Photovoltaic/Thermal (PV/T) System as Innovative Solution to Increase Solar Energy Conversion Efficiency

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Abstract— Photovoltaic (PV) modules and solar thermal collectors are convensional solar systems that convert solar radiation into electricity and heat energy respectively. PV modules generate clean electricity and ideal for use in developing countries where human settlement is scattered in remote rural areas and no grid electricity is available. However, electrical conversion efficiency of commercial PV modules is still low (~20%) hence about 80% of the incoming solar energy is lost as waste heat which raises module temperature resulting into a reduction in its electrical efficiency. Hybrid photovoltaic/thermal (PV/T) solar collectors are innovative systems that generates heat and electricity simultaneously hence increases solar energy conversion efficiency of a PV module. A PV/T system is a PV module with a heat exchanger attached behind it for passing a colder fluid (usually air or water) for extracting useful heat and hence cooling the PV module. In the present work, a parametric model based on heat transfer between adjacent components of a PV/T air collector under natural flow was developed. The model was coded in FORTRAN 95 and validated from experimental data measured on a similar experimental model. The validated model was used to study theoretically the effects of some design and operating parameters on the channel wall heat flux. The results show that increasing thermal conductivity of tedlar increases the heat flux transferred from the two channel walls while increasing the thickness of the back EVA decreases the heat flux transferred from the two walls to airflow

Keywords-- heat flux, modeling, PV laminate, PV/T collector, thermal resistance.

I. INTRODUCTION

Energy is an intrinsic component in economic and human development all over the world. The energy demand has been on the rise due to the industrial and population growths in many countries worldwide. The convectional energy sources, particularly petroleum fuels, which have been the major sources of energy, are getting exhausted and their utilization has contributed greatly to global warming. The combustion of fossil fuels emits greenhouse gases (GHG), mainly CO₂, which are discharged to the atmosphere.

The GHGs accumulate in the troposphere and forms a skin layer which prevents escape of reradiated infrared radiation into the outer space but instead reflect it back causing the atmospheric temperature to increase hence global warming [1]. Thus, the challenge of any economy today is the provision of affordable energy to meet the rapidly growing demand of energy while simultaneously satisfying the increasing concern on the earth’s climate change.

Meeting the increasing energy demand in a sustainable way will not be possible without major changes in the energy supply and conversion systems. The shift to renewable energy resources, especially solar energy, is envisaged to be a practical solution to meet the world’s future energy demand as well as mitigating the adverse effects of climate change. The sun is an enormous source of energy in the universe and any known forms of energy owe its existence to the sun either directly or indirectly. The advantage of solar energy is its ability to be harnessed to provide the two widely sought forms of energy – heat and electricity, using various types of solar technologies. Photovoltaic (PV) systems are solar energy technologies which intercept sunlight and convert it into direct current (dc) electricity and are ideal for rural applications where grid electricity is not available. Solar thermal collectors, on the other hand, are solar technologies that collect the incoming solar radiation and convert it into heat through a heat transfer fluid (usually water or water) for heat production. A disparity exists on the extent of application of solar technologies between the developed and developing world. The application of both PV and solar thermal systems are high in developed countries but low in developing countries, mainly African continent, due to lack of awareness and high initial cost to majority of the rural population.

The solar conversion efficiency of commercial PV modules varies between 5-20% depending on the cell technology. This means that at least 80% of the incoming solar radiation is lost as waste heat in the PV module.
The waste heat is lost partly to the atmosphere, which contributes to global warming, while the remaining manifests as temperature rise in the solar cells. The rise in cell temperature, especially crystalline silicon solar cell, lowers its electrical conversion efficiency below its rating \[2\] hence cooling is beneficial. Hybrid photovoltaic/thermal (PV/T) systems are solar technologies that combine photovoltaic and solar thermal systems in one unit and are capable of producing both electrical and thermal energy simultaneously. Thus, PV/T systems are innovative solutions of increasing solar energy conversion efficiency in one unit compared to individual PV or solar thermal collector mounted side-by-side. The major benefit of PV/T system is the cooling achieved with the circulating colder fluid. The cold fluid will extract the heat from module and maintains cells’ temperatures, which in turn maintains the PV efficiency within acceptable level. The basic structure of a PV/T system consists of a PV module with a heat exchanger attached behind for heat extraction with a proper natural or forced fluid circulation. The heat extracted by the fluid is channeled through proper ducting for low temperature applications such as water-heating for domestic chores, space heating in buildings and drying in agricultural and industrial sectors.

Over the last few decades, efforts have been devoted to improving the performance of PV/T systems while reducing their costs. The early work on the PV/T systems was carried out by Wolf \[3\] who proposed the possibility of combined generation of heat and electricity from a PV installation for residential use. Numerous experimental and theoretical studies have been done since the inception of PV/T system, both water- and air type PV/T systems. The focus has been on the design aspects that will result in higher efficiencies \[4-10\]. More recent works on PV/T systems focused mainly on design configurations and operating conditions that would result in increased electrical and thermal efficiencies \[11-15\]. These studies, however, have not considered the thermal resistance and hence temperature gradients across the thickness of the PV laminate. Study of this thermal resistance provides a leeway to identify the mechanisms to increase the amount of heat extracted from the PV laminate to the flowing air in the channel. This paper presents theoretical analysis of a PV/T air system under natural flow mode. The effects of thermal resistance of the back tedlar and the thickness of the EVA adhesive between the cells and tedlar back on the heat flux to the air flow from the channel walls are presented.

The results show that increasing thermal conductivity of tedlar increases the heat flux transferred from the two channel walls while increasing the thickness of the back EVA decreases the heat flux transferred from the two walls to airflow.

II. THEORETICAL MODEL

Fig. I shows a schematic diagram of the PV/T Air system studied and the heat exchange between adjacent components of the PV/T system themselves and its surrounding.

![Fig. I: Schematic diagram of a PV/T Air system](image)

The system consists of a PV laminate, a rectangular air channel and a back insulation. The circulation of air in the duct is by natural convection. The PV laminate consists of the solar cells, the top glass cover and the tedlar joined together using EVA adhesive as shown in Fig. II. Energy balance equations between PV laminate, airflow in the duct, channel back wall and surrounding environment are usually constituted to solve for PV/T components’ temperatures and useful heat gain and have been reported in many papers \[8\]. These equations were used in the theoretical model developed.

![Fig. II: Nodal temperatures across the layers of PV laminate](image)
A. Thermal Analysis

The heat transfer paths across the PV/T components are shown in Fig. III [9]. The heat transfer between the components of PV laminate is by conduction, while the heat lost at the top of the glass cover of the PV module is by radiation and convection due to wind blow above it. The heat is transferred from the channel walls to the airflow by convection and adequate back insulation is assumed making it adiabatic hence no heat loss through the back of the channel.

\[ R_{\text{top}} = \frac{L_i}{2 K_{sl}} + \frac{L_{\text{eva},t}}{k_{\text{eva},t}} + \frac{L_g}{k_g} \]  

(2)

Where \( L_i \), \( L_g \) and \( L_{\text{eva},t} \) are the thickness of silicon solar cell, glass cover and top EVA layer respectively while \( k_{sl} \), \( k_{\text{eva},t} \) and \( k_g \) are the thermal conductivities of these materials in the same order.

The heat conducted downward, \( q_{\text{bottom}} \), passes through the bottom EVA adhesive to the tedlar back which is eventually transferred by convection to airflow and by radiation into the channel back wall. It is calculated as:

\[ q_{\text{bottom}} = R_{\text{bottom}} A_{pv} (T_c - T_{tb}) \]  

(3)

Where \( R_{\text{bottom}} \) is the thermal resistance of bottom EVA adhesive and \( T_{tb} \) is the tedlar temperatures. The thermal resistance of the bottom EVA adhesive is given by

\[ R_{\text{top}} = \frac{L_i}{2 K_{sl}} + \frac{L_{\text{eva},b}}{k_{\text{eva},b}} + \frac{L_b}{k_b} \]  

(4)

\( L_b \) and \( k_b \) are the thickness and thermal conductivity of tedlar respectively.

The useful heat gain, \( q_u \), received by the airflow in the duct is contributed by the heat convection from the channel walls. \( q_u \) is large if the amount of heat lost at the top, \( q_t \), and that lost through the back insulation, \( q_b \), are very low:

\[ q_u = q_1 + q_2 \]  

(5)

Where \( q_1 \) is the heat transferred from the tedlar to airflow and \( q_2 \) is the heat transferred from the channel back wall to air flow. The channel walls transfer heat to airflow by convection and are given respectively by:

\[ q_1 = A_{c} h_{t-f} (T_{f} - T_{j}) \]  

(6a)

\[ q_2 = A_{c} h_{b-f} (T_{b} - T_{j}) \]  

(6b)

Where \( A_c \) is collector area, \( h_{t-f} \) is convective heat transfer coefficient from tedlar to airflow, \( h_{b-f} \) is convective heat transfer coefficient from channel back wall to airflow, \( T_j \) is mean air temperature in the duct and \( T_b \) is the back wall temperature. Since the back insulation is assumed to be adiabatic, hence the heat lost by conduction through back insulation is zero so that \( h_{t-f} \) is considered to be equal to \( h_{b-f} \) [14]:

\[ h_{t-f} = h_{b-f} = h_c \]  

(7)
Where $h_c$ is coefficient of heat transfer by convection from the channel walls to air flowing in the duct. Since the airflow is by natural convection, the flow in the duct is assumed to be laminar, hence the convective heat transfer coefficient has can be evaluated by [15]:

$$h_c = \frac{Nu k}{D_h} \quad (8)$$

Where $Nu$ is the Nusselt number, $k$ is thermal conductivity of air and $D_h$ is hydraulic diameter. The number expresses the ratio of convective to conductive heat transfer across the boundary layer and can be evaluated by the empirical correlation given by Hollands et al [16]:

$$Nu = 1 + 1.44 \left[ 1 - \frac{1708}{Ra \cos \theta} \right] (\sin(1.8\theta))^{1/6} + \left( \frac{Ra \cos \theta}{5830} \right)^{1/3} - 1 \quad (9)$$

Where $\theta$ is tilt angle of the collector while $Ra$ is called Raleigh number and is given by

$$Ra = \frac{l^3 \rho^2 g \beta \Delta T}{\mu} \quad (10)$$

Where $l$ is length of collector, $\rho$ is density of air, $g$ is acceleration due to gravity, $\mu$ is the dynamic viscosity of air, is $\beta$ is thermal expansivity of air, $\Delta T$ is temperature difference between the channel walls and $Pr$ is Prandtl number.

The hydraulic diameter for non-circular ducts is normally given as [17]:

$$D_h = \frac{2(W \times H)}{(W + H)} \quad (11)$$

Where $W$ and $H$ are channel width and depth respectively.

III. RESULTS AND DISCUSSION

A. Model Validation

Validation of the model was done by comparing theoretical results generated from the model with experimental data measured on a similar prototype system. Fig. IV and fig. V show the comparison between the theoretical and experimental values of both the PV and the back plate temperatures.

The results show that the theoretical and experimental values agree very well.

The model was then used to analyze the performance of the PV/T systems under various design aspects and operating conditions.

Fig. IV: Validation of model using PV temperature

Fig. V: Validation of model using back absorber plate temperature

B. Effects of Mass Flow rate

Fig. VI shows that the heat fluxes $q_1$ and $q_2$ increase with mass flow rate. This is due to the fact that the thin boundary fluid layer (viscous sub layer) which would otherwise increase the heat transfer resistance between the teflon and the working fluid is broken at high values of mass flow rate. This will increase the rate of heat extraction from the walls.
C. Effects of Thermal Conductivity of Tedlar

The results in fig. VII shows that an increase in the thermal conductivity of tedlar leads to a corresponding increase in the amount of heat transferred to the air from both surfaces of the air channel. This in turn will lead to a decrease in the PV cell temperature, which increases electrical efficiency. The results shows further that both heat fluxes tend to saturate when the thermal conductivity of tedlar is between 0.03 to 0.04 W/mK.

D. Effects of thickness of bottom EVA layer

The heat fluxes $q_1$ and $q_2$ as depicted in Fig. VIII both decreases with the thickness of bottom EVA layer. This is caused by the increase of thermal resistance of the EVA layer as its thickness increases.

### IV. Conclusion

The mechanisms to increase the wall heat flux are highly desirable for the overall efficiency of the PV/T system to be optimum. The results show that the heat transfer from the channel walls to the airflow increases as the thermal resistance of the tedlar increases. Thus, in order to increases the performance or efficiency (both thermal and electrical) of a PV/T system, tedlar of high thermal conductivity needs to be used. The results indicate that optimum thermal resistance occurs between 0.03 to 0.04 W/mK. On the other hand, as the thickness of bottom EVA adhesive layer increases, the heat fluxes from both walls decreases hence reduce both thermal and electrical efficiency of the PV/T systems. Hence for optimum performance of the PV/T systems, the EVA adhesive layer should be made as thin as is reasonably achievable but taking into considerable stability of bonding at high temperature due to thermal stresses.

### REFERENCES


