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Experimental Investigation of Single Pass, Double Duct Photovoltaic Thermal (PV/T) Air Collector with CPC and Fins

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Abstract: The temperature of photovoltaic modules increases when it absorbs solar radiation, causing a decrease in efficiency. This undesirable effect can be partially avoided by applying a heat recovery unit with fluid circulation (air or water) with the photovoltaic module. Such unit is called photovoltaic/thermal collector (pv/t) or hybrid (pv/t). An experimental investigation of a solar air heater with photovoltaic cell located at the absorber with compound parabolic collector (CPC) and fins have been developed and tested. The performance of the photovoltaic, thermal and combined pv/t collector over range of operating conditions and the results was discussed. Results at solar irradiance of 400 W/m^2 showed that the combined pv/t efficiency is increasing from 27.50 % to 40.044 % at mass flow rates various from 0.0316 to 0.09 kg^{-1} s.

Key words: hybrid pvt solar collector, single-pass, fins, CPC, thermal and electrical efficiency

INTRODUCTION

Solar energy is one of the most important source of renewable energy that world needs. The major applications of solar energy can be classified into two categories, Thermal system and Photovoltaic system. Normally, these systems are used separately. In conventional solar thermal system, external electrical energy is required to circulate the working fluid through the system. In conventional photovoltaic system, high incident solar irradiance on (PV) panel should give high electrical output. However, high incident will increase the temperature of the solar cells and that will decrease the efficiency of the panel. Therefore, to achieve both higher cell efficiency and higher electrical output we must cool the cells by removing the heat in some way. To eliminate an external electrical source from the thermal system and to cool the cells in photovoltaic system we integrate a photovoltaic panel with solar air/water heater collector, this can make when photovoltaic cells pasted directly on the flat plate absorber. This type of system is called photovoltaic-thermal collector (PV/T) or hybrid (PV/T) and this system has advantage such as it can be used to generate both thermal and electrical energy simultaneously, cooling PV improves efficiency, heat can be used in space heating or for drying system, it is less costly than two separate unites and it is very attractive in case the available roof surface is limited.

A number of researches and development programs have been carried out to improve the applications of solar energy systems. Several design of photovoltaic thermal solar air collector has been proposed in the past. Among the first, Kern and Russel[1] are the first who give main concept of photovoltaic thermal collector using water or air as the working fluid. Florschuetz[2] has extended the Hottel-Willer model to analysis steady state combined photovoltaic/thermal collector with simple modification of the conventional parameters of the original model by assuming that a liner correlation between efficiency of solar cell array and its temperature over its operating temperature range. Hendrie and Raghuraman[3] have been made a comparative experimental study in (pv/t) collectors with liquid and air as the heat removal fluid (working fluid). Cox and Raghuraman[4] suggested air type photovoltaic thermal system by analysis the effect of various design variables on the performance of the system. Lalovic *et al*.[5] fabricated photovoltaic thermal collector using amorphous Silicon pv cell and its performance was tested. Garg *et al*.[6] presented the theoretical study of (pv/t) collector with reflectors; they found that the system is well suited for solar drying applications. Bharagava *et al*.[7] and Prakash[8] reported the effect of air mass flow rate, air channel depth and packing factor. Sopain[9] have successfully demonstrated the improved performance of steady state double pass collector over the single pass collector due to efficient cooling of pv cells. Bergene and Lovvik[10]

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found that the thermal efficiency may increase only by a factor of 0.1 if flow rate increase from 0.001 to 0.075 kg^{-1} s. Sopian *et al*.[11] developed and tested a double pass photovoltaic collector suitable for solar drying applications and they comparison between theoretical and experimental results. Tripanagnotopoulos *et al*.[12] built and tested various photovoltaic thermal collector models with both water and air as the working fluids. Zondag *et al*.[13] compared the efficiency of seven different design types photovoltaic thermal collectors. Othman *et al*.[14] investigate the performance of double pass (pv/t) air heater with fins fixed in the bottom of absorber, the system theoretically under steady state conditions and experimentally was studied. They conclude that it is important to use fins as integral part of the absorber surface in order to achieve meaningful efficiencies for both thermal and electrical output of photovoltaic solar collector. Y. B. Assoa[15] developed simplified steady state 1-D mathematical model of (pv/t) bi-fluid (air and water) collector with a metal absorber. A Parametric study (numerically and experimentally) to determine the effect of various factors such as the water mass flow rate and thermal performance was studied. Simulation results were compared with the experimental results.

In this investigation, an experimental model of prototype single pass with both sides of the absorber photovoltaic-thermal PV/T solar air collector with CPC and fins was studied. The PV/T was tested experimentally to determine its photovoltaic, thermal and combined photovoltaic thermal performance over range of operating conditions and the results was discussed.

MATERIALS AND METHODS

Experimental Setup: The solar collector considered in this study has three essential static components: a glazing on the top, a plate containing numerous solar cells and a bottom plate. The experimental setup is shown in Fig 1. The size of the collector is 85.5 cm wide and 122 cm long, the air enters through both sides of the absorber in a single pass at the same time (The air flows between top glass and absorber plate and between absorber and bottom plates). The inlet temperature to the collector can be adjusted by heating the inlet air to the collector. CPC with concentration ratio (CR) of 1.86 is used as a reflector and located parallel to the air flow. 29 rectangular fins with density of 0.384 fin/cm, each fin 2.5 cm high and thickness of 0.1 cm attached along the length of the back of the absorber plate. 23 tungsten halogen lamps each rated at 500W used to simulate solar irradiance during the test. The intensity of the incoming solar irradiance was measured by Eppley pyranometer. Ambient temperature and other temperatures at several positions of the system were measured by k-type thermocouple. The mass flow rate was measured by using air flow sensing element van type probe head which connected direct to the data logger. Dasy Lab Software is used to record the required parameters such as the temperatures (inlet, outlet, absorber, glass cover and ambient) and intensity of the solar simulator. The schematic model of single pass double duct pv/t solar collector with CPC and fins is shown in Fig. 2.

Methodology: The lighting control of the simulator has been adjusted to obtain the required radiation levels. The solar collector has been operated at varying inlet temperature, air flow rate and radiation conditions. Air is circulated for 30 min prior to the period in which data are taken; data include radiation, temperatures (inlet, end of the first pass, outlet, room, glass cover (top and bottom), absorber plate (top and bottom) and back-plate) and mass flow rate. The mass flow rate varies from 0.0316 kg^{-1} s to 0.09 kg^{-1} s and the radiation varies from 400 to 700 W/m^2.

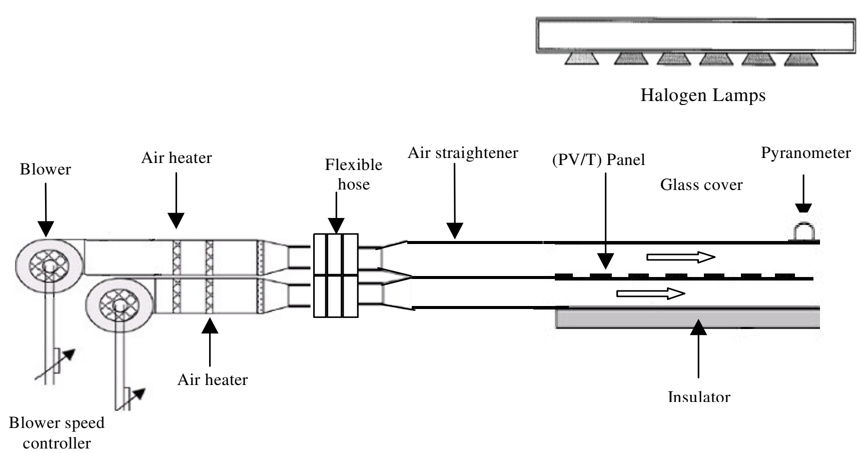

Fig. 1: Indoor testing facility of Single pass, double duct solar collector

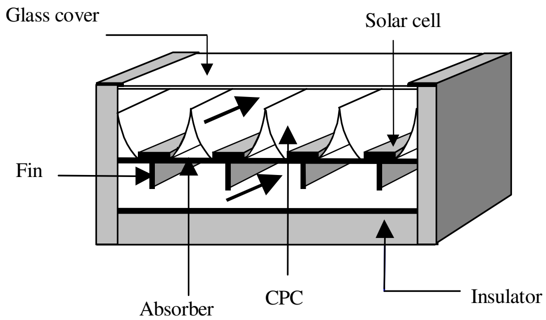

Fig. 2: The schematic model of Single pass, double duct (PV/T) solar collector with CPC and fins

Theoretical Background: The transient mathematical formulation has been written under the following assumptions: (i) Air behaves as an incompressible fluid; (ii) The thermal contact between solar cells and the absorber where they are mounted on, is good enough for not making the distinction between their respective temperature; (iii) Heat losses are neglected since we assume that both channels are correctly sealed preventing any leakage of air from the collector.

The thermal energy balance equations for the different nodes of the system are as follows:

For glass cover:

$$t_1\rho_1 C_1 \frac{\partial T_1}{\partial t} = \alpha_g \mathrm{I}_{\mathrm{tot}}(CR)(1+\tau_g \mathrm{P}_p \mathrm{P}_R^{2n'}) + h_{r1,s}(T_s - T_1) + h_{c1,w}(T_w - T_1) + h_{c1,2}(T_2 - T_1) + h_{r1,3}\frac{A_{ab(T)}}{A_c}(T_3 - T_1) + S_1 k_1 \frac{\partial^2 T_1}{\partial x} \quad (1)$$

For air stream in upper channel:

$$H_1 \rho_{air} C_{air} \frac{\partial T_2}{\partial t} = \frac{-m^{\cdot}_{air} C_{air}}{H1}\frac{\partial T_2}{\partial x} + h_{c1,2}(T_2 - T_1) + h_{c3,2}\frac{A_{ab(T)}}{A_c}(T_2 - T_3) \quad (2)$$

For absorber plate:

$$t_3\rho_3 C_3 \frac{\partial T_3}{\partial t} = \tau_g \alpha_p \mathrm{I}_{\mathrm{u}}(CR)\mathrm{P}_R^{n'} d[1+(\frac{\mathrm{P}_p \mathrm{P}_g \mathrm{P}_R^{2n'}}{CR})](1-P) + \tau_g \alpha_{pv} I_u P(CR)\mathrm{P}_R^{n'} d[1+(\frac{\mathrm{P}_{pv}\mathrm{P}_g \mathrm{P}_R^{2n'}}{CR})](1-\eta_{pv}) + h_{c3,2}\frac{A_{ab(T)}}{A_c}(T_2 - T_3) + h_{r3,1}\frac{A_{ab(T)}}{A_c}(T_1 - T_3) + h_{c3,4}\frac{A_{ab(T)}}{A_c}\eta_p(T_4 - T_3) + h_{r3,5}\frac{A_{ab(T)}}{A_c}(T_5 - T_3) + S_3 k_3 \frac{\partial^2 T_3}{\partial x} \quad (3)$$

For air stream in lower channel:

$$H_2 \rho_{air} C_{air} \frac{\partial T_4}{\partial t} = -\frac{m^{\cdot}_{air} C_{air}}{W}\frac{\partial T_4}{\partial x} + h_{c5,4}(T_4 - T_5) + h_{c3,4}\frac{A_{ab(B)}}{A_c} * \eta_p (T_4 - T_3) \quad (4)$$

For back plate:

$$t_5\rho_5 C_5 \frac{\partial T_5}{\partial t} = U_b(T_a - T_5) + h_{c5,4}(T_4 - T_5) + h_{r5,3}\frac{A_{ab(B)}}{A_c}(T_3 - T_5) + S_5 k_5 \frac{\partial^2 T_5}{\partial x} \quad (5)$$

The performance parameters of combined photovoltaic thermal solar collector are obtained in terms of the solar cell efficiency and the thermal efficiency. The thermal efficiency of the double pass collector with CPC and fins is as follows:

$$\eta_{th} = \frac{\mathrm{m}^{\cdot}\, \mathrm{c_p} \int (\mathrm{T_0} - \mathrm{T_i})\, \mathrm{dt}}{A_c\, \mathrm{CR} \int \mathrm{I_{tot}}\, \mathrm{dt}}$$

The solar cell efficiency is as follows:

$$\eta_{pv} = \eta_{\text{ref}} \, [1 - 0.0045 \, (T_{\text{pav}} - T_{\text{ref}})]$$

Where the ηref is the reference efficiency of the solar cell at Tref = 25 °C which is in our study 10%. The efficiency of the combined photovoltaic thermal collector is defined as the sum of thermal efficiency and electrical efficiency as:

$$\eta_{pv/t} = \eta_{\text{thermal}} + \eta_{\text{electrical}}$$

The electrical efficiency is as follows:

$$\eta_{elect} = \frac{\int \tau_g \, I_u \, \eta_{pv} \, \alpha_{pv} \, P \, CR \, d \, \rho_R^{n'} \, [1 + (\frac{\rho_{pv} \, \rho_g \, \rho_R^{2n'}}{CR}) \, dt}{CR \int I_{tot} \, dt}$$

where:

$$I_u = \frac{I_{tot}}{CR}$$

RESULTS AND DISCUSSION

The electrical maximum power of the collector increase with the radiation intensity increase as can be seen in Fig. 3. The air temperature rise decrease with increasing of mass flow rate as shown in Fig. 4.

Figure 5 shows the effect of radiation intensity on the temperature at various flow rates. In this Figure it can see that the temperature rise linearly to the solar radiation, so the collector which operate with high solar radiation levels experience high temperature rise. It can see also that at the same solar radiation the collector which operates at low mass flow rate will experience high temperature rise too.

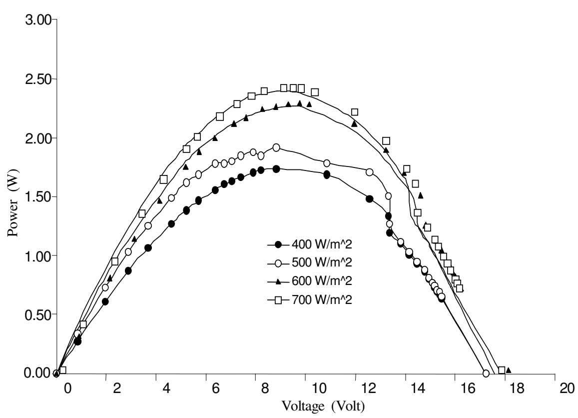

Fig 3: Power against voltage at mass flow rate of 0.0316 kg^{-1} s and T_i = 35 °C

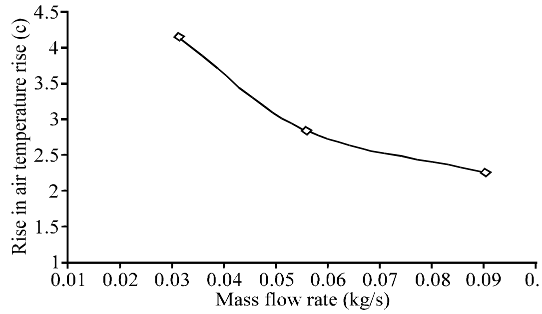

Fig 4: Variation of maximum air temperature rise with air specific mass flow rate at Solar Irradiance 400 W/m^2 and Ti = 30 C^0

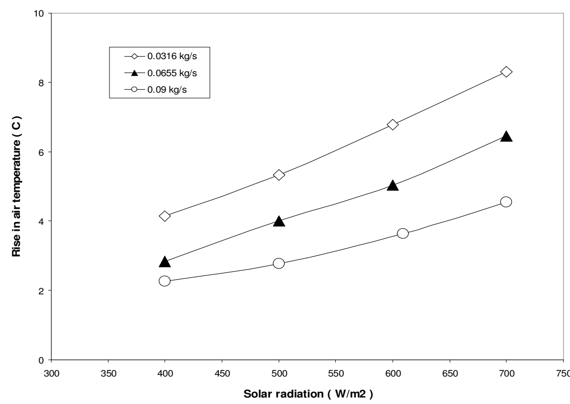

Fig 5: The effect of solar radiation on the temperature rise at various mass flow rate at Ti = 30 °C

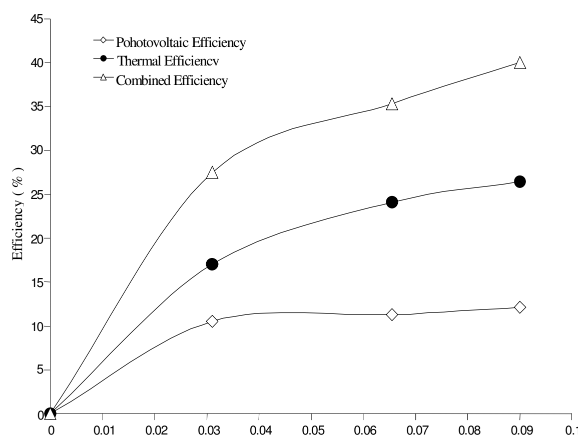

Fig 6: The effect of mass flow rate on efficiencies at Solar Irradiance 400 W/m^2 and Ti = 30 °C

The effect of the mass flow on the efficiencies (photovoltaic, thermal and combined pv/t) of the collector was shown in Fig 6. The experimental results show that, when the collector is operating at high mass floe rate; the efficiencies (photovoltaic, thermal and combined pv/t) were increase. This is expected when the photovoltaic panel is cooled by the incoming air. As seen in fig 6. the photovoltaic efficiency is varies from 10.50 to 12.09% at solar radiation of 400 W/m^2 and inlet temperature of 30 °C. The thermal efficiency is varies from 17 to 26.433%. The combined pv/t efficiency is varies from 27.50 to 40.044%. We can see that the combined pv/t efficiency is decrease at low flow rate because the mean photovoltaic temperature is high. Therefore, cooling of the photovoltaic cells by increasing the mass flow rate will increase the combined photovoltaic thermal efficiency.

CONCLUSION

Performance curves of the single pass, double duct solar collector with CPC and fins have been obtained. Results show that the electricity production in a PV/T hybrid module decreases with increasing temperature of the air flow. This implies that the air temperature should be kept as low as possible. On the other hand, the system should deliver hot air for other purposes. A trade off between maximizing electricity production and producing hot air of useful temperatures is thus necessary. The simultaneous use of hybrid PV/T, CPC and fins have a potential to significantly increase in power production and reduce the cost of photovoltaic electricity.

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Nomenclature:

A = Surface area (m2)
C = Specific heat (J kg^{-1} K^{-1})
CR = concentration ratio of CPC
d = Gap loss correction
h = Heat transfer coefficient (Wm^{-2} K^{-1})
H_1 = Height between glazing and PV-plate (m)
H_2 = Height between glazing and PV-plate bottom plate (m)
I = Solar irradiance (Wm^{-2})
k = Thermal conductivity (W m^{-1} k^{-1})
$m^{\cdot}$ = Mass flow rate (kg s^{-1})
$\grave{n}$ = average number of reflection for radiation passing through CPC inside the acceptance-half angle
P = Solar cell packing factor
t = Thickness (m)
T = Temperature (K)
U_b = Heat loss coefficient (Wm^{-2} K^{-1})
W = Collector width (m)

Subscripts
a = Ambient
ab(T) = Top absorber surface
ab(B) = Bottom absorber surface
c = Convective
P = Reflector
r = Radiative
tot = Total
1 = Glass cover
2 = Working fluid (air) at first channel
3 = Absorber plate
4 = Working fluid (air) at second channel
5 = Back plate

Greek letters
ρ = density (kg m^{-3})
λ = Thermal conductivity (Wm^{-1} K^{-1})
α = Absorptivity
η = Efficiency
τ = Transmitivity
ε = Emissivity

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