INTERNATIONAL JOURNAL OF SCIENTIFIC & TECHNOLOGY RESEARCH VOLUME 1, ISSUE 11, DECEMBER 2012 ISSN 2277-8616

A Steady State Thermal Model For Photovoltaic/Thermal (PV/T) System Under Various Conditions

R. K. Koech, H. O Ondieki, J. K. Tonui, S. K Rotich

Abstract:- The increasing environmental concerns and the escalating conventional energy supply costs are creating a resurgence of interest in renewable energy resources. Hybrid Photovoltaic/Thermal (PV/T) solar technology is a relatively new solar conversion technology which convert the incident solar radiation into usable electrical and thermal energy simultaneously. The basis of this technology is the negative temperature coefficient of the electrical conversion efficiency of crystalline PV cells that leads to reduction in performance of installed PV panels at high irradiance levels. In addition, the commercially available PV modules have relatively low efficiencies of not more than 20% meaning that 80% or more of the incoming solar radiation is wasted and converted as heat, raising the operating temperature of the module. A low temperature fluid, usually water or air, is circulated through the heat exchanger attached to PV back to extract the excess heat from the panel hence cooling it in the process. The heat extracted can be harnessed and used for low temperature applications like space heating and ventilation in buildings or drying applications in agricultural and industrial sectors. In this study, a steady state thermal model of a PV/T air solar collector was developed, validated from experimental data and then used to study the effects of various parameters on the performance of the system. The results indicate that increasing the air mass flow rate when the design parameters are optimum will result into a significant increase in the overall performance of the system.

Key words:- Solar radiation, PV panel, PV/T collector, thermal model, electrical efficiency, heat exchanger

INTRODUCTION

Energy plays a very important role wherever man lives and works. The living standard and prosperity of a nation vary directly with the increase in the use of energy. The global energy demand is increasing rapidly due to industrial growth, population growth as well as increased and extensive use of electrical gadgets. As human needs know no bounds, today most of the nations worldwide have been experiencing the problem of power shortages. This is more critical among the developing countries which seek to catch up with the economic development which has been attained by industrialized countries. In addition, climate change, caused by Green House Gas (GHG) emissions resulting from the use of conventional energy resources is

NOMENCLATURE

A_c	Collector area (m^2)
C_p	Specific heat capacity of air ($J\ kg^{-1}\ K^{-1}$)
H	Height of duct (m)
h_c	Convective heat transfer coefficient at heated surfaces ($Wm^{-2}\ K^{-1}$)
h_{t-f}	Convective heat transfer coefficient at tedlar ($Wm^{-2}\ K^{-1}$)
$h_{r,t-b}$	Radiative heat transfer coefficient from tedlar to back plate ($Wm^{-2}\ K^{-1}$)
h_{b-f}	Convective heat transfer coefficient at tedlar ($Wm^{-2}\ K^{-1}$)
k	Thermal conductivity ($Wm^{-1}k^{-1}$)
L	Collector length (m)
W	Collector width (m)
G	Incident solar radiation (Wm^{-2})
T	Temperature (K)

Greek Symbols

$\dot{m}$	mass flow rate
α	Absorptivity
η	Efficiency
β	Temperature coefficient of the efficiency

Subscripts

a	Ambient
b	Back plate
c	PV Cell
g	Glass
f	Fluid
i	Inlet
o	Outlet
r	Reference
tb	Tedlar back
t	Top
si	Silicon
EVA t	Top EVA layer
EVA b	bottom EVA layer

- R. K. Koech*, H.O Ondieki, J.K. Tonui, and S.K Rotich
- School of Science, Department of Physics Chepkoilel University College.
- P.O Box 1125 – 30100, Eldoret, Kenya
- Tel: 0727 414 962.
- E-Mail: rkkoech09@gmail.com

an eminent disaster [1].Meeting this energy demand in a sustainable manner calls for major transformations in the energy sector. A vast transition to renewable energy resources such as solar energy is the best option in this regard and also for alleviating poverty in developing countries where the majority of people do not have access to modern forms of energy. Renewable energy resources, due to their inherent decentralised nature can contribute, to a greater extent, to this goal. Hybrid photovoltaic/thermal (PV/T) system, which converts incident solar energy into both electrical and thermal energy, is one of the best options with regards to this. In a typical PV panel, only 5-20% of the incident sunlight is converted into electricity, while over 80% is converted into heat and thrown away [2]. In a PV/T module, this heat can be extracted and used effectively by attaching a heat exchanger behind the PV module with either air or water as a heat transport medium. This will allow the PV component to operate at its peak electrical output and mitigates the degradation problem of the PV cells due to overheating. The system therefore, generates thermal energy in addition to electrical energy from one surface area. This is highly desirable in that it solves the growing problem of "competing roof space," which occurs when a roof is covered completely in standard modules leaving no room for other solar technologies. Research in PV/T systems has been ongoing since the mid 1970s and various designs of the system have been developed and studied theoretically, numerically and experimentally [3-9]. The most recent works on these systems focus on finding the system design and operating factors which would result in increased electrical and thermal efficiencies [10-13]. The research work performed to date has revealed the potential of the hybrid technology for a variety of applications [14]. In this study, a steady state thermal model of a PV/T air solar collector under natural flow mode was developed, validated from experimental data and then used to study the effects of various parameters on the performance of the system.

THEORETICAL ANALYSIS

The PVT/Air system studied in this work is consists of a PV laminate, a rectangular air channel, a back absorber plate and back insulation as shown in figure 1.

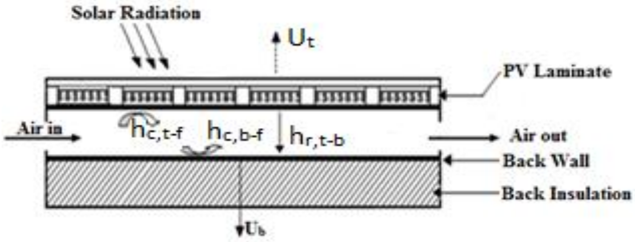

Figure 1: Cross-sectional view of the PVT air collector

The PV laminate is also made up of solar cells sandwiched between a glass cover on top and a tedlar at the bottom using Ethylene Vinyl Acetate (EVA) as an adhesive. The heat generated at the solar cells is transferred among the components of the PV laminate are shown in Figure 2.

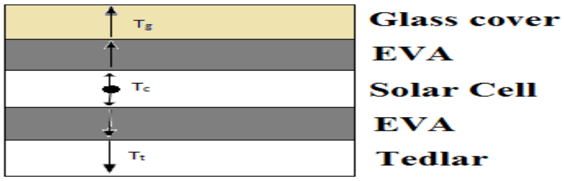

Figure 2: Heat transfer across the layers of PV laminate

The energy balance equations for the various components of the PV/T Air system are:

Glass cover

$$\propto_g G + P q_{up} = U_t (T_g - T_a) \qquad (1)$$

Where U_t, P and q_{up} are the top loss coefficient, the packing factor and the amount of heat conducted upwards from the solar cells respectively. q_{up} is calculated as:

$$q_{up} = R_{up} (T_c - T_g) \qquad (2)$$

Where R_{up} is the upward thermal resistance and obtained as:

$$R_{up} = \frac{\left(L_{si}/_2\right)}{k_{si}} + \frac{L_{eva\,t}}{k_{eva\,t}} + \frac{L_g}{k_g} \qquad (3)$$

PV Cell.

The energy absorbed by the PV cells is converted to electricity and heat. The heat produced is distributed as per the energy balance equation given below:

$$\tau_g \alpha_c G \left(1 - \eta_{pv}\right) = q_{up} + q_{down} \qquad (4)$$

q_{down} is the amount of heat conducted downwards from the solar cells and is given by:

$$q_{down} = R_{down} (T_c - T_t) \qquad (5)$$

Where R_{down} is calculated as:

$$R_{down} = \frac{\left(L_{si}/_2\right)}{k_{si}} + \frac{L_{eva\,b}}{k_{eva\,b}} + \frac{L_t}{k_t} \qquad (6)$$

Tedlar

$$\tau_g \alpha_t G(1 - P) + P q_{down} = h_{rt-b} (T_{tb} - T_b) + h_{ct-f} \left(T_{tb} - T_f\right) \qquad (7)$$

Air Flow in the duct

$$\dot{m} \mathrm{C_p} (T_o - T_i) = A_c \left[h_{c,t-f} \left(T_{tb} - T_f\right) + h_{c,b-f} (T_b - T_f)\right] \qquad (8)$$

Back absorber plate

On the bottom plate, the heat gained from the back surface of tedlar through the radiative heat transfer process is shared as heat gain by the airflow in the duct and heat loss through the back insulation:

$$h_{r,t-b}(T_{tb} - T_b) = h_{c,b-f}(T_b - T_f) + U_b(T_b - T_a) \qquad (9)$$

Where U_b is the back loss coefficient.

It is assumed that the rear surface of the duct is well-insulated, so that this surface is effectively adiabatic, and all the energy reaching it by radiation from the front surface is transmitted back into the fluid by convection. Hence $U_b = 0$ and $h_{c,t-f}$ can be considered equal to $h_{c,b-f}$ so that [14]

$$h_{c,t-f} = h_{c,b-f} = h_c \qquad (10)$$

For laminar flow in a duct between parallel plates, the convective heat transfer coefficient can be obtained as [15]

$$h_c = \frac{N_u k}{D_h} \qquad (11)$$

N_u is the nusselt number that gives the ratio of convective to conductive heat transfer across (normal to) the boundary, D_h is the hydraulic diameter which for non-circular ducts is calculated as [15]

$$D_h = \frac{4(W \times H)}{2(W + H)} \qquad (12)$$

Performance Indicators

The performance of the system is specified in terms of its electrical and thermal efficiencies

(i) Electrical Efficiency

The electrical efficiency was calculated as:

$$\eta_e = \eta_r(1 - \beta(T_c - T_r)) \qquad (13)$$

Where β is the temperature coefficient of the efficiency of a crystalline PV module and is equal to 0.0045, η_r is the reference efficiency of the PV cell at the reference temperature, T_r (usually 25 °C) [16].

(ii) Thermal Efficiency

The thermal efficiency of the system was calculated using the equation

$$\eta_{th} = \frac{Q_u}{G.A_c} \qquad (14)$$

Where Qu is the useful heat transferred to the air in the duct.

COMPUTATIONAL METHODOLOGY

The expressions for the temperatures of the glass cover, the PV cells, the tedlar, the flowing air and the back plate were obtained from equations (1), (4), (7), (8) and (9). These together with equations (13) and (14) were then coded into FORTRAN95 simulation program and solved through iterations.

RESULTS AND DISCUSSION

(i) Effects of irradiance

The influence of irradiance on the electrical and thermal efficiencies of the PVT/Air system is shown in figure 3. The air mass flow rate, wind velocity and the ambient temperature were fixed at 0.015 kg/m^3/s, 1.5 m/s and 25^0 C respectively. The results indicate that the thermal efficiency increases with irradiance whereas the electrical efficiency decreases. The increase in thermal efficiency at high irradiance is due to the increase in the temperature of the tedlar and the back plate which implies that more heat will be transferred to the air in the duct. The observed decrease in electrical efficiency is due to the increase in the PV cell operating temperature with irradiance.

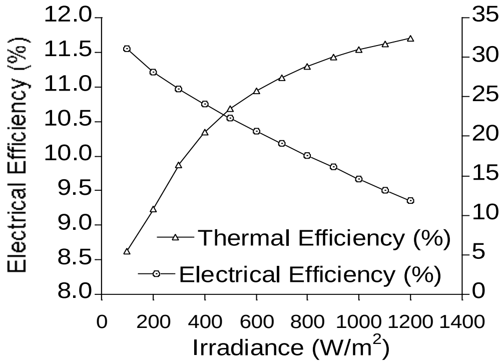

Figure 3: Effects of irradiance on electrical and thermal efficiencies

(ii) Effects of Ambient Temperature

Figure 4 shows the effects of ambient temperature on the performance of PV/T Air system. It is observed that an increase in ambient temperature results into a decrease in both the electrical and thermal efficiencies. This is a consequence of the fact that at high ambient temperatures, the fluid inlet temperature to the duct is also high leading to poor heat extraction from the PV cells.

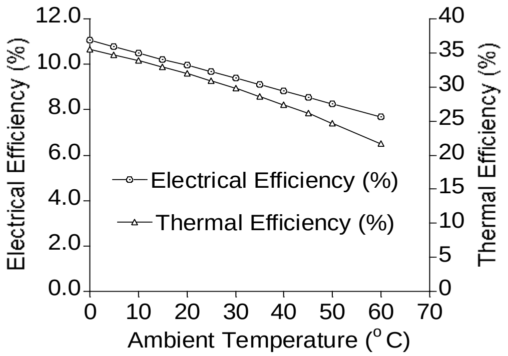

Figure 4: Effects of Ambient Temperature on Electrical and Thermal Efficiencies

(iii) Effects of Collector Length

The length of the PV/T air collector was varied while keeping the number of PV cells constant. The effect of this on the system performance is shown in figure 5. It is observed that the thermal efficiency increase with an increases with the length of the collector though the electrical efficiency decreases. This is explained by the decrease of the packing factor as the length increases. This results into an increase in the amount of solar radiation directly absorbed by the tedlar through the inter-cell spaces. This reduces the rate of heat transfer from the PV Cells to the tedlar but increases the heat transfered to the air. The variations in the efficiencies, however, tend to be very minimal at large collector lengths due to an increase in the amount of heat loss at the top cover.

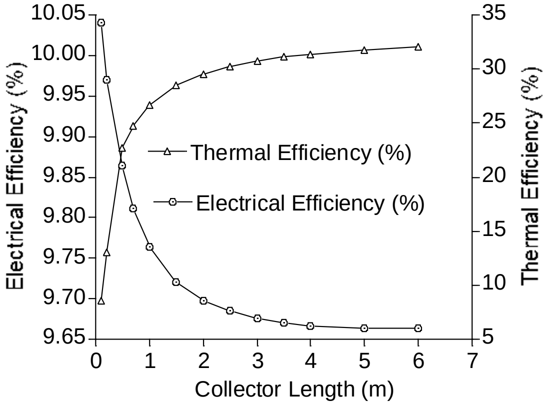

Figure 5: Effect of Collector Length

(iv) Effect of thermal conductivity of tedlar

The effect on the efficiency of the collector was investigated by varying the thermal conductivity of tedlar from 0.0005-0.1 $Wm^{-1}k^{-1}$. It was observed (from figure 6) that an increase in the thermal conductivity of tedlar leads to a corresponding increase in both the electrical and thermal efficiency of the system. This is caused by the increase in the amount of heat transferred to the air and the corresponding decrease in the PV cell temperature as the thermal conductivity of tedlar increases.

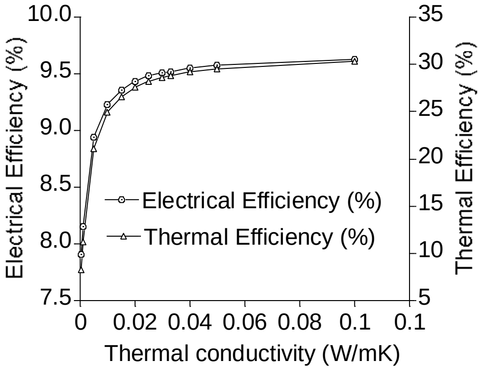

Figure 6: Effect of thermal conductivity of tedlar

(v) Effect of mass flow rate

The effect of the air mass flow rate on the electrical and thermal performance of the PV/T Air collector is shown in figure 7. As observed from the figure, the thermal and the electrical efficiencies increase as the mass flow rate increases. This is due to the fact that when the mass flow rate increases; the amount of heat extracted by the air in the duct increases. The more the amount of heat extracted by the air, the lower the PV module temperature and hence the higher electrical and thermal efficiencies.

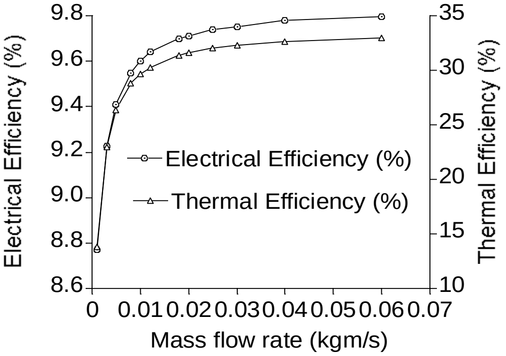

Figure 7: Effects of mass flow rate

CONCLUSION

It was observed that a reduction in the thermal resistance of the tedlar through an increase in its thermal conductivity form 0.0005-0.025 W/mk leads to an increase in electrical and thermal efficiency by about 20% and 24% respectively. Increasing the mass flow rate when thermal resistance below the solar cells is very low will lead to a significant increase in the overall performance of the system.

REFERENCES

[1] Sanchez B.A. and Poschen P. (2009) “The social and decent work dimensions of a new Agreement on Climate Change; *A Technical Brief*

[2] Chow T.T. “A review on photovoltaic/thermal hybrid solar technology.” *Applied Energy* 87 (2010) 365–379 doi:10.1016/j.apenergy.2009.06.037

[3] Cox, C.H. and S.C. Raghuraman, 1985. Design considerations for flat-plate photovoltaic/thermal collectors. Solar Energy, 35: 237-242.

[4] Garg, H.P., R.K. Agarwal and A.K. Bhargava, 1991. Study of a hybrid solar system-solar air heater combined with solar cells. Energy Convers. Manage., 31: 471-479.

[5] Sopian, K., K.S. Yigit, H.T. Liu, S. Kakac and T.N. Veziroglu, 1996. Performance analysis of photovoltaic thermal air heaters. Energy Convers. Manage., 37: 1657-1670

[6] Hegazy, A.A., 1999. Comparative study of the performances of four photovoltaic/thermal solar air collectors. Energy Convers. Manage., 41:861-881

[7] Tonui J. K. and Tripanagnostopoulos Y., “Improved PV/T solar collectors with heat extraction by forced or natural air circulation," *Renewable Energy*, 32(4), 2007, pp. 623–637.

[8] Ibrahim A., Othman M.Y., Ruslan M.H., Alghoul M.A., M.Yahya, and A. Zaharim and K. Sopian "Performance of Photovoltaic Thermal Collector (PVT) With Different Absorbers Design"**,** Issue 3, Volume 5, March 2009

[9] Jin G.L, Ibrahim A., Chean Y.K, Daghigh R., Ruslan H., Mat S. Othman M.Y and Sopian K. "Evaluation of Single-Pass Photovoltaic-Thermal Air Collector with Rectangle Tunnel Absorber", *American Journal of Applied Sciences* 7 (2): 277-282, 2010 ISSN 1546-9239

[10] Tiwari A, Sodha M.S. "Parametric study of various configurations of hybrid PV/thermal air collector: Experimental validation of theoretical model", *Solar Energy Materials & Solar Cells* 91 (2007):17–28

[11] Joshi A.S, Tiwari A, Tiwari GN, Dincer I, Reddy BV. "Performance evaluation of a hybrid photovoltaic thermal (PV/T) (glass-to-glass) system." *Int J. Therm Sci* 2009; 48:154–64.

[12] Barnwal, P. and Tiwari, G.N. "Experimental Validation of Hybrid Photovoltaic-Thermal (PV/T) Greenhouse Dryer under Forced Mode," *International Journal of Food Engineering* 6(6), 2010, Article 17. DOI: 10.2202/1556-3758.1451

[13] Sarhaddi F., Farahat S., Ajam H., Behzadmehr A., Adeli M. M. "An improved thermal and electrical model for a solar photovoltaic thermal (PV/T) air collector", *Applied Energy* 87 (2010):2328–2339.

[14] Riffat S.B. and Cuce E. "A review on hybrid photovoltaic/thermal collectors and systems." *Int. J. Low-Carbon Tech.* (2011) doi: 10.1093/ijlct/ctr016 First published online: July 21, 2011

[15] Lee W.M., Infield D.G, Gottschalg R. "Thermal modeling of building integrated photovoltaic system," *Proc. 17th, European PV Solar Energy Conference*, Germany 2001, vol.III pp.2754-2757.

[16] Zondag H.A,, De Vries D.W, Van Helden W.G.J., van Zolingen R.J.C., van Steenhoven A.A. The yield of different combined PV-thermal collector designs Solar Energy 74 (2003) 253–269