THERMAL MODELING AND EXPERIMENTAL VALIDATION OF NATURALLY VENTILATED SOLAR GREENHOUSE FOR VEGETABLE CROP PRODUCTION IN AN INDIAN COMPOSITE CLIMATE

N.L.Panwar
S.C.Kaushik
Centre of Energy Studies
Indian Institute of Technology, Delhi
Hauz Khas, New Delhi 110016, India

Surendra Kothari
Department of Renewable Energy Engineering
Maharana Pratap University of Agriculture and Technology
Udaipur 313001, Rajasthan, India

ABSTRACT

Greenhouse cultivation appears a viable option for healthy, nutritive and high-yield crop produces. This can also be used in off-season for crop cultivation. This communication deals with thermal modeling and experimental investigation of naturally ventilated solar greenhouse with shading net. It is found that such type of structure is not found suitable for growing crops during the month of May-June, particularly, in Rajasthan climatic conditions.
Thermodynamic analysis of greenhouse in terms of energy and exergy analysis is presented to predict the actual performance conditions. Exergy transfer analysis in the greenhouse is also presented in this communication. We have also examined the economic feasibility of two vegetable crops (i.e., cucumber and tomato) cultivated in a naturally ventilated greenhouse, estimating the net present worth (NPW), cost- benefit ratio, payback period and internal rate of return for these crops on year- round cultivation. The cost-benefit ratio has demonstrated that growing cucumbers and tomatoes can be economically viable in this climatic region.

1. INTRODUCTION

The protected cultivation has been adapted globally for vegetable and horticulture crop production. It provides favourable microclimatic conditions for plant's growth, and allowing higher yield and better quality as compared with open field conditions [1,2]. Such a cultivation practice was originally implemented at the northern latitudes to provide suitable microclimatic conditions to plants, where usually they will not grow optimally [3]. The crop cultivation practice under greenhouse conditions seems a viable option for healthy, nutritive and high-yield crop produces. This can also be used as an off-season crop cultivation. Basically, the greenhouse is a closed and isolation structure in which agricultural operation such as sowing, weeding, irrigation, etc. can be performed. Such structure eliminating extensive migration of pests into greenhouses and create more favourable environment that is essential for plant growth and productivity [4-6].

The expansion of crop and flower production in various types of greenhouse during the recent years has enabled the growth of agricultural products through the entire year [7]. There are number of scientists, researchers and academicians who have worked out the thermal model to predict the microclimatic conditions of greenhouse for crop production [8-18]. However, limited literature is available on modeling of naturally ventilated greenhouse with shading net. Greenhouse is having internal shading net to cut excess solar radiation during summer and act as a thermal screen during winter season. Keeping this in view an attempt has been made to develop a thermal model for naturally ventilated type greenhouse for growing tomato crop. The other objective of this study is to analyse the energetic and exergetic performance of greenhouse in actual use under composite climatic condition of Indian state Rajasthan.

2. EXPERIMENTAL NATURALLY VENTILATED SOLAR GREENHOUSE

The naturally ventilated solar greenhouse is made of galvanized tubular structure in aerodynamic shape. The front view of the experimental greenhouse is presented in Fig. 1. Low-density ultra violet radiation stabilized polythene of 200 micron thickness was used as a cover of greenhouse. Misting system has been provided with 80 misting nozzle connected with 16 LDPE pipe and monoblock pump. Misting system was used extensively in summer condition, which generally prevails in the month of May. A gravity fed drip irrigation system was provided to fulfil the water requirement inside the greenhouse. The sowing bed was prepared for growing crop, the width of bed was kept 75 cm and the distance between two beds was kept 30 cm; total 15 such beds were prepared inside the greenhouse. Seed was sown both sides to the bed and about 1500, seeds were grown inside the greenhouse.

Fig. 1: Front view of naturally ventilated greenhouse

3. THERMAL MODELLING OF GREENHOUSE WITH SHADING NETS

Mathematical model of a greenhouse for growing vegetable crops during off season has been developed. The shading nets were provided inside the greenhouse, which divide the greenhouse in two parts, hence two temperature layers are considered inside it. One is above the shading net, and second one is below the shading net, where actual cultivation operation is being performed. Thermal flux generated in typical greenhouse is illustrated in Fig. 2.

In order to write an energy balance equation for each component of the greenhouse, the following assumptions have been made.

1. The greenhouse air is well mixed at all times so that no temperature or moisture gradient exists in the air.
2. The temperatures of the internal air, crops and cover materials were in a steady state.
3. Crop was planted on sowing bed, the width of bed was kept 75 cm and the distance between two beds was kept 30 cm.
4. The heat transfer from greenhouse air to floor is neglected.

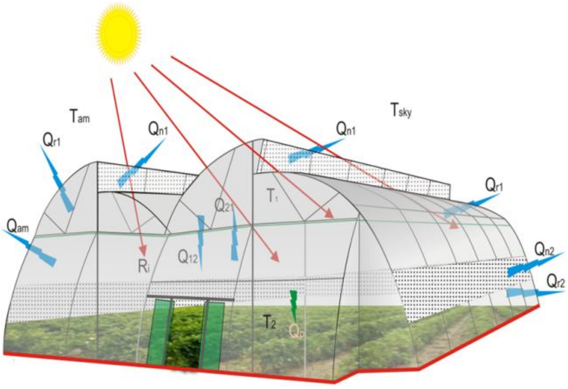

Fig. 2: Schematic diagram of greenhouse thermal model

Chen et al. [19] developed a model which reveals the effect of temperature in the greenhouse with shading nets. They cover greenhouse with one external shading net, and another shading is also provided inside the greenhouse. The present model is inspired from their study and applied it for composite climatic condition of Udaipur in Indian state Rajasthan.

3.1 Thermal Flux for Upper Layer

Solar energy is main source of energy input. The net input thermal flux at upper layer depends on transmittance of greenhouse cover is as follows:

$$Q_{in_1} = \tau_o A_1 I_s \qquad \text{...(1)}$$

Energy flow to ambient atmosphere by heat transfer

$$Q_{am_1} = A_1 h_{gc} (T_1 - T_{am}) \qquad \text{...(2)}$$

Shading net works as thermal screen and there is scope of heat thermal interaction between upper and lower layer. This can be presented as follows:

$$Q_{12} = A_{shd} U_{shd} (T_1 - T_2) \qquad \text{...(3)}$$

Energy exchange by natural ventilation is given by

$$Q_{n1} = AR_1 \, \rho \, C_p (T_1 - T_{am}) \qquad \text{...(4)}$$

AR_1 is natural air exchange rate and it is adapted from Roy et al. [20]

$$AR_1 = \frac{A_{op1}}{2} C_d \left[2g \, \frac{\Delta \mathrm{T}}{T_{am}} \frac{H_1}{4} \right]^{0.5}$$

$$AR_1 = 0.5 \, A_{op1} \, C_d \left[g \, \frac{(\mathrm{T}_{\mathrm{av}} - T_{am}) H_1}{2 T_{am}} \right]^{0.5}$$

$$T_{\mathrm{av}} = \frac{(T_1 V_1 + T_2 V_2)}{V_1 + V_2}$$

Radiative heat transfer at upper layer is given by

$$Q_{r1} = \varepsilon_{gc} \, F_{1s} \, \sigma \, A_{shd} (T_1^4 - T_{sky}^4) \qquad \text{...(5)}$$

The correlation with sky temperature (T_s) and ambient temperature (T_{am}) is adapted from Duffie and Becman [21]

$$T_{sky} = 0.0552(T_{am})^{1.5}$$

Thus the energy balance equation for the upper layer is

$$\tau_o A_1 I_s = A_1 h_{gc}(T_1 - T_{am}) + A_{shd} h_{shd}(T_1 - T_2) + AR_1\, \rho\, C_p(T_1 - T_{am}) + \varepsilon_{gc}\, F_{1s}\, \sigma\, A_{shd}(T_1^4 - T_{sky}^4) \quad ...(6)$$

3.2 Heat Transfer Model of the Lower Layer

Input flux at lower layer depends on the transmittance of both greenhouse cover and shading net, hence the net input solar flux reaching at lower layer is given by;

$$Q_{in_2} = \tau_0 \tau_{in} I_s\, A_2 \qquad ...(7)$$

Energy flow to ambient atmosphere by heat transfer is

$$Q_{am_2} = A_2\, h_{gc}(T_2 - T_{am}) \qquad ...(8)$$

The energy exchange between upper and lower layer is

$$Q_{21} = A_{shd} U_{shd}(T_2 - T_1) \qquad ...(9)$$

Energy exchange by natural ventilation from lower layer is

$$Q_{n2} = AR_2\, \rho\, C_p(T_2 - T_{am}) \qquad ...(10)$$

$$AR_2 = 0.5\, A_{op2}\, C_d \left[g\, \frac{(\mathrm{T_{av}} - T_{am}) H_2}{2T_{am}}\right]^{0.5}$$

Energy exchange by natural ventilation at lower layer by upper layer vent is

$$Q_{n12} = AR_1\, \rho\, C_p(T_1 - T_2) \qquad ...(\ 11)$$

Radiative heat transfer at lower layer

$$Q_{r2} = \varepsilon_{shd}\, F_{2s}\, \sigma\, A_f(T_2^4 - T_{sky}^4) \qquad ...(12)$$

Absorption of thermal energy by shading net is

$$Q_{ab} = \alpha\, A_{shd}(1 - \tau_{in})\tau_0 I_s \qquad ...(13)$$

Heat transfer due to crop transpiration is given by

$$Q_p = \lambda\, E_t\ A_f P_f \qquad ...(14)$$

The transpiration model of tomatoes is adopted from the HORTITRANS model [14]

$$E_t = \frac{a I_s}{\lambda} + \frac{h_t}{\lambda \gamma}\left(P_{ws} - \frac{P_{vp}}{1000}\right)$$

$$a = 0.154 \ln(1 + 1.1\, LAI^{1.3})$$

$$h_t = 1.65\, LAI\ \left[1 - 0.56 \exp\left(\frac{-R_i}{13.0}\right)\right]$$

$$R_i = \tau_0 \tau_{in} I_s$$

$$\gamma = 0.066\, k\ Pa\, K^{-1}$$

λ= 2260 kJ kg^{-1}

Saturation vapour pressure (P_{ws}) is calculated by Weiss (1977) expression

$$P_{ws} = 0.61078 \exp(17.2694\, T_2) / (T_2 + 237.3)$$

The temperature dependent partial vapor pressure can be evaluated by the following expression (Fernandez and Chargoy1990):

$$\mathrm{P_{vp}} = \exp\left(25.317 - \frac{5144}{\mathrm{T_2}}\right) \times 10^{-3}$$

Thus the energy balance equation for lower layer is given by

$$\tau_0 \tau_{in} I_s A_2 = A_2 h_{gc}(T_2 - T_{am}) + A_{shd} h_{shd}(T_1 - T_2) + AR_2\, \rho\, C_p(T_2 - T_{am}) + AR_1\, \rho\, C_p(T_1 - T_2) + \ \varepsilon_{shd}\, F_{2s}\, \sigma\, A_f(T_2^4 - T_{sky}^4) + \alpha\, A_{shd}(1 - \tau_{in})\tau_0 I_s + \lambda\, E_t\, A_f P_f \qquad ...(\ 15)$$

3.3 Solution Procedure

Matlab 2010a is used for computing the unknown parameters T_1 & T_2 of equations 6 and 15. The flow chart of solution is illustrated in Fig. 3.

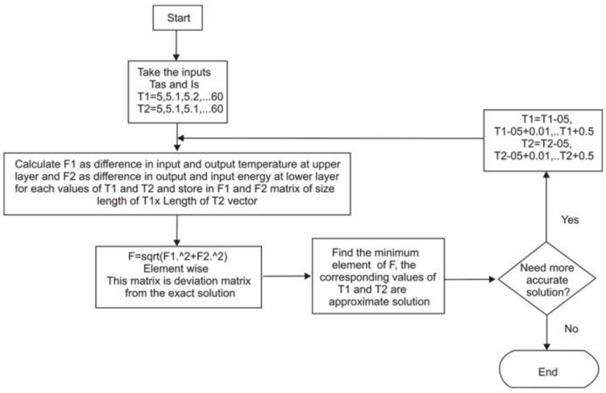

Fig. 3: Flow chart of thermal model of naturally ventilation greenhouse

3.4 Energy Analysis of greenhouse

Energy available inside the greenhouse is mainly utilized for enhancing the greenhouse air temperature. Enhancement of temperature improves the microclimatic conditions of greenhouse air. The energy input is mainly depended on depended on available solar radiation, greenhouse area and cover transmissivity of greenhouse cover.

The energy input to the greenhouse can be written as:

$$Q_{in} = \tau_0 \tau_{in} I_s A_2$$

Energy out depends on the temperature difference between greenhouse air and ambient conditions. It can be express as:

$$Q_{0ut} = \dot{m}_a C_a(T_2 - T_{am})$$

Energy efficiency

$$\eta = \frac{Q_{out}}{Q_{in}} \qquad ...(16)$$

3.5 Exergy Analysis of greenhouse

The term exergy is defined as the maximum amount of useful work that can be obtained from a system [24]. The rational efficiency based on the concept of exergy is a true measure of the performance of solar thermal systems. The energy efficiency is the quantitative assessment of energy whereas exergy is the qualitative assessment of energy. The exergy input at lower layer of greenhouse can be written as:

$$Ex_{in} = \tau_0\ \tau_{in}\ A_{gc}\ I_s \left[1 - \frac{4}{3}\left(\frac{T_{am}}{T_s}\right) + \frac{1}{3}\left(\frac{T_{am}}{T_s}\right)^4\right]$$

Where T_s=6000 K

Exergy output

$$Ex_{out} = \dot{m}_a C_a(T_2 - T_{am}) \left[1 - \frac{T_{am}}{T_2}\right]$$

Exergy efficiency

$$\eta_{II} = \frac{Ex_{out}}{Ex_{in}} \quad ...(17)$$

3.6 Thermal Exergy Transfer

The exergy transfer at lower layer is calculated by estimating the exergy losses in different heat transfer modes in greenhouse. The scope of exergy losses in lower layer is in ventilation at both upper and lower layer, heat transfer due to long wave radiation; heat transferred to be ambient, crop transpiration and some unaccountable losses inside the greenhouse is also considered. The unaccountable exergy losses may be due to heat transfer to the ground through conduction and plant canopy and bed etc.. The exergy losses in various heat transfer routes at lower layer of greenhouse are estimated as follows:

Exergy loss during ventilation at lower layer

$$Ex_{Ln1} = Q_{n1}\left[1 - \frac{T_{am}}{T_2}\right] \quad \dots (18)$$

Exergy loss during ventilation at upper layer

$$Ex_{Ln21} = Q_{n21}\left[1 - \frac{T_{am}}{T_2}\right] \quad \dots (19)$$

Exergy loss due heat transfer to ambient

$$Ex_{Lam} = Q_{am}\left[1 - \frac{T_{am}}{T_2}\right] \quad \dots (20)$$

Exergy loss during heat transfer due to long wave radiation

$$Ex_{Lr2} = Q_{r2}\left[1 - \frac{T_{am}}{T_2}\right] \quad \dots (21)$$

Unaccountable thermal exergy losses

$$Ex_{Lua} = Q_{ua}\left[1 - \frac{T_{am}}{T_2}\right] \quad \dots (22)$$

Exergy transfer due to heat transfer from lower layer to upper layer

$$Ex_{T21} = Q_{21}\left[1 - \frac{T_2}{T_1}\right] \quad \dots (23)$$

Exergy transfer due heat absorbed by shading net

$$Ex_{Tab} = Q_{ab}\left[1 - \frac{T_{am}}{T_{shading}}\right] \quad \dots (24)$$

Where,

$$T_{shading} = \frac{T_1 + T_2}{2}$$

Exergy transfer due to heat absorbed by plant during transpiration

$$Ex_{Tp} = Q_{p2}\left[1 - \frac{T_{am}}{T_p}\right] \quad \dots (25)$$

Where,

$T_p = T_2$

Total exergy losses can be written as:

$$\sum Ex_L = Ex_{Ln1} + Ex_{Ln21} + Ex_{Lam} + Ex_{Lr2} + Ex_{Lua}$$

Total exergy transfer can be written as:

$$\sum Ex_T = Ex_{T21} + Ex_{Tab} + Ex_{Tp}$$

The exergy balance equation can be written as:

$$Ex_{in} - \left(Ex_{out} + \sum Ex_L + \sum Ex_T\right) = Ex_{Dest} \quad \dots (26)$$

2.7 Statistical Analysis of Proposed Model

In order to assess the consistencies between predicted and measured air temperature, a statistical analysis has been carried out. The standard error (*SE*), Root mean square error (*RSME*) and coefficient of correlation (*r*) parameters used in the study are defined as [25]:

Standard error (*SE*)

$$SE = \frac{\sigma}{\sqrt{n}} \quad ...(27)$$

Where

$$\sigma = \left[\frac{\sum_{i=1}^{n}(x_{exp} - x_{pre})^2}{n-1}\right]^{1/2}$$

Root Mean Square Error (*RMSE*)

$$RMSE = \frac{1}{n}\sqrt{\sum_{i=1}^{n}\left[x_{i,exp} - x_{i,pre}\right]^2} \quad ...(28)$$

A relationship for the correlation coefficient (*r*) which may be preferable is as follows:

$$r = \frac{n\sum x_{exp}x_{pre} - (\sum x_{exp})(\sum x_{pre})}{\left[n\sum x_{exp}^2 - (\sum x_{exp})^2\right]^{1/2}\left[n\sum x_{pre}^2 - (\sum x_{pre})^2\right]^{1/2}} \quad \dots(29)$$

Where x_{exp} and x_{pre} are experimentally recorded and theoretical greenhouse air temperature, n is the number of observation.

3.8 Techno Economic Assessment

To assess the economic viability of greenhouse four different economic indicators namely net present worth (NPW), internal rate of return (IRR), benefit cost ratio (B/C ratio) and payback period have been used.

3.8.1 Net Present Worth

The net present worth is the difference between the present value of cash inflows and the present value of cash outflows. It is used in capital budgeting to analyze the profitability of the project. The net present worth can be computed as follows:

$$NPW = \sum_{t=1}^{t=n}\frac{B_t - C_t}{(1+i)^t} \quad \dots(30)$$

where,

B_t = benefit in each year (US$)

C_t = cost in each year (US$)

t =1,2,…..,n

i = discount rate (%)

3.8.2 Cost-Benefit-Ratio

Cost-benefit analysis is a technique for evaluating a project or investment by comparing the economic benefits with the economic costs of the activity. The cost-benefit ratio is a formal selection criterion of acceptability of project, and it should be one or greater.

Mathematically cost-benefit ratio can be computed as follow:

$$Cost - benefit\ ratio = \frac{\sum_{t=1}^{t=n}\frac{B_t}{(1+i)^i}}{\sum_{t=1}^{t=n}\frac{C_t}{(1+i)^i}} \quad \dots (31)$$

3.8.3 Internal Rate of Return

Internal rate of return is the interest rate at which the net present worth of the cash flow of a project equal to zero. Internal rate of return is the discount rate, i such that

$$\sum_{t=1}^{t=n} \frac{B_t - C_t}{(1+i)^t} = 0 \qquad \ldots (32)$$

3.8.4 Pay Back Period

The payback period is the length of time from the installation of the greenhouse until the net value of the incremental production stream reaches the total amount of the capital investment. It shows the length of time between cumulative net cash outflow recovered in the form of yearly net cash inflows.

The following assumptions were made to assess the economic feasibility of naturally ventilated greenhouse:

a) the life of greenhouse structure is 20 years.
b) the life of greenhouse cover is five years.
c) discount rate is 10 percent.
d) two crops of cucumber and two crops of tomato can be grown in a year inside greenhouse.

4. RESULTS AND DISCUSSION

4.1 Thermal performance of greenhouse

The developed model can predict greenhouse air temperature. Temperature inside the greenhouse for both upper and lower layer was recorded at regular intervals of time from 9:00 hours to 17:00 hours. It was found that temperature at upper layer is always higher than corresponding to lower layer. The shading net was used inside the greenhouse which reduces the transmission level of solar radiation to lower layer that is why the temperature at lower layer is lower than upper layer. The difference between ambient and lower layer temperature was varying from 2-5 ^{o}C for the months January-April, 2012 during these months and ambient temperature was varying from 12 – 35 ^{o}C. Theoretically calculated greenhouse air temperature at lower layer is 1-3 ^{o}C higher than experimental values. Similar trend was found for the month July- December. But greenhouse air temperature during months May - June is 8- 11^{o}C higher than ambient temperature as shown in Fig. 4 and Fig. 5 respectively, such difference can be reduced by using misting system, but it required frequent cooling. Scarcity of water and irregular electricity supply does not allow for using greenhouse during these months in Rajasthan state.

Statistical analysis between theoretical and experimentally recorded greenhouse air temperature shows good correlation. The values of the correlation coefficients (*r*) for lower layer are greater than 0.97 for all the months; it demonstrates that, the proposed model can provide good fitness with experimental values.

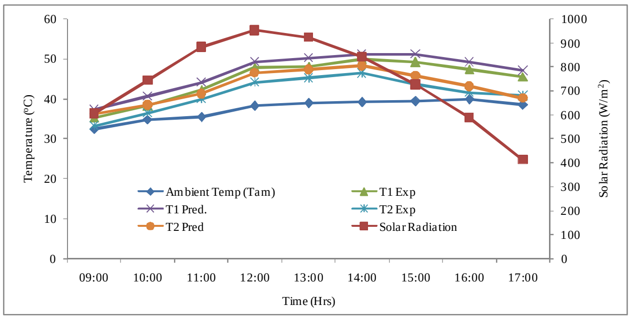

Fig. 4: Experimental and predicted greenhouse air temperature for the month May, 2012

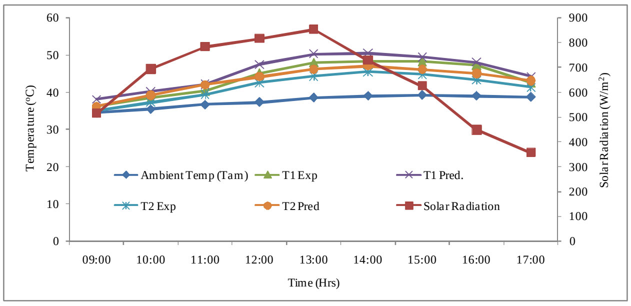

Fig. 5: Experimental and predicted greenhouse air temperature for the month June, 2012

4.2 Energy and Exergy analysis

Exergy is defined as the maximum useful amount of work that can be produced by a system or a flow of matter or energy as it comes to equilibrium with a reference environment [26]. Exergy is a true measurement of the quality or grade of energy, and it can be destroyed in the thermal system. In the present study, both energy and exergy analysis was carried out for lower layer of greenhouse with the equations (16-17). The predicted energy and exergy efficiencies for all the months were higher than that experimentally calculated. Month January and December show higher energy and exergy efficiency at 17:00 hours in spite of low solar radiation, because of maintaining high inside air temperature with the help of shading net, which acts as a thermal screen. Hence the naturally ventilated type greenhouse can provide favourable air temperature during winter season.

In protected cultivation practices, such as structure is constructed for providing desirable air temperature, relative humidity and solar radiation Even though with high solar radiation, greenhouse air temperature can be reduced by misting, more air exchange, etc. the energy loss from each mode of heat transfer were calculated to identifying the accountable energy losses. The average experimental and theoretical energy efficiency was varying from 1.71 - 3.63 % and 2.70 – 6.50 % respectively, and corresponding average exergy efficiency was varying from 0.021- 0.046 % and 0.048 – 0.124% respectively.

Experimental energy efficiency during the winter month of December, 2011 and January, 2012was 3.325 % and 3.634 % and exergy efficiency was varying from 0.038% - 0.046 % as presented in Table 2. It is a fact that both energy and exergy output is the function of temperature whereas the input is the function of collector area and solar insolation. Though, solar greenhouse is having more solar collector area but less temperature rise as compared to other solar thermal devices. This is the main reason for low energy and exergy efficiency. In spite of having low efficiencies such a system is capable to provide favourable microclimatic condition for plant propagation.

TABLE 2: ENERGY AND EXERGY EFFICIENCY OF NATURALLY VENTILATED SOLAR GREENHOUSE

Months	Energy Efficiency (%)		Exergy Efficiency (%)	
	Exp.	Pred.	Exp.	Pred.
July, 2011	2.941	4.983	0.039	0.108
Aug.,2011	2.887	4.401	0.040	0.083
Sept., 2011	2.662	4.057	0.035	0.075
Oct. ,2011	2.544	3.889	0.034	0.071
Nov., 2011	2.869	4.572	0.036	0.074
Dec., 2011	3.325	6.185	0.038	0.107
Jan. 2012	3.634	6.502	0.046	0.124
Feb. 2012	2.810	4.392	0.035	0.083
March, 2012	1.716	2.701	0.021	0.048
April, 2012	1.916	2.900	0.024	0.049
May, 2012	2.140	3.098	0.035	0.066
June, 2012	2.586	3.847	0.040	0.079

4.3 Exergy Transfer

The heat loss was calculated by using equation 18-25. Equation 26 was used to estimate total exergy transfer in greenhouse. Fig 4 reveals the theoretical exergy flow during the month March, 2012. The exergy transfer 4919.04 kJ/day was found in crop transpiration, and it is about 1.126 % of exergy input. Ventilation at upper layer lifted the heat from lower layer of greenhouse during this process about 1304.13 kJ/day exergy is being lost. Exergy loss at lower layer ventilation is about, 94.74 kJ/day. Total theoretical exergy transfer during the month March was calculated about 428527.31 kJ/day, which is about 98.11% of exergy input.

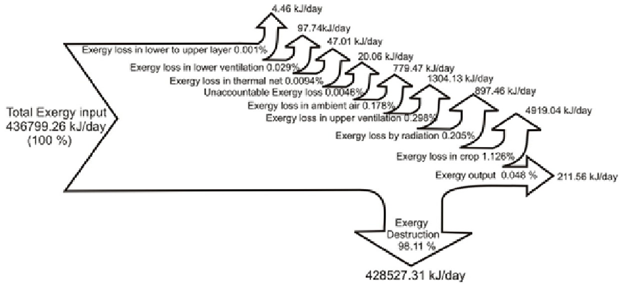

Fig. 4: Theoretical Exergy flow during the month March, 2012

Experimental exergy transfer during the March, 2012 in different heat transfer routes are demonstrated in Fig.5. The maximum energy is utilized by plant during transpiration; during this process, 3666.40 kJ/day of exergy is being lost. Unaccountable thermal exergy losses were calculated about 93.76 kJ/day, and it is 0.021 % of exergy input. Total exergy transfer is estimated 431884.67 kJ/day, which is about 98.87 % of exergy input.

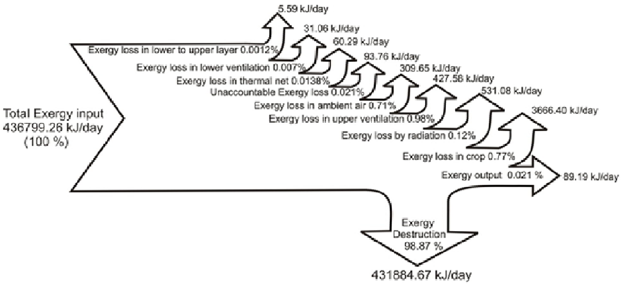

Fig. 5: Experimental Exergy flow during the month March, 2012

4.4 ECONOMIC EVALUATION

The freshly harvested greenhouse vegetable products were launched in the local market. As market price of a product does not remain constant, the average price was selected to assess its economic feasibility. The annual income from cucumber and tomato is about 6125.86 US$ and 4320.00 US$ respectively. The surcharge for these crops was 1175.00US$, which included labour, and fertilizer cost.

The economic indicator used to assess the economic feasibility of the greenhouse is presented in Table 3. The net present worth for cucumber and tomato crop was found to be about 28314.59 US$ and 15993.92 US$, respectively. The cost-benefit ratio of cucumber (2.17) was higher as compared to that of tomato (1.77). As the cost-benefit ratio is greater than one for these crops, such crops seem to be economically viable. As far as the payback period is concerned, it was about 5 years and 3 months for cucumber and about 6 year and 11 months for tomato. Thus, despite high production, tomato's payback period was higher than that of cucumber. The internal rate of return for cucumber and tomato crop is about 35 % and 20% respectively.

TABLE 3: ECONOMIC INDICATORS OF SELECTED CROPS

Crop	NPW (US$)	B-C ratio	Payback Period	IRR
Cucumber	28341.60	2.17	5 yrs 3 months	35 %
Tomato	15993.94	1.77	6 yrs 11 months	20 %

5. CONCLUSIONS

The developed thermal model can be used to predict greenhouse air temperature at lower layer. Under cold climate, crops can be cultivated inside the greenhouse which can not be grown outside at a low temperature. The theoretical greenhouse air temperature has good correlation with experimental values. The values of the correlation coefficients (r) of all months are above 0.97; it shows that the developed model is having a good fit with experimental values. It was found that greenhouse air temperature during the month May-June is above 40 °C, it is increasing water requirements for irrigation and misting to control the temperature. It can be concluded that naturally ventilated greenhouse is not found suitable for crop production during these months in Rajasthan state of India.

The cost-benefit ratio, demonstrated that growing cucumbers and tomatoes can be economically viable in this climatic region.

Both energy and exergy efficiency of greenhouse are low as compared to other solar thermal devices because the input energy and exergy are the function of area and solar radiation where as output energy and exergy are the function of the temperature gradient. Greenhouse is having more surface area with fewer temperature gradients, which results in low efficiencies. In the greenhouse specially used for crop production, we have low-temperature gain that is why the maximum amount of incoming exergy is destroyed during the process.

6. NOMENCLATURE

A_1	surface are of upper layer, m^2
A_2	wall surface are of lower layer, m^2
A_f	floor area, m^2
A_{op1}	opening area of upper layer, m^2
A_{op2}	opening area of lower layer, m^2
A_{shd}	shading net area, m^2
AR_1	Natural air exchange rate in upper layer, m^3s^{-1}
AR_2	Natural air exchange rate in lower layer, m^3s^{-1}
C_d	discharge coefficient
C_p	air specific heat, J kg^{-1} $^oC^{-1}$
E_t	transpiration rate, kg $m^{-2}s^{-1}$
F_{1s}	shape factors for the sky as seen from the upper layer
F_{2s}	shape factors for the sky as seen from the lower layer
g	gravitational acceleration, ms^{-1}
H_1	opening height of upper layer, m
H_2	opening height of lower layer, m
h_{gc}	convective heat transfer coefficient between upper layer and ambient air, W m^2 K^{-1}
h_{shd}	convective heat transfer coefficient between upper layer and lower layer, W m^2 K^{-1}
I_s	solar radiation, Wm^{-2}
LAI	leaf area index
P_{ws}	air saturated vapour pressure inside air, kPa
P_{vp}	Vapour pressure inside the air, kPa
Rh	relative humidity,%
R_i	incoming solar radiation at lower layer of the greenhouse, W m^{-2}
T_1	upper layer temperature, ^oC
T_2	lower layer temperature, ^oC
T_{am}	ambient temperature
T_{ave}	average temperature of greenhouse, °C
T_{sky}	sky temperature, K
V_1	volume of the upper layer, m^3
V_2	volume of the lower layer, m^3
α	absorptance of shading nets
ρ	air density, kg m^{-3}
σ	Stephan-Boltzman constant, W m^{-2} K^{-4}
ε_{gc}	thermal emittance of cover materials
ε_{shd}	thermal emittance of shading net materials
τ_0	transmittance of greenhouse cover
τ_1	transmittance of shading nets
λ	latent heat of vaporization, kJ kg^{-1}
γ	thermodynamic psychrometric constant, kPa K^{-1}

7. ACKNOWLEDGEMENTS

The author (NLP) gratefully acknowledges Maharana Pratap University of Agriculture and Technology, Udaipur (Rajasthan), India and Indian Institute of Technology, Delhi for sponsorship under the quality improvement programme of the Government of India. Author (SCK) acknowledges the PDA grant from IIT- Delhi.

8. REFERENCES

(1) Bot, G.P.A. (2001) Developments in indoor sustainable plant production with emphasis on energy saving. Computers and Electronics in Agriculture , 30, pp.151–165.

(2) Panwar, N.L., Kaushik, S.C., Kothari, S. (2011) Solar greenhouse an option for renewable and sustainable farming. Renewable and Sustainable Energy Reviews, 15, pp. 3934– 3945.

(3) Rodríguez, E.F., Kubota C., Giacomelli, G.A., Tignor M.E., Wilson S.B., McMahon M. (2010) Dynamic modeling and simulation of greenhouse environments under several scenarios: A web-

based application. Computers and Electronics in Agriculture, 70, pp. 105–116.

(4) Hanafi, A., Papasolomontos, A. (1999) Integrated production and protection under protected cultivation in the Mediterranean region. Biotechnology Advances, 17, 183-203.

(5) Al-Helal, I.M., Alhamdan, A.M.(2009) Effect of arid environment on radiative properties of greenhouse polyethylene cover. Solar Energy, 83, pp. 790-798.

(6) Panwar, N.L., Kothari, S., Rathore, N.S., 2009. Protected Cultivation of Medicinal Plant in Composite Climate of Indian State Rajasthan. American-Eurasian J. Agric. & Environ. Sci., 5 (5), 633-637.

(7) Feuilloley, P., Issanchou, G. (1996) Greenhouse covering materials measurement and modelling of thermal properties using the hot box method, and condensation effects. J Agric Eng Res, 65, pp. 129–42.

(8) Guttormsen, G. (1972) The effect of perforation on temperature condition in plastic tunnel. J Agric Eng Res, 17, pp. 172–7.

(9) Kindelam, M. (1980) Dynamic modelling of greenhouse environment. Trans ASAE 23(5), pp. 1232–6.

(10) Arinze, E.A., Schoenau, G.J., Besant, R.W. (1984) A dynamic thermal performance simulation model of energy conserving greenhouse with thermal storage. Trans ASAE 27,pp. 508–19.

(11) Cooper, P.I., Fuller, R.J.(1983). A transient model of the interaction between crop, environment and greenhouse structure for predicting crop yield and energy consumption. J Agric Eng Res, 28,pp. 401–17.

(12) Seginer, I., Dvora, K., Peiper, U.M., Levav, N. (1988) Transfer coefficients of several polyethylene greenhouse covers. J Agric Eng Res, 39,pp. 19–37.

(13) Silva, M.A., Miguel, A., Rosa, R. (1991) Thermal radiation inside a single span greenhouse with a thermal screen. J Agric Eng Res, 49,pp. 285–98.

(14) Jolliet, O. (1994) HORTITRANS, a model for predicting and optimizing humidity and transpiration in greenhouse in greenhouse. J Agric Eng Res 57,pp. 23–37.

(15) Teitel, M., Tanny, J. (1999) Natural ventilation of greenhouses: experiments and model. Agric Forest Meteorol 96, pp. 59–70.

(16) Tavares, C., Goncalves, A., Castro, P., Loureiro, D., Joyce, A. (2001) Modelling an agriculture production greenhouse. Renew Energy 22, pp. 15–20.

(17) Kothari, S., Panwar, N.L. (2007) Steady state thermal model for predicting micro-climate inside the greenhouse. Inst Eng (India) J Agric Eng ,88, pp. 52–5.

(18) Kumar, K.S., Jha, M.K., Tiwari, K.N., Singh, A., 2010. Modeling and evaluation of greenhouse for floriculture in subtropics. Energy Build, 42,pp. 1075–83.

(19) Chen, C., Shen, T., Weng, Y. (2011) Simple model to study the effect of temperature on the greenhouse with shading nets. African Journal of Biotechnology, 10(25), pp. 5001-5014.

(20) Roy, J.C., Boulard, Y., Kittas, C., Wang, S. (2002) Convective and ventilation transfers in greenhouses, Part 1: the greenhouse considered as a perfectly stirred tank. Biosyst. Eng. 83, pp. 1-20.

(21) Duffie, J.A., Beckman, W.A. (1991) Solar engineering of thermal processes. New York: John Wiley &Sons.

(22) Wiess A. (1997) Algorithms for the calculation of moist air properties on a hand calculator. Amer.Soc. Ag. Eng. 23,pp. 1133-1136.

(23) Fernandez, J., Chargoy, N. (1990) Multistage indirectly heated solar still. Solar Energy 44, pp. 215-223.

(24) Panwar , N.L., Kaushik, S.C., Kothari, S. (2012) A review on energy and exergy analysis of solar dying systems. Renew Sust Energ Rev, 16, pp. 2812-2819.

(25) Holman JP (2010) Experimental Methods for Engineers. Tata McGraw-Hill, India

(26) Dincer, I. (2000) Thermodynamics, exergy and environmental impact. Energy Sour 22,pp. 723-732.