Thermal Analysis of Photovoltaic Integrated Greenhouse Solar Dryer

Sumit Tiwari, Rohit Tripathi, G. N. Tiwari

Abstract—Present study focused on the utilization of solar energy by the help of photovoltaic greenhouse solar dryer under forced mode. A single slope photovoltaic greenhouse solar dryer has been proposed and thermal modelling has been developed. Various parameters have been calculated by thermal modelling such as greenhouse room temperature, cell temperature, crop temperature and air temperature at exit of greenhouse. Further cell efficiency, thermal efficiency, and overall thermal efficiency have been calculated for a typical day of May and November. It was found that system can generate equivalent thermal energy up to 7.65 kW and 6.66 kW per day for clear day of May and November respectively.

Keywords—Characteristics curve, Photovoltaic, Thermal modelling, Thermal efficiency.

I. INTRODUCTION

RYING is one of the oldest food preservation techniques. Solar drying is the best among all drying processes as it is environmental friendly and economical. For food, demand is more than supply so the demand and supply gap for the food is rapidly growing due to population growth. The scarcity of food can be resolved either by increasing the supply of food or by controlling population growth or by both [1]. In developing countries, lack of suitable technology, lack of marketing channels, improper cultivation and fertilization, high postharvest losses, improper transportation lead to a food loss from 10% to 40%. The process of drying (solar drying) is unquestionably cheapest method among all available drying processes because it does not require any expensive setup and energy source. For dying of plants, seeds, fruits, meat, fish, wood, and other agricultural or forest products as a means of preservation, open-air sun drying has been used since ancient time. Open sun drying has some limitations like, possible degradation due to biochemical or microbiological reactions, discoloration, insect infestation, lack of ability to control the drying process and so on. As we know that fruits like apricot, fig, grape, plum, and peach have been dried over centuries, but recently some other agricultural products like mango, apple, banana, pineapple, and pear have been also gaining importance [2]. Further to improve the quality of agricultural products, solar dryers came into existence. Solar dryers have been developed for two modes of operation namely natural mode and forced mode. Many researchers found that forced mode drying is better than natural mode of drying in terms of controlling drying parameters [3], [4]. Smitabhindu et al. [5] derived a mathematical model for drying of bananas as a crop with the help of solar dryer under forced mode. In mathematical model, two differential equations are derived for collector and drying cabinet respectively. Further, program was developed on FORTRON and optimized collector area and the recycle factor was found to be 26 m² and 90%, respectively. Kumar and Tiwari [6] developed a thermal model of greenhouse dryer under forced mode for jaggery drying.

Integration with photovoltaic (PV) module of greenhouse dryer creates it free from grid connectivity for forced mode of operation. Barnwal and Tiwari [7] analyzed and compared the open sun drying with semi-transparent PV incorporated greenhouse drying. Semi-transparent PV modules were installed on the south inclined roof of the dryer to get maximum solar radiation. Solar greenhouse dryer coupled with PV-ventilation [8] used for drying of banana and peeled longan have been simulated and experimented. By experimentation, it was found that drying time is less in case of greenhouse drying comparative to open sun drying and further observed that greenhouse air temperature varies from 31 to 58°C and 30 to 60°C for peeled longan and banana respectively. Kumar and Tiwari [9] observed the effect of mass on heat transfer coefficient in open as well as greenhouse drying under forced mode on onion flakes. It was found that moisture evaporation rate in greenhouse was more than open sun drying during off sunshine hour.

II. EXPERIMENTAL SETUP

In the experimental setup, PV integrated greenhouse dryer has been taken. Experimental setup consists of three PV modules, DC fan (1 to 2), and a drying chamber. Photovoltaic module used in this drying system used for three purposes one is to give power to DC fan, second excess power to store or to use in other solar operated systems and third to avoid direct exposure of crop to avoid discoloration.

DC fans connected with photovoltaic panel are place at north wall of PVT dryer. At the bottom of the PVT dryer has clearance of 0.1 m height for fresh air circulation. It has floor area of 1.025 m \times 1.04 m and total volume is 0.71 m³. Upper and lower heights of the PVT dryer are 1.04 m and 0.4 m respectively. Inclination of roof facing due south is 30⁰. The working principle of solar dryer is based on greenhouse effect in which short wave length solar rays can penetrate the glass envelope but after absorption sort wavelength converted into long wavelength. Due to low energy of long wavelength rays

Sumit Tiwari is with the Indian Institute Technology, Delhi, New Delhi, India (corresponding author phone: +91-11-26596469; e-mail engg.sumit85@ gmail.com).

Rohit Tripathi and G.N. Tiwari are with the Indian Institute Technology, Delhi, and New Delhi, India (e-mail: rohittripathi30.iitd@gmail.com, gntiwari@ces.iitd.ac.in).

are unable to escape from the system and responsible for increasing the temperature of the system.



Fig. 1 (a) Front view of greenhouse dryer



Fig. 1 (b) Back side view of greenhouse dryer

III. THERMAL MODELLING

The following assumptions have been taken for thermal modelling

- i. Heat capacity of metal used in greenhouse is neglected
- ii. Thin layer drying has been considered
- iii. Single tray has been used in modelling

a) Energy balance equation for PV

$$\alpha_c \tau_g \beta_c I(t) A_m = U_{tca} (T_c - T_a) A_m + U_{bcr} (T_c - T_r) A_m + \tau_g \beta_c \eta_c I(t) A_m$$
(1)

b) Energy Balance equation for crop

$$\begin{aligned} \alpha_{cr}\tau_g^{3}(1-\beta_c)I(t)A_m + \alpha_{cr}\tau_gA_c\sum I(i) + U_{bcr}(T_c - T_r)A_c \\ = M_{cr}C_{cr}\frac{dT_{cr}}{dt} + h_{cr}(T_{cr} - T_r)A_c \end{aligned}$$
(2)

c) Energy equation for green house chamber

$$\dot{M}_{f}C_{f}(T_{r}-T_{a}) = \dot{M}_{f}C_{f}(T_{r}-T_{fo}) + \Sigma(UA)(T_{r}-T_{a})$$
(3)

In the steady state condition,

Thermal energy lost from the system=Thermal energy carried away by hot air

$$A_{c}h_{cr}(T_{cr} - T_{r}) = \dot{M}_{f}C_{f}(T_{r} - T_{a})$$

$$T_{r} = \frac{A_{c}h_{cr}T_{cr} + \dot{M}_{f}C_{f}T_{a}}{A_{c}h_{cr} + \dot{M}_{f}C_{f}}$$
(4)

Putting the value of T_c and T_r from (1) and (4) in (2)

$$\frac{dT_{cr}}{dt} + \frac{1}{M_{cr}C_{cr}} (U_{tcra} + \frac{U_{tra}A_{c}h_{cr}T_{cr}A_{c}}{A_{c}h_{cr} + \dot{M}_{f}C_{f}})T_{cr} = \frac{1}{M_{cr}C_{cr}} ((PF(\alpha_{c}\tau_{g}\beta_{c} - \tau_{g}\beta_{c}\eta_{c})A_{c} \quad (5)$$
$$+ \alpha_{cr}\tau_{g}^{3}(1 - \beta_{c})A_{m})I(t) + \alpha_{cr}\tau_{g}A_{c}\sum I(i) + (U_{tcra} + \frac{U_{tra}A_{r}h_{cr}T_{cr}A_{c}}{A_{c}h_{cr} + \dot{M}_{f}C_{f}})T_{a})$$

$$\frac{dT_{cr}}{dt} + aT_{cr} = f(t) \tag{6}$$

where,
$$a = \frac{1}{M_{cr}C_{cr}} (U_{lcra} + \frac{U_{tra}A_{l}h_{cr}T_{cr}A_{c}}{A_{c}h_{cr} + \dot{M}_{f}C_{f}})T_{cr}$$
 and

$$f(t) = \frac{1}{M_{cr}C_{cr}} ((PF(\alpha_{c}\tau_{g}\beta_{c} - \tau_{g}\beta_{c}\eta_{c})A_{c} + \alpha_{cr}\tau_{g}^{3}(1 - \beta_{c})A_{m})I(t)$$

$$+\alpha_{cr}\tau_{g}A_{c}\sum I(i) + (U_{tcra} + \frac{U_{tra}A_{l}h_{cr}T_{cr}A_{c}}{A_{c}h_{r} + \dot{M}_{f}C_{f}})T_{a})$$

From (6),

v

$$T_{cr} = \frac{f(t)}{a} (1 - e^{-at}) + T_{cro} e^{-at}$$
(7)

Crop temperature (Tcr) can be calculated by (7). T_r and T_c can be calculated by putting the value of T_{cr_i} in (4) and (1). Cell efficiency can be written as [10]

$$\eta_c = \eta_o (1 - \beta_o (T_c - T_o)) \tag{8}$$

The module efficiency can be written as

$$\eta_m = \tau_g \beta_c \eta_c \tag{9}$$

Electrical energy from PV module can be written as

$$\dot{Q}_{u,el} = \eta_m A_m I(t) \tag{10}$$

Thermal energy gain from greenhouse dryer can be written as

$$\dot{Q}_{u,th} = \dot{M}_{f} C_{f} (T_{fo} - T_{a})$$
(11)

$$\dot{Q}_{th,ov} = \dot{Q}_{u,th} + \frac{\dot{Q}_{el}}{0.38}$$
(12)

Thermal efficiency can be evaluated by the help of

$$\eta_{th} = \frac{\dot{M}_{f}C_{f}(T_{fo} - T_{a})}{I(t)A}$$
(13)

Overall thermal efficiency can be calculated as

$$\eta_{ov,th} = \eta_{th} + (\eta_c / 0.38) \tag{14}$$

IV. RESULT AND DISCUSSION

The hourly variations of solar intensity and ambient temperature have been taken for May and November. Fig. 2 shows variation of total solar radiation, diffuse radiation, and ambient temperature. It is clear that for Delhi climatic conditions the solar radiation, diffuse radiation, and ambient temperature is more in May.



Fig. 2 Hourly Variation of total solar radiation, diffuse radiation and ambient temperature with respect to time for May and November



Fig. 3 Hourly Variation of solar cell temperature and solar cell efficiency with respect to time for May and November

Fig. 3 shows the variation of solar cell efficiency and solar cell temperature with respect to time. Figure shows that as the cell temperature increases the efficiency of cell decreases as expected from (8). Further, it is clear with graph that electrical efficiency is more in November.

Fig. 4 shows the hourly variation of ambient temperature, cell temperature, greenhouse chamber temperature, crop

temperature and outlet air temperature which is coming by help of MATLAB programming for May and November.

Fig. 5 shows hourly variation of overall thermal energy $(Q_{th,ov})$ with respect to time for a typical clear day of May and November. It was found that overall thermal energy increases up to 12 noon and further it decreases as the solar radiation decreases. Overall thermal energy for May and November found to be 7.65 kWh and 6.66 kWh per day respectively. Further, Fig. 6 shows the variation of electrical energy throughout a day. Overall thermal energy for May and November found to be 1.90 kWh and 1.91 kWh per day respectively. According to graph, the solar radiation is less in November but electrical energy is more due to higher solar cell efficiency.



Fig. 4 Hourly variation of ambient temperature (T_a) , cell temperature (T_c) , greenhouse chamber temperature (T_r) , crop temperature (T_{cr}) and outlet air temperature for a typical clear day of May and November



Fig. 5 Hourly variation of overall thermal energy $(Q_{th,ov})$ with respect to time for May and November

International Journal of Electrical, Electronic and Communication Sciences ISSN: 2517-9438 Vol:10, No:1, 2016

 A_m

 A_i

 h_o

 h_1

kg

lg

Ν

 T_c

 T_{cr}

 T_r

 α_c

 β_c

γ



Fig. 6 Hourly variation of electrical energy (Qelov) with respect to time for May and November



Fig. 7 Hourly variation of overall thermal efficiency (η_{th}) and electrical efficiency $(\eta_{ov,th})$ with respect to time for May and November

Fig. 7 shows hourly variation of overall thermal and electrical efficiency. From the graph it is clear that overall thermal efficiency is more in the case of May and electrical energy is more in the case of November.

V. CONCLUSION

From the present study, following conclusion can be made as the cell temperature increases corresponding efficiency decreases. Total overall thermal energy for a clear day of May and November found to be 7.65 kWh and 6.66 kWh respectively. Electrical energy for a clear day of May and November found to be 1.91 kWh and 1.9 kWh respectively. Maximum overall thermal efficiency can be achieved 64 and 69 percent for November and May respectively. Analysis shows that there is very less output difference in summer and winter season so PV integrated greenhouse dryer can be used throughout the year. It is recommended that by increasing the roof area of greenhouse, more electricity can be produced which can be used for appliances in villages where grid connectivity is not available.

NOMENCLATURE

Area of crop surface (m^2) A_c

- Area of module (m^2)
- Area of all side wall of dryer (m²)
- C_f Specific heat of air (J/kg K)
- Specific heat of crop (J/kg K) C_{cr}
- Diameter of fan (m) d
- E_{in} Embodied energy (kWh)
- Eaout Total energy output per year (kWh)
- Heat transfer coefficient (htc) inside solar drying chamber hi (W/m^2K)
- h_{cr} Total htc from crop surface to solar drying chamber (W/m^2K) Convective htc from crop surface to solar drying chamber h_{crc} (W/m^2K)
- Evaporative htc from crop surface to solar drying chamber hcrev (W/m^2K)
 - Heat transfer coefficient from top of module to ambient (W/m^2K)
 - Heat transfer coefficient from wall of dryer to ambient (W/m^2K)
- I(t)Solar intensity (W/m^2)
- I(i) Solar intensity on the wall of drying chamber (W/m²)
 - Thermal conductivity of glass (W/mK)
 - Thickness of glass cover (m)
- \dot{M}_{f} Mass flow rate of air (kg/s)
- M_{cr} Mass of crop (kg)
 - Fan speed (RPM)
- P_{fan} Power of fan (W)
- P_{Tr} Partial pressure at green house chamber temperature (N/m²)
- P_{Tcr} Partial pressure at crop temperature (N/m²) T_a
 - Ambient temperature (⁰C)
 - Cell temperature (⁰C)
 - Crop temperature (^{0}C)
 - Drying chamber temperature (^{0}C)
- Heat transfer coefficient from bottom of module to drying U_{bcr} chamber (W/m²K)
- Heat transfer coefficient from top of module to ambient air U_{tca} (W/m^2K)
 - Absorptivity of solar cell
- Absorptivity of crop α_{cr}
 - Packing factor of module
 - Relative humidity
- Solar cell efficiency η_c
- Module efficiency η_m v
 - Wind velocity (m/s)
- Air velocity in drying chamber (m/s) v_l τ_g
 - Transmissivity of glass

APPENDIX I

Formulae used to calculate different heat transfer coefficients used in thermal analysis are as:

$$\begin{aligned} v_{1} &= \frac{\pi^{2} d^{3} N}{4 \times 60 \times A_{c}} & \dot{M}_{f} = \rho A_{c} v_{1} \\ h_{cr} &= h_{crc} + h_{crew} & h_{crc} = 2.8 + 3 v_{1} \\ h_{crev} &= \frac{0.01667 h_{crc} (P_{Tcr} - \gamma P_{Tr})}{T_{cr} - T_{r}} & h_{o} = 5.7 + 3.8 v \\ U_{tcra} &= (A_{c} h_{cr} \dot{M}_{f} C_{f}) / (A_{c} h_{cr} + \dot{M}_{f} C_{f}) \\ h_{1} &= 2.8 + 3 v & h_{i} = 2.8 + 3 v_{1} \\ U_{bca} &= 2 \times ((l_{g} / k_{g}) + (1 / h_{i}))^{-1} & U_{tca} &= ((l_{g} / k_{g}) + (1 / h_{o}))^{-1} \end{aligned}$$

 $U_{wra} = (l_g / k_g) + (1 / h_1)$ $UA = A_m U_{tca} + A_i U_{wra}$ $P_{Tcr} = \exp(25.317 - (5144 / (273 + T_{cr})))$ $P_{Tr} = \exp(25.317 - (5144 / (273 + T_r)))$

APPENDIX II

Various design parameters taken for calculation of different temperatures:

$\alpha_c = 0.9$	$\tau_{g} = 0.9$	$\beta_{\rm c} = 0.6543$
$\eta_0 = 0.15$	$\alpha_{\rm cr} = 0.6$	$M_{cr} = 2 \text{ kg}$
C_{cr} = 3900 J/kg K	$\gamma = 0.4$	v=1 m/s
$A_m = 1.3264 \text{ m}^2$	$A_i = 1.3264 \text{ m}^2$	$A_c = 1.2666 \text{ m}^2$
C_{f} =1005 J/kg K	$k_g = 0.816 \text{ w/mK}$	<i>d</i> =0.1 m
N=1100 rpm	$l_g = 0.003 \text{ m}$	$ ho = 1 \text{ kg/m}^3$

REFERENCES

- Esper A and Muhlbauer W. Solar drying an effective means of food preservation," Renewable Energy 1998; 15: 95–100.
 Guine RPF and Castro JAAM. Experimental Determination and
- Computer Fitting of Dessorption Isotherms of D. Joaquina Pears. Food and Bioproducts Processing 2002; 80(C):149-154. Pawar RS, Takwale MG, Bhide VG. Solar drying of custard powder.
- [3] Energy Convers Manage 1995; 36:1085-96.
- Barnwal P, Tiwari GN. Grape drying by using hybrid photovoltaic-thermal (PV/ T) greenhouse dryer: an experimental study. Solar [4] Energy2008; 82:1131-44.
- Smitabhindu R, Janjai S, Chankong V. Optimization of a solar-assisted [5] drying system for drying bananas. Renew Energy 2008; 33:1523-31.
- [6] Kumar A, Tiwari GN. Thermal modelling and parametric study of a forced convection greenhouse drying system for jaggery: an experimental validation. International Journal of Agricultural Research 2006; 1(3):265-79.
- Barnwal P and Tiwari GN. Grape drying by using hybrid photovoltaic-[7] thermal (PV/T) greenhouse dryer: An experimental study. Sol. Energy 82, 1131-1144 (2008).
- [8] Janjai S, Lamlert N, Intawee P, Mahayothee B, Bala BK, Nagle M. Experimental and simulated performance of a PV-ventilated solar greenhouse dryer for drying of peeled longan and banana. Solar Energy 2009; 83:1550-65.
- Kumar A, Tiwari GN. Effect of mass on convective mass transfer [9] coefficient during open sun and greenhouse drying of onion flakes. Journal of Food Engineering 2007; 79:1337–50.
- [10] Evans DL. Simplified method for predicting PV array output. Sol. Energy 27, 555–560 (1981).