Exergy analysis of building integrated semitransparent photovoltaic thermal (BiSPVT) system

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1. Introduction

Building integrated photovoltaic thermal (BiPV) system is one of the most promising solution for energy conservation in a building across the world for clean environment and sustainable climate. There are various studies on (i) opaque photovoltaic (OPV) and semitransparent photovoltaic (SPV) modules and (ii) opaque photovoltaic thermal (OPVT) and semitransparent photovoltaic thermal (SPVT) modules integrated with roof and façade, Agrawal and Tiwari [1,2]. These systems can meet the requirement of electricity, thermal energy and day lighting in building. Various studies have also been carried out to analyze the energy and exergy performances of photovoltaic (PV) and photovoltaic thermal (PVT) systems [3–7]. Saloux et al. [8] have defined exergy as qualitative aspect of energy which is the available share of energy. Exergy analysis have been considered as a powerful tool to evaluate the systems especially the ones that involve various energy sources. Both first law and second law of thermodynamics can be used to calculate the exergy of a model and this helps to identify the main source of exergy losses [9,10]. Vats and Tiwari [11] have evaluated energy and exergy performance of BiSPVT system and compared various types of PV modules without considering the day lighting factor. The corresponding electrical efficiency for HIT (heterojunction comprised of a thin amorphous silicon PV cell on top of a crystalline silicon cell) and a-Si (amorphous silicon cell) type is 16% and 6% respectively and annual thermal exergy was found to be maximum in HIT type (2497 kWh). Dávi et al. [12] have found that the electrical demand covered by PV varies from 29% to 51% annually. Baljit et al. [13] have compared the building integrated photovoltaic (BiPV) and building integrated photovoltaic thermal (BiPVT) technologies and found that better performance is achieved in the latter technique in terms of thermal and electricity production. Thus, BiPV can be used in construction industry for energy efficient buildings.

Joshi et al. [14] have studied the thermal and exergy efficiency of PV and PVT systems. They have found that exergy efficiency of PVT systems (11.6–16%) is greater than the exergy efficiency of PV system (8–14%) by using Petela’s formula [15]. Chow et al. [16] have developed PV ventilated glazing technology to reduce the cooling load and day lighting. They have reported that 0.45–0.55 of solar transmittance is capable of achieving best energy...
Nomenclature

\[ A \] \text{ area, m}^2 \\
\[ c_a \] \text{ specific heat of air, J/kg K} \\
\[ c_c \] \text{ specific heat of solar cell, J/kg K} \\
\[ c_f \] \text{ specific heat of floor, J/kg K} \\
\[ E_c \] \text{ electrical power, W} \\
\[ E_{\text{th}} \] \text{ rate of exergy of solar radiation of PV module, W} \\
\[ E_{\text{th,night}} \] \text{ rate of exergy of solar energy through non-packing area of PV module, W} \\
\[ E_{\text{th}} \] \text{ total thermal exergy, W} \\
\[ E_{\text{th,sys}} \] \text{ rate of thermal exergy from floor to room 1 air, W} \\
\[ E_{\text{th,ref}} \] \text{ rate of thermal exergy from PV module to room 1 air, W} \\
\[ h_0 \] \text{ outside heat transfer coefficient, W/m}^2 \text{ K} \\
\[ h_c \] \text{ convective heat transfer coefficient W/m}^2 \text{ K} \\
\[ h_{c,\text{eff}} \] \text{ constant, } - \\
\[ h_{\text{r,1}} \] \text{ heat transfer coefficient of room 1, W/m}^2 \text{ K} \\
\[ f(t) \] \text{ solar intensity, W/m}^2 \\
\[ k \] \text{ thermal conductivity, W/m K} \\
\[ L \] \text{ thickness of roof, m} \\
\[ M_a \] \text{ mass of air, kg} \\
\[ M_c \] \text{ mass of solar cell, kg} \\
\[ M_f \] \text{ mass of floor, kg} \\
\[ N \] \text{ number of air changes per hour, } - \\
\[ T \] \text{ temperature, } ^\circ\text{C} \\
\[ T_0 \] \text{ room 2 air temperature, } ^\circ\text{C} \\
\[ T_1 \] \text{ room 1 air temperature, } ^\circ\text{C} \\
\[ T_s \] \text{ sun surface temperature, K} \\
\[ U_b \] \text{ overall heat transfer coefficient from floor to air conditioned room, W/m}^2 \text{ K} \\
\[ U_{\text{th,1}} \] \text{ overall heat transfer coefficient from solar cell to room 1 through glass cover, W/m}^2 \text{ K} \\
\[ U_{\text{th,2}} \] \text{ constant, } - \\
\[ U_{\text{th,ref}} \] \text{ overall heat transfer coefficient from room to bottom of roof, W/m}^2 \text{ K} \\
\[ U_{\text{th,ca}} \] \text{ overall heat transfer coefficient from solar cell to ambient through glass cover, W/m}^2 \text{ K} \\
\[ V \] \text{ volume of room, m}^3 \\
\[ Q_{\text{U,th}} \] \text{ rate of hourly thermal energy, W} \\
\[ n_{\text{ex}} \] \text{ overall exergy efficiency, } \% \\
\[ n_{\text{th}} \] \text{ overall hourly thermal exergy, } \% \\
\[ n_{\text{th,ex}} \] \text{ thermal exergy efficiency, } \% \\

Greek symbols

\[ \alpha \] \text{ absorptivity, } - \\
\[ \beta \] \text{ packing factor, } - \\
\[ \beta_0 \] \text{ temperature coefficient, } ^\circ\text{C}^{-1} \\
\[ \eta_c \] \text{ electrical efficiency at standard test condition, } - \\
\[ \tau \] \text{ transmissivity, } - \\

Subscript

\[ 0 \] \text{ time independent Fourier coefficient} \\
\[ 1 \] \text{ room 1} \\
\[ 2 \] \text{ room 2} \\
\[ (i) \] \text{ case (i)} \\
\[ (ii) \] \text{ case (ii)} \\
\[ a \] \text{ ambient air} \\
\[ c \] \text{ solar cell} \\
\[ f \] \text{ floor of room 1} \\
\[ g \] \text{ glass} \\
\[ m \] \text{ PV module} \\
\[ R \] \text{ roof} \\

savings. Li et al. [17] have studied the energy performance and cost analysis of solar PV system with day lighting. Further they have found that 1203 MWh annual electricity can be saved if such a system is integrated to the building. Zogou and Staporntzis [18] have introduced opaque PV modules on south facing double facades to increase the building efficiency in terms of electrical power. Ara- vind et al. [19] have presented a comprehensive review on the PV architecture and its implementation on eco-tourism for a model lodge in Malaysia as a case study. Riza et al. [20] have presented a sizing optimization methodology of panel and battery capacity in a standalone PV system with lighting load. Farshchimonfared et al. [21] have examined the optimization of PVT system integrated with the residential building and have found that better overall energy output with lower temperature can be obtained with a larger collector depth. Mainzer et al. [22] have presented a technical potential for BiPVT system mounted on roof top of a residential building in Germany. PV potential for the same was determined to be 30% which was due to non-consideration of non-residential buildings. Ordenes et al. [23] have concluded that PV system on rooftop yields 45% more energy in comparison to façade due to maximum insolation on roof. Vats et al. [24] have also carried out study to analyze the effect of packing factor of BiSPVT on energy and exergy of the system. They have reported that there is decrease in solar cell electrical efficiency with increase in the packing factor of PV module due to rise in solar cell temperature without considering the day light factor. Chen et al. [25] have found that there is thermal output of 8.5–10 kW from BiPVT roof with surface area of 64 m². Further, Vats and Tiwari [26] have derived an expression for building integrated semitransparent photovoltaic thermal (BiSPVT) and building integrated opaque photovoltaic thermal (BiOPVT) systems with and without air duct for roof and façade. They have found that there are 18 °C and 2.3 °C rise in maximum and minimum indoor room air temperature for semitransparent photovoltaic thermal roof (without air duct) and opaque photovoltaic thermal façade (with air duct) respectively. Recently, Tiwari et al. [27] have developed a periodic analysis of BiSPVT system for two storey building without air-conditioning to analyze the thermal performance. It was found that 300–400 mm should be the optimum roof thickness in order to minimize the decrement factor. First floor could be used for crop drying since the maximum indoor temperature achieved was 47 °C.

From in the above studies, we have observed that none of the above researchers have considered the analysis of building integrated semitransparent photovoltaic thermal (BiSPVT) systems by considering electrical, thermal and day lighting together in terms of exergy. They have also not considered the effect of number of air changes between room and ambient air.

In this paper, an attempt has been made to evaluate an overall exergy analysis for BiSPVT system by considering thermal and electrical energy and day lighting factor. Effect of number of air changes per hour from room 1 to the outside air has also been considered.

2. Building integrated semitransparent photovoltaic thermal (BiSPVT) system

![Fig. 1 shows a cross sectional view of building integrated semitransparent photovoltaic thermal (BiSPVT) system](image-url)
due to large thickness of slab between room 1 and room 2. Thermal side losses in rooms 1 and 2 from walls have been neglected to simplify the analysis. The dimensions of the system, various heat loss coefficients and design parameters have been given in Table 1. In this case, roof of room 1 has been considered as semi-transparent photovoltaic module as shown in Fig. 1 and hence it referred as BiSPVT system. It is clear from this figure that there is direct transmission of solar radiation through non-packing area of semitransparent PV module which is finally absorbed by floor of room 1. Also there is thermal energy transferred from (i) back of PV module and (ii) floor to room air by convection and hence there is an increase in the room air temperature. Such system can be used for many purposes namely sun bath, solar drying, crop cultivation etc. There can be a provision of heat transfer from room air to outside air under natural and forced mode of operation to maintain low temperature inside room 1 during summer. In this paper, numerical computations have been carried out for a typical winter climatic condition of Varanasi (UP), India.

3. Thermal modelling

The energy balance equations of Room 1 (Room under study) of building integrated semitransparent photovoltaic thermal system have been written based on the following assumptions:

1. Thermal side losses for both the rooms have been neglected for simplification of analysis.
2. Room 2 has been considered as air-conditioned i.e., constant room temperature (room below present study) due to large roof thickness.
3. Steady-state heat conduction losses for roof of room 2 has been considered.
4. There is no temperature gradient along thickness of semitransparent PV module and room 1 air column.
5. Air changes are considered to be constant.

3.1. Energy balance for BiSPVT

Following Tiwari et al. [27], energy balance equation for roof of BiSPVT can be written as:

\[
\alpha_c \frac{L_s}{\beta} - A_m = U_{int} (T_r - T_a) + U_{bcr} (T_c - T_r) + A_m + \frac{\alpha_s L_s}{\beta} \eta_e
\]

where \( \beta A_m \) is the area of solar cells in PV modules (packing area of semitransparent roof).

\[
U_{int} = \frac{1}{\frac{1}{R_s} + \frac{1}{R_{int}} - 1} = \frac{1}{\frac{1}{R_s} + \frac{1}{R_{bcr}} - 1} = 0.1754 + 0.0033^{-1}
\]

and,

\[
U_{bcr} = \frac{1}{\frac{1}{R_{bcr}} + \frac{1}{R_s}}
\]

Eq. (1) can be rewritten as follows:

\[
T_c = \frac{\alpha_s L_s}{\beta} (T_a - \eta_e) + U_{int} T_a + U_{bcr} T_r
\]

For known solar cell temperature (\( T_c \)), solar cell electrical efficiency (\( \eta_e \)) can be determined from the following expression:

\[
\eta_e = \frac{1 - \beta_0 (T_c - 25)}{1 - \beta_0 (T_a - 25)}
\]

After substituting an expression for \( T_c \) from Eq. (2) in Eq. (3a), one gets an analytical expression for electrical efficiency of solar cell (\( \eta_e \)) as

\[
\eta_e = \frac{1 - \beta_0 (T_s I(t) / \beta + U_{int} (T_a - 25) + U_{bcr} (T_r - 25))}{1 - \beta_0 (T_s I(t) / \beta + U_{int} + U_{bcr})}
\]

The above equation depends on room 1 air temperature. Further, Eq. (3b) is applicable for

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**Table 1**

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Values</th>
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<tr>
<td>( A_s )</td>
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<td>( A_m )</td>
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<td>( C_t )</td>
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<td>( k_{concrete} )</td>
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<tr>
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**Fig. 1.** Cross sectional view of a room with building integrated semi-transparent thermal system.
Once air temperature for room 1 is known from Eq. (8) for a given climatic and design parameters, solar cell and floor temperature can be obtained from Eqs. (2) and (5) respectively. Further, solar cell electrical efficiency can be determined from Eqs. ((3a) and (3b)).

### 3.2. Electrical energy

An electrical power of PV which is of high grade can be calculated as:

\[
\dot{E}_e = \eta_e \cdot \tau_2 \cdot I(t) \cdot A_m \beta
\]

where \(\eta_e\) is given by Eq. (3b).

### 3.3. Exergy analysis

Since thermal energy available to room from floor and back of PV module are low grade energy and hence it is required to be converted into thermal exergy to evaluate an overall exergy of the BiSPVT system.

Following [4,3,28,29], the rate of thermal exergy can be calculated as follows:

- Case (i) Using second law of thermodynamics for high operating temperature,
  - From floor to room air:
    \[
    \dot{E}_{\text{thf}(i)} = Q_f \left(1 - \frac{T_r}{T_f}\right).
    \]
  where \(Q_f = A_f h_f (T_f - T_r)\)
  - From rear of PV module to room air:
    \[
    \dot{E}_{\text{thb}(i)} = Q_f \left(1 - \frac{T_a}{T_r}\right).
    \]
  where \(Q_f = A_f h_f (T_r - T_a)\)

• Total hourly thermal exergy is given by:
  \[
  \dot{E}_{\text{thh(i)}} = \dot{E}_{\text{thf}(i)} + \dot{E}_{\text{thb}(i)}
  \]

Case (ii) Using first law of thermodynamics for low operating temperature,

- From floor to room air:
  \[
  \dot{E}_{\text{thf(ii)}} = A_f h_f \left(\frac{T_f - T_r}{T_a - T_r}\right) \ln\left[\frac{T_f + 273}{T_a + 273}\right]
  \]
- From rear of PV module to room air:
  \[
  \dot{E}_{\text{thb(ii)}} = A_f h_f \left(\frac{T_r - T_a}{T_r - T_f}\right) \ln\left[\frac{T_r + 273}{T_f + 273}\right]
  \]
• Total hourly thermal exergy is given by:

$$\dot{E}_{\text{th(ii)}} = \dot{E}_{\text{thex}(ii)} + \dot{E}_{\text{thci}(ii)}$$  \hspace{1cm} (11c)

Therefore, total hourly thermal energy is:

$$\dot{Q}_{\text{th}} = \dot{A}_f h_i (T_f - T_r) + \dot{A}_h h_i (T_e - T_r)$$  \hspace{1cm} (11d)

3.4. Illumination

Radiometry is the science to measure the radiant energy based on the absolute power. Luminosity which is a function of human brightness sensitivity is used to weigh the radiant power at specified wavelength.

An exergy of solar radiation through non-packing area, $[\beta(1-\beta)A_m]$ of PV module [15,28] is given by:

$$\dot{E}_{\text{sun, daylight}} = \{A_m I(t)(1-\beta)\} \left[1 - \frac{4}{3} \left(\frac{T_a}{T_f}\right) + \frac{1}{3} \left(\frac{T_a}{T_r}\right)^4\right] \text{Watt}$$  \hspace{1cm} (12a)

In terms of illumination, 1 W = 100 lx.

Eq. (12a) will determine the natural light (day lighting) in room 1 of BiSPVT system for human brightness sensitivity.

3.5. Total exergy

The total exergy can be determined by adding electrical power (Eq. (9)), thermal energy (either Eqs. (10c) or (11c)) and day lighting (Eq. (12a)).

So, total exergy of BiSPVT system is given by

Net output exergy = $\dot{E}_{\text{ex}} + \dot{E}_{\text{thex}(ii)} + \dot{E}_{\text{sun, daylight}}$

3.6. Input exergy

An exergy of solar radiation on PV module $[A_m]$ [15,28] is the net input exergy which is given by:

$$\dot{E}_{\text{sun}} = \{A_m I(t)\} \left[1 - \frac{4}{3} \left(\frac{T_a}{T_f}\right) + \frac{1}{3} \left(\frac{T_a}{T_r}\right)^4\right] \text{Watt}$$  \hspace{1cm} (12b)

where $T_a$ and $T_r$ in Eqs. (12a) and (12b) are in Kelvin.

3.7. Exergy efficiency

Thermal exergy ($\eta_{\text{th,ex}}$) and an overall exergy efficiency ($\eta_{\text{ex}}$) of BiSPVT can be evaluated as follows:

i. Using Eqs. (11c) and (12b), thermal exergy efficiency is given by:

$$\eta_{\text{th,ex}} = \frac{\dot{E}_{\text{thex}(ii)}}{\dot{E}_{\text{sun}}}$$  \hspace{1cm} (13a)

ii. Using Eqs. (9), (11c), (12a) and (12b), an overall exergy efficiency is given by:

$$\eta_{\text{ex}} = \frac{\dot{E}_{\text{ex}} + \dot{E}_{\text{thex}(ii)} + \dot{E}_{\text{sun, daylight}}}{\dot{E}_{\text{sun}}}$$  \hspace{1cm} (13b)

3.8. Thermal efficiency

An overall hourly thermal efficiency can also be evaluated by:

$$\eta_{\text{th}} = \frac{\dot{Q}_{\text{th}}}{I(t)A_g}$$  \hspace{1cm} (14)

4. Methodology

Following methodology has been adopted for numerical computation:

Step 1: For a given hourly variation of solar radiation, ambient air temperature data (Fig. 2) and design parameters (Table 1), calculations have been made for the temperature of room 1 ($T_r$) for different number of air changes using Eq. (8) and the results have been shown in Fig. 3a.

Step 2: After knowing the hourly variation of room air temperature ($T_r$), Fig. 3a, the hourly variation of solar cell ($T_c$), electrical efficiency of solar cell ($\eta_c$) and floor temperature ($T_f$) are calculated using Eqs. (2), (3b) and (5) and the results are shown in Figs. 4–6.

Step 3: The electrical power from semitransparent PV module roof is evaluated by using Eq. (9). With help of Figs. 2 and 5, effect of number of air changes per hour on hourly variation of electrical power has been shown in Fig 7a.

Step 4: By using the hourly data of Figs. 3a and 6 for room 1 air and floor temperature, hourly thermal exergy based on high and low operating temperatures from floor to room air and from back of PV module to room air for different number of air changes has been evaluated and shown in Figs. 7b and 7d respectively. By using Figs. 7c and 7d. Finally, hourly thermal exergy ($\dot{E}_{\text{thex}(ii)}$) has been evaluated and shown in Fig. 7e.

Step 5: Hourly day light savings has been calculated using Eq. (12a) as shown in Fig. 7f.

An overall hourly exergy of BiSPVT system is sum of hourly exergy due to thermal and electrical power and day lighting.
Step 6: Thermal and exergy efficiencies have been calculated using Eqs. (9), (11a), (11c), (11d), (12a), (13a), (13b) and (14) and represented in Table 2.

5. Results and discussion

Fig. 3a shows the hourly variation of room 1 air temperature for number of air changes between 0 and 4. It can be seen that the...
Room air temperature decreases with increase of number of air changes due to increase in transfer of thermal energy from room to outside. Further there is shift of maxima of room air temperature with respect to maxima of solar intensity (Fig. 2). It is due to fact that we have assumed that there are no heat losses through walls and thermal energy is stored during peak hours. Such system can be used for thermal heating of a building along with electrical energy demand for the same building. For \( N = 4 \), room air temperature can be considered within comfort temperature range and excess hot air available can be used for thermal heating of another room in the building. Further, fluctuations are noticed in the internal room temperatures since the room temperature changes with change in the solar intensity. Thermal load levelling can be calculated as:

\[
TLL = \frac{T_{r,\text{max}} - T_{r,\text{min}}}{T_{r,\text{max}} + T_{r,\text{min}}}
\]

(14)

Therefore, Thermal load levelling (TLL) is represented in Fig. 3b, which clearly illustrates that as number of air changes increases, there is a drop in TLL. There should be minimum fluctuations for comfortable indoor temperature.

Further it is to be noted that the solar cell temperature is also reduced marginally at large number of air change (\( N = 4 \)) (Fig. 4). In this case, solar cell electrical efficiency is increased for higher electrical power to the building (Fig. 5). These results are in accordance with the results reported by Vats and Tiwari [11]. Further, it should be noted that there is marginal effect of number of air change on solar cell electrical efficiency and solar cell temperature.
However, there is significant effect on floor temperature due to number of air as shown in Fig. 6. The floor temperature decreases with increase in number of air changes as per our expectation. Electrical power is always considered as equivalent to exergy due to high grade energy. There is an insignificant effect of number in air changes on electrical power as shown in Fig. 7a due to marginal effect of air changes on solar cell electrical efficiency as shown in Fig. 5. In order to evaluate thermal exergy, hourly variation of floor temperature has been calculated by using Eq. (5).

High variations are observed in the time interval between 19 and 25, when the solar intensity is zero in room air temperature (Fig. 3a) and floor temperature (Fig. 6). This is because during the day time, heat is stored into the roof and in off sun shine hours, heat is released to the room slowly.

Eq. (9) has been used to calculate hourly electrical power as shown in Fig. 7a by using the data of Figs. 2 and 5 respectively and found that there is no effect of number of air change on electrical power of BiSPVT.

Fig. 7b represents thermal exergy of room 1 of the BiSPVT system for high operating temperature and low operating temperatures. Further calculations have been done on the basis of low operating temperature (\( T_{th} \)).

Figs. 7c and 7d show the hourly variation of thermal exergy due to floor and PV module temperature and it has been observed that number of air change has significant effect on thermal exergy due to floor in comparison with thermal exergy due to PV module temperature. The \( T_r \) plotted in Fig. 6 has been used to calculate the hourly variation of thermal exergy with effect of number of air changes from floor to room air using Eq. (11a) as shown in Fig. 7c. It is noted, that with increase in number of air changes, the thermal exergy from floor to room air decreases. Fig. 7e gives the hourly variation of total thermal exergy inside room 1.

The hourly variation of illumination in terms of W/m² is shown in Fig. 7f by using Eq. (12a). This is also equivalent to artificial day lighting and be considered as exergy as pointed out by Petala [15]. The illumination will only depend on packing factor of PV module and it should be as minimum as possible because it affects the electrical power of the system from solar cell.

An overall hourly and daily exergy of BiSPVT system has been shown in Figs. 8a and 8b respectively and it can be seen that electrical and illumination power dominates in comparison with thermal exergy and further there is marginal effect of number of air change on an overall exergy. Total thermal exergy has no considerable effect with or without vent. 1.15% change in overall daily exergy from \( N_1 = 0 \) to \( N_1 = 4 \) is seen in Fig. 8b due to with and without vent in the system respectively.

Further, thermal and exergy efficiency have been calculated using Eqs. (9), (11a), (11c), (11d), (12a), (13a), (13b), and (14) as represented in Table 2.

### 6. Experimental validation

Brief description of the proposed system for experimental validation has been described by Tiwari et al. [30]. In the present case, the side losses have been neglected by placing the thermocool insulation of 0.05 m thickness in all sides and PVT air collector has been removed. The dimensions of the setup are 0.8 m (length), 1.0 m (width) and 0.7 m (height). Various design parameters taken for the calculations of room air temperature and solar cell temperature are given in Table 3. The east and south facing view of the experimental setup has been shown in Fig. 9.

Hourly variation of solar intensity, ambient temperature (\( T_a \)), room air temperature (\( T_r \)), solar cell temperature (\( T_c \)) has been measured for \( N_1 = 0 \) for a typical clear day conditions prevalent on 16th September 2016 at New Delhi, India from 7:00 to 17:00 h. The hourly variation of solar intensity and ambient temperature for the month of September is shown in Fig. 10.

The theoretical results (\( T_h \)) and experimental value (Ex) for room air temperature (\( T_r \)) and solar cell temperature (\( T_c \)) has been shown in Fig. 11.

It has been observed that there is a fair agreement between theoretical and experimental values of room air temperature and solar cell temperature with correlation coefficient (\( r \)) equal to 0.97, calculated by using the following equation [30].

\[
r = \frac{N \sum X_i Y_i - (\sum X_i)(\sum Y_i)}{\sqrt{N \sum X_i^2 - (\sum X_i)^2} \sqrt{N \sum Y_i^2 - (\sum Y_i)^2}}
\]

\( r > 0 \) indicates a positive linear relationship; \( r < 0 \) indicates a negative linear relationship and \( r = 0 \) indicates no linear relationship between two variables.

### Table 2
Thermal and exergy efficiency.

<table>
<thead>
<tr>
<th>Case</th>
<th>Thermal efficiency (%)</th>
<th>Exergy efficiency (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>( N_1 = 0 )</td>
<td>( N_1 = 2 )</td>
</tr>
<tr>
<td>Electrical energy</td>
<td>17.03</td>
<td>19.69</td>
</tr>
<tr>
<td>Thermal energy</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>Day lighting</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>Total thermal exergy</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>Overall thermal exergy</td>
<td>–</td>
<td>–</td>
</tr>
</tbody>
</table>

### Table 3
Various design parameters taken for the calculations of room air temperature and solar cell temperature for experimental validation.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>( A_t )</td>
<td>1.266 m²</td>
</tr>
<tr>
<td>( A_m )</td>
<td>1.3264 m²</td>
</tr>
<tr>
<td>( A_R )</td>
<td>1.3264 m²</td>
</tr>
<tr>
<td>( h_0 )</td>
<td>5.7 W/m² K</td>
</tr>
<tr>
<td>( h_c )</td>
<td>2.8 W/m² K</td>
</tr>
<tr>
<td>( h_1 )</td>
<td>2.8 W/m² K</td>
</tr>
<tr>
<td>( k_e )</td>
<td>0.09 W/m K</td>
</tr>
<tr>
<td>( k_R )</td>
<td>0.67 W/m K</td>
</tr>
<tr>
<td>( L_r )</td>
<td>0.003 m</td>
</tr>
<tr>
<td>( L_R )</td>
<td>0.6 m</td>
</tr>
<tr>
<td>( M_a )</td>
<td>6.72 kg</td>
</tr>
<tr>
<td>( V )</td>
<td>5.6 m³</td>
</tr>
<tr>
<td>( \alpha_i )</td>
<td>0.9</td>
</tr>
<tr>
<td>( \beta_i )</td>
<td>0.89</td>
</tr>
<tr>
<td>( \beta_0 )</td>
<td>0.0045°C</td>
</tr>
<tr>
<td>( \tau_0 )</td>
<td>0.15</td>
</tr>
<tr>
<td>( L_{air} )</td>
<td>1.2 kg/m³</td>
</tr>
<tr>
<td>( \tau_e )</td>
<td>0.9</td>
</tr>
<tr>
<td>Roof inclination</td>
<td>30°</td>
</tr>
</tbody>
</table>
7. Conclusion

Based on the present study, following conclusions have been drawn:

a. There are 26.81% increase, 6.28% decrease and 1.15% increase in the daily thermal energy, daily thermal exergy and overall thermal exergy with number of air changes from 0 to 4.

b. Drop in peak room air temperature and floor temperature with increase in the air change per hour from 0 to 4 was found to be 22.5 °C and 18.98 °C respectively.

c. There is drop in peak room air temperature by 22.5 °C and floor temperature by 18.98 °C with increase in the air change per hour.

d. Experimental validation of theoretical model has been carried out with \( r = 0.97 \).

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References


