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Research Paper :

Performance evaluation of an earth to air heat exchanger integrated greenhouse during winter period

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ABSTRACT

This article describes the analytical approach and experimental findings for utilization of stored thermal energy of ground in space heating by an earth air heat exchanger system. The appropriate thermal model has been developed for solar greenhouse combined with earth air heat exchanger. The same concepts can be applied for the feasibility of using earth air heat exchanger not only for greenhouse heating but also for thermal heating of a residential building, poultry farming, goat rearing, aquaculture pond etc. by exploring the immense thermal energy of ground. A complete numerical model has been developed to investigate the potential of using the stored thermal energy of ground for space heating with the help of an earth to air heat exchanger (EAHE) system integrated with the greenhouse located in the premises of IIT, Delhi, India. The analysis was based on quasi-steady state condition. Experiments were conducted extensively during winter period from November 2002 to March 2003, but the model, developed, was validated against the clear and sunny days. The performance of the system was evaluated in terms of total heating potential obtained from EAHE, coefficient of performance (COP) and thermal load leveling. The heating potential of the system has also been standardized by the characteristic curve for greenhouse similar to that of flat plate collector. Temperatures of greenhouse air were found to be on an average 7-8^0 C more than the same greenhouse when operating without earth air heat exchanger. The temperature fluctuations of greenhouse air were also less when operated with EAHE as compared to without EAHE. Predicted and measured values of greenhouse air temperature in the model developed, exhibited fair agreement.

Key words : Greenhouse, Solar energy, Earth air heat exchanger, Coefficient of performance (COP), Thermal load leveling, Modeling.

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.*, 1994). 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 use of low-cost and alternative heating system is, therefore, of primary importance for a greenhouse to provide optimum indoor conditions during winter months. Efforts to decrease energy consumption have directed the researchers to use alternative energy sources for heating of greenhouse. Several types of passive solar systems and techniques have been proposed and used (Santamouris *et al.*, 1996 and Barral *et al.*, 1999) for exploitation of stored thermal energy of ground for space heating during winter periods and cooling in summer days. As the ground is treated as an easily accessible heat source or heat sink for year round use, the coupling of greenhouse with ground by using buried pipes may be a viable solution for heating during winter and cooling during summer period. In buried pipe systems, the stored thermal energy of earth is usually extracted with the help of an arrangement called earth air heat exchanger (EAHE). An earth air heat exchanger system herein is defined (Puri, 1987) as the study of heat transfer between soil, tubes and air flowing through the tube when the tubes are placed below the ground surface at a certain depth where temperature of soil remains nearly constant throughout the year. As air travels the length of the tube, it gets heated in the winter period and gets cooled during the summer period resulting in the space conditioning due to its entry into the enclosed space. Earth air heat exchanger system has the potential of being used throughout the year. Hence, considering the importance of EAHE as a simple, inexpensive and alternative source of energy, the primary objective of present study is to investigate the performance of EAHES, as an alternative energy source and conservation method for heating of greenhouse in the composite climate of India.

METHODOLOGY

The EAHE under study was used in the greenhouse located in the premises of IIT, 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 ^{0}C while mean minimum is close to 9 ^{0}C. The greenhouse combined with EAHE was of even span type of greenhouse with floor area 6m x 4m. and was oriented from east to west direction. The EAHE was installed outside in west side of the greenhouse. Total length and diameter of buried pipes used were 39m and 0.06m, respectively. EAHE also consisted of PVC pipes buried under bare surface at the depth of 1m 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 uniform mixing of air. The isometric view of experimental greenhouse with EAHE is shown in Fig. 1. Experiments were conducted continuously for two days in a week in clear and sunny days from Nov'2002 to March'2003 with 1st day without any heating arrangement and 2nd day with EAHE system. However, the experimental validation was done for typical date (clear sunny day) of observations *i.e.*, on 23-01-03 for greenhouse 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 the help of calibrated solarimeter and mercury thermometer, respectively.

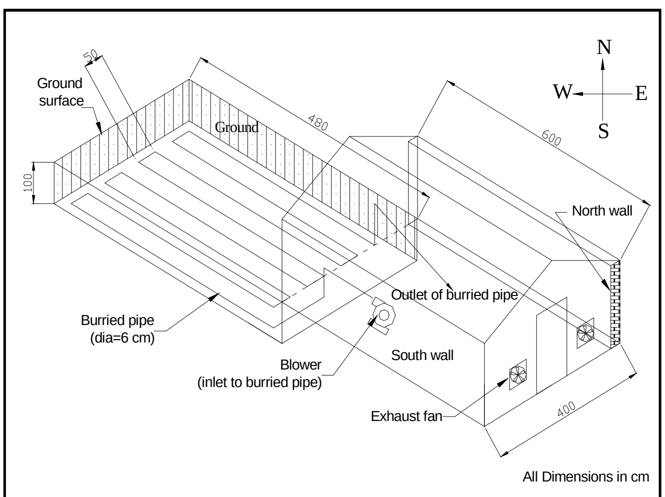

Fig. 1 : Isometric view of even span greenhouse integrated with EAHE arrangement

Thermal analysis :

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

– Analysis is based on quasi steady state conditions,

– There is no radiative heat exchange between the walls and roofs of greenhouse, due to negligible temperature differences,

– Flow of air is uniform along the length of buried pipes,

– Heat flow is one-dimensional.

Energy balance equations for north wall, floor and room air of greenhouse are as follows:

North wall:

$$\alpha_n(1-r_n)F_n(1-r)\{\sum A_iI_i\tau_i\} = h_{nr}(T|_{y=0} - T_r)A_n + h_{na}(T|_{y=0} - T_a)A_n \qquad ..... (1)$$

Floor :

$$\alpha_g(1-r_g)(1-F_n)(1-r)\{\sum A_iI_i\tau_i\} = h_{gr}(T|_{x=0} - T_r)A_g - h_{g\infty}(T|_{x=0} - T_{\infty})A_g \qquad ..... (2)$$

At larger depths, the temperature of ground is assumed to be equal to ambient air temperature, Ta = T_a then Eq. (2) becomes

$$\alpha_g(1-r_g)(1-F_n)(1-r)\{\sum A_iI_i\tau_i\} = h_{gr}(T|_{x=0} - T_r)A_g + h_{g\infty}(T|_{x=0} - T_a)A_g \qquad ..... (3)$$

Greenhouse air:

$$h_{nr}(T|_{y=0} - T_r)A_n + h_{gr}(T|_{x=0} - T_r)A_g + \dot{Q}_u = \sum A_iU_i(T_r - T_a) + 0.33NV(T_r - T_a) + M_aC_a\frac{dT_r}{dt} \qquad ..... (4)$$

The term *i.e.* Q_u in Eq. (4) is the useful thermal energy obtained from earth air heat exchanger arrangement and is expressed by the equation

$$\dot{Q}_u = F_R\dot{m}_aC_a(T_0 - T_{fi}) \qquad ..... (5)$$

where, $F_R = 1 - e^{-\frac{2\pi r_1 h_{gf}}{\dot{m}_aC_a}L}$. Now eliminating $T|_{y=0}$ from Eq. (1) and after rearrangement,

$$h_{nr}(T|_{y=0} - T_r) = F_1\frac{I_{effN}}{A_n} - U_n(T_r - T_a) \qquad .....(6)$$

where, $I_{effN} = \alpha_n(1-r_n)F_n(1-r)(\sum A_iI_i\tau_i)$,

$F_1 = \frac{h_{nr}}{h_{nr} + h_{na}}$ and $U_n = \frac{(h_{nr})(h_{na})}{(h_{nr} + h_{na})}$

Similarly eliminating $T|_{x=0}$ from Eq. (3) and after rearrangement,

$$h_{gr}(T|_{x=0} - T_r) = F_2 \frac{I_{effF}}{A_g} - U_g(T_r - T_a) \qquad .....(7)$$

where, $I_{effF} = \alpha_g(1 - r_g)(1 - F_n)(1 - r)(\Sigma A_i I_i \tau_i)$,

$F_2 = \frac{h_{gr}}{h_{gr} + h_{g\infty}}$, $U_g = \frac{(h_{gr})(h_{g\infty})}{(h_{gr} + h_{g\infty})}$ and $T_{fi} = T_r$

Now substituting Eqs. (6) and (7) in Eq. (4) and simplifying, Eq. (4) can be written in the following first order differential equation,

$$\frac{dT_r}{dt} + aT_r = B(t) \qquad .....(8)$$

where, $B(t) = \frac{F(t) + (UA)_{eff} T_a}{M_a C_a}$ and $a = \frac{a_1}{M_a C_a}$,

$F(t) = F_1 I_{effN} + F_2 I_{effF} + F_R \dot{m}_a C_a T_o$

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

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

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

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

$U_e = U_{ww} = U_{sr} = U_{nr} = U_s = U$

$h_{na} = [\frac{L_n}{K_n} + \frac{1}{h_0}]^{-1}$, $h_{g\infty} = [\frac{L_g}{K_g}]^{-1}$,

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

$U = [\frac{1}{h_i} + \frac{1}{h_0}]^{-1}$, $h_{nr} = h_{gr} = h_i$. The analytical solution of Eq. (8) can be written as

$$T_r = \frac{\overline{B(t)}}{a}(1 - e^{-at}) + T_{ro} e^{-at} \qquad ..... (9)$$

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 Eq. (9), the temperature of air inside greenhouse, combined with earth air heat exchanger can be determined for analysis.

RESULTS AND DISCUSSION

The energy balance equation derived for EAHE have been solved with the help of a computer program based on Matlab software. The design and operating parameters given in Table 1 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 (c_r) and root mean square of per cent deviation (e_r). 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 factors for EAHE have been calculated by following the procedure given by Abdel-Khalik (1976) for a flat-plate collector with serpentine tubes. 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) and heating potential as per the following expressions

$$TLL = \frac{T_{r,max} - T_{r,min}}{T_{r,max} + T_{r,min}} \text{ and } Q_h = \Sigma \dot{m}_a C_a (T_d - T_{sc}) \Delta t$$

Thermal load leveling gives an idea about the fluctuation of temperatures 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_0 were recorded with

Table 1 : Input parameters used for computations

Parameters	Values	Parameters	Values	Parameters	Values
A_e	8.3 m^2	h_i	2.8 $W/m^2\,^0C$	N	1-300
A_f	24.0 m^2	h_0	5.7 $W/m^2\,^0C$	r_1	0.03m
A_n	12.0 m^2	h_{na}	1.9 $W/m^2\,^0C$	U	1.8 $W/m^2\,^0C$
A_s	12.0 m^2	h_{gr}	5.7 $W/m^2\,^0C$	v	0.5-1.5 m/s
A_{nr}	13.8 m^2	h_{nr}	5.7 $W/m^2\,^0C$	V	60 m^3
A_{sr}	13.8 m^2	K_n	0.84 W/m^0C	r_g	0.2
A_{ww}	10.0 m^2	K_g	0.52 W/m^0C	r_n	0.2
C_a	1012 J/kg ^0C	L^t	39m	α_g	0.4
F_n	0.09-0.15	L_g	1m	α_n	0.6
F_R	0.72	m_a	0.02 kg/s	^{2}	0.5
h_{gf}	2.8 $W/m^2\,^0C$	M_a	72 kg		

the help of data logger through the thermocouples located at the depth of 1.0m under EAHE arrangement.

The hourly variations of temperature for ambient air, greenhouse air when operating with EAHE for typical winter day (23-01-2003) and without EAHE (22-01-2003) have been presented in Fig. 2. From the figure, it is seen that the minimum as well as maximum temperatures for ambient air, greenhouse air with EAHE and without EAHE varied between 5-20 ^{0}C, 13-24 ^{0}C and 5-28 ^{0}C, respectively confirming the less fluctuations of temperature inside the greenhouse as compared to ambient air and greenhouse air without EAHE. The temperature of ground on the above day at the depth (1m) in which the EAHE system was installed was recorded to be about 23 ^{0}C. By examining closely the daily temperature profiles

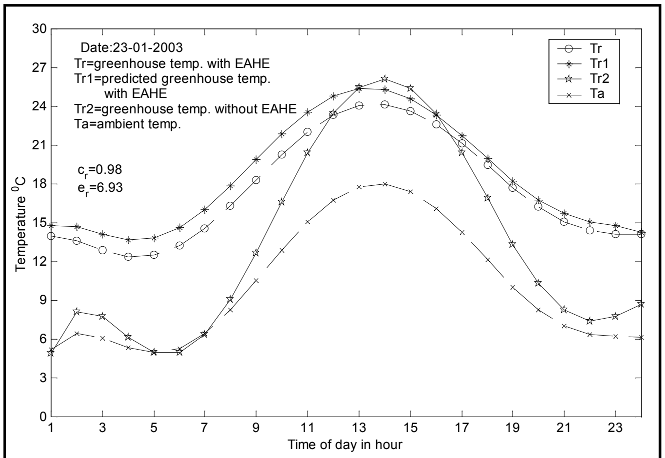

Fig. 2 : Hourly variations of greenhouse air temperature for typical winter day by EAHE

of greenhouse air, it was found that the delivery temperatures of EAHE were 7-9 ^{0}C higher than the suction temperatures from 6 pm to 9 am (heating of greenhouse air). (C_r) as 0.98 and (e_r) as 6.93.

After knowing the suction and delivery temperatures of EAHE as well as mass flow rate, the diurnal variations of total heating potential obtained from the system for the typical day in the winter months were calculated and have been shown in Fig. 3. Similarly the total heating potentials in each winter months have been shown in Fig. 4. 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. Similarly the values of thermal load leveling achieved for typical days in each month have been calculated and presented in Fig. 5 in order to know the efficacy of the system during the study. From the computed results, it is

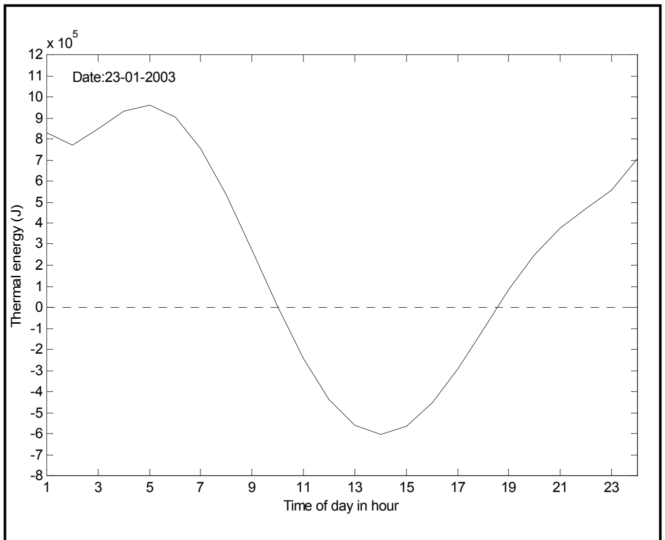

Fig. 3 : Hourly variations of heating potential by EAHE for typical winter day

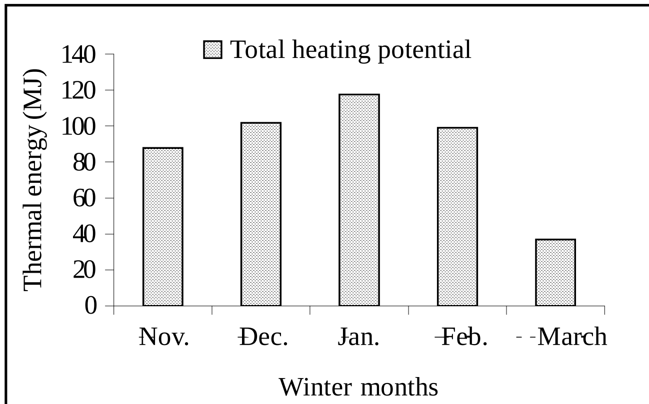

Fig. 4 : Monthly variations of total heating potential during experimentations

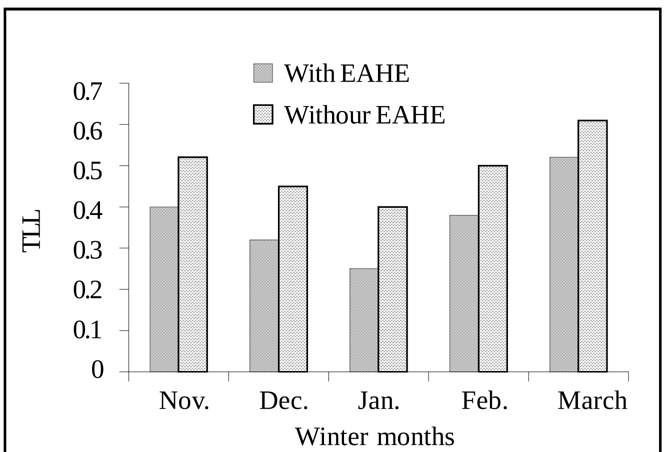

Fig. 5 : 5 Monthly variations of thermal load leveling (TLL) during experimentations

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 daily swings of temperatures of air in greenhouse. From the above results, the main conclusions for the present study are as follows:

– There occurs 7 –8 ^{0}C rise of temperatures for greenhouse air during winter period due to the use of EAHE as compared to without EAHE,

– Relative fluctuations of temperatures for greenhouse air are less in EAHE arrangement than without that system

–The predicted and experimental temperatures of greenhouse air in the model developed, exhibit fair agreement.

Nomenclature :

A- Area, m^2; C_a- Specific heat of air, J/kg ^{0}C; F_n- Fraction of solar radiation falling on north wall, dimensionless, decimal; F_R- Heat removal factor for earth air heat exchanger (EAHE) from underground earth's surface; h_i -Heat transfer coefficient from greenhouse cover to inside greenhouse air, W/m^2 0C, (2.8+3.0v), (Duffie and Beckman, 1991); h_0 -Heat transfer coefficient from greenhouse cover to ambient, W/m^2 0C, (5.7+3.8v), (Duffie and Beckman, 1991); h_{gf}-Convective heat transfer coefficient from underground earth's surface to flowing air inside the buried pipes, W/m^2 ^{0}C ; $h_g\infty$-Heat transfer coefficient from floor to larger depth of ground, W/m^2 ^{0}C; h_{na}-Heat transfer coefficient from north brick wall to ambient, W/m^2 ^{0}C; h_{nr}-Heat transfer coefficient from surface of north wall to greenhouse air, W/m^2 ^{0}C; h_{gr}- Heat transfer coefficient from floor to greenhouse air, W/m^2 ^{0}C; I-Solar radiation falling on inclined surface or greenhouse cover, W/m^2; K -Thermal conductivity, W/m ^{0}C; K_g-Thermal conductivity of ground, W/m ^{0}C; L-Thickness, m; L$^{|}$-Total length of buried pipes (EAHE), m; m_a-Mass flow rate of air entering into the buried pipes, kg/s; M_a-Total mass of air in greenhouse enclosure, kg; N-Number of air changes per hour; Q_h-Heating 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-Temperature, ^{0}C; T_d-Delivery temperature, ^{0}C; T_0-Temperature of ground in which pipes are spread in EAHE, ^{0}C; T_{ft}-Temperature of inlet fluid (air) or temperature at suction point, ^{0}C for EAHE; T_{sc}-Suction temperature, ^{0}C; U-Overall heat transfer coefficient for greenhouse cover, W/m^2 ^{0}C; U_g-Overall heat transfer coefficient from greenhouse air to floor, W/m^2 ^{0}C; v-Velocity of air, m/s; V-Volume of greenhouse, m^3; *Greek letters:*a-Absorptivity, dimensionless; τ-Transmissivity, dimensionless; ∞-Infinity (at larger depth); *Subscript:* α-Ambient; e-East wall of greenhouse; g-Floor of greenhouse; i-Different walls and roofs of greenhouse; n-North wall; r-Greenhouse room; s-South wall; nr-North roof; sr-South roof; ww-West wall.

Table 1 : Input parameters used for computations

Parameters	Values	Parameters	Values	Parameters	Values
A_e	8.3 m^2	h_i	2.8 W/m^2 ^{0}C	N	1-300
A_f	24.0 m^2	h_O	5.7 W/m^2 ^{0}C	r_1	0.03m
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A_{nr}	13.8 m^2	h_{nr}	5.7 W/m^2 ^{0}C	V	60 m^3
A_{sr}	13.8 m^2	K_n	0.84 W/m^{0}C	r_g	0.2
A_{ww}	10.0 m^2	K_g	0.52 W/m^{0}C	r_n	0.2
C_a	1012 J/kg ^{0}C	L$'$	39m	α_g	0.4
F_n	0.09-0.15	L_g	1m	α_n	0.6
F_R	0.72	m_α	0.02 kg/s	τ	0.5
h_{gf}	2.8 W/m^2 ^{0}C	M_a	72 kg		

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