Research on Theory and Experiment for Partially Covered PV/T Solar System

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Abstract—According to the structural features of partially covered photovoltaic/thermal (PV/T) solar system, the theory model and optimum design method of the partially covered PV/T solar system is established. The effect of different design parameters on the performance of the partially covered PV/T solar system is analyzed by using the theory model. Meanwhile, the prototype of the partially covered PV/T solar system was designed, and the characteristics of the partially covered PV/T solar system are studied by experiment at Chuxiong City. Experimental results show that the glass cover is essential for improving the thermal efficiency of the PV/T solar system, which related to the transmittance and thickness of the glass cover. In addition, the thermal efficiency will decrease with increasing covering area of the PV modules on the PV/T solar collector. Under the condition of the covering area of 0.8m2 for the PV modules, the thermal efficiency and the output power of the prototype are 40.2% and 25.1W, respectively. Under the condition of covering area of 1.02m2 for the PV modules, the thermal efficiency and output power of the prototype are 36% and 33.6W, respectively. Thus, the partially covered PV/T solar system has batter practicality, and can meet the need of the ordinary rural families in lighting electricity and hot water.

Keywords-Photovoltaic/thermal (PV/T); Partially Covered; Theory Mode; Practicability; Solar system

I. INTRODUCTION

The PV/T solar system was proposed by Kern and Russell[1]. The basic theory of the PV/T solar system was introduced, and the efficiency of solar energy could be more than 60% in theory[2]. In recent years, the PV/T solar system has been widely studied due to the aggravation of energy resources shortage[3]. For example, the integrated photovoltaic and thermal solar system (IPVTS) was studied by experiment[4]. The results showed that the primary energy saving efficiency of IPVTS exceeds 0.60 which was higher than for a conventional solar water heater or pure PV system. Rosell introduced the advantages of the PV/T solar system, and the low concentration technologies were combined into a PV/T system to increase the solar energy conversion efficiency[5]. The thermal efficiency of the system reached 60%. Coventry et al. developed the so called CHAPS (combined heat and power solar) PV/T collector, which the collector involves a parabolic trough of concentration ratio of 37 times with monocrystalline silicon cells and a two-axis tracking system[6]. Bhargava et al. studied performance of PV/T system air heater in experiment and theory[7-10]. The theory thermal efficiency of PV/T system can reach 65%[9].

In a word, PV/T solar system has higher solar energy conversion efficiency and business application value in theory. However, the practicability of PV/T solar system is worse due to the contradiction of working temperature of the PV/T collector and conversion efficiency[11-15]. In the paper, in order to improve practicability of PV/T system, the optimization design theory mode is established on the basis of the structure of partially covered PV/T solar collector and related theory, the effect of different design parameters on the output water temperature, and the output useful thermal energy and output power of the PV/T solar systems is analyzed. In addition, the prototype of the partially covered PV/T solar system is designed, and the characteristics are studied by experiment.

II. THE DESIGN THEORY OF PV/T SOLAR COLLECTOR

A. *Photothermal characteristics of PV modules*

In the photovoltaic generation, only 5-15% of incident solar radiation can be converted into electricity, with the greater percentage converted into heat. The temperature of the PV modules will rise with increasing of the incident solar radiation. The relationship between the temperature of the PV modules and the solar irradiation can be expressed[4] as follows:

$$t_{cell} = t_a + (NOCT - 20) \cdot \frac{E_a}{800} \quad (1)$$

Where, tcell is the temperature of the PV modules. ta is the ambient temperature. NOCT (Nominal Operating Cell Temperature) is defined as the PV module temperature in standard reference environment, defined as follows: solar irradiation 800W/m2, ambient temperature 20℃ and wind velocity 1m/s. NOCT is 47℃ for PV modules with plastic substrate. Ea is solar irradiation.

In addition, the photoelectric conversion efficiency of the PV modules will drop with the increase of the temperature for the PV modules. For the silicon PV modules, the conversion efficiency of the PV modules will drop 0.45% with the increase by 1K. The relationship between the photoelectric conversion efficiency and the temperature of the PV modules could be expressed [11] as follows:

$$\eta_{el} = \eta_0 [1 - 0.0045(t_{cell} - 298K)] \quad (2)$$

Among, η0 is the photoelectric conversion efficiency of the temperature for the PV modules at 298K. tcell is the temperature of the PV modules.

There are two advantages to integrate the PV modules on the surface of flat plate thermal collector. Firstly, the heat of PV modules can be used to heating water or air, and the utilizing efficiency of solar energy is improved. Secondly, the temperature of PV modules will be dropped because the heat of PV modules is carried away by the water or air, the conversion efficiency of PV modules will be improved.

B. *Design and theory of PV/T solar collector*

The PV/T solar collector is designed by integrated the PV modules on the surface of flat plate thermal collector, which can simultaneous produce the electric energy and thermal energy. The inner structure of the PV/T solar collector is shown in Fig. 1. The total efficiency of the PV/T solar collector involves the electric efficiency (ηpv) and thermal efficiency (ηth).

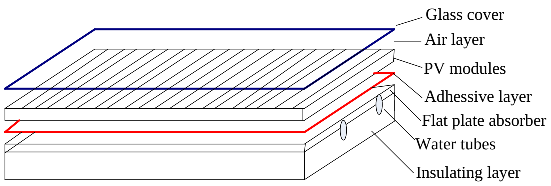


Figure 1. Inner structure diagram of PV/T solar collector

- Thermal efficiency model of PV/T solar collector

According to the structure of the PV/T solar collector, the useful heat Q_U is given based on the theory of the flat plate thermal collector[16] as follows:

$$Q_U = (1-\xi) A F_t [E_a(\tau a)_e - U_L(t_m - t_a)] + \xi A F_{pvt} [(E_a(\tau a)_e - U_L(t_m - t_a)] \quad (3)$$

Where, (τα)e is the transmittance-absorptance product. UL is the overall collector heat loss coefficient. tm is the average temperature of thermal collector. ta is the temperature of the ambient. ξ is the PV modules covering factor. Ea is the solar irradiation. Ft is the efficiency factor of the flat plate collector [16]. Fpvt is the efficiency factor of the PV/T solar collector. A is the overall area of PV/T solar collector.

Where, the efficiency factor of the PV/T solar collector can be expressed according to the structure of PV/T solar collector as follows:

$$F_{pvt} = \frac{\frac{1}{U_L}}{W\left[\frac{1}{U_L[D + (W-D)F_P]} + \frac{1}{W \cdot h_{ca}} + \frac{1}{C_b} + \frac{1}{\pi D_i h_{f,i}}\right]} \quad (4)$$

Where,

$$F_P = \frac{\tanh[m_p(W-D)/2]}{m_p(W-D)/2}$$

$$m_p = \sqrt{\frac{U_L}{K_{abs} \cdot L_{abs} + K_{pv} \cdot L_{pv}}}$$

Among, W is the tube spacing. D is the outside tube diameter. Di is the inside tube diameter. hca is the heat transfer coefficient of the bond between the flat plate collector and PV modules. hf.i is the heat transfer coefficient of fluid. Cb is the conductance of the bond between the fin and tube. Kabs is the thermal conductivity of the fin. Labs is the thickness of fin. Kpv is the thermal conductivity of the PV modules. Lpv is the thickness of the PV modules.

Thus, the thermal efficiency of PV/T collector can be expressed as follows:

$$\eta_{th} = \frac{Q_u}{AE_a} = (1-\xi)F_t(\tau a)_e + \xi F_{pvt}(\tau a)_e - \left[\frac{(1-\xi)F_t U_L(t_m - t_a)}{E_a} + \frac{\xi F_{pvt} U_L(t_m - t_a)}{E_a}\right] \quad (5)$$

The hot water temperature can be expressed on the basis of the thermodynamics as follows:

$$T_f = \frac{\left[(1-\xi)AF_t[E_a(\tau a)_e - U_L(NOCT-20)\cdot\frac{E_a}{800}]\right.}{mC_p} + \frac{\left.\xi AF_{pvt}[(E_a(\tau a)_e - U_L(NOCT-20)\cdot\frac{E_a}{800}]\right]t}{mC_p} + T_i \quad (6)$$

Where, m is the water mass. C_p is the specific heat capacity of water. T_i is the initial temperature of water.

- Electric efficiency of PV modules in PV/T solar collector

The output electric efficiency of PV modules can be expressed as follows:

$$\eta_{pv} = \tau k \eta \left[1 - 0.0045(t_a + ((NOCT-20)\cdot\frac{E_a}{800} - 298K)\right] \quad (7)$$

Where, τ is the transmittance of glass cover. k is the output efficiency coefficient of PV modules, which shows the effect of working point on conversion efficiency of PV modules. η is the conversion efficiency of PV modules. t_a is the temperature of ambient.

The output power of PV modules can be expressed as follows:

$$P_o = \tau k \eta \left[1 - 0.0045(t_a + ((NOCT-20)\cdot\frac{E_a}{800} - 298K)\right] A_{pv} E_a \quad (8)$$

Where, A_{pv} is the effective area of PV modules.

C. *Characteristic analysis of the PV/T solar system*

The effect of the solar irradiation and covering area of PV modules on PV/T solar system is analyzed using the theory model of PV/T solar collector and the structure parameters of the PV/T solar collector (as Table 1).

TABLE I. STRUCTURE PARAMETERS TABLE OF PV/T SOLAR COLLECTOR

Parameter name	Value
PV/T solar collector area	$4m^2$
Initial temperature of water (T_i)	293/K
Emission coefficient of glass cover(ε_g)	0.88
thermal conductivity of insulating layer (K_e)	$0.045/W.m^{-1}.K^{-1}$
Perimeter of thermal collector (P)	8/m
Thickness of fin (L_{abs})	0.002/m
Thickness of back insulating layer (L_b)	0.05/m
Thermal conductivity of the fin (K_{abs})	$390/W.m^{-1}.K^{-1}$
Tube spacing (W)	0.095/m
Heat transfer coefficient of fluid (h_{fi})	$300 /W.m^{-2}.K^{-1}$
Transmittance of glass cover (τ)	0.9
Conversion efficiency of PV modules (η)	15%
Glass cover layer(N)	1
Water mass	200kg
Emission coefficient of collector (ε_p)	0.95
Thickness of PV/T thermal collector (L_{pv})	0.10/m
Thickness of side insulating layer (L_{edge})	0.04/m
Outside tube diameter (D)	0.02/m
Inside tube diameter (Di)	0.015/m
Thermal conductivity of back insulating layer (K_b)	$0.045/W.m^{-1}.K^{-1}$
Thermal conductivity of the PV modules (K_{pv})	$84/ W.m^{-1}.K^{-1}$
Heat transfer coefficient of the bond between the Flat plate collector and PV modules (h_{ca})	$45 /W.m^{-2}.K^{-1}$
Conductance of the bond between the fin and tube (C_b)	$45 /W.m^{-1}.K^{-1}$
Transmittance-absorptance product $(\tau\alpha)_e$	0.8
Output efficiency coefficient of PV modules (k)	0.8
Temperature of the ambient(t_a)	293/K

- Effect of solar irradiation and covering area on the photothermal characteristics

Under the condition of different covering area of PV modules, the relationship of PV/T solar system thermal efficiency and solar irradiation are shown in the Fig. 2

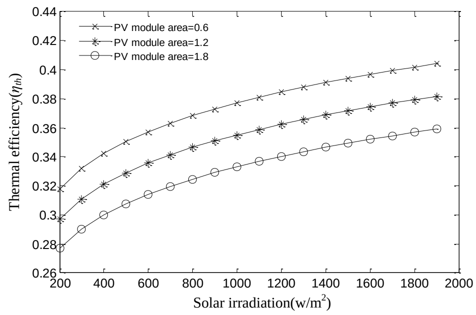


Figure 2. Effect of irradiance on system thermal efficiency

In Fig. 2, the thermal efficiency of PV/T solar system increase with increasing the solar irradiance, and the thermal efficiency of PV/T solar system decrease with increasing covering area of PV modules under same condition of the solar irradiance.

- Effect of solar irradiation and covering area on the output power characteristics

Under the condition of different covering area for PV modules, the relationship of PV/T solar system output power and solar irradiation are shown in the Fig. 3.

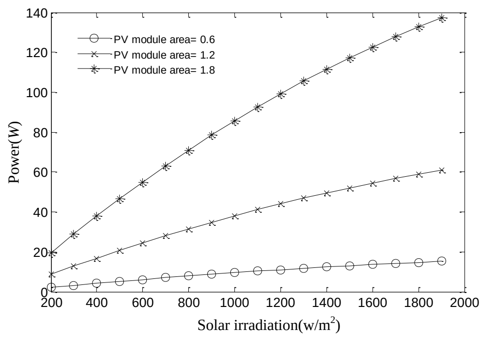


Figure 3. Effect of irradiance on system output power

In Fig. 4，the output power of PV/T solar system increase with increasing solar irradiance, and the output power increase with increasing covering area of PV modules under same condition of solar irradiance.

III. PROTOTYPE OF THE PV/T SOLAR SYSTEM AND EXPERIMENT

A. *Prototype of the partially covered PV/T solar system*

The prototype of partially covered PV/T solar system is designed, which consists of two partially covered flat plate PV/T collectors with area of $2m^2$, the water tank insulation of 200L, the silicic acid battery of 80Ah and the charge controller, etc. The covering area of PV modules is $0.8m^2$ (the effective area of $0.68m^2$ for the PV modules). The prototype is shown in the Fig. 4.

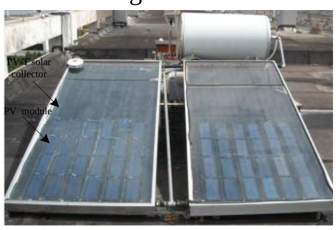


Figure 4. Prototype of the PV/T solar system

B. Experiment system and theory

The experiment test system is designed which consisted of the multi-channel data acquisition system, the irradiance meter (TB-2), five temperature transmitters and platinum resistances, where TB-2 is used to measure the solar irradiance, The platinum resistance and the temperature transmitter are used to detect temperature signal and convert to voltage signal. All test results are stored in the computer through multi-channel data acquisition system. The test content include the solar irradiance, the environment temperature, the PV modules temperature, the water temperature, the PV modules output current and voltage, etc. The test system is showed in the Fig. 5.

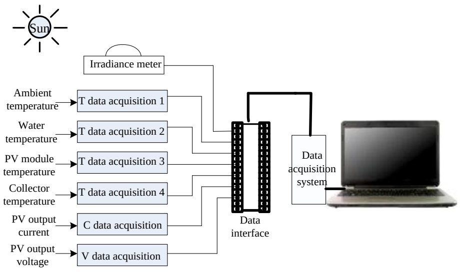


Figure 5. Test system structural diagram of the PV/T solar system

In addition, thermal efficiency η_{th} and output power of PV/T solar system is defined using the thermodynamics theory and the electrician theory as follows:

$$\eta_{th} = \frac{MC_p(T_f - T_i)}{HA} \tag{9}$$

$$P_o = U_o I_o \tag{10}$$

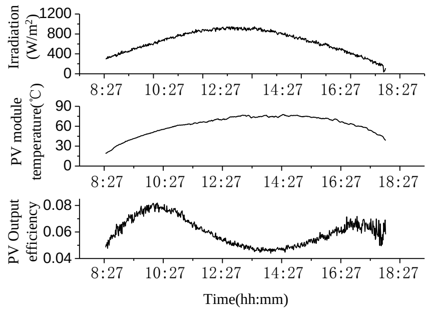
$$\eta_{pv} = \frac{P_{pv}}{A_{pv} E_a} \tag{11}$$

Where, M is the water mass in tank insulation. C_p is the specific heat capacity of water. T_i and T_f are the initial temperature and highest temperature, respectively. H is receiving overall energy per unit area in the whole measurement period. P_o is the average output power of PV/T system. A is the overall area of PV/T solar collector. A_{pv} is the effective area of PV/T solar collector. P_{pv} is the real time output power of PV/T system.

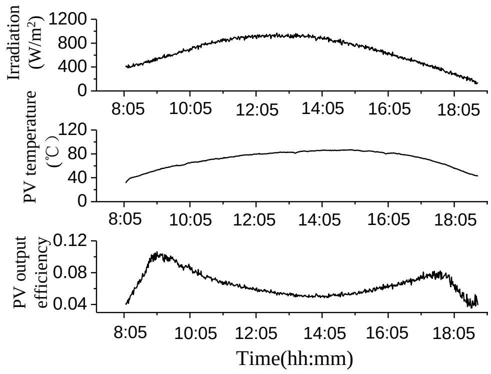
C. Prototype experiment and analysis

Firstly, the effect of glass cover on the characteristics for the prototype of PV/T solar system is studied at Chuxiong City (from 8 April to 11 April, 2013). Under the condition of different glass covers (no glass cover, the thickness of 2mm, 3mm and 4mm) on PV/T solar collector, the hot water temperature, the solar irradiation, the PV modules temperatures, output voltage and current of PV modules are tested in the prototype. Experiment results show that the effect of the glass cover on the performance of the PV/T solar system is obvious. Under the condition without glass cover, the average output efficiency of PV modules is 6.4% at 8:27-15:27, the heat efficiency is lower only 26.4%, and the hot water temperature only reach 50℃. Under the condition with glass cover, the thermal efficiency of electric efficiency the system related to the transmittance and thickness of glass cover. For example, under the glass thickness of 2mm, the thermal efficiency of system and the average output efficiency of the PV modules are 40.2% and 6.4%, respectively. Under the glass thickness of 4mm, it's 28.0% and 5.3%, respectively.

Secondly, the effect of the covering area of PV modules on the performance of PV/T solar system is studied by experiment at Chuxiong City (8 April, 2013 and 14 June, 2013). Covering areas of PV modules are 0.8m^2 and 1.01m^2, respectively (the effective areas of 0.68m^2 and 0.85m^2 for PV modules). The performances of two PV/T solar systems are tested at 8 April and 14 June, 2013. The solar irradiation, the temperature of PV modules and the PV output efficiency are showed in the Fig. 6.



a. Prototype of covering area 0.8m2

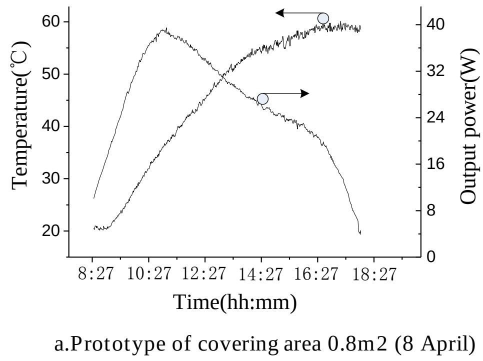


b. Prototype of covering area 1.01m2

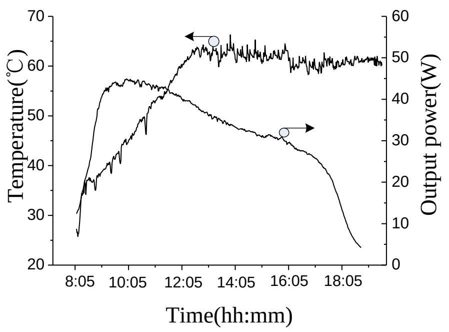
Figure 6. Characteristics of PV modules in the prototype

In the Fig. 6(a), the average solar irradiation is 725W/m^2 at 8:27-16:27. In the Fig. 6(b), the average solar irradiation is 770W/m^2 at 8:27-16:27. The temperature of PV modules rises with the increase solar irradiation. The output electric efficiency of the PV modules reduces with the increase of temperature. These results are consistent to the theory analysis.

Under the condition of two covering areas, the output power and water temperature of prototype are showed in the Fig. 7.



a.Prototype of covering area 0.8m2 (8 April)



b. Prototype of covering area 1.01m^2

Figure 7. Characteristics of water temperature and power

In the Fig. 7(a), the hot water temperature reaches 60℃, and the thermal efficiency is 40.2%. In addition, the average output power of PV modules is 25.1W from 8:30-18:30. In the Fig. 7(b), the hot water temperature reaches 65℃, and the thermal efficiency is 36%. The average output power of PV modules is 33.7W from 8:30-18:30. According to the experiment results, the thermal efficiency of prototype decreases with increasing covering area of PV modules. Experiment results are consistent to the theory analysis.

The experiment results show the output power of PV modules in the prototype can supply four energy-saving lamps (9W) to work for six hours at night. Hence, the prototype of PV/T solar system had batter practicality and could meet the basic need of the ordinary rural families in lighting electricity and hot water.

IV. CONCLUSION

The optimization design theory of partially covered PV/T solar system is established on the basis of the structure for PV/T solar collector, the basic theory of flat plate thermal collector and photothermal characteristics of PV modules. The effect of different design parameters on characteristics of the partially covered PV/T solar system is analyzed using the design theory. The design process of partially covered PV/T solar system can be simplified by using the design theory. The prototype of partially covered PV/T solar system is designed, and the effect of glass cover and covering area of PV modules on the characteristics of the prototype is studied at Chuxiong City. Experiment results show that the glass cover is essential for improving the thermal efficiency of PV/T solar system, and the output electric efficiency and the thermal efficiency of the system related to the transmittance and thickness of glass cover. Moreover, the thermal efficiency of the PV/T solar system will decreases with increasing covering area of PV modules. Experiment results are consistent to the theory analysis. In addition, under the condition of covering area of PV modules (1.02m^2), the average output power of prototype is 33.7W and the hot water temperature can reach above 65℃. The electric energy of the prototype can supply four energy-saving lamps (9W) to work for six hours at night. So, the partially covered PV/T solar system has batter practicality, and can meet the basic need of the ordinary rural families in lighting electricity and hot water.

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