PHOTOVOLTAIC THERMAL (PV/T) COLLECTORS: A REVIEW

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ABSTRACT

An extensive amount of research on PV-thermal collectors has been carried out over the last 25 years. This paper aims at presenting a review of the most available literature on PV/T collectors. The review is presented in a thematic way, in order to enable an easier comparison of the findings obtained by various researchers, especially on parameters affecting PV/T performance (electrical and thermal). The review covers analytical and numerical models, simulation and experimental work and qualitative evaluation of thermal/electrical output.

1. INTRODUCTION

Photovoltaic thermal (PV/T) collectors are devices that simultaneously convert solar radiation into electricity and heat. A PV/T collector shown in figure 1, typically consists of a PV module on the back of which an absorber plate, a heat extraction device, is attached.

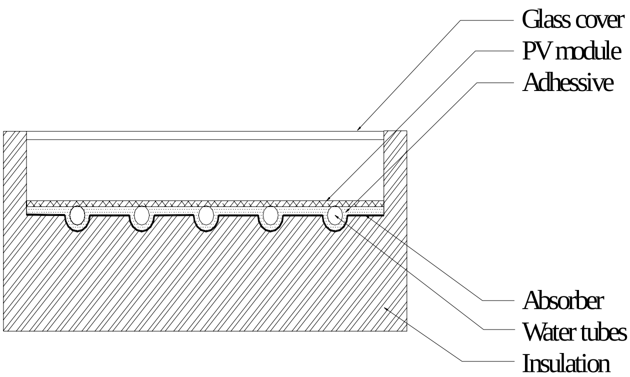

Fig. 1 Cross section of a PV/T collector

The purpose of this extraction device is twofold. Firstly, to cool the PV module and thus improve its electrical performance and secondly to collect the thermal energy produced, which would have otherwise been lost as heat to the environment. This collected heat could be used, for example, for space heating or for domestic uses (showers and washing).

A considerable amount of work has been carried out during the last 25 years and a review of the most important available literature on liquid and air PV/T collectors is presented.

2. PERFORMANCE OF PV/T COLLECTORS

2.1 Analytical Models

Several analytical and numerical models have been developed, by various researchers, predicting the performance of PV/T collectors. The steady state thermal efficiency (η_{th}) of a conventional flat plate solar collector is calculated by (Duffie and Beckman, 1991):

$$\eta_{th} = \frac{Q_u}{G} \tag{1}$$

and the useful collected heat (Q_u) is given by:

$$Q_u = \dot{m} C_p (T_o - T_i) \tag{2}$$

Or, it is simply the difference between the absorbed solar radiation and the heat losses:

$$Q_u = A_c[S - U_L(T_{p,m} - T_a)] \quad (3)$$

As in the previous equation the mean absorber plate temperature ($T_{p,m}$) is difficult to calculate or measure since it is a function of collector design, the incident solar radiation and the entering fluid conditions, Hottel and Whillier (as explained in Duffie and Beckman, 1991) modified equation (3) as follows:

$$Q_u = A_c F_R[S - U_L(T_i - T_a)] \quad (4)$$

where,

$$F_R = \frac{\dot{m}C_p}{A_c U_L}\left[1 - e^{-\frac{A_c U_L F'}{\dot{m}C_p}}\right] \quad (5)$$

$$F' = \frac{\frac{1}{U_L}}{W\left[\frac{1}{U_L[D_o + (W - D_o)F]} + \frac{1}{C_b} + \frac{1}{\pi D_i h_{fi}}\right]} \quad (6)$$

$$F = \frac{\tanh(x)}{x} \quad (7)$$

and

$$x = \sqrt{\frac{U_L}{k\delta}}\left(\frac{W - D_o}{2}\right) \quad (8)$$

The electrical efficiency (η_{el}) of a PV/T collector is calculated by (Tripanagnostopoulos et al. 2002):

$$\eta_{el} = \frac{\mathrm{I_m} V_m}{G A_c} \quad (9)$$

and typically, the dependence of the PV module electrical efficiency on the module temperature is given by (Zondag et al. 2003):

$$\eta_{el} = \eta_o\left(1 - 0.0045\left[T - 25^o C\right]\right) \quad (10)$$

Florschuetz (1979), extended the well known Hottel-Whillier analytical model for flat plate collectors so that with simple modifications it applies to combined PV/T collectors and all existing relations and supporting information available in the literature (such as the collector efficiency factor, *F’* and the heat removal factor, F_R) still apply. It was concluded that for practical purposes *F’* and F_R of the PV/T collector may be considered identical to *F’* and F_R of the thermal collector.

Bergene and Lovvik (1995), proposed a detailed model predicting the performance of PV/T collectors that was based on energy transfer analysis and to some extent on the models for flat plate solar collectors presented by Duffie and Beckman (1991). The model predicts PV/T efficiency (thermal + electrical) to be about 60 to 80%.

Sandnes and Rekstad (2002) have also developed an analytical model for the PV/T collector by modifying the well known models for flat plate collectors to include the effects of the additional solar cells. Good agreement between the simulation and the experimental results was found.

Sopian et al. (1996) analyzed with steady state models the performance of single and double pass PV/T air collectors. The results showed that double-pass PV/T collectors have superior efficiencies. Typically thermal, electrical and combined (thermal + electrical) efficiencies for single-pass collectors were 24-28, 6-7, 30-35%, respectively and for double-pass collectors were higher at 32-34, 8-9, 40-45%, respectively. In addition, thermal and combined efficiencies increased as the packing factor (defined as the fraction of the absorber area covered by photovoltaic cells) decreased. However, electrical efficiency decreased slightly. It was emphasized that the improved performance of the double-pass PV/T collector (compared to the single-pass) was achieved at very little increase in collector capital cost.

2.2 Numerical models

Zondag et al. (2002) prepared and run four numerical models for predicting PV/T collector yield. One 3D dynamic and three steady state (3D, 2D and 1D) models. The simple 1D steady state model performed almost as good as the much more time consuming 3D dynamic model. However, the 2D and 3D models provide more detailed information required for further collector optimization.

Since the 3D dynamic model developed by Zondag et al (2002) was an extensive one (typically uses 2.5 hr simulation time for 1 hr real life equipment operation), Chow (2003) developed an explicit dynamic model, based on control volume finite difference approach for a single glazed PV/T collector. The model can generate results for hourly performance analysis, including instantaneous thermal / electrical gains and efficiencies. It was found that the maximum combined efficiency of a perfect collector can be over 70% and can decrease to less than 60% for a low quality collector.

2.3 Modeling and simulation

Kalogirou (2001) modeled and simulated a PV/T system using the well known TRNSYS simulation program and a typical meteorological year for Nicosia, Cyprus. The annual electrical efficiency of the standard PV system increased from 2.8% to 7.7% for the PV/T system operating at the obtained optimum flow rate (25 l/hr).

Garg and Adhikari (1997) simulated the performance of single and double glass configurations PV/T air heating collectors. They found that increasing cell density results in very large values of electrical efficiency, although thermal efficiency drops. The combined efficiency increased with increase in collector length, mass flow rate and cell density and decreased with increases in duct depth.

Cox and Raghuraman (1985) performed computer simulations towards improving the solar absorptance and reducing the IR (infrared) emittance of flat plate air PV/T collectors. They found that air PV/T collectors are generally less efficient than liquid ones due to low PV cell packing factor, low solar absorptance, high IR emittance and poor absorber to air heat transfer coefficient. A low emissivity layer was added to the PV cells so that the resulting combination was effectively a selective absorber. Moreover, low iron glass resulted in high thermal efficiency due to reduced top loss coefficient and lower electrical efficiency as a result of reduced glass transmissivity. None of the other features significantly affected electrical performance. The efficiencies with and without a selective absorber were virtually the same. The dominant control of the electrical efficiency was the glass transmissivity. The optimum combination of an air PV/T collector was found to consist of gridded-back PV cells, a nonselective secondary absorber and a high transmissivity / low emissivity glass above the photovoltaic cells.

2.4 Experimental work

Tripanagnostopoulos et al. (2002) built and tested various PV/T collector models with both water and air as working fluids. The performance of these models was boosted by diffused reflectors made of flat aluminum sheets. It was found that the water heat extraction results to a lower PV temperature than that of air heat extraction because water temperature from mains (20^{o}C) was lower than that of ambient air (29^{o}C). The authors believe that the much higher heat transfer coefficient of water, compared to that of air, is a second possible reason. Therefore, there is an advantage of using water instead of air as heat removal fluid especially during the warm periods. The electrical efficiency of the basic PV/T_{water} model was 3.2% higher than that of the simple PV module and an additional advantage of using PV/T instead of plain PV modules comes from the higher thermal output. Moreover, a PV/T system with booster diffuse reflectors of concentration, C=1.35, can achieve a percentage increase of electrical efficiency up to 19.2% (compared to that of the simple PV module), at an additional PV/T cost for the reflectors of only about 4%.

Lalovic et al. (1986) built a PV/T collector using amorphous silicon photovoltaic cell and its performance was tested. The diameter of the copper tubes was 12 mm and tube spacing was 12 cm. The transmittance-absorptance product ($\tau\alpha$) for the hybrid collector was rather low, i.e. 0.53 and the slope of the performance characteristic was also low 3.25 W/mK and showed that the collector behaved as a double glazed collector with a selective surface. It was noted that in order to increase the efficiency of PV/T collectors, the aluminum back electrode of PV panels could be replaced by indium tin oxide (ITO) which is transparent to solar spectrum above 0.5 μm. In this way a part of the solar radiation not absorbed by the amorphous layers would pass onto the absorber plate, which now has to be black.

Sopian et al. (2000) developed and tested a double pass PV/T collector suitable for solar drying applications. Comparisons were made between the experimental and the theoretical results and close agreement between the two values were obtained.

2.5 Parameters (factors) affecting PV/T performance

A number of parameters have been identified to affect PV/T performance. These include mass flow rate, inlet temperature of working fluid, number of covers, absorber to fluid thermal conductance and absorber plate design parameters such as tube spacing, tube diameter and fin thickness. An analysis of these parameters follows:

2.5.1 Covered vs uncovered PV/T collector

Sandnes and Rekstad (2002) explained that the effect of adding a glass cover to the PV/T collector, is to reduce the heat losses to the surroundings. However, the energy absorptance is also reduced by reflection (around 10%) from the glass. They found that the simulated total electrical energy output over a day for the plain PV module was 306.9 Wh, for the PV/T without glass cover was 339.3 Wh and for the PV/T with glass cover was 296.2 Wh.

Fujisawa and Tani (1997) found that the thermal performance of the single covered PV/T was as high as that of the flat plate collector (FPC) and that of the coverless PV/T collector was inferior owing to the lack of heat-insulating layer of air. On the other hand, the coverless PV/T collector produced the highest electrical energy.

Zondag et al (2003) reported that the uncovered sheet and tube collectors perform poorest due to large heat losses. Moreover, electrical efficiency of sheet and tube collectors with two covers strongly deteriorates due to the second cover.

2.5.2 Mass flow rate

Bergene and Lovvik (1995) found that the thermal efficiency may increase only by a factor of 0.10 if flow rate increases from 0.001 to 0.075 kg/s (the PV/T collector area was not given). Consequently, they suggest that when the flow rate is around 0.001 kg/s, there is not much to gain on increasing it further. It was also pointed out that with respect to electrical efficiency, flow rate is one of the most important parameters (the other being inlet fluid temperature). Moreover, at low flow rates the electrical efficiency increases when *W/D* increases, whereas at high flow rates the opposite occurs. In his study, Chow (2003) showed that as mass flow rate in the tube increases from 0.002 to 0.016 kg/s, for a 2 m^2 PV/T collector area (i.e. 0.001 to 0.008 kg/sm^2), the thermal and electrical efficiencies also increase.

Garg and Agarwal (1995), carried out simulations for different solar cell areas, mass flow rates and different water masses by solving the governing equations using an iterative finite difference method. The system was composed of a PV/T collector, storage tank, pump and differential control. The optimum flow rate was found to be 0.03 kg/s, for a 2 m^2 PV/T collector area (i.e. 0.015 kg/sm^2), for maximum thermal collector efficiency. However, electrical efficiency was found to decrease at 0.03 kg/s and was minimum when solar insolation was maximum (which is expected as at this time absorber temperature is maximum); the average electrical efficiency and the average daily combined efficiency increased as the total water mass increased (by increasing number of tubes, i.e. decreasing tube spacing) and the higher the mass flow rate was, the higher the solar cell efficiency.

Morita, Fujisawa and Tani (2000) determined that maximum exergetic efficiencies for single cover (of 13.36%) and coverless (of 11.92%) PV/T collectors occur at optimum flow rates of 0.0014 and 0.0049 kg/s, respectively, for a PV/T collector area of 0.61 m^2 (i.e. 0.002 and 0.008 kg/sm^2, respectively).

Furthermore, Kalogirou (2001) in his simulations using TRNSYS, found the optimum flow rate to be 25 l/hr (0.007 kg/s), for a 2.54 m^2 PV/T collector area (i.e. 0.003 kg/sm^2).

Garg and Adhikari (1997) & (1999) and Sopian et al (2000), in testing the performance of PV/T air heating collectors noticed that increasing air mass flow rate reduces cell and outlet temperatures and consequently increases thermal and electrical efficiency.

2.5.3 Absorber plate parameters

Bergene and Lovvik (1995), elaborated on the effect of tube spacing to tube diameter ratio (*W/D*). It was found that:

a) The thermal efficiency is approximately halved when *W/D* increases from 1 to 10, by keeping *W* constant. It was also emphasized that different results are expected when increasing *W* whilst keeping *D* constant.
b) The fact that the speed of cooling liquid increases when tube diameter is decreased does not compensate for losses from the fin.
c) Increasing *W/D* from 1 to 10, decreases outlet fluid temperature.
d) Even though electrical efficiency is not heavily affected by fin size, combined efficiency is largely dependent on fin size.
e) If thermal efficiency is of any importance, its dependence on the relative tube diameter should be weighted against the cost of the tubes

2.5.4 Absorber to fluid thermal conductance

As Florschuetz (1979) pointed out, exceedingly large values of absorber to fluid thermal conductance, U_f, are not required for the heat removal factor, F_R, to be within a reasonable value, especially with collectors of at least one glazing. Design approaches must be undertaken carefully since they may increase the pressure drop to unacceptably high values or increase costs for what may only be marginal improvements in performance.

Chow(2003), refers to the two manufacturing defects found in PV/T collectors (imperfect adhesion between PV plate and absorber plate, imperfect bonding between absorber plate and tubes) and for a range of thermal conductances 10000 W/mK to 25 W/mK (perfect to defective), found that the maximum combined efficiency of a perfect collector can be over 70% and for a low quality collector, may decrease to less than 60%.

2.5.5 Design types

Zontag et al. (2003) compared the efficiency of seven different design types of PV/T collectors. They observed that:

a) All channel concepts have a substantially higher efficiency than sheet and tube due to the better heat transfer characteristics of channels.
b) In the case of free flow panel, evaporation strongly reduces the thermal efficiency and condensate on top of the glass causes additional reflection.
c) Since the sheet and tube design is the easiest to manufacture (and is only 2% less in efficiency), it is the most promising of the different design concepts examined.

3. QUALITATIVE EVALUATION OF THERMAL / ELECTRICAL OUTPUT

Electrical and thermal energies are not qualitatively the same as explained by Fujisawa and Tani (1997); thermal energy cannot produce work until a temperature difference exists between a high temperature source and a low temperature source, but electrical energy can completely transform into work irrespective of the ambient conditions. Use of exergy, defined as the maximum theoretical useful work obtainable from a system as it returns to equilibrium with the environment, enables qualitative evaluation by comparing electrical and thermal energy based on the same standard. The results showed that the coverless PV/T collector produced 8% more electrical energy than a standard PV module did and produced

41% of the thermal exergy of the FPC. Moreover, the coverless PV/T collector produced the largest available total (electrical + thermal) exergy of 80.8 kWh, whereas the PV module and the FPC produced 72.6 kWh and 6.0 kWh, respectively. It is clear that the total exergy of the coverless PV/T collector was 11% higher than the PV module and 1287% higher than the FPC. The output density (exergy gain divided by installation area) of the coverless PV/T was the highest, 76% higher than with use of separate PV module and FPC (the output density of the single cover PV/T was 57% higher).

Morita, Fujisawa and Tani (2000) performed a numerical analysis and determined the optimum operating conditions by using exergetic evaluation for single and no cover PV/T collectors. They developed a steady state energy equilibrium equation based on the analytical model on PV/T collectors of Cox and Raghuraman (1985). As mentioned earlier, the maximum exergetic efficiencies were for single cover 13.36% and for coverless 11.92%. The corresponding optimum flow rates were 0.0014 and 0.0049 kg/s, respectively and the corresponding optimum fluid temperatures were 83.6^{o}C and 38.3^{o}C, respectively. It is clear that the cover glass has the function of raising the maximum exergetic efficiency and the optimum outlet temperature. It is also clear that in order to obtain the most thermal exergy, the electrical exergy has to be sacrificed. On the other hand, when one desires to obtain positive electrical exergy, coverless PV/T is more useful than PV/T with cover as the total exergetic efficiency of coverless PV/T and medium fluid temperature (25^{o}C), surpasses that of PV/T with cover (11.28% and 10.31%).

The significance of an exergy comparison is not clear, according to Coventry and Lovegrove (2003), if electrical or mechanical work is not the only desired output from the system, such as when the thermal output is hot water used directly for showers and washing. They used three different methodologies (thermodynamic, market based and environmental) for determining an electrical-to-thermal energy value ratio. For the thermodynamic methodology, a power plant is 40% efficient and it is thus equivalent to assuming an electrical/thermal value ratio of 2.5. However, low temperature hot water from a PV/T is not as thermodynamically useful as high temperature steam from a coal-fired boiler. For the renewable energy market methodology, the grid connected photovoltaics levelised energy cost (defined as the unit price of energy output that would result in the system having a zero net present value 'NPV' over its lifetime) was found to be US $ 0.367/kWh and the solar hot water levelised energy was found to be US $ 0.087/kWh. Thus, the ratio of electrical to thermal value is 4.24. This means that electricity is 4.24 times more valuable than hot water. In the environmental valuation approach, based on avoided emissions from the use of PV/T, the ratio of electrical to thermal avoided CO_2 emissions was found to be 7.58 (including life cycle emissions). They suggest that the most realistic energy ratio for a PV/T collector is the renewable energy market (i.e. 4.24), although they admit that there is no simple answer for determining what energy value ratio should be used, rather the ratio should be a parameter selected for the circumstance applicable to a particular installation.

4. CONCLUSIONS

A review of the available literature on liquid and air PV/T collectors which covers the work of the last 25 years was presented. The following conclusions have been reached:

It was found from analytical and numerical models that PV/T efficiencies could range from over 70% for a perfect collector and to less than 60% for a low quality collector.

Air PV/T collectors are generally less efficient than liquid PV/T collectors. Moreover, since the sheet and tube design is the easiest to manufacture and is only 2% less efficient, it is the most promising of design concepts.

For practical purposes the collector efficiency factor (F') and the heat removal factor (F_R) of a PV/T collector could be considered identical to the corresponding ones of a thermal collector.

The thermal performance of a coverless PV/T collector is reduced especially at high temperatures due to the lack of heat-insulating layer of air. However, coverless PV/T collectors have a better electrical performance.

The optimum flow rate was found to be in the range of 0.001 to 0.008 kg/sm^2, whereas a value of 0.015 kg/sm^2 was also reported and thus, optimum flow rate studies could be investigated further.

The thermal efficiency was approximately halved when the tube spacing to tube diameter ratio (*W/D*) was increased from 1 to 10 (by keeping *D* constant). It was emphasized that different results could be expected when increasing *W* whilst keeping *D* constant and further investigation on this issue should be carried out.

Exceedingly large values of absorber to fluid thermal conductance are not required for the heat removal factor F_R to be within a reasonable value, especially with collectors of at least one glazing.

It was suggested that the most realistic energy value ratio is the renewable energy market (i.e. 4.24), although there is no simple answer in determining what energy value ratio should be used in comparing electrical and thermal energy output, of PV/T collectors, based on the same standard.

Finally, further work should be carried out aiming at improving the efficiency of PV/T collectors and reducing their cost, making them more competitive and thus aid towards global expansion and utilization of this environmentally friendly renewable energy device.

NOMENCLATURE

A_c PV/T collector area [m^2]
C_b conductance of the bond between the fin and tube [W/mK]
C_p specific heat of fluid [J/kg K]
D_i inside tube diameter [m]
D_o outside tube diameter [m]
F fin efficiency
F' collector efficiency factor
F_R heat removal factor
G solar irradiance [W/m^2]
h_{fi} heat transfer coefficient of fluid [W/m^{2}K]
I_m PV current at maximum power point [A]
k thermal conductivity of the fin [W/mK]
$\dot{m}$ fluid mass flow rate per unit collector area [kg/s m^2]
Q_u useful collected heat by collector [W/ m^2]
S absorbed solar energy [W/ m^2]
T temperature of PV module [K]
T_a temperature of the ambient [K]
T_i fluid inlet temperature [K]
T_o fluid outlet temperature [K]
$T_{p,m}$ average plate temperature [K]
U_L overall collector heat loss coefficient [W/m^{2}K]
V_m PV voltage at maximum power point [V]
W tube spacing [m]

Greek Symbols

δ fin thickness [m]
η_{el} PV/T electrical efficiency
η_o PV electrical efficiency at standard conditions
η_{th} PV/T thermal efficiency
$\tau\alpha$ transmittance absorptance product

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