Performance of Winter Greenhouse Coupled with Solar Photovoltaic and Earth Air Heat Exchanger

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ABSTRACT

The application of solar energy through photovoltaic system and earth air heat exchanger (EAHE) has been studied with the help of a simplified mathematical model for heating of a greenhouse. The temperatures of air inside the greenhouse have been compared from the photovoltaic thermal system (PV/T) without air collector, with air collector (during sun shine hours) and with EAHE (during off sun shine hours) along with the overall efficiency (thermal and electrical) of PV/T system. Numerical computations have been carried out for a typical winter day of composite climate of New Delhi, India. The heating potential of the system is evaluated in terms of coefficient of performance (COP) and thermal load leveling. The heating potential has also been standardized by the characteristic curve of greenhouse similar to that of flat plate collector. The values of coefficient of performance were highest in the month of January (2.8), followed by December (2.45), February (2.1) and November (1.94). However, in the month of March its value was below the dashed line (value less than 1) indicating the system needs to be discontinued during this month. The results revealed that the required temperature for air inside the greenhouse can be maintained during the winter period and overall efficiency can also be increased if the system is operated with PV/T device (with air collector) during day time and EAHE in night time.

Keywords: Solar energy, greenhouse, photovoltaic system, earth air heat exchanger, thermal load leveling, thermal modeling, India.

1. INTRODUCTION

India receives enormous amount of solar energy on an average of the order of 5 $kWh/m^2/day$ for about 300 days in a year. It can be used as thermal energy to produce hot water/ air, to heat indoor space, to dry the industrial and agricultural products etc. It can also be used to convert sunlight directly to electricity by photovoltaic (PV) and is now being used for a variety of applications. Hence solar photovoltaic (SPV) is one of the technology, which address itself to utilize the nature's gift (solar energy) in the form of electrical as well as thermal energy. Jones and Underwood (2001) have studied the temperature profile of a photovoltaic (PV/T) module in non-steady conditions. They have carried out experimental observations for cloudy as well clear sky conditions. They found that PV module temperature varies in the range of 27-52^oC for an ambient air temperature (24.5^oC). The carrier of thermal energy associated with the PV module can be air or water. The integrated arrangements for utilizing thermal energy as well as electrical energy, with a photovoltaic module are referred to as the hybrid PV/T system. The rate of the thermal energy obtained from hybrid (PV/T) system is supplied to the greenhouse for heating purpose. Tiwari and Sodha (2006) have studied the thermal performance of a hybrid photovoltaic thermal (PV/T) air collector for New Delhi climatic condition.

Heating of greenhouse is one of the most energy consuming activities during winter periods. Lack of heating has adverse effects on the yield, cultivation time, quality and quantity of the products in the greenhouse (Santamouris et al., 1994a). But studies on greenhouse heating strategies have shown that the cost of heating even exceeds 30% of the overall operational cost of the greenhouse (Coffin, 1985). Due to high relative cost of energy, only a small number of greenhouse owners can afford to the use of auxiliary heating systems. The system is therefore of primary importance for a greenhouse to provide optimum indoor conditions during winter months. Kumari et al. (2007) studied the performance evaluation of greenhouse having passive or active heating in different climatic zones of India.

Efforts to decrease energy consumption have directed the researchers to use alternative energy sources for heating of greenhouse. Different types of passive solar systems and techniques have been proposed and used Santamouris et al. (1996), Barral et al. (1999), Bargach et al. (2000) for the substitution of conventional fuels with solar energy as a low cost technology. As solar energy is the ideal source of energy for space heating particularly in the northern hemisphere where it is available sufficiently. Also it is practically inexhaustible and its use does not result in pollution. Efforts to harness solar energy have been accelerated during the last decade as world demand for energy grows (Saravia et al., 1997). In all the heat collection systems, the basic strategy is to reduce the heat losses and at the same time to store the surplus energy for use during the energy shortage period. Continuous research in this area and several successful demonstration projects has resulted in rapid advancements and commercialization of these technologies with satisfactory results.

The greenhouses, which utilize solar energy for heat purposes, are equipped with heat collection systems integrated into the cell of the greenhouse. The important heat storage mediums are namely water, latent heat materials, rock bed, buried pipes etc. Out of these storage mediums, buried pipes systems have gained increasing acceptance for better and easy exploitation of thermal energy from the ground (Santamouris et al., 1994b). The photovoltaic system combined with buried pipe system is also a feasible method not only to provide thermal energy to the greenhouse but also to supply electrical energy for the blower used in the buried pipe system resulting in the indirect way of increasing the overall thermal and electrical efficiency of photovoltaic system.

Hence considering the importance of buried pipe system (Earth air heat exchanger system; EAHE) as a simple, inexpensive and alternative source of energy, the system has been integrated with photovoltaic cell in Indian Institute Technology, model greenhouse, New Delhi, during the whole winter period with a view to study its thermal performance for heating of the greenhouse through a model, developed, in the composite climate of New Delhi, India.

2. MATERIALS AND METHODS

2.1 Description of Photovoltaic and EAHE Combined Greenhouse System

An air is taken as the medium for transport of thermal energy in hybrid PV/T air collector. Sixteen PV modules with each having an effective area of 0.605 m^2 are connected in series. The panel with effective area of 1.62m ×6.5m is mounted on a galvanized iron structure with the air duct below the module. The inclination of the iron structure supporting PV modules which can be varied to received maximum solar intensity and also heating/cooling of the greenhouse as per requirement during winter and summer periods respectively. In winter, the inclination of PV/T is kept in such a manner that it closes the gap between duct and roof of the greenhouse to increase the inside temperature of greenhouse. In summer, the gap is introduced to lower the inside temperature of greenhouse. There is provision to measure the temperature of the inlet and outlet air by using temperature sensors. The fans of capacity 12W each have been provided at the inlet to induce the flow of air below the duct for extracting thermal energy available at the back of PV module. The fans are run by a DC battery (12V and 120Ah). A part of electrical energy generated is used to operate the fans to be used for forced air circulation inside the duct and supplied to the greenhouse for heating purpose as shown in Figure 1.

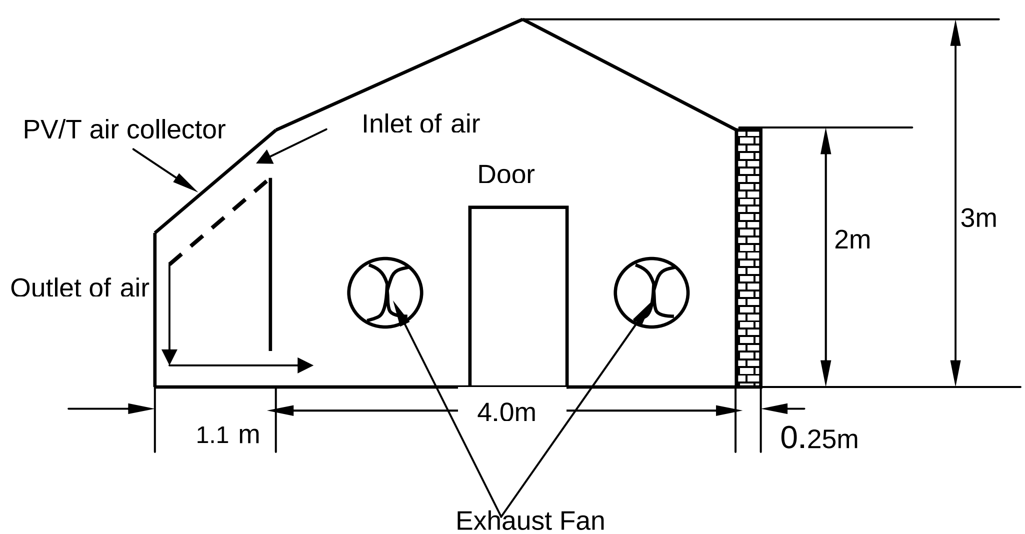

Figure 1. Front view of PV/T integrated greenhouse

The EAHE under study was installed in the west of the experimental greenhouse located in the premises of Indian Institute of Technology, Delhi, India. The climate of the place is composite i.e., it remains hot dry for five months, warm and humid for three months, moderate for one month and cold for three months. The absolute minimum temperature of ambient air during winter period is close to 4^{o}C while mean minimum is close to 9^{o}C. The greenhouse combined with EAHE was of even span type of greenhouse with floor area 6 m x 4 m and was oriented from east to west direction. Total length and diameter of buried pipes used were 39 m and 0.06 m respectively. EAHE also consisted of PVC pipes buried under bare surface at the depth of 1 m in a serpentine manner with 8 nos. of turns. The blower was attached in the suction end of the EAHE. The suction and delivery ends of EAHE were placed in the southwest and northwest corners of the greenhouse for allowing uniform mixing of air. The isometric view of experimental greenhouse integrated with photovoltaic system and EAHE is shown in Figure 2(a). Experiments were conducted continuously for two days in a week in clear and sunny days from January 2006 to March 2006 and November 2006 to December 2006. However the experimental validation was done for typical date (clear sunny day) of observations i.e., on 23-01-06 for greenhouse arrangement with EAHE, since January is the coldest month for Delhi. Hourly observations of solar radiation and temperatures of air for ambient condition, greenhouse enclosure, suction end and delivery end were recorded during the experimentation with

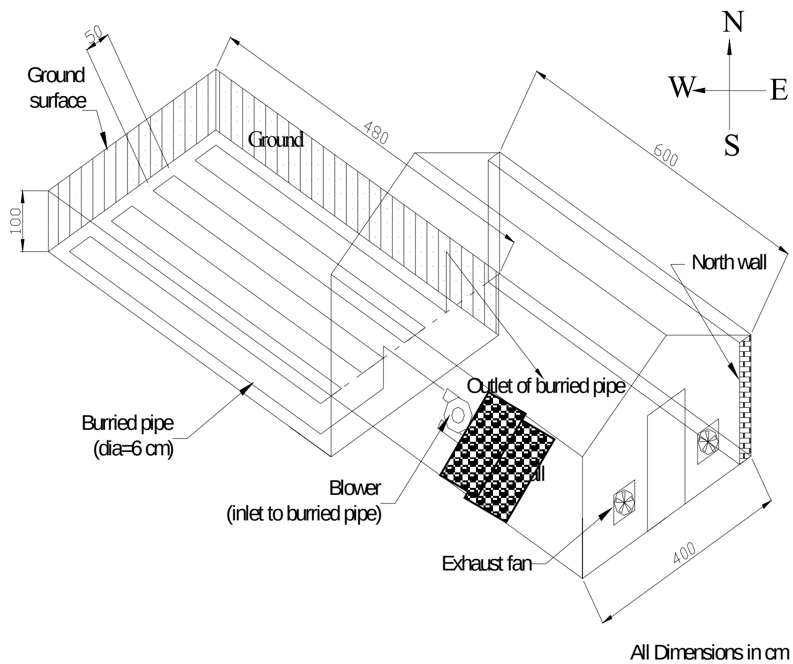

Figure 2(a). Isometric view of even span greenhouse integrated with PV/T and EAHE arrangement.

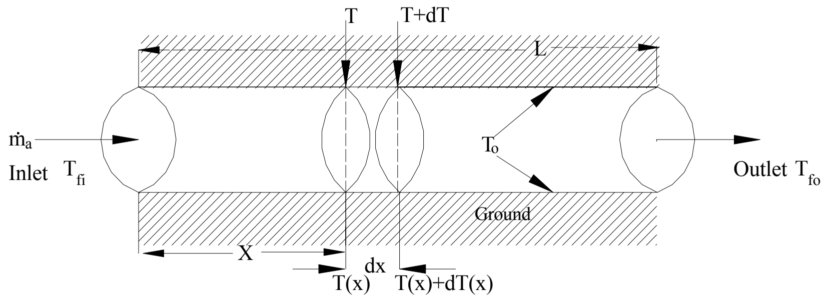

Figure 2(b). Energy exchange between ground and flowing air in elementary segment of the buried pipe.

the help of calibrated solarimeter and mercury thermometer, respectively. PV panel has been integrated with greenhouse to fulfill the electrical energy demands in the greenhouse. A part of electrical energy generated is used to operate the fans to be used for forced air circulation inside the duct. The rest of electrical energy is utilized for blower of earth air heat exchanger. The specifications of the silicon solar cell at 1000 W/m^2 at 25 ^{o}C (standard test conditions) used in the PV module are as follows. (i) Fill factor = 0.72; (ii) Short circuit current (I_{sc}) = 4.8 A; (iii) Open circuit voltage (V_{oc}) = 21.7 V; (iv) Area of single solar cell = 0.0139 m^2 and (v) Efficiency of solar cell = 15 %.

3. THERMAL ANALYSIS

3.1 Thermal Analysis of PV/T Air Collector

Thermal modeling has been carried out for hybrid PV/T air collector and EAHE to find out the outlet air temperature from both the system and then use of this useful thermal energy for greenhouse heating during winter season.

Energy balance for different components of hybrid PV/T air collector can be written as:

Energy balance, Tiwari and Sodha (2006):

1. For PV module:

$$\tau_G[(\alpha_c I(t)\beta_c) + (1-\beta_c)\alpha_T I(t)]bdx = bdx[\{U_T\{T_c - T_a) + h_T(T_c - T_{bs}\} + \tau_G \eta_c I(t)\beta_c] \quad (1)$$

2. For Back surface of tedlar:

$$bdxh_T(T_c - T_{bs}) = bdxh_t(T_{bs} - T_{air}), \text{ With air flow} \quad (2a)$$

$$bdxh_T(T_c - T_{bs}) = bdxh_t(T_{bs} - T_r) \text{ Without air flow} \quad (2b)$$

3. For air flowing below the tedlar

$$bdxh_t(T_{bs} - T_{air}) = \dot{m}_a c_a \frac{dT_{air}}{dx} dx + bdxU_b(T_{air} - T_a) \quad (3)$$

By solving equation (1), one gets

$$T_c = \frac{(\alpha\tau)_{eff} I(t) + U_T T_a + h_T T_{bs}}{U_T + h_T} \quad (4)$$

where

$$(\alpha\tau)_{eff} = \tau_G\left[\alpha_c\beta_c + \alpha_T(1-\beta_c) - \eta_c\beta_c\right]$$

By solving equation (2a), one gets

$$T_{bs} = \frac{h_{p1}(\alpha\tau)_{eff} I(t) + U_{tT}T_a + h_t T_{avg}}{h_t + U_{tT}} \tag{5}$$

where,

$$U_{tT} = \frac{h_T U_T}{U_T + h_t};\ h_{p1} = \frac{h_T}{U_T + h_T}$$

Using Equations (4) and (5a), Equation (3) can be rewritten as

$$b[h_{p1}h_{p2}(\alpha\tau)_{eff} I(t)] = \dot{m}_a c_a \frac{dT_{air}}{dx} + bU_L(T_{air} - T_a) \ldots. \tag{6}$$

where,

$$U_L = (U_b + \frac{h_t U_{tT}}{U_{tT} + h_t});\ h_{p2} = \frac{h_t}{U_{Tt} + h_t}$$

The solution of the above equation is given by

$$T_{air} = \left[\frac{h_{p1}h_{p2}(\alpha\tau)_{eff} I(t)}{U_L} + T_a\right]\left[1 - e^{\frac{-bU_L}{\dot{m}_a c_a}x}\right] + T_r\left[1 - e^{\frac{-bU_L}{\dot{m}_a c_a}x}\right] \tag{7}$$

The outlet air temperature of hot air can be obtained as

$$T_{airout} = T_{air}/x = L = \left[\frac{h_{p1}h_{p2}(\alpha\tau)_{eff} I(t)}{U_L} + T_a\right]\left[1 - e^{\frac{-bU_L}{\dot{m}_a c_a}L}\right] + T_r\left[e^{\frac{-bU_L}{\dot{m}_a c_a}L}\right] \tag{8a}$$

The average air temperature can be obtained as

$$T_{avg} = \left[\frac{h_{p1}h_{p2}(\alpha\tau)_{eff} I(t)}{U_L} + T_a\right]\left[1 - \frac{1 - e^{\frac{-bU_L}{\dot{m}_a c_a}L}}{\frac{-bU_L}{\dot{m}_a c_a}}\right] + T_r\left[\frac{1 - e^{\frac{-bU_L}{\dot{m}_a c_a}L}}{\frac{-bU_L}{\dot{m}_a c_a}}\right] \tag{8b}$$

After knowing an average air temperature, an average solar cell and tedlar back surface (T_{bs}) temperature can be calculated from Equations (4) and (5) respectively.

The rate of thermal energy obtained from hybrid PV/T air collector with and without airflow is

$$\dot{q}_U = \dot{m}_a c_a (T_{airout} - T_r) = \frac{\dot{m}_a c_a}{U_L}\left\{\left(h_{p1}h_{p2}(\alpha\tau)_{eff} I(t) - U_L(T_r - T_a)\right\}\left[1 - e^{\frac{-bU_L}{\dot{m}_a c_a}L}\right] \tag{9}$$

The thermal efficiency of hybrid PV/T air collector is

$$\eta_{th} = \frac{\sum \dot{q}_U}{\sum I(t) \times b \times L} \tag{10}$$

The temperature dependent electrical efficiency of PV system is

$\eta_{el} = 1 - 0.0045(T_c - 25)$ *(refered Tiwari and Sodha (2006))*

(11a)

where T_c is the average solar cell temperature obtained from Eq. (4)

The electrical thermal efficiency can be calculated as

$$\eta_{elth} = \frac{\eta_{el}}{0.38} \qquad (11b)$$

The overall efficiency of greenhouse integrated with PV/T system

$$\eta_{ov} = \eta_{th} + \eta_{elth} \qquad (12)$$

The useful thermal energy obtained from Equation 9 can be used for thermal heating/cooling of a greenhouse.

3.2 Energy Balance Equations for Photovoltaic and EAHE Combined Greenhouse System

The energy balance equations for different components of greenhouse combined with photovoltaic system and earth to air heat exchanger can be written as:

a) North wall

$$\alpha_n(1-r_n)F_n(1-r)\{\Sigma A_i I_i \tau_i\} = h_{nr}(T|_{y=0} - T_r)A_n + h_{na}(T|_{y=0} - T_a)A_n \qquad (13)$$

b) Floor

$$\alpha_g(1-r_g)(1-F_n)(1-r)\{\sum A_i I_i \tau_i\} = h_{gr}(T|_{x=0} - T_r)A_g - h_{g\infty}(T|_{x=0} - T_\infty)A_g \qquad (14)$$

At larger depths, the temperature of ground is assumed to be equal to ambient air temperature, $T_\infty = T_a$, then Equation (14) becomes

$$\alpha_g(1-r_g)(1-F_n)(1-r)\{\Sigma A_i I_i \tau_i\} = h_{gr}(T|_{x=0} - T_r)A_g + h_{g\infty}(T|_{x=0} - T_a)A_g \qquad (15)$$

c) Greenhouse air

$$h_{nr}(T|_{y=0} - T_r)A_n + h_{gr}(T|_{x=0} - T_r)A_g + \dot{q}_u + \dot{Q}_u = \sum A_i U_i (T_r - T_a)$$
$$+ 0.33NV(T_r - T_a) + M_a C_a \frac{dT_r}{dt} \qquad (16)$$

The terms i.e., $\dot{q}_u$ in Equation (16) is the useful thermal energy obtained from photovoltaic system and $\dot{Q}_u$ is the useful thermal energy obtained from EAHE and is expressed by the equation,

$\dot{Q}_u = F_R \dot{m}_a C_a (T_0 - T_{fi})$ (*refered M.K. Ghosal and G.N.Tiwari)*

(17)

where

$$F_R = 1 - e^{-\frac{2\pi r_1 h_{gf}}{\dot{m}_a C_a} L'}$$

Now eliminating $T|_{y=0}$ from Equation (13) and after rearrangement,

$$h_{nr}(T|_{y=0} - T_r) = F_1 \frac{I_{effN}}{A_n} - U_n(T_r - T_a) \qquad (18)$$

where

$I_{effN} = \alpha_n(1-r_n)F_n(1-r)(\Sigma A_i I_i \tau_i)$, $F_1 = \frac{h_{nr}}{h_{nr} + h_{na}}$ and $U_n = \frac{(h_{nr})(h_{na})}{(h_{nr} + h_{na})}$

Similarly eliminating $T|_{x=0}$ from Equation (15) and after rearrangement,

$$h_{gr}(T|_{x=0} - T_r) = F_2 \frac{I_{effF}}{A_g} - U_g(T_r - T_a) \tag{19}$$

where

$$I_{effF} = \alpha_g(1-r_g)(1-F_n)(1-r)(\Sigma A_i I_i \tau_i)\,;\; F_2 = \frac{h_{gr}}{h_{gr}+h_{g\infty}}\,;\; U_g = \frac{(h_{gr})(h_{g\infty})}{(h_{gr}+h_{g\infty})} \text{ and } T_{fi} = T_r$$

Now substituting Equations (18) and (19) in Equation (16) and simplifying, Equation (16) can be written in the following first order differential equation,

$$\frac{dT_r}{dt} + aT_r = B(t) \tag{20}$$

where

$$B(t) = \frac{F(t) + (UA)_{eff} T_a}{M_a C_a} \text{ and } a = \frac{a_1}{M_a C_a}\,;\; F(t) = F_1 I_{effN} + F_2 I_{effF} + F_R \dot{m}_a C_a T_o$$

$$(UA)_{eff} = U_n A_n + U_g A_g + 0.33NV + (\Sigma A_i U_i)\,;$$

$$a_1 = U_n A_n + U_g A_g + 0.33NV + (\Sigma A_i U_i) + F_R \dot{m}_a C_a$$

$$(\Sigma A_i I_i \tau_i) = (A_e I_e \tau_e + A_{ww} I_{ww} \tau_{ww} + A_{sr} I_{sr} \tau_{sr} + A_{nr} I_{nr} \tau_{nr} + A_s I_s \tau_s)$$

$$(\sum A_i U_i) = (A_e U_e + A_{ww} U_{ww} + A_{sr} U_{sr} + A_{nr} U_{nr} + A_s U_s)\,;\; U_e = U_{ww} = U_{sr} = U_{nr} = U_s = U$$

$$h_{na} = [\frac{L_n}{K_n} + \frac{1}{h_0}]^{-1}\,,\; h_{g\infty} = [\frac{L_g}{K_g}]^{-1},\; U_n = [\frac{1}{h_i} + \frac{L_n}{K_n} + \frac{1}{h_0}]^{-1},\; U_g = [\frac{1}{h_{gr}} + \frac{1}{h_{g\infty}}]^{-1}\,;\; U = [\frac{1}{h_i} + \frac{1}{h_0}]^{-1},$$

$$h_{nr} = h_{gr} = h_{gf} = h_i\,.$$

The analytical solution of Equation (20) can be written as

$$T_r = \frac{\overline{B(t)}}{a}(1 - e^{-at}) + T_{ro} e^{-at} \tag{21}$$

where, T_{ro} is the greenhouse air temperature at $t = 0$ and $\overline{B(t)}$ is the average of $B(t)$ for the time interval 0 and t, and a is constant during the time. From Equation (21), the temperature of air inside greenhouse, combined with earth air heat exchanger can be determined for analysis.

3.3 Instantaneous Thermal Efficiency (η_i) Characteristic Curves for Greenhouse

The instantaneous thermal efficiency (η_i) is defined as the ratio of thermal energy used in raising temperature of greenhouse air from T_{ro} to T_r to input energy and is expressed as

$$\eta_i = \frac{M_a C_a (T_r - T_{ro})}{t(\sum A_i I_i)} \tag{22}$$

Putting the expressions of T_r, $B(t)$, $F(t)$, $(UA)_{eff}$, a and a_1 in Equation (22) and simplifying, the instantaneous thermal efficiency becomes,

$$\eta_i = F'[(\alpha\tau)_{eff} - U_{eff} \frac{T_{ro} - T_{eff}}{I}] \tag{23}$$

where, $F' = \dfrac{1-e^{-at}}{at}$; $(\alpha\tau)_{eff} = \dfrac{F_1 I_{effN} + F_2 I_{effF}}{\sum A_i I_i}$; $U_{eff} = \dfrac{a_1}{\sum A_i}$; $I = \sum I_i$;

at is dimensionless;

$$T_{eff} = \frac{F_R \dot{m}_a C_a T_o + (UA)_{eff} T_a}{a_1}$$

and F' is the efficiency factor for greenhouse (dimensionless). Equation (23) is the function of design and climatic parameters and is similar to the characteristic equation for flat plate collector (Duffie and Beckman, 1991). This equation is helpful for comparison and standardization of various heating methods inside the greenhouse.

4. COMPUTATIONAL PROCEDURE AND INPUT PARAMETRES

The energy balance equations derived for greenhouse with photovoltaic system and EAHE have been solved with the help of a computer program based on Matlab 7 software. The design and operating parameters given in Table-1 and Table-2 have been used as input parameters for the mathematical model developed. The closeness of predicted and experimental values has been presented with coefficient of correlation *(r)* and root mean square of percent deviation (*e*). Solar radiation falling on different walls and roofs of greenhouse was calculated with the help of Liu and Jordan (1962) formula by using the beam and diffuse components of solar radiation incident on the horizontal surface. The heat removal factor for EAHE has been calculated from steady state energy mechanism as shown in Figure 2b and as per Equation (17). The mass flow rate of the circulating air was kept constant with 100 kg/hour. The performance of EAHE has been evaluated in terms of thermal load leveling (TLL) (Singh and Tiwari, 2000) heating potential and COP as per the following expressions:

$$TLL = \frac{T_{r,\max} - T_{r,\min}}{T_{r,\max} + T_{r,\min}} ;$$

$$Q_h = \sum \dot{m}_a C_a (T_d - T_{sc})\,\Delta t$$

$$\text{and}\; COP = \frac{output\ energy}{Energy\ spent\ to\ get\ output\ energy}$$

Thermal load leveling gives an idea about the fluctuations of air temperature inside the greenhouse. The less the fluctuations, the better is the environment for plants inside the greenhouse. In winter, TLL should have lower values by incorporating heating method due to the increase of $(T_{r,\max} + T_{r,\min})$ as well as decrease of $(T_{r,\max} - T_{r,\min})$ as compared to TLL without heating arrangement. The temperatures of ground i.e., T_o were recorded with the help of data logger through the thermocouples located at the depth of 1.0 m under EAHE arrangement.

Table 1. Input parameters used for computations for hybrid PV/T air collector

Parameters	***Values***	***Parameters***	***Values***	***Parameters***	***Values***
C_a	$1012 J/kg\,^oC$	η_c	0.12	kg	$0.52 W/m\,^oC$
ζi	0.5	hp	$30.25 W/m^2\,^oC$	Lg	0.003 m
ζ_G	0.95	α_T	0.5	k_G	$1.0\ W/m\,^oC$
βc	0.83	α_c	0.9	U	$3.5\ W/m^2\,^oC)$

Table 2. Input parameters used for computations for greenhouse combined with EAHE

Parameters	***Values***	***Parameters***	***Values***	***Parameters***	***Values***
A_e	$8.3\ m^2$	h_i	$2.8 Wm^{-2}\,^0C^{-1}$	N	1-300
A_f	$24.0\ m^2$	h_o	$5.7\ Wm^{-2}\,^0C^{-1}$	r_1	0.03 m
A_n	$12.0\ m^2$	h_{na}	$1.9\ Wm^{-2}\,^0C^{-1}$	U	$1.8\ Wm^{-2}\,^0C^{-1}$
A_s	$12.0\ m^2$	h_{gr}	$5.7\ Wm^{-2}\,^0C^{-1}$	v	$0.5\text{-}1.5\ m\ s^{-1}$
A_{nr}	$13.8\ m^2$	h_{nr}	$5.7\ Wm^{-2}\ \ ^0C^{-1}$	V	$60\ m^3$
A_{sr}	$13.8\ m^2$	K_n	$0.84 Wm^{-1}\,^0C^{-1}$	r_g	0.2
A_{ww}	$10.0\ m^2$	K_g	$0.52 Wm^{-1}\,^0C^{-1}$	r_n	0.2
C_a	$1012\ Jkg^{-1}\,^0C^{-1}$	L'	39 m	α_g	0.4
F_n	0.09-.15	L_g	1 m	α_n	0.6
F_R	0.64	$\dot{m}_a$	$0.02\ kg\ s^{-1}$	τ	0.5
h_{gf}	$2.8 Wm^{-2}\,^0C^{-1}$	M_a	72 kg		

5. RESULTS AND DISCUSSION

Equation 4 has been used for calculating solar cell temperature (as shown in Figure. 3). It has been observed that solar cell temperature of photovoltaic/thermal (PV/T) without airflow is higher than the solar cell temperature of hybrid PV/T air collector due to low values of heat transfer from the back surface unlike PV/T air collector. It is also seen that there is rise of around 10^{o}C solar cell temperature of PV/T without airflow. Equation 5 has been used for calculating tedlar back surface temperature (as shown in Figure 4). It is concluded that room air temperature of photovoltaic/thermal (PV/T) without airflow is higher than the room air temperature of hybrid PV/T air collector due to direct transfer of thermal energy from back surface of tedlar to the greenhouse air. Figure 5 shows hourly variation thermal efficiency. It can be concluded that thermal efficiency of hybrid photovoltaic/thermal (PV/T) air collector is higher than the thermal efficiency of photovoltaic/thermal (PV/T) without airflow due to low operating temperature. It is also calculated that thermal efficiency of hybrid photovoltaic/thermal (PV/T) air collector is around 34% and the thermal efficiency of photovoltaic/thermal (PV/T) without airflow is around 8.5%.

The performance of EAHE on heating of greenhouse during nighttime has also been studied with respect to total heating potential, coefficient of performance (COP) and thermal load leveling. PV/T with airflow was used during daytime and EAHE was used in nighttime to enhance the system efficiency.

After knowing the suction and delivery temperatures of EAHE as well as mass flow rate, the hourly variations of total heating potential obtained from the system for the typical day in the winter months during night time were calculated and similarly the total heating potentials obtained from EAHE for a typical day in each winter months have been computed and presented in Figure 6. From the results, it is seen that the heating potentials obtained from EAHE were higher in the month of January followed by December, February, November and March. The higher value of heating potential in January (coldest month) is due to the more differences of temperature in suction and delivery ends. The coefficient of performance determined for typical day in each month has also been discussed in Figure 7 to know the applicability of the system. The values of coefficient of performance were highest in the month of January (2.8), followed by December (2.45), February (2.1) and November (1.94). However, in the month of March its value was below the dashed line (value less than 1) indicating the system needs to be discontinued during this month. The values of thermal load leveling achieved for typical days in each month have been calculated and presented in Figure 8 in order to know the efficacy of the system during the study. From the computed results, it is seen that the values of TLL in each month for greenhouse with EAHE were lower than those without EAHE proving the former to be more effective for reducing the fluctuations of temperature of air in greenhouse.

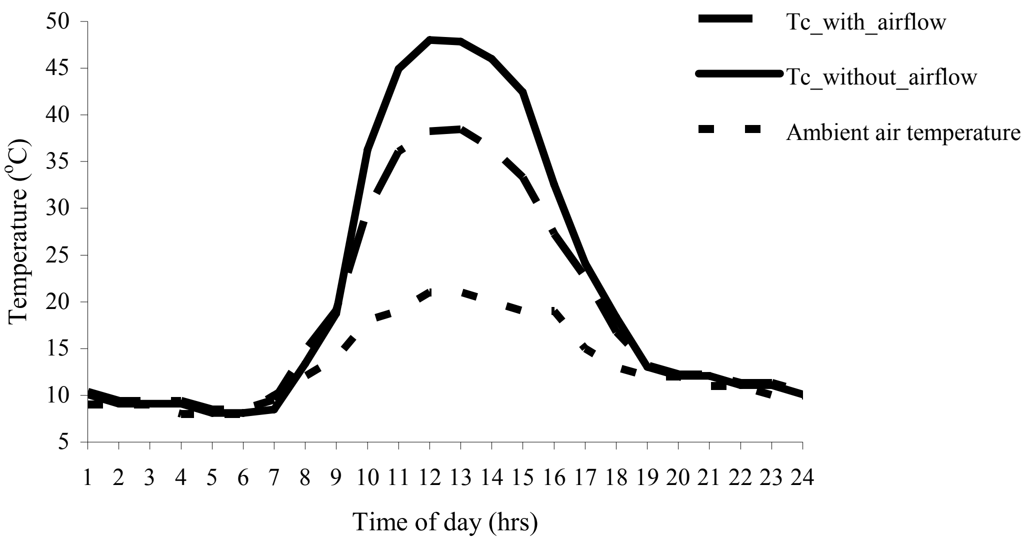

Figure 3. Hourly variation of solar cell temperature

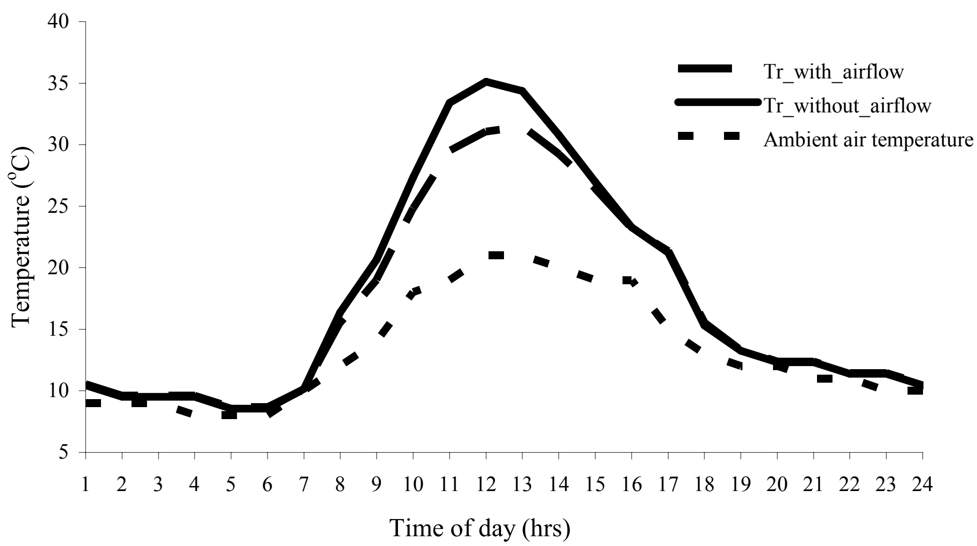

Figure 4. Hourly variation of room air temperature

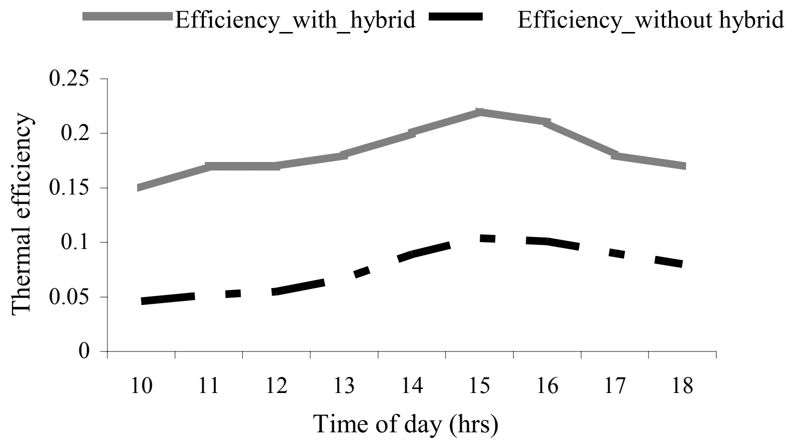

Figure 5. Hourly variation of thermal efficiency

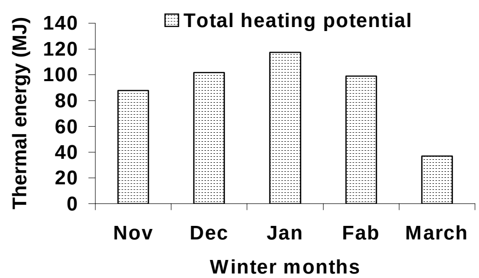

Figure 6. Monthly variations of total heating potential obtained from EAHE during experimentations

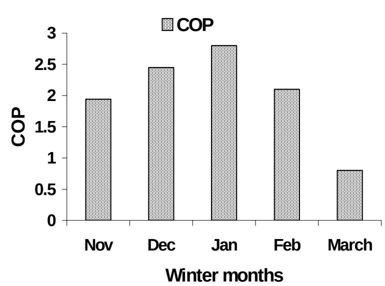

Figure 7. Monthly variations of coefficient of performance (COP) with EAHE

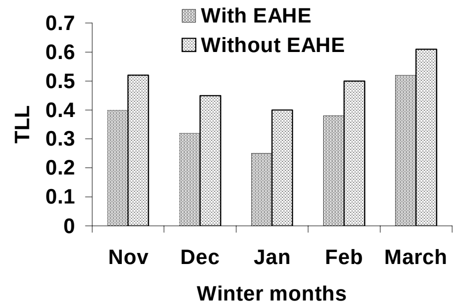

Figure 8. Monthly variations of thermal load leveling (TLL) during experimentation

6. CONCLUSIONS

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

(i) It is observed that solar cell temperatures are higher in case of photovoltaic/thermal (PV/T) without airflow due to direct transfer of thermal energy into the greenhouse.
(ii) It is observed that greenhouse air temperatures are higher in case of photovoltaic/thermal (PV/T) without airflow due to direct transfer of thermal energy into the greenhouse.
(iii) The thermal efficiency of a hybrid photovoltaic thermal (PV/T) air collector is higher due to low operating temperature. It can be concluded that thermal efficiency of hybrid photovoltaic/thermal (PV/T) air collector is higher than the thermal efficiency of photovoltaic/thermal (PV/T) without airflow due to low operating temperature. It is also calculated that thermal efficiency of hybrid photovoltaic/thermal (PV/T) air collector is around 34% and the thermal efficiency of photovoltaic/thermal (PV/T) without airflow is around 8.5%.
(iv) There occurs 7–8^{o}C rise of temperatures for greenhouse air during winter period particularly in nighttime due to the incorporation of EAHE as compared to without EAHE.
(v) There occurs 6-7^{o}C decrease of air temperature during daytime by use of PV/T air collector.
(vi) Relative fluctuations of temperature for greenhouse air are less by use of PV/T air collector in daytime and EAHE in nighttime.
(vii) The experimental and theoretical results show fair agreement.

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9. NOMENCLATURE

A	Area, m^2
C_a	Specific heat of air, J kg $^{-1}$ $^0C^{-1}$
F_n	Fraction of solar radiation falling on north wall, dimensionless, decimal
F_R	Heat removal factor for EAHE from underground earth's surface

h_i Heat transfer coefficient from greenhouse cover to inside greenhouse air, $Wm^{-2}\,{}^0C^{-1}$, (2.8+3.0v),
h_o Heat transfer coefficient from greenhouse cover to ambient, $Wm^{-2}\,{}^0C^{-1}$, (5.7+3.8v),
h_{gf} Convective heat transfer coefficient from underground earth's surface to flowing air inside the buried pipes, $W\,m^{-2}\,{}^0C^{-1}$
$h_{g\infty}$ Heat transfer coefficient from floor to larger depth of ground, $W\,m^{-2}\,{}^0C^{-1}$
h_{na} Heat transfer coefficient from north brick wall to ambient, $W\,m^{-2}\,{}^0C^{-1}$
h_{nr} Hea transfer coefficient from floor to greenhouse air, $W\,m^{-2}\,{}^0C^{-1}$
h_T Conductive heat transfer coefficient through tedlar, $W\,m^{-2}\,{}^0C^{-1}$
h_t Convective heat transfer coefficient from back surface of tedlar to the working fluid, $W\,m^{-2}\,{}^0C^{-1}$
h_{p1} Penalty factor due to presence of solar cell material, tedlar and EVA
h_{p2} Penalty factor due to presence of interface between tedlar and working fluid through absorber plate
I Solar radiation falling on inclined surface or greenhouse cover, $W\,m^{-2}$
K Thermal conductivity, $W\,m^{-1}\,{}^oC^{-1}$
K_g Thermal conductivity of ground, $Wm^{-1}\,{}^oC^{-1}$
L Thickness, m
L' Total length of buried pipes (EAHE), m
$\dot{m}_a$ Mass flow rate of air entering into the buried pipes, $kg\,s^{-1}$
M_a Total mass of air in greenhouse enclosure, kg
N Number of air changes per hour
Q_c Cooling potential offered by EAHE for greenhouse air, J
Q_u Useful thermal energy obtained from EAHE for greenhouse air, W
R Reflectivity from greenhouse cover, dimensionless, decimal
r_g Reflectivity from greenhouse floor, dimensionless, decimal
r_n Reflectivity from north wall, dimensionless, decimal
r_1 Radius of buried pipe in EAHE, m
t Time in second
Δt Time interval in hour
T_a Ambient temperature, ${}^0C$
T_∞ Temperature at larger depth (Infinity), ${}^0C$
T_c Solar cell temperature, ${}^0C$
T_{bs} Tedlar back surface temperature, ${}^0C$
T_r Greenhouse room air temperature, ${}^0C$
T_d Delivery temperature, ${}^0C$
T_o Temperature of ground in which pipes are spread in EAHE, ${}^0C$
T_{fi} Temperature of inlet fluid or temperature at suction point, ${}^0C$ for EAHE
T_{sc} Suction temperature, ${}^0C$
U Overall heat transfer coefficient for greenhouse cover, $W\,m^{-2}\,{}^0C^{-1}$
U_g Overall heat transfer coefficient from greenhouse air to floor, $W\,m^{-2}\,{}^0C^{-1}$
U_T Conductive heat transfer coefficient from solar cell to air through tedlar, $W\,m^{-2}\,{}^0C^{-1}$
U_b Overall heat transfer coefficient from bottom to ambient, $W\,m^{-2}\,{}^0C^{-1}$
U_{tT} Overall heat transfer coefficient from glass to tedlar through solar cell, $W\,m^{-2}\,{}^0C^{-1}$

$(UA)_{eff}$	Effective overall heat loss from greenhouse, W $m^{-2}\,{}^0C^{-1}$
v	Velocity of air, m s^{-1}
V	Volume of greenhouse, m^3
e	Root mean square percent deviation,%
r	Correlation coefficient, Dimensionless
α_T	Absorptivity of tedlar, dimensionless
α_c	Absorptivity of solar cell, dimensionless
η_c	Efficiency of solar cell, dimensionless
η_{th}	Thermal efficiency of solar cell, %
η_{el}	Electrical efficiency of solar cell, %
η_{elth}	Thermal equivalent to electrical efficiency of solar cell, %
ζ_G	Transmissivity of glass, dimensionless
βc	Packing factor of solar cell, dimensionless
$(\alpha\tau)_{eff}$	Effective transmittance-absorptance product for greenhouse

Subscript

e	East wall of greenhouse
g	Floor of greenhouse
i	Different walls and roofs of greenhouse
n	North wall
s	South wall
nr	North roof
sr	South roof
ww	West wall