regard to relative humidity.

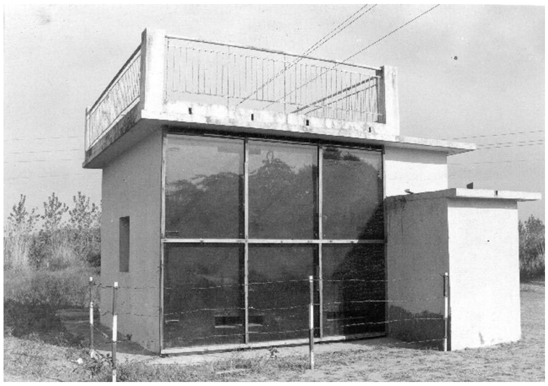


Fig. 9. Photograph showing overall view of the passive model 2 building.

NOMENCLATURE

A	cross sectional area (m^2)
A_c	collector area (m^2)
A_f	flow area (m^2)
C	heat capacity rate ($W\ K^{-1}$)
$C_{p,air}$	specific heat of air ($kJ\ kg^{-1}\ K^{-1}$)
D_H	hydraulic diameter (m)
F'	collector efficiency factor (dimensionless)
f	friction factor (dimensionless)
g	acceleration due to gravity (ms^{-2})
I	solar radiation intensity on the collector surface (Wm^{-2})
K	loss coefficient at duct opening (dimensionless)
L_c	length of solar chimney, characteristic length (m)
m	mass flow rate of air ($kg\ h^{-1}$)
M_{air}	molecular weight of air ($kg\ kmol^{-1}$)
P_{atm}, P_{air}	atmospheric pressure (Nm^{-2})
R	universal gas constant ($kJ\ kmol^{-1}\ K^{-1}$)
T	temperature (K)
U_L	overall heat loss coefficient of collector ($Wm^{-2}\ K^{-1}$)
V	velocity of air (ms^{-1})
η_c	collector efficiency (dimensionless)
ρ	density of air ($kg\ m^{-3}$)
$\tau\alpha$	effective transmittivity–absorptivity product (dimensionless)

Subscripts

1	inlet
2	outlet
a, air	air
a,1	bottom chimney air
a,2	top chimney air

avg average
c convection
f water film surface

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