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PERFORMANCE EVALUATION OF AN INTEGRATED PHOTOVOLTAIC/THERMAL (PV/T) AND EARTH AIR HEAT EXCHANGER (EAHE) GREENHOUSE

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ABSTRACT

Heating and cooling of greenhouse is one of the most energy consuming operations among the various activities performed for protected cultivation. Lack of heating has adverse effects on the yield, cultivation time, quality and quantity of the products in the greenhouse (Santamouris et al, 1994). The researchers have been directed to the use of alternative energy sources for heating of greenhouse in order to decrease energy consumption. Different types of passive solar systems and techniques have been proposed and used for the substitution of conventional fuels with solar energy as a low cost technology. Therefore coupling of greenhouse with the earth through buried pipes is the right approach for thermal heating and cooling purposes. Stable temperature of earth at the depth of about 1 m has directed the researchers towards the use of ground as a heat source and for heat storage as well as dissipation for passive heating and cooling applications.
Keywords: Thermal Modeling, green house, photovoltaic, heat exchanger

Thermal Modeling

The energy balance equations for various components of greenhouse combined with photovoltaic and earth air heat exchanger can be written on the basis of following assumptions.

(i) Analysis is based on quasi-steady state condition.
(ii) Air flow between the tedlar base and wood structure is uniform for the forced mode of operation.
(iii) The ohmic losses in the solar cells are negligible.
(iv) Radiative exchange among walls and roofs inside greenhouse is neglected due to negligible temperature differences.
(v) Flow of air is uniform along the length of buried pipes.
(vi) There is no radiative heat exchange between the sides of the buried pipe.

Energy Analysis (Thermal output)

In the present study, thermal energy generated by the PV modules and earth air heat exchanger. The daily rate of thermal energy (W) available from PV module has been obtained from Eq. (2.9a) in Chapter II,

$$\left(\dot{q}_u\right)_{daily} = F_R\left\{h_{pi}h_{p2}\left(\alpha\tau\right)_{eff} I\left(t\right) - U_L\sum\left(T_r - T_a\right)\right\} \qquad (4.11)$$

The daily rate of useful thermal energy available from EAHE has been obtained

$$\left(\dot{Q}_u\right)_{daily} = F_R^{'} M_a C_a \sum(T_0 - T_r) \qquad (4.12)$$

The daily total rate of useful thermal energy available from PV module and EAHE has been obtained

$$\left(\dot{Q}_{utot}\right)_{daily} = \left(\dot{q}_u\right)_{daily} + \left(\dot{Q}_u\right)_{daily} \qquad (4.13)$$

The monthly thermal energy in kWh is given by

$$\left(\dot{Q}_{utot}\right)_{monthly} = \frac{\sum_{i=1}^{N}\left(\dot{Q}_{utot}\right)_{daily} \times n_o}{1000} \qquad (4.14)$$

From the above equation, one gets yearly thermal energy output in kWh

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$$\left(\dot{Q}_{utot}\right)_{yearly} = \sum_{i=1}^{12}\left(\dot{Q}_{utot}\right)_{monthly} \quad (4.15)$$

Electrical output

The annual electrical energy obtained from PV module and EAHE $\left(E_{netel}\right)_{yearly}$ is given by

$$\left(E_{netel}\right)_{yearly} = \eta \times \mathrm{A} \times \mathrm{I(t)}_{avg} \times N_o \times n_o \quad (4.16)$$

where $\eta = \dfrac{\eta_i + \eta_f}{2}$

η_i = Initial conversion efficiency at which the module starts its operation

η_f = Predicted conversion efficiency at which it fails

$t_o = N_o \times n_o$

where, η is the efficiency of PV module, *A* is area of module, N_o is number of sunshine hours, n_o is number of days that fall in different weather condition and $[I(t)]_{avg}$ is the annual average intensity for four different types weather condition.

Exergy output

In case of photovoltaic and earth air heat exchanger integrated greenhouse, the yearly exergy input will be sum of yearly thermal energy and yearly net electrical energy savings obtained and is calculated for different weather conditions.
The monthly exergy output of a greenhouse, syahrul et al., (2002) can be obtained as follows:

$$\left(\dot{Q}_{exergy}\right)_{monthly} = \sum\left(1 - \frac{T_a + 273}{T_r + 273}\right) \times \left(\dot{Q}_{utot}\right)_{monthly} \quad (4.17)$$

where $\left(\dot{Q}_{utot}\right)_{monthly}$ has been calculated from Eq. (4.14)

Similarly one gets yearly exergy in kWh.

$$\left(\dot{Q}_{exergy}\right)_{yearly} = \sum_{i=1}^{12}\left(\dot{Q}_{exergy}\right)_{monthly} \quad (4.18)$$

Similarly one gets yearly exergy output $\left(\dot{Q}_{exth}\right)_{yearly}$ in kWh is the sum of yearly thermal energy and yearly net electrical energy savings obtained.

$$\left(\dot{Q}_{exth}\right)_{yearly} = \left(\dot{Q}_{exergy}\right)_{yearly} + \left(E_{netel}\right)_{yearly} \quad (4.19)$$

The overall annual thermal energy output $\left(Q_{th}\right)_{overall}$ has been obtained in kWh

$$\left(Q_{th}\right)_{overall} = \left(\dot{Q}_{exth}\right)_{yearly} + \frac{\left(E_{netel}\right)_{yearly}}{0.38} \quad (4.20)$$

The exergy efficiency of PV/T integrated greenhouse is defined in Chapter III by Hephalsi (2008) as follows:

$$\eta_{Ex} = \left(\frac{\left(\dot{Q}_{exth}\right)_{yearly}}{\dot{E}x_{in}}\right) \times 100 \quad (4.21)$$

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Computational procedure and input parameters

The energy balance equations derived for greenhouse coupled with photovoltaic system and earth air heat exchanger (EAHE), have been solved with the help of a computer program, based on Matlab 7.0 software. The design and operating parameters given in Table 1.1 have been used as input parameters for the developed mathematical model. Solar radiation falling on different walls and roof of greenhouse has been calculated with the help of Liu and Jordan formula using the beam and diffuse components of solar radiation incident on the horizontal surface. The heat removal factor (F'_R) for earth air heat exchanger (EAHE) has been determined to be 0.72 from the procedure given by Abdel-Khalik for a flat plate collector with serpentine tube as well as 0.74 from the steady state energy mechanism as shown in Fig. 4.1(b) and as per Eq. (4.6). The mass flow rate of the circulating air has been kept constant at 100 kg/hour. The performance of earth air heat exchanger has been evaluated both in terms of its heating and cooling potential as per the following expressions:

$$Q_h = M_a C_a \sum (T_d - T_{sc}) \Delta t \; ; \qquad Q_c = M_a C_a \sum (T_{sc} - T_d) \Delta t$$

Table 1.1 Input parameters used for greenhouse combined with EAHE

Para-meters	Values	Para-meters	Values	Para-meters	Values
A_e	8.3 m^2	h_i	2.8 $Wm^{-2}\,^oC^{-1}$	N	1-300
A_f	24.0 m^2	h_o	5.7 $Wm^{-2}\,^oC^{-1}$	r_1	0.03m
A_n	12.0 m^2	h_{na}	1.9 $Wm^{-2}\,^oC^{-1}$	U	1.8 $Wm^{-2}\,^oC^{-1}$
A_s	12.0 m^2	h_{gr}	5.7 $Wm^{-2}\,^oC^{-1}$	v	0.5-1.5 ms^{-1}
A_{nr}	13.8 m^2	h_{nr}	5.7 $Wm^{-2}\,^oC^{-1}$	V	144 m^3
A_{sr}	13.8 m^2	K_n	0.84 $Wm^{-2}\,^oC^{-1}$	r_g	0.2
A_{ww}	10.0 m^2	K_g	0.52 $Wm^{-2}\,^oC^{-1}$	r_n	0.2
C_a	1012 $Jkg^{-1}C^{-1}$	L'	39m	α_g	0.4
F_n	0.09-0.15	L_g	1m	α_n	0.6
F_R	0.64	m_a	0.02 kg s^{-1}	τ	0.5
h_{gf}	2.8 $Wm^{-2}\,^oC^{-1}$	M_a	72 kg		

Results and discussion

Eq. has been used for calculating greenhouse air temperature under four (a, b, c and d type) weather conditions for New Delhi for three following cases.

I. Only photovoltaic is operated for 24 hours.
II. Only earth air heat exchanger is operated for 24 hours.
III. Photovoltaic is operated during daytime for 12 hours and earth air heat exchanger is operated during night time for 12 hours.

Design and operating parameters used for numerical computations are given in Table 4.1. Fig. 4.2 shows the hourly variation of temperature of ambient air and greenhouse air when operated with photovoltaic for 24 hours (without the operation of earth air heat exchanger). It has been observed that greenhouse air temperature with the operation of photovoltaic/thermal (PV/T) system is around 8-9^{o}C higher, than the ambient air temperature at 1 pm, due to direct transfer of thermal energy from photovoltaic module to the greenhouse, while it is almost equal to the ambient temperature during night. Hourly variation of temperature of ambient air and greenhouse air when operated with earth air heat exchanger for 24 hours (without the operation of photovoltaic/thermal system) for a typical winter day is shown in Fig. 4.3. In this case it is seen that

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greenhouse air temperature is around 8-9°C higher than the ambient air temperature at 1 pm, while it is 6-7°C higher at 6 pm, due to continuous flow of hot air from earth air heat exchanger to the greenhouse. Fig. 4.4 shows the hourly variations of temperature of ambient air and greenhouse air when operated with photovoltaic/thermal system during daytime for 12 hours and with earth air heat exchanger during night time for 12 hours for a typical winter day. It is concluded that the air temperature inside the greenhouse increases by 7-8°C as compared to ambient air both during day and night due to direct transfer of thermal energy from photovoltaic to greenhouse during daytime and continuous flow of hot air from earth air heat exchanger to greenhouse during night time, which is the best suited for plant growth during winter period.

Fig. 4.2 Hourly variations of temperature of ambient air and greenhouse air when operated with PV/T for 24 hours for a typical winter day

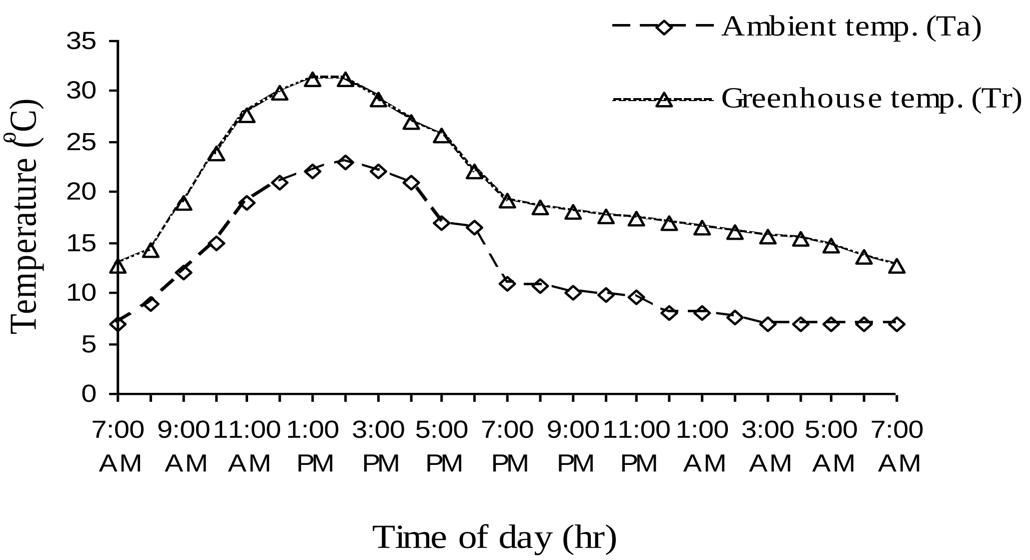

Fig. 4.3 Hourly variations of temperature of ambient air and greenhouse air when operated with EAHE for 24 hours for a typical winter day

Eqs. (4.5) and (4.6) have been used for calculating the rate of useful thermal energy (MJ) for photovoltaic/thermal (PV/T) and earth air heat exchanger (EAHE) integrated greenhouse. Fig. 4.5 shows the variation of hourly useful thermal energy (MJ) when operated with photovoltaic (PV/T) system during daytime and with earth air heat exchanger (EAHE) during night time. It has been observed that at 12 pm, useful thermal energy is calculated as 33 MJ with the operation of photovoltaic/thermal (PV/T) system, while between 5-6 pm, the useful thermal energy decreases due to fall of temperature during evening. It then increases to 24.5 MJ with the operation of earth air heat exchanger during night.

Eq. (4.15) has been used for calculating the yearly thermal energy obtained from photovoltaic and earth air heat exchanger integrated greenhouse from which the monthly thermal energy is then derived for four different types weather conditions for New Delhi. Eq. (4.16) has been used for calculating the monthly net electrical energy savings available from photovoltaic and earth air heat exchanger integrated greenhouse.

Eqs. (4.18) and (4.20) have been used for calculating total yearly exergy and yearly thermal energy. The monthly thermal energy has been calculated during the month of January, February, March, November and December when operated with photovoltaic during daytime and with earth air heat exchanger during night time. Similarly during the month of April, May, June, July, August, September and October when earth air heat exchanger (EAHE) is operated for 24 hrs, monthly thermal energy has been calculated. It has been calculated that 22577.9 kWh thermal energy can be obtained annually from a, b, c, and d type weather conditions for New Delhi (Table 4.2).

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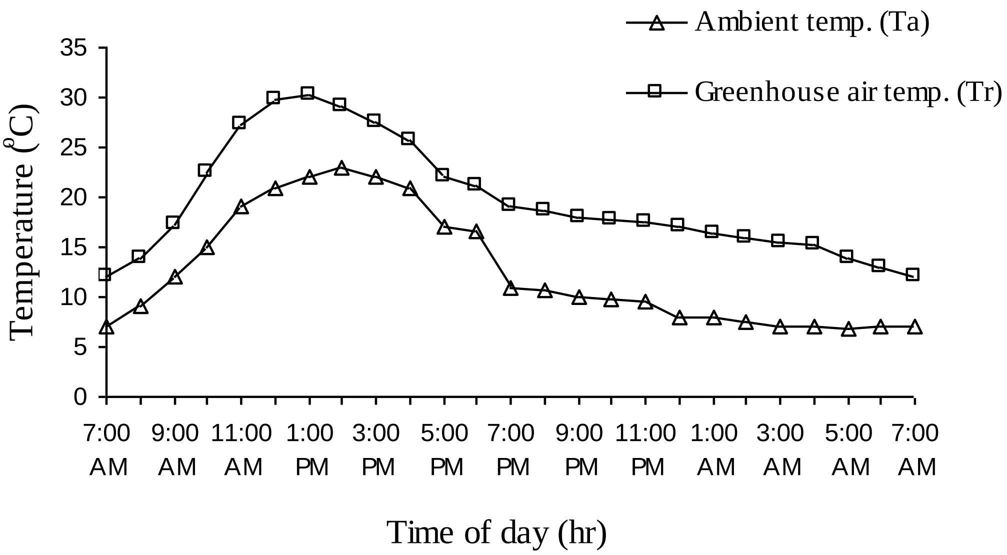

Fig. 4.4 Hourly variations of temperature of ambient air and greenhouse air when operated with PV/T during daytime and EAHE at night for a typical winter day.

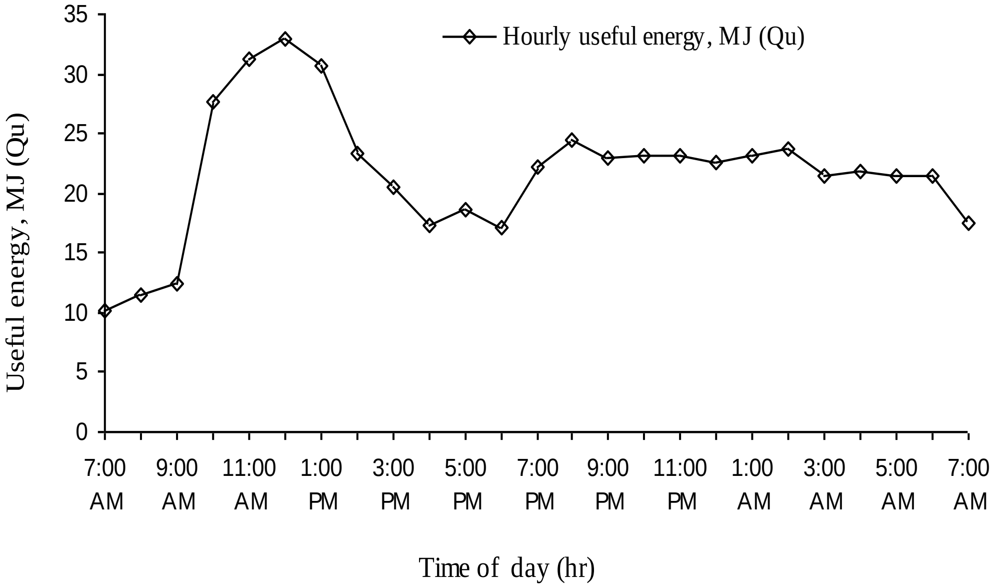

Fig. 4.5 Variation of hourly useful energy (MJ) when operated with PV/T during day time and EAHE at night for a typical winter day

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Table 4.2 Monthly thermal energy obtained from PV/T and EAHE integrated greenhouse for a, b, c and d type weather conditions for New Delhi.

Months	**a Type**	**b Type**	**c Type**	**d Type**	**Monthly thermal energy obtained (kWh)**
	Thermal Energy obtained (kWh)				
January	268.4	857.3	1138	884.5	3148.2
February	249.5	334.4	942.1	658.4	2184.4
March	302.6	373.4	595.3	409.7	1681.0
April	181.7	429.3	621.1	223.6	1455.7
May	440.4	399.2	1301.5	657.2	2798.3
June	181.7	58.1	853.3	536.8	1629.9
July	87.6	181.1	436.5	729.3	1434.5
August	31.1	173.3	106.2	308.2	618.8
September	379.6	135.3	535.8	521	1571.7
October	299.3	881.1	746.2	171.9	2098.5
November	292.1	454.6	431.1	73.1	1256.9
December	265.1	770.7	1057.7	607.3	2700.0
Annual	2979.1	5047.8	8770.8	5781	**22577.9**

- ✓ January, February, March, November and December
  6a.m to 6 p.m. - Operated with photovoltaic
  6p.m to 6 a.m. - Operated with earth air heat exchanger (EAHE).
- ✓ April, May, June, July, August, September and October
  Operated with earth air heat exchanger for 24 hrs

Table 4.3 Monthly net electrical energy savings obtained from PV/T and EAHE integrated greenhouse for a, b, c and d type weather conditions for New Delhi.

Months	**a Type**	**b Type**	**c Type**	**d Type**	**Monthly net electrical energy savings obtained (kWh)**
	Net electrical energy savings obtained (kWh)				
January	16.3	41.1	26.4	7.6	91.4
February	14.6	19.8	28.5	8.1	71.0
March	22.8	30.1	33.7	17.8	104.4
April	12.7	23.7	24.4	9.1	69.9
May	10.3	20.6	27.4	9.5	67.8
June	7.1	10.6	19.8	9.7	47.2
July	1.9	6.9	19.8	16.6	45.2
August	2.4	7.4	11.2	15.3	36.3
September	8.4	8.8	21.4	8.5	47.1
October	15.2	24.8	20.1	2.1	62.1
November	25.2	30.9	18.6	3.2	77.9
December	14.5	28.9	34.2	7.9	85.5
Annual	151.4	253.6	285.5	115.4	**805.9**

Table 4.4 Monthly overall exergy obtained from PV/T and EAHE integrated greenhouse for a, b, c and d type weather conditions for New Delhi.

Months	**Monthly Exergy obtained (kWh)**	**Monthly net electrical savings (kWh)**	**Overall exergy obtained (kWh)**
January	40.9	91.4	132.32
February	22.9	71.0	93.9
March	27.7	104.4	132.1
April	7.2	69.9	77.1
May	15.4	67.8	83.2
June	3.5	47.2	50.7
July	7.1	45.2	52.3
August	0.7	36.3	37.0
September	23.8	47.1	70.9
October	26.2	62.2	88.4
November	2.8	77.9	80.7
December	21.8	85.5	107.3
Annual	200.3	805.9	**1006.2**

Table 4.5 **Monthly overall thermal energy obtained from PV/T and EAHE greenhouse for a, b, c and d type weather conditions for New Delhi.**

Months	**Monthly thermal energy obtained (kWh)**	**Monthly equivalent thermal energy obtained (kWh)**	**Overall thermal energy obtained (kWh)**
January	3148.2	240.8	3389.0
February	2184.4	187.4	2371.8
March	1681.0	275.1	1956.1
April	1455.7	184.3	1640.0
May	2798.3	179.3	2977.6
June	1629.9	150.0	1779.9
July	1434.5	119.5	1554.0
August	618.8	96.1	714.9
September	1571.7	124.1	1695.8
October	2098.5	163.8	2262.3
November	1256.9	205.1	1462.0
December	2700.0	225.4	2925.4
Annual	22577.9	2150.9	**24728.8**

Table 4.3 shows monthly net electrical energy savings available from photovoltaic and earth air heat exchanger integrated greenhouse for a, b, c and d type weather conditions for New Delhi. It has been concluded that 805.9 kWh net electrical energy savings obtained annually. The overall exergy and total thermal energy have been calculated 1006.2 kWh (Table 4.4) and 24728.8 kWh (Table 4.5) annually, respectively. Eq. (4.21) has been used for calculating the yearly exergy efficiency from photovoltaic and earth air heat exchanger integrated greenhouse. It has been calculated as 5.5%. In the previous chapter, exergy efficiency without the use of earth air heat exchanger had been calculated as 4% by using Eq. (3.21).

Conclusions

On the basis of present study, the following conclusions have been made.

(i) Relative fluctuations of temperature for greenhouse air are less by use of photovoltaic/thermal (PV/T) air collector during daytime and earth air heat exchanger (EAHE) in night time.

(ii) Case III has been considered as suitable for plant growth for winter period. It can be concluded that the overall temperature of air inside the greenhouse increases by 7-8^{o}C than the ambient air, when operated with photovoltaic (PV/T) during daytime and with earth air heat exchanger (EAHE) in night time.

(iii) Net electrical energy savings has been also obtained 805.9 kWh annually (as shown in Table 4.3).

(iv) Yearly overall exergy and thermal energy have been calculated 1006.2 kWh (shown in Table 4.4) and 24728.8 kWh respectively, as shown in Table 4.5.

(v) Exergy efficiency when operated with photovoltaic (PV/T) during daytime and with earth air heat exchanger (EAHE) in night time is around 5.5%. This is as compared to an exergy efficiency of 4% when the greenhouse is operated without an EAHE.

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