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Energy conservation in honey storage building using Trombe wall

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ABSTRACT

This paper investigates energy conservation, mitigation of CO_2 emissions and economics of retrofitting for a honey storage building with Trombe wall for winter heating application. The passive heating potential of Trombe wall for a honey storage building was estimated using TRNSYS building simulation software. This honey storage building is located at Gwalior (latitude: 26°14′N) in India. During winter months, the room air temperature of building falls below the required temperature range of 18–27 °C which is suitable for honey storage. So, the room air temperature range is maintained in the building using a 2.3 kW capacity electrical oil filled radiator (or room air heater) which accounts for the major energy consumption of the building on an annual basis. On account of which there are significant CO_2 emissions into the atmosphere from the honey storage building. Hence, this case study was conducted to recommend the passive heating concept to the stakeholders of the building so as to conserve the energy requirement for room air heating. The investigation showed that the room air temperature can be easily maintained in the range suitable for honey storage using a vented Trombe wall. The experimental work was carried out for the existing building on a typical clear day of harsh winter month of January to validate the results of TRNSYS model of the present building. The statistical error analysis showed a good agreement between model and experimental results. This investigation concludes that there is potential of energy conservation up to 3312 kWh/year and associated reduction in CO_2 emissions (~33 tonne/year) using a Trombe wall. Also, the retrofitting of building is economically viable as the simple payback period is only about 7 months.

1. Introduction

With the severe energy crisis worldwide, the utilization of energy has become a vital issue and the conservation of energy has acquired prime importance. A substantial energy conservation opportunity exists in the building. The energy is required in a building for room air heating, cooling, ventilation, lighting, etc. However, the maximum energy is utilized in buildings for room air conditioning. The building energy requirement can be reduced to great extent if proper passive solar features are incorporated in the building during the design level. The use of passive building concept for achieving thermal comfort inside a building is a growing concern world over for the building energy conservation. The basic principle in passive solar architecture is to size, orient and locate its components to take maximum advantage of the climate and the surroundings for natural comfort conditioning of the building. Based on the thermal load calculations for different sizes of the passive solar elements, one can decide the appropriate size from the energy conservation point of view for the given environmental conditions. Hence, it is required to integrate building design with the thermal performance results of passive building elements. A Trombe wall concept is one of the passive heating examples for heating of a honey storage building.

A conventional Trombe wall as shown in Fig. 1 [1] comprises a south-facing massive thermal wall with a clear outer glazing and a convective air cavity in-between them. It has been used worldwide and had many improvements in the past decades due to advantages, such as simple configuration, high efficiency, zero running cost [2]. However, the application of a Trombe wall has been restricted because of its visible black-matt surface of the blackened massive wall underneath the clear glass for achieving better thermal absorption performance because of which it does not find aesthetic acceptance among users. Further, it causes overheating in summer. In order to solve these problems, a novel Trombe structure with PV cells module known as a PV-Trombe wall was designed by Ji et al. [3] as shown in Fig. 2. A PV-Trombe wall for summer cooling operates like a PV-wall; its simulation model has been developed by Yang et al. [4]. Furthermore, Yang

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Nomenclature

e	root mean square of percent deviation (%)
HP	heating potential (kJ h^{-1})
n	number of observations
N	north
NE	north-east
NW	north-west
r'	coefficient of correlation
S	south
SE	south-east
SW	south-west
T_a	ambient air temperature (°C)
T_r-Direct gain	room air temperature with direct gain on SE wall (°C)
T_r-expt	room air temperature observed during experiments (°C)
T_r-SE wall black	room air temperature with south-east wall black (°C)
T_r-UTW	room air temperature with unvented Trombe wall on SE wall (°C)
T_r-VTW	room air temperature with vented Trombe wall on SE wall (°C)
T_r-without retrofit	room air temperature before retrofit (°C)
UTW	unvented Trombe wall
VTW	vented Trombe wall
X_{pred}	predicted value
X_{expt}	experimental value

Subscripts

a	ambient air
expt	experimental
pred	predicted value
r	room air

et al. [5] investigated the heat transfer across a PV wall entirely covered with PV cells and calculated the heat gain and cooling load.

Most of the studies on a Trombe wall are concerned with its winter heating. For example, Smolec and Thomas [6] have done the theoretical calculations for the temperature distribution of a Trombe wall by using a thermal network and compared the results with experimental data. The thermal performance of Trombe walls and roof pond systems was presented by Sodha et al. [7] for passive heating and cooling of building respectively. Chen et al. [8] have investigated the airflow in a Trombe wall and deduced that the airflow is the function of the height of the air duct. Buzzoni et al. [9] conducted the numerical simulation for the Trombe wall with thermal insulation on the southern wall and two solar ducts, and these numerical results were compared with experimental data. Mootz and Bezian [10] performed a numerical study of a ventilated facade panel structured like a composite Trombe–Michel wall. Besides, Gan [11] carried out the numerical simulation of a Trombe wall for summer cooling by using the CFD technique and investigated the effect of the distance between the wall and glazing, wall height, glazing type, and wall insulation on the thermal performance of a Trombe wall. Raman et al. [12] developed an improved solar passive system, which can provide thermal comfort throughout the year in composite climates. However, there were few studies that dealt with round the year performance for different seasons, and gave little information about the influence of the Trombe wall system on the thermal environment of the test room.

The TRNSYS software uses transfer function method for simulation of building. The transfer function method is widely adopted for studying the effect of various building design parameters, thermal interaction of building envelope and optimal operation strategy of building thermal system mentioned by Chen [13]. A room transfer function (RTF) relates a room output (of interest) to an environmental thermal source or auxiliary heat. Room thermal loads or temperatures can be directly computed through the room transfer function as reported by Chen [13]. The transfer function method given by Chen [13] is more computationally efficient because only outputs of interest need to be calculated and there is no constraint on the computation time step. The transfer function method for single zone building was computed by Giorgio et al. [14].

A simple methodology for the energetic simulation of buildings including elements with phase change materials using the TRNSYS software was given by Manuel et al. [15]. The simulation of building using TRNSYS and comparison of the results from TRNSYS with neural model show that there is a good agreement between them as shown by Assimakopoulos et al. [16]. The TRNSYS software was used by Valerio and Stefano [17] for obtaining the thermal performance of retrofitted building in Rome. They obtained reduction in CO_2 emissions by a considerable amount because of significant energy saving due to retrofitting of building.

In this paper, the thermal performance of a single zone honey storage building integrated with Trombe wall is analyzed using TRNSYS software. In this software, the building model is prepared based on the inputs like building construction details, thermal properties of materials, details of Trombe wall and orientation of building. The simulation results of the retrofit building show that Trombe wall is sufficient to maintain room air temperature suitable for honey storage. It is estimated that there is a fairly good agreement between the results of TRNSYS model of building without retrofit and experimental observed data recorded on 15 January 2004.

2. Honey storage building

The honey has a shelf life of 2 years. It is important to store honey in sterilized and sealed airtight containers. The honey storage temperature should be maintained between 18 and 30 °C. The constructional details and the orientation of the existing honey storage building located at Gwalior (India) (latitude: 26°14′N, longitude: 78°15′E, elevation: 207 m above MSL) are given below.

2.1. Building construction details

The construction details of the existing honey storage building are given below:

1. The storage building has a store room with an attached bathroom as shown in Fig. 1.
2. All external walls are three-layered with middle layer composed of 22 cm thick brick wall and both the side walls are cement plastered. The plaster thickness is 1.5 cm for inside layer and 2.0 cm for outside layer. The height of each wall is 3 m.
3. Roof is also a three-layered structure having inside layer of limestone tile (15 cm thick), middle layer of cement mortar (2.5 cm thick) and outermost layer of cement plaster (2.5 cm thick). The roof has a length of 7.13 m and width of 3.05 m.

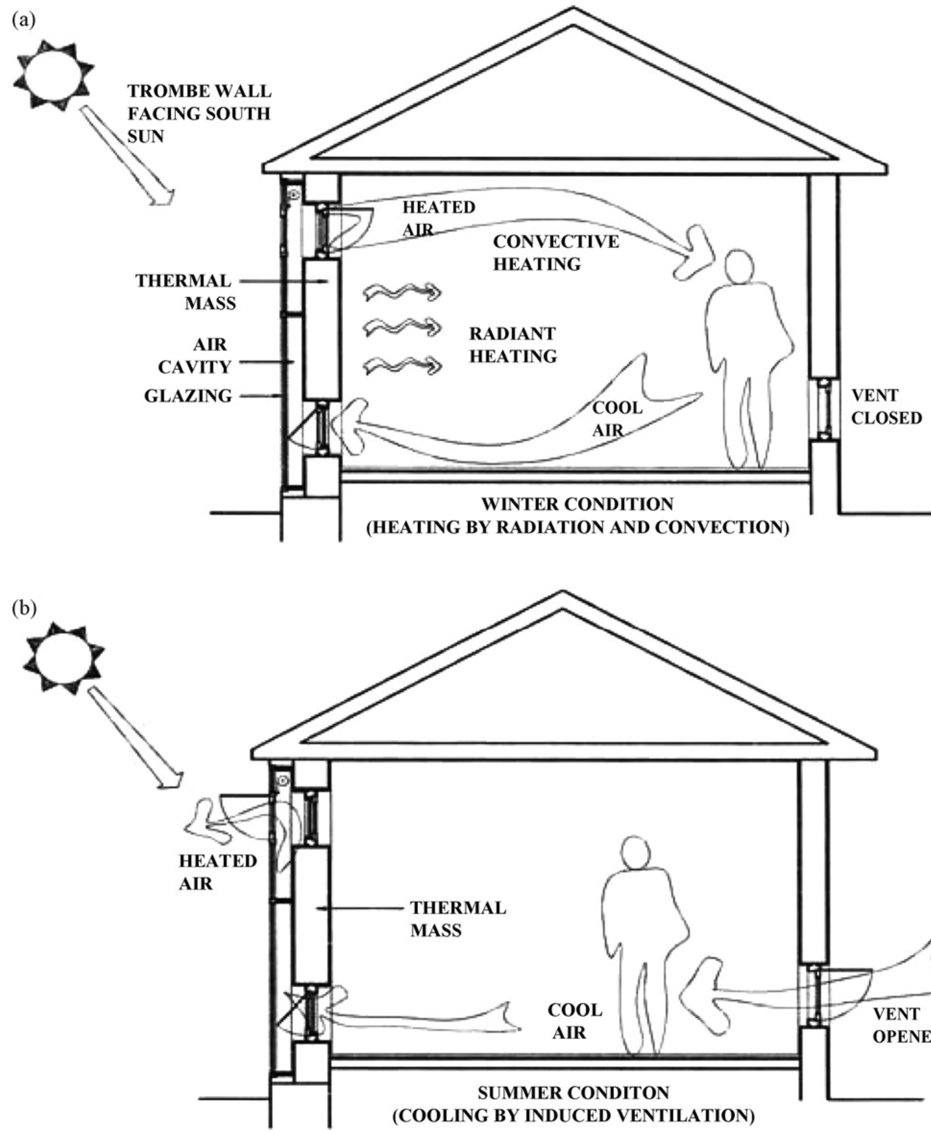

Fig. 1. A conventional Trombe wall during (a) winter and (b) summer [1].

4. The ground is made of first layer of cement mortar (10 cm thick), second layer of sand gravel (25 cm thick) and the last layer of soil or mud phuska (40 cm thick) after this layer it is assumed that ground is exposed to a boundary maintained at 25 °C.
5. There are two identical windows on the north-west wall. The dimensions of window are height of 0.914 m and width of 1.828 m. Window is made of plywood of thickness 2.5 cm. The windows open inside. Windows are not provided with overhangs.

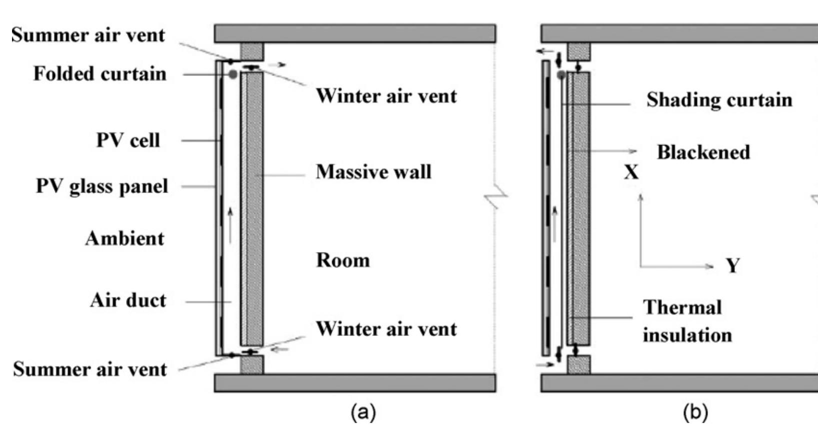

Fig. 2. PV-Trombe wall for (a) winter heating and (b) summer cooling [3].

Table 1
Thermophysical properties of building materials

Material	Density (kg/m^3)	Specific heat (kJ kg^{-1} K^{-1})	Thermal conductivity (W m^{-1} K^{-1})
Brick tile	1892	0.88	0.798
Mud brick	1731	0.88	0.750
Mud phuska	1622	0.88	0.519
Cement plaster	1762	0.84	0.721
Cement mortar	1648	0.92	0.719
GI sheet	7520	0.50	61.060
Plywood	640	1.76	0.174
Limestone tile	2420	0.84	1.800
Sand grave	2240	0.84	1.740

6. A single steel door is on the south-east wall. The dimensions of door are 2.134 m height and 0.914 m width. The door is made of 0.5 cm thick GI metal sheet. The door opens inside.

The thermal properties of the construction materials used for the building are given in Table 1. The orientation of building with respect to due south is shown in Fig. 1.

2.2. Building orientation

The building plan view is shown in Fig. 3. The orientation of building is mentioned with respect to due south. The honey is stored in store room and the other room is rarely used as bathroom during day.

2.3. Simulated building

The building plan view shown in Fig. 3 is simplified to single zone building because the bathroom is in rare use. This single zone building is simulated using TRNSYS software. The results of this software are validated using experimental data. The plan view of single zone simulated building is given below in Fig. 4. The retrofitted vented Trombe wall considered for south-east orientation of building which has the following specifications is shown in Fig. 5

The spacing between wall and glazing is 10 cm, vent outlet area is each 1% of wall surface area (0.015 m^2 each vent area). There are two vents, one vent is 0.3 m above wall foundation and another vent is 0.3 m below roof level. The distance between vents is kept 2.4 m. The Trombe wall glazing area is equal to wall area of width 5 m and height 3 m.

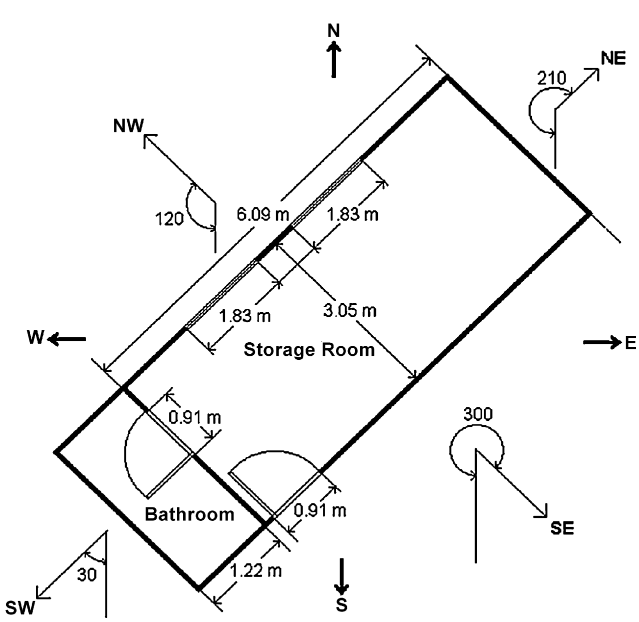

Fig. 3. Schematic plan view of actual honey storage building at Gwalior [1].

2.4. Assumptions

The following assumptions are made during modeling of the building using TRNSYS software.

1. The building is a single zone building since the bathroom usage is only once in a day.
2. The building is mainly used for storage; hence low infiltration gain with 1.5 ACH.
3. Doors and windows are assumed to be always closed for simulation of building.
4. Roof is assumed horizontal, since the roof slope is negligible to drain out roof water.
5. Only the room air heat capacity is considered and rest all isothermal masses are neglected.
6. The absorptivity of wall and roof surfaces is 0.6 and each material layer is assumed to be homogeneous.
7. The black surfaces are assumed to have absorptivity 0.9.
8. The outside and inside heat transfer coefficients are constant and the values are 22 and 6 W m^{-2} K^{-1}, respectively, for both horizontal and vertical surfaces.
9. The ground surface of building is assumed to conduct heat to the boundary maintained at 25 °C.
10. All passive heating concepts like wall painted black, Trombe wall and direct gain using glass window are assumed to be retrofitted on south-east surface with area 15 m^2 (5 m × 3 m).

2.5. Building simulation

The existing building has to be analyzed based on thermal performance over a whole year data. The thermal load calculation for building with huge input data, if done manually, is tedious and a time-consuming process. There also exists a possibility of making errors in the calculations. Thus to reduce the time consumption and tediousness in calculations, simulation software packages are used. With the use of popular and reliable simulation packages one can do thermal load calculations with ease for different combinations of input parameters for either doing parametric analysis or for studying effect of different configurations of building components.

The thermal analysis of Trombe wall retrofitted building is done for one complete year based on the input data of ambient air temperature and solar radiation data from Mani and Rangarajan [18]. Thermal performance analysis of honey storage building is done using TRNSYS software package by Chel and Nayak [1].

3. TRNSYS building simulation software

The thermal performance of honey storage building is done using TRNSYS software. This software is developed by university of Wisconsin, Madison, USA. It was developed in 1974, and has been continually upgraded since then, strengthening its capabilities tremendously. It is modular in nature and contains many

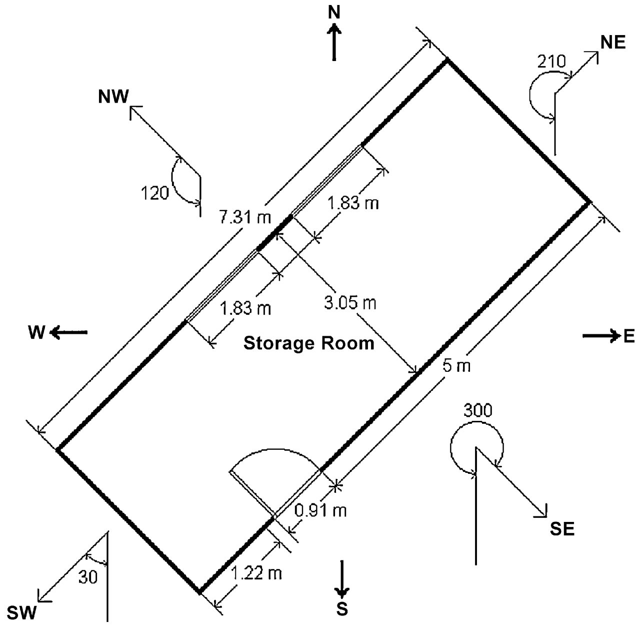

Fig. 4. Schematic plan view of single zone building for simulation using TRNSYS [1].

subroutines for various systems including building. In this software basic code is written in FORTRAN language. The software is used for building dynamic simulation based on transfer functions technique. The flow diagram for building simulation using TRNSYS is shown in Fig. 6.

3.1. Thermal performance of building using TRNSYS

The thermal performance of existing single zone honey storage building is obtained using TRNSYS software. The room air temperature of the building was predicted for harsh winter conditions for the month of January using the input climatic parameters like ambient air temperature and solar radiation data from Mani and Rangarajan [18] and the building design parameters with constructional details of Trombe wall and roof.

3.2. Experimental validation of TRNSYS simulation software

Thermal performance of existing building is analyzed using different passive building heating concepts like black painted south-east wall, unvented Trombe wall, vented Trombe wall and direct gain glass window. All these passive heating concepts are analyzed for south-east wall of surface area 15 m^2 (5 m × 3 m). The simulation results of retrofitted building with vented Trombe wall show hat the room air temperature is in the range of 18.5–22.8 °C for harsh winter of January month as shown in Fig. 7(a). Also, the heating potential of various passive heating concepts/techniques are as shown in Fig. 7(b). The results show that room air temperature is maintained highest in case of vented Trombe wall. Hence, it is recommended to retrofit the existing building with vented Trombe wall on south-east wall.

The experiments were conducted for recording room air temperature in the month of January and it is found that there is very good agreement between the TRNSYS results and experimental observed data with correlation coefficient value 0.96 and root mean square percent error value 3.73% as shown in Fig. 8. The correlation coefficient and root mean square percent error values are calculated using following expressions.

3.2.1. Coefficient of correlation (r')

When predicted values are validated with the experimental data, correlation between predicted and experimental values is presented with a coefficient known as coefficient of correlation. The coefficient of correlation can be evaluated by the use of following expression:

$$r' = \frac{n\sum_i^n x_i y_i - \sum_i^n (x_i)\sum_i^n (y_i)}{\sqrt{n\sum_i^n x_i^2 - \left(\sum_i^n x_i\right)^2}\sqrt{n\sum_i^n y_i^2 - \left(\sum_i^n y_i\right)^2}} \qquad (1)$$

If the value of the coefficient of correlation is greater than zero it means there is positive relationship between experimental observation and theoretical values and at its maximum value, i.e. 1, means there is perfect relationship. Similarly for values less than zero there is negative relationship between experimental observations and theoretical values and when the value of correlation coefficient is zero it means there is no relationship.

3.2.2. Root mean square of percent deviation (e)

The predictions are made with the help of thermal modeling. The predicted values are validated with the experimental data. Here the closeness of predicted values and experimental data can be presented in terms of root mean square of percent deviation (e). The expression used for this purpose is as follows:

$$e = \sqrt{\frac{\sum_i^n (e_i)^2}{n}} \qquad (2)$$

where $e_i = (X_{\text{pred}} - X_{\text{exp}})/X_{\text{pred}}$ and n is the number of observations.

4. Results and discussion

The hourly values of room air temperature for retrofitted building are obtained and plotted using TRNSYS for one complete

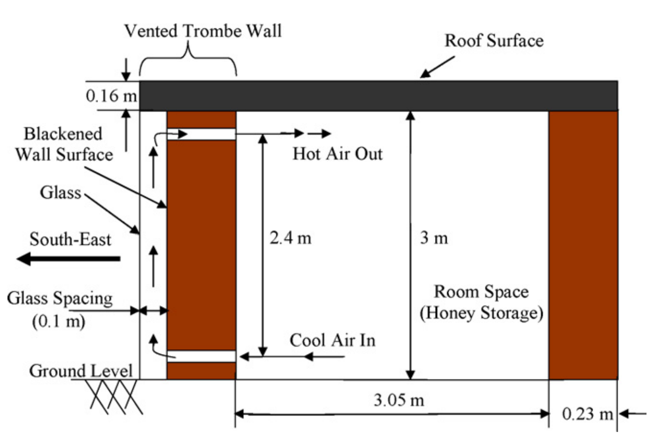

Fig. 5. Vented Trombe wall retrofitted on the south-east wall of size (5 m × 3 m).

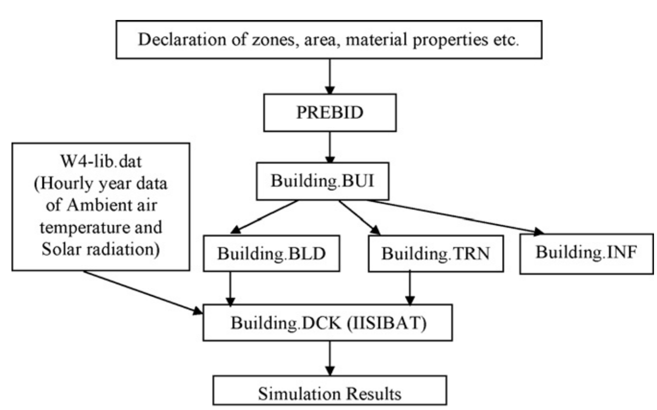

Fig. 6. Flow diagram of building simulation using TRNSYS [1].

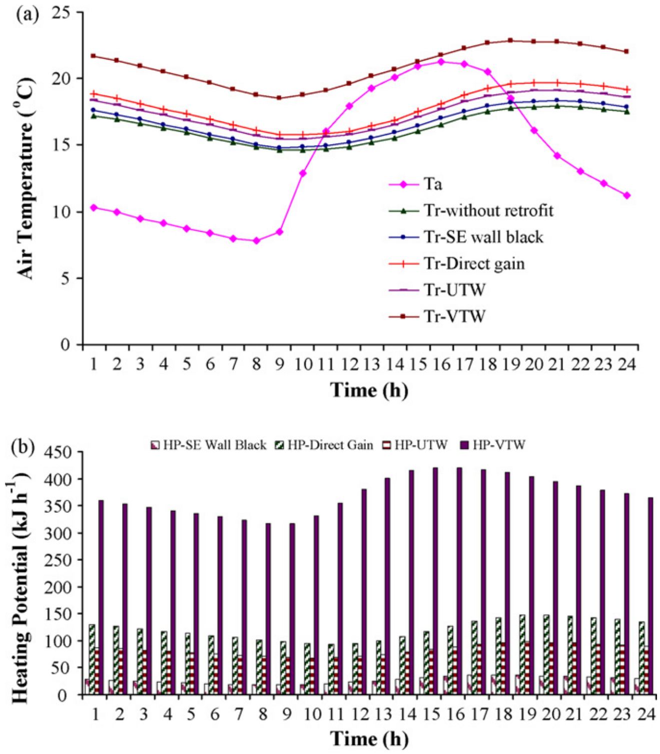

Fig. 7. (a). Room air temperature for different retrofits on south-east wall. (b) Heating potential for different retrofits on south-east wall.

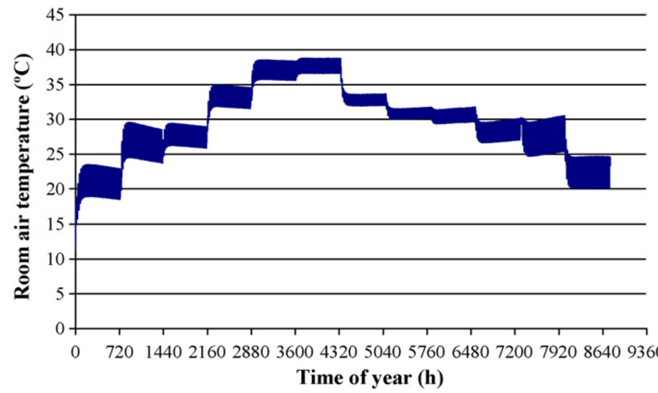

Fig. 9. Hourly predicted room air temperature for building integrated with vented Trombe wall using TRNSYS for 1 year [1].

year using monthly average ambient air temperature and solar radiation input data from Mani and Rangarajan [18]. The year round performance of building retrofitted with vented Trombe wall in winter and sun shaded south east wall in summer season using TRNSYS software is as shown in Fig. 9.

The thermal performance of the building for the month of harsh winter condition for different passive building heating concepts has the following key results.

1. When all walls are painted black individually then comparison showed that north-east wall is least concerned for heating and south-east wall has maximum heating effect among all walls. Roof has maximum heating effect as compared to south-east wall. When south-east wall is painted black, room air temperature predicted in the range of 14.9–18.5 °C for harsh winter month (January).

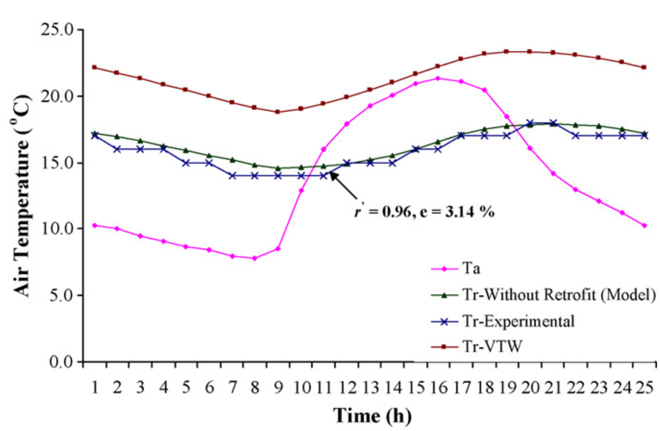

Fig. 8. Validation of TRNSYS model with experimental room air temperature.

2. When south-east wall is retrofitted to unvented Trombe wall, simulation results show that room air temperature predicted to be in the range of 15.4–19.1 °C in harsh winter month. This needs improvement like providing vents so that during daytime air gets heated and circulated into the building to heat room air and during night time close these vents and shade the Trombe wall using movable insulation to avoid heat loss to ambient. During nighttime, the heat absorbed by the wall in daytime gets lost inside the building by convection and thereby heats the inside room air temperature.
3. The improvements in the unvented Trombe wall are included in the vented Trombe wall as shown in Fig. 5. When the south-east wall is retrofitted with vented Trombe wall the results were promising; room air temperature predicted to be in the range of 19–23.3 °C for harsh winter (January) month. This room air temperature range is suitable for honey storage inside the building to avoid crystallization of honey.
4. When south-east wall is converted into direct gain concept for the existing building then the room air temperature is predicted to be in the range of 15.8–19.7 °C for harsh winter month. Hence, this option is not sufficient to maintain room air temperature above 18 °C for honey storage.

5. Economic feasibility study of retrofitting building with Trombe wall

5.1. Energy conservation and economics of retrofitting a honey storage building

In the winter months (cold and dry climate), the stakeholder of the honey storage building is using oil filled radiator (model: NYAK-11, voltage: 230 V to 50 Hz, trade name: Midea, power: 2.3 kW) to heat the room air daily for 12 h at night for four winter months (i.e. November, December, January and February). While in the summer season (hot and dry climate), it is observed that the maximum outside ambient air temperature reaches 45–55 °C while maximum room air temperature reaches 35–40 °C. Hence, the stakeholder of the building uses a desert cooler of rating 746 W (or 1 HP) to cool the room air daily for 12 h during the day for the four summer months (i.e. March, April, May and June). The desert cooler draws in room air through a moistened mesh and blow it out again into the room; this process cools and humidifies the room air. The desert coolers are frequently installed in every household located in hot and dry climatic zone like Gwalior in India. Therefore, the building under consideration requires heating in winter months and cooling in summer months. Hence, it is mandatory that the Trombe wall should be under shade using movable insulation or any other means of sun shade during summer season.

Based on the power rating and number of hours of operation in the year for air heater (oil filled radiator) and desert cooler, the present annual energy consumption of the building is 4404 kWh/year which comprises of 3312 kWh/year for air heater and 1092 kWh/year for desert cooler. Hence, it is a very energy intensive honey storage building. The annual electricity bill payable by the stakeholder is Rs.13,212 $year^{-1}$ assuming the present cost of electricity Rs. 3 kWh^{-1} in India. After retrofitting of the building with vented Trombe wall air heating, it is estimated that the energy consumption will reduce to 1092 kWh/year and the electricity bill Rs. 3276 $year^{-1}$. Hence, there is large saving of energy 3312 kWh/year for heating room air in winter months. This energy conservation is reflected in saving of electricity bill of Rs. 9936 $year^{-1}$ due to retrofit of building using Trombe wall.

The Trombe wall retrofit to building requires five glass pieces of size 1 m × 3 m to cover south-east wall of size 5 m × 3 m. The international cost of double strength clear glass of thickness 5 mm (3/16″) and size 1 m × 3 m (39.37″ × 118.112″ rectangle) is Rs. 6280 ($157, assume $1 = Rs. 40). Hence, the total international cost of glass to cover the south-east wall is Rs. 31,400 ($ 785). In India, the cost of 5 mm thick clear glass is Rs. 40 ft^{-2}. Therefore, the cost of glass for 15 m^2 (161.46 ft^2) is estimated to be Rs. 6458.4 in India. The total cost of labor charge for two persons for 2 days work for making vents in the building and installing glass is Rs. 1000 and cost of movable insulation cloth in India is Rs. 1000.

The saving of electricity bill is Rs. 9936 $year^{-1}$ and international total cost of purchase (for glass and cloth) and installation Rs. 33,400, the simple pay back period for Trombe wall retrofit is estimated as about 3.4 years and while in India the total cost of purchase and installation is only Rs. 6658 which will be paid back within 7 months. Hence, in present case it is more economically viable and feasible option for retrofit of building using Trombe wall for winter heating application for existing honey storage building.

This shows there is conservation of energy inside the building used for honey storage during winter months. The energy can be conserved during summer season using passive cooling technique, e.g. retrofit the roof with additional layer of adobe brick tile (3.8 cm thick) or retrofit with inverted air cavity cups and cover the gaps between brick tiles or cups with water proofing mixture of cement mortar and commercial water proofing liquid. This investigation is practically more labor intensive and costly and hence not investigated due to constraints from stakeholder. The other option for passive cooling is evaporative cooling of roof surface which requires large amount of water availability which is not feasible for the location during summer season and hence desert cooler is the only option at present for the stakeholder of the building.

5.2. Mitigation of CO_2 emissions

The effect of retrofitting of building with Trombe wall has shown considerable amount of energy conservation 3312 kWh/year, this mitigates atmospheric CO_2 emissions released by a power plant. An average carbon dioxide (CO_2) equivalent intensity for electricity generation from coal is approximately 0.98 kg of CO_2/kWh [19]. Hence, the reduction in CO_2 emissions into the atmosphere by energy conservation due to retrofit is 3250 kg/year (∼33 tonne/year).

Hence, passive building heating concept like Trombe wall is an environment friendly options for natural heating of building located in cold climatic conditions of the world. The Trombe wall concept has been extensively adopted in European countries but the black surface of wall hinders its aesthetic view [3]. But, the recent studies shows there are advances in design for Trombe wall for better aesthetic look and thermal performance by replacing glass with PV modules and integrate it with the Trombe wall shown in Fig. 2 [3]. Recently, Jibao et al. [20] investigated the thermal performance of a classical/conventional Trombe wall and a composite Trombe–Michel wall. The models were developed by Jibao et al. [20] with the finite differences method and the results were compared with TRNSYS.

6. Conclusions and recommendations to stakeholder of building

The investigation of Trombe wall for honey storage building has proven its importance for natural heating of building in winter months. The use of Trombe wall passive heating of building provides an opportunity for conserving considerable amount of electrical energy for heating room air for honey storage requirement.

The recommendations for retrofitting the honey storage building are based on the thermal performance results of TRNSYS. The following recommendations can be made for honey storage building for winter conditions to maintain inside zone temperature above 18 °C and below 30 °C for better performance of honey storage building.

1. The south-east wall surface is completely black painted with mat finish.
2. The vented Trombe wall of size 5 m width and 3 m height as shown in Fig. 5 is retrofitted on south-east wall.
3. During winter climatic conditions, the two vents of Trombe wall are kept open during the day and closed during the night. Also, during night the vents are covered with night movable insulation cloth.
4. During summer climatic conditions, completely shade the Trombe wall with the movable insulation in order to avoid heat gain through Trombe wall. The stakeholders are already using desert cooler during summer for 12 h during daytime for room air cooling in the month of March, April, May and June. During summer, it is preferred to go for shading of roof of the building to cut the excessive heat gain.

Acknowledgements

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