PERFORMANCE STUDIES OF EARTH AIR TUNNEL CUM GREENHOUSE TECHNOLOGY

G. N. TIWARI*, R. F. SUTAR, H. N. SINGH and R. K. GOYAL

†Centre for Energy Studies, Indian Institute of Technology, Hauz Khas, New Delhi 110 016, India

(Received 5 May 1997)

Abstract—We present performance studies of an earth air tunnel cum greenhouse technology in terms of instantaneous thermal efficiency. Analytical expressions have been obtained for heating/cooling conditions of a greenhouse. The results are in accordance with the experimental results obtained for the same system in Greece.

Solar energy   Greenhouse technology   Earth air tunnel

NOMENCLATURE

A = Area (m^2)
A_p = Area of plant (m^2)
A_D = Area of door (m^2)
A_{ET} = Cross-sectional area of tunnel (m^2)
h_b = Heat transfer coefficient between greenhouse floor and ground beneath (W/m^2°C)
$h(t)$ = Overall heat transfer coefficient from enclosed room to ambient through canopy cover (W/m^2°C)
h_D = Heat transfer coefficient between room air and ambient air through door (W/m^2°C)
h_6 = Heat transfer coefficient between floor and air inside greenhouse (W/m^2°C)
h_p = Convective heat transfer coefficient between plant surface and air inside greenhouse (W/m^2°C)
h_{pr} = Total convective and evaporative heat transfer coefficient from plant to enclosure (W/m^2°C)
M_p = Heat capacity of plant (J/°C)
P = Partial pressure of water vapour at temperature T (N/m^2)
Q_L = Rate of total heat loss from inside greenhouse to outside and from floor to beneath (W)
$S_T(t)$ = Solar intensity (W/m^2)
T = Temperature inside ground at greater depth (°C)
t = Time (s)
T_a = Ambient air temperature (°C)
T_p = Plant temperature (°C)
T_R = Greenhouse enclosure air temperature (°C)
$T|_{x=0}$ = Greenhouse floor temperature (°C)
U_{bG} = Overall heat transfer coefficient from enclosed room to inside ground at far distance through floor (W/m^2°C)
U_{eff} = Effective total heat loss coefficient (W/m^2°C)
U_{pa} = Total heat loss coefficient including external, internal, bottom and ventilation losses (W/m^2°C)
V = Wind velocity (m/s)
V_0 = Rate of heat transfer due to infiltration (W/m^2°C)
V_1 = Rate of heat transfer due to ventilation (W/m^2°C)

Greek letters

γ = Relative humidity
ϵ = Effective fraction of energy utilised
α_p = Absorptivity of plant
α_g = Absorptivity of greenhouse cover
τ = Fraction of energy transmitted through cover
η = Instantaneous thermal loss efficiency factor

Subscripts

E = East
g = Floor
N = North
0 = Initial
P = Plant
R = Roof
S = South
W = West

INTRODUCTION

High temperature during the summer season is adverse to greenhouse crops. It is important to note the temperature of the plant (T_p) and the greenhouse enclosure (T_R) were of the order of about 50°C and 40°C, respectively, during the summer with ventilation effect. Further, it is important to note that there were significant changes in these temperatures with an increase of ventilation beyond the optimum flow rate. It has also been observed during the experimental study at the Indian Institute of Technology, Delhi, India, that most of the cucumber plants were damaged due to high enclosed air temperature at high levels of solar intensity.

In order to reduce the greenhouse enclosure temperature further, an external cooling arrangement is required. The level of cooling depends mainly on the average ambient temperature and the insolation level. There are basically three component of a greenhouse, namely, root media, environment and thermal conditions, which become the basic requirements for optimum growth of crops for maximizing yield. The design of such an ideal greenhouse will depend on the local climatic condition. In India, there are basically six climatic zones [1]. Each zone would require a variation in the design for optimum performance and efficiency, and hence, there should be six types of greenhouses for Indian climatic conditions. In each type of greenhouse, either thermal heating or cooling is required to achieve optimum enclosure environmental conditions, as mentioned earlier [2].

After knowing the temperatures for optimum growth of the vegetables, flowers and other horticultural crops during off season production for maximum yield, a suitable greenhouse can be designed, including one of the following heating or cooling concepts.

(a) Heating concepts: i, direct gain; ii, isolated gain; iii, conventional heating. (b) Cooling concepts: i, ventilation; ii, earth air tunnel; iii, evaporative cooling.

In this paper, an attempt has been made to verify the validity of a mathematical model developed by Sutar and Tiwari [2] by considering the following heat losses.

(a) External heat losses: i, upward heat loss from enclosed room air to ambient through canopy cover; ii, downward heat loss from enclosed room air to the ground beneath. (b) Temperature dependent internal heat losses: i, convective heat loss; ii, evaporative heat loss.

It has been observed that the nature of the analytical results predicted by Sutar and Tiwari [2] is exactly the same as observed experimentally and which are reported in the present paper.

INSTANTANEOUS THERMAL EFFICIENCY

Following Sutar and Tiwari [2], the analytical expression for the plant temperature as a function of the design and climatic parameters of the system can be written as

$$T_p = \frac{\overline{f(t)}}{a}(1 - e^{-at}) + T_{p0}\,e^{-at} \tag{1}$$

where

$$f(t) = F(t)/M_p$$
$$F(t) = [\alpha_p\tau + h_0(\tau_{eff2} + h\tau_{eff1})]S(t) - h_0 v_0 + Q_{ET} + U_{pa}T_a$$
$$U_{pa} = [1/H + (1/A_p h_{pr})]^{-1}$$
$$H = h(t) + H_D A_D + V_1 + U_{bG}A_G \text{ (Appendix)}$$
$$a = U_{pa}/M_p$$
$$U_{bG} = h_b h_G/(h_b + h_a)$$
$$h = -h_G/(h_0 + h_a)$$
$$h_0 = A_p h_{pr}/(H + A_p h_{pr})$$
$$\tau_{eff1} = \alpha_g(1 - \alpha_p)\tau$$
$$\tau_{eff2} = (1 - \alpha_g)(1 - \alpha_p)\tau.$$

From equation (1), the average plant temperature can be calculated as:

$$\bar{T}_p = \frac{1}{t}\int T_p\,dt.$$

The above equation, after integration, becomes

$$\bar{T}_p = \frac{\bar{f}(t)}{a}\left(1 - \frac{1-e^{-at}}{at}\right) + T_{p0}\frac{1-e^{-at}}{at}. \quad (2)$$

With the help of equation (2), an analytical expression for the thermal loss efficiency factor can be written as

$$\eta_i = [U_{pa}(T_p - T_a)/S_T(t)] = (\alpha\tau)_{eff} + U_{eff}[(T_{pa} - T_a)/S_T(t)] \quad (3)$$

where

$$(\alpha\tau)_{eff} = [\alpha_p\tau + h_0(\tau_{eff2} + h\tau_{eff1})] - [(h_0V_0 + \epsilon\dot{m}C_a\Delta TA_{ET})/S_T(t)](1 - R_1)$$
$$U_{eff} = U_{pa}R_1$$
$$R_1 = (1 - \exp(-at))/at.$$

Equation (3) represents the behaviour of a straight line with gradient $m = U_{eff}$ and intercept $C = (\alpha\tau)_{eff}$.

Further, an analytical expression for an instantaneous thermal efficiency of a greenhouse can be defined as

$$\eta_{ig} = \frac{M_p(T_p - T_{p0})}{S_T(t)}.$$

With the help of equation (2), the above equation can be expressed as

$$\eta_{ig} = \frac{M_p(1-e^{-at})}{U_{pa}}\left[\left\{\alpha_p\tau + h_0(\tau_{eff2} + h\tau_{eff1}) - \frac{h_0v_0 + \epsilon\dot{m}C_a\Delta TA_{ET}}{S_T(t)}\right\} - U_{pa}\frac{T_{p0} - T_a}{S_T(t)}\right]. \quad (4)$$

Equation (4) represents the behaviour of a straight line with gradient $m = -U_{pa}$, which is similar to the characteristic curve of this condition for a flat plate collector.

ANALYTICAL RESULTS AND DISCUSSION

It is important to observe that, for at <1, equations (3) and (4) reduce to $\eta_i \approx \eta_{ig} \approx 0.0$. This condition refers to the case of a greenhouse which has either a large value of M_p (heat capacity) or a small time interval. The smaller time implies that the solar radiation has not been used in controlling the environment condition in summer, which is the basic requirement of a summer

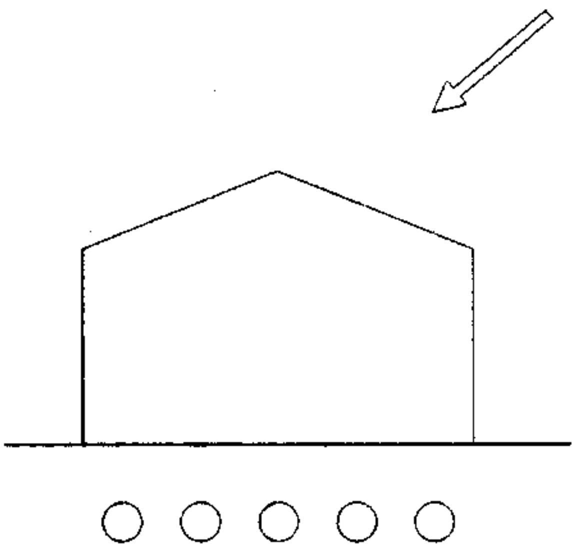

Fig. 1. Cross-sectional view of the greenhouse earth air tunnel.

Table 1. Total solar radiation in MJ/m^2 day for Agrinion (Greece) [3]

Month	Computed	Measured
January	8.22	11.24
February	16.22	21.43
March	24.82	26.07
April	25.40	22.60
May	17.80	12.54
June	8.69	7.29
July	6.67	10.66
August	14.62	17.43
September	20.29	25.23
October	25.24	22.42
November	18.52	12.77
December	8.89	6.56

greenhouse. This supports arguments from the cooling point of view. It is achieved by providing shading over the cover.

Further, for at >1, equations (3) and (4) reduce to

$$\eta_i = [\alpha_p \tau + h_0(\tau_{eff2} + h\tau_{eff1}) - h_0 v_0 + \epsilon \dot{m} C_a \Delta T A_{ET})/S_T(t)] \quad (5)$$

and

$$\eta_{ig} = \frac{M_p}{U_{pa}}\left[\left\{\alpha_p \tau + h_0(\tau_{eff2} + h\tau_{eff1}) - \frac{h_0 v_0 + \epsilon \dot{m} C_a \Delta T A_{ET}}{S_T(t)}\right\} - U_{pa}\frac{T_{p0} - T_a}{S_T(t)}\right]. \quad (6)$$

It refers to the case of a greenhouse which has either a smaller value of M_p or a longer period interval to use solar radiation for heating.

Since in winter, there should not be any infiltration/ventilation, hence $v_0 = 0.0$, and $\Delta T = T_a - T_s$ becomes negative because $T_s > T_a$. In this case, the gain term becomes positive, which again supports the case of heating the greenhouse.

NUMERICAL RESULTS AND DISCUSSION

In order to validate the developed model for a greenhouse with the air tunnel attachment, climatological and design data of a greenhouse situated in Greece has been adopted from Santamouris *et al.* [3, 4]. The greenhouse is located in Arginion in southwestern Greece (latitude 38°5′N) and is used for growing roses. The area of the greenhouse is 1000 m^2. Five PVC tubes, 30 m long and 22 cm in diameter, are buried under the greenhouse at a depth of 1.5 m, as shown in Fig. 1.

The measured data of the total daily solar intensity (monthly average) for each month and the measured data of the ambient and indoor air temperatures for a characteristic day of each

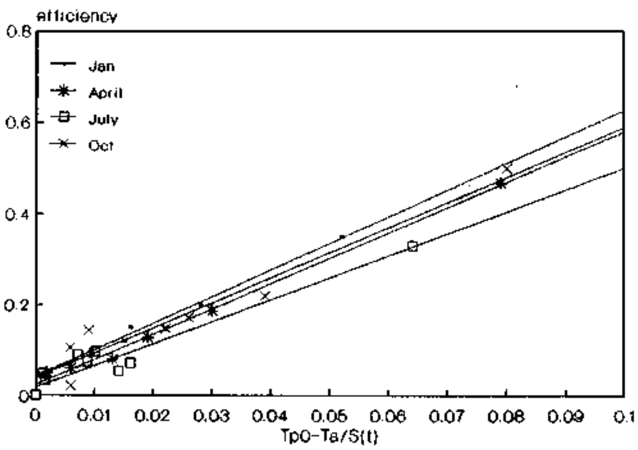

Fig. 2. Performance curves for a greenhouse with tunnel attachment.

Table 2. Daily average solar intensity available in Agrinion (Greece) computed from total average intensity for each month over a five-year period [3]

Month Time	January	February	March	April	May	June	July	August	September	October	November	December
6:00	—	—	—	48.68	108.61	138.81	124.39	69.42	5.65	—	—	—
7:00	—	—	92.08	188.81	266.40	299.71	283.46	216.44	121.25	38.97	—	—
8:00	75.81	138.75	244.67	364.50	445.15	476.08	460.27	392.91	282.19	163.47	85.10	58.34
9:00	190.81	278.04	406.96	535.72	612.99	639.73	625.16	562.11	447.36	308.70	203.90	164.32
10:00	300.13	402.11	543.52	675.12	747.66	770.40	757.10	698.99	584.47	435.69	315.41	287.65
11:00	375.54	485.39	633.10	765.31	834.26	854.26	841.85	787.32	673.91	520.30	391.90	339.76
12:00	402.20	514.54	664.18	796.43	864.08	883.11	871.02	817.78	704.87	549.83	418.89	365.37
13:00	375.54	485.39	633.10	765.31	834.26	854.26	841.85	787.32	673.91	520.30	391.90	339.76
14:00	300.13	402.11	543.52	675.12	747.66	770.40	757.10	698.99	584.47	435.69	315.41	287.65
15:00	198.81	278.04	409.96	535.72	612.99	639.73	625.16	562.11	447.36	308.70	203.90	164.32
16:00	75.81	138.75	244.67	364.50	445.15	476.08	460.27	392.91	282.19	163.47	85.10	58.34
17:00	—	—	92.08	188.81	266.40	299.71	283.46	216.44	121.25	38.97	—	—
18:00	—	—	—	48.68	108.61	138.81	124.39	69.42	5.65	—	—	—
W/m^2	2286.76	3123.11	4504.84	5952.72	6894.21	7241.08	7055.51	6272.14	4934.53	3484.08	2411.52	2025.54
MJ/m^2	8.22	11.24	16.22	21.43	24.82	26.07	25.40	22.60	17.80	12.54	8.69	7.29

Table 3. Hourly ambient and greenhouse temperature variation at Agrinion (Greece) for the four months under study [4]

Month	January		April		July		October	
Time	In	Out	In	Out	In	Out	In	Out
6:00	12.5	10.0	16.0	9.0	19.0	19.0	9.5	9.0
7:00	12.0	11.5	18.0	15.0	19.5	19.5	9.5	9.0
8:00	14.5	12.5	20.0	19.0	28.0	22.0	9.0	8.5
9:00	16.5	13.0	29.5	29.0	30.0	27.0	20.0	17.0
10:00	18.0	14.5	31.0	29.0	35.0	30.0	28.0	22.0
11:00	20.0	14.5	35.0	29.5	40.0	34.0	33.0	25.0
12:00	21.0	14.0	37.0	30.0	44.0	35.0	39.5	28.0
13:00	23.5	15.0	36.0	27.0	48.0	38.0	39.3	28.0
14:00	24.0	15.0	40.0	29.0	44.0	36.0	39.0	28.0
15:00	22.5	14.0	40.0	30.0	40.0	35.0	37.0	27.0
16:00	20.0	12.5	39.0	29.0	41.0	36.0	36.0	24.0
17:00	18.0	10.5	37.0	24.0	42.0	38.0	30.0	22.0
18:00	15.0	10.0	33.0	20.0	40.0	34.0	23.0	21.0

month (Table 1) reported by Santamouris is considered for calculation. The value of the overall heat loss coefficient U_{pa} is taken as 6.814 W/m$^{2\circ}$C [5].

Using the method suggested by Duffie and Beckman [6] to calculate the hourly intensity from the total daily radiation, the values for hourly solar intensity were obtained for Arginion for each month (Table 2). The hourly variation of the inside and outside temperatures for typical months have been given in Table 3.

The amount of thermal loss efficiency factor for the greenhouse and the ratio of $(T_{p0}-T_a)/S_T(t)$ were calculated for each month. The variation for each month is shown in Fig. 2.

It can be observed that there is a good agreement between the suggested behaviour of previous work done by Sutar and Tiwari [2], equation (3) and the nature of these curves.

CONCLUSIONS

On the basis of the above study, it is inferred that the proposed model is in accordance with the experimental results observed by Santamouris [3]. Further, the proposed model can be used to optimize the design parameters for heating and cooling of a greenhouse for a given climatic condition.

REFERENCES

1. Bansal, N. K. and Minke, G., Climatic zones and rural housing in India, *Scientific Series of the International Bureau*, KFA, Julich, 1988.
2. Sutar, R. F. and Tiwari, G. N., Energy, 1996, **21**(1), 61–65.
3. Santamouris, M., Arginion, A. and Vallindras, M., Solar Energy, 1994, **52**(5), 371–378.
4. Santamouris, M. and Katsoulis, B. D., Solar and Wind Technology, 1989, **6**(1), 79–84.
5. Garzoli, K. and Blackwell, J., J. Agril. Engg. Res., 1973, **18**, 205–216.
6. Duffie, J. A. and Beckman, W. A., in *Solar Engineering of Thermal Processes*. John Wiley & Sons, New York, 1991.
7. Watmuff, J. H., Charters, W. W. S. and Proctor, D., Complex, 1977, **2**, .

APPENDIX

The $h(t)$ is an overall heat loss coefficient from an enclosed room air to ambient through transparent canopy cover and can be expressed as

$$h(t) = \left[\frac{1}{h_1} + \frac{1}{h_2}\right]^{-1}$$

where h_1 and h_2 are internal and external heat loss coefficients and are expressed as:

(a) Internal total heat loss coefficient

$$h_1 = h_{pc} + h_{pr}.$$

An expression for h_{pr} is given in the text, and it can also be considered as a temperature dependent parameter, if required:

(b) External total heat loss coefficient

The external heat transfer coefficient is generally considered as [6]

$$h_2 = 5.7 + 3.0V.$$

However, Watmuff [7] pointed out that the above expression includes radiative losses. He proposed a new expression for the convective heat loss coefficient as

$$h_{ca} = 2.8 + 3.8V.$$