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Research on PVT Module Operating at High Temperature

Lv Weizhong

Gansu Natural Energy Research Institute, Lanzhou, P. R. China

Email address:
luwz@163.com

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Abstract: At present, the research and development of PVT modules by researchers and engineers worldwide is still in the stage of small-scale production and research and development. Most PVT modules use ordinary photovoltaic cells. In order to ensure their best operating efficiency, the output hot water temperature is generally not more than 30°C. To obtain high temperature hot water, secondary heating is required, such as using heat pump, so the overall system cost is high. Based on the above problems, this paper studies and develops a new PV-thermal integrated module, re-optimizes the overall structure, selects the characteristic high-temperature resistant crystalline silicon photovoltaic cell (black silicon) and solar special heat-absorbing coating to improve the operating temperature of the PVT module, and uses graphene heat conductive material to increase the contact area of heat conduction and heat transfer, which is packaged and processed. After a series of experimental tests, the operating temperature of the PVT module reaches 60°C, and it can stably obtain high-quality hot water above 50°C. The PVT module can work under high temperature conditions for a long time, effectively improving the overall energy conversion efficiency of the system, and the generated hot water can directly meet the needs of daily life and space heating without secondary heating, has a good market development prospect.

Keywords: PVT, High Temperature, Solar Energy Coating, Black Silicon, Graphene

1. Introduction

At present, the research on PVT module (Based on PV module, increases the utilization of heat, and can meet the requirements of photoelectric, thermal applications at the same time.) at nation and abroad is still in the stage of exploration and development and small-scale production, and its technology is still upgrading [1-8]. In this regard, foreign researchers have made similar products. They can obtain 20°C-30°C low-quality hot water by using ordinary photovoltaic cells combined with traditional flat plate collector technology [2]. They also need to use a secondary heat pump system for heating. The overall system control is complex and the cost is very high. Some domestic enterprises are trying to develop similar products, but they can only obtain low-temperature hot water, which also needs secondary heating [7]. The comprehensive conversion efficiency of energy is very low, and it is often not used in winter. Therefore, based on the above defects, the research developed a new photovoltaic photothermic integrated PVT module. By selecting high temperature resistant crystalline silicon photovoltaic cells [11], special heat absorbing coatings for solar energy [12, 13] and graphene heat conducting materials [15, 16], the optimal operating temperature of PVT module is controlled at 60°C, and finally high-quality hot water of about 50°C is obtained, which also improves the energy conversion efficiency of PVT module [14].

2. Overall Structure Design

2.1. Design of Heat Absorbing and Conducting Layer for Power Generation

In order to facilitate processing and market promotion, the traditional flat plate collector frame (1m x 2m) is used for the integrated transformation of new PVT frame. Traditional solar flat plate collectors usually use aluminum-based heat exchange layer sprayed with blue film or black chromium, with a thickness of only 0.3 ~ 0.6mm. Considering the packaging strength, 1mm thick metal aluminum plate is used in this study. The metal aluminum plate surface of prepackaged photovoltaic cells is roughened, and then sprayed with special solar energy coating RLHY-2337. After thorough drying, it is integrated with the selected crystalline silicon photovoltaic cells. The EVA selected for packaging is high temperature resistant EVA, and its thermal conductivity is between 0.5W/m·K and 2W/ m·K [9, 10]. Through computer simulation experiments, 158mm x 158mm photovoltaic cells are fully paved within 2 square meters, with a maximum of 72 tiles. In this study, 60 pieces are laid in series (see Figure 1), so there is still a large space around the photovoltaic cell array. On the basis of ensuring photovoltaic power generation, the power generation heat absorption and heat conduction layer of the PVT module can also absorb more solar energy. According to the design requirements, the air temperature of the surface of the packaged PVT module can be increased from the maximum 80°C of the ordinary photovoltaic modules to more than 110°C.

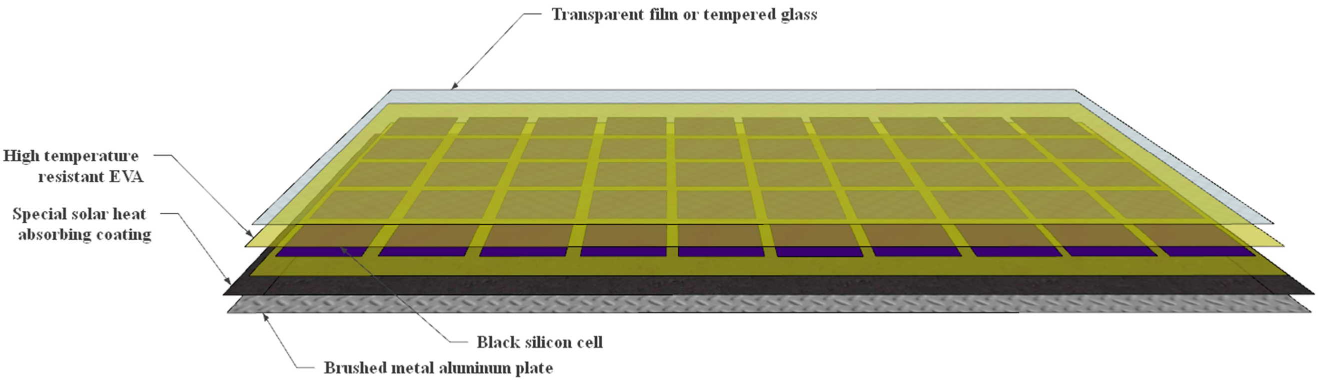

Figure 1. *Layered diagram of PVT module with power generation, heat absorption and heat conduction layer.*

At present, there are many kinds of photovoltaic cells on the market, the processes are different. Traditional crystalline silicon cells can only convert 3/4 of the energy in the solar spectrum into electrical energy, but cannot convert the remaining infrared spectrum into electrical energy. Only new photovoltaic cells such as black silicon can do this [17-23]. Therefore, the introduction of black silicon cells into PVT module can make use of its full spectrum power generation characteristics, and the additional power generated in the infrared spectrum and the resulting additional heat energy can further increase the conversion efficiency of PVT module [20]. According to the latest research results, if the secondary annealing process of black silicon cells is completed [22], its temperature coefficient will be greatly reduced and the power generation efficiency will not be significantly attenuated due to temperature rise [23].

Table 1 lists the light decay rate, crack rate, mechanical load decay rate and cost of different crystalline silicon photovoltaic cells. Polycrystalline black silicon cells have some characteristics that other traditional crystalline silicon photovoltaic cells do not have. In addition to the advantages of low light attenuation rate, the main thing is that black silicon cells can generate power in full spectrum.

Table 1. *Photoinduced decay, mechanical load characteristics and cost of different crystalline silicon cells.*

Technology type	Photo-induced decay rate	Cracking rate	Mechanical load decay rate	Cost of single-chip cell
PERC single crystal single side	high	high	high	high
PERC single crystal double-sided	high	high	high	high
N-type single crystal double-sided	none	low	low	high
Polycrystal black silicon	low	low	low	low

2.2. Design of Tube Sheet Heat Transfer Layer

In the traditional flat plate collector, the welding surface between the heat conducting metal aluminum plate and the red copper heat pipe is only connected by a linear weld with a width of less than 1mm. In many cases, there will be false welding, which will affect the heat transfer efficiency. On this basis, a special process is added, that is, a layer of graphene sealant is filled at the joint between the aluminum based photovoltaic cell array and the red copper heat pipe to increase the thermal conductivity area [15].

2.3. Overall Design

The PVT module in this study adopts the shape of traditional solar flat plate collector, which is convenient for processing and production [12, 24]. The grid type red copper heat pipe core consists of 9 pieces Φ 10 branch pipes and 2 Φ 20 header, with four inlets and outlets, which is consistent with the traditional flat plate collector structure, and can be conveniently connected in series and parallel. The frame of the whole PVT module is made of plastic steel, and the back plate is made of galvanized steel sheet.

The design technical indicators of PVT module are as follows:

1) Dimensions

Lighting surface size: 1945 X 995 mm Lighting area: 1.94 m^2.

Total area size: 1950 X 1000 mm Total area: 1.95 m^2.

2) Heat transfer working medium

Unfrozen liquid (-30°C- 200°C).

3) Power generation:
Rated power: 280Wp.
4) Operating temperature
Normal operating environment temperature: -20°C - 80°C.
Optimal cycle temperature: 55°C-60°C.

3. System Test

3.1. System Structure

The PVT components verification and test system includes two sets of PVT module, two groups of 12V 200AH batteries, 1000W mains complementary inverter, 24V charge and discharge control unit, and intelligent temperature sensing control and pipeline control system.

It mainly consists of six parts: 1) Two sets of PVT module; 2) Intelligent control system; 3) Over temperature protection system; 4) 100L secondary heat exchange water tank; 5) Output measurement and detection unit (photovoltaic power generation and hot water); 6) Environmental meteorological acquisition system unit.

3.2. Operating Conditions

The test and verification system has two sets of PVT module installed, which can run simultaneously in parallel, and one set of PVT module can run independently. On the premise of perfect measures of heat preservation and frost resistance for circulating pump and outlet pipe, the system can be operated all-weather. Except for special weather conditions, more than 90% of the power consumed by the verification system comes from PVT module. The highest operating temperature of PVT module is 60°C, and the system will take protective measures automatically to avoid PVT module damage caused by over-high temperature. See Figure 2 for a diagram of the system structure.

In Figure 2, S is a manual valve, D is an electric valve, T is a temperature probe, and P is a circulating pump.

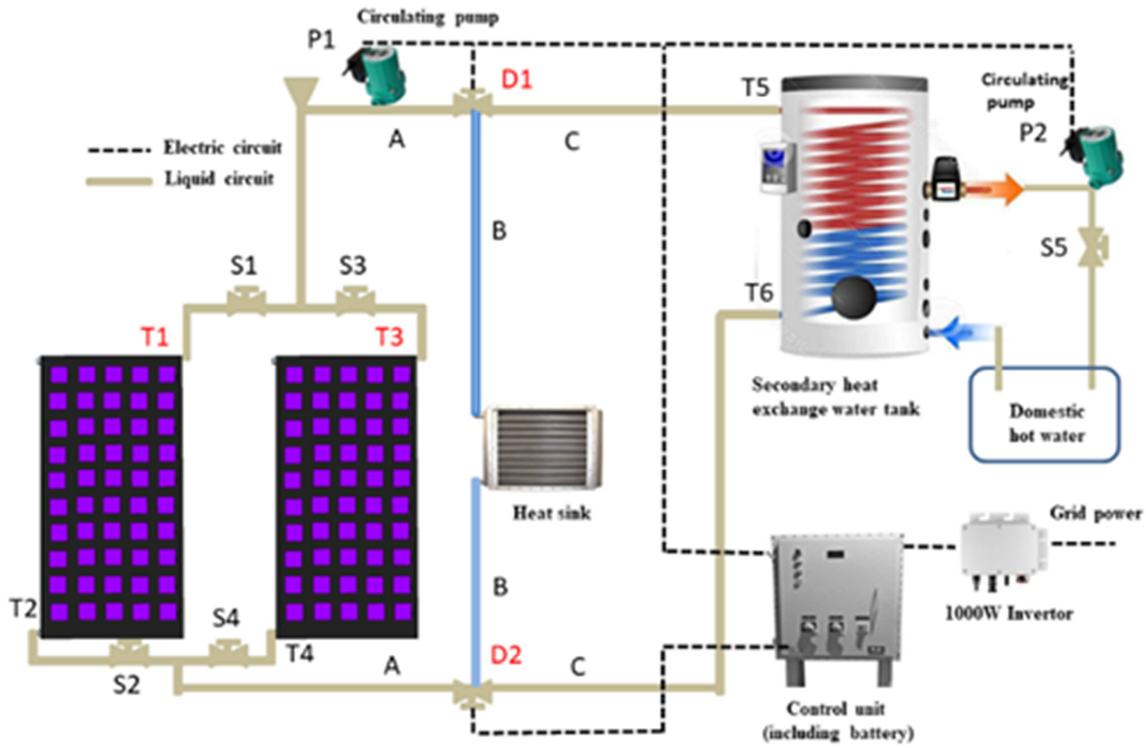

Figure 2. *Structure and operation diagram of PVT module verification test system.*

Control node process:

1) When T1 or T3<60°C, D1 and D2 connect the A and C pipelines, when T1 or T3≥55°C, start P1, when T1 or T3<45°C, close P1.
2) When T1 or T3 ≥ 60°C, D1 and D2 are connected to pipelines A and B, and P1 starts to enter a small cycle. When T1 or T3 is less than or equal to 45°C, D1 and D2 are connected to pipelines A and C, and P1 is closed.

3.3. System Actual Test

The PVT system test method adopts the first law of thermodynamics [25-27], which is evaluated by the total efficiency η_0 of photovoltaic, photo-thermal, and η_0 can basically reflect the energy gain of PVT in quantity.

$$\eta_0 = \eta_1 + \eta_e \tag{1}$$

Where: η_0 is the total photovoltaic and photo-thermal efficiency of PVT system, %; η_1 is the thermal efficiency of PVT system, %; η_e is the power generation efficiency of PVT system, %.

In addition to formula (1), there are also literatures that propose to use the comprehensive efficiency of photovoltaic and photo-thermal E_f as the evaluation index of PVT system. This evaluation index takes into account the quantity and grade of electric energy and heat energy, E_f can reflect the ability of the solar energy captured by the PVT system to convert into electric energy and heat energy.

$$E_f = \eta_1 + \frac{\eta_e}{\eta_{power}} \tag{2}$$

Where: E_f is the comprehensive photovoltaic, photo-thermal efficiency of PVT system, %; η_{power} refers to the power generation efficiency of conventional coal-fired power plants (the power generation efficiency of conventional coal-fired power plants in China is generally 35% - 42%).

Intermittent testing has been carried out since January 2021. In winter, when the ambient temperature is below 0°Cand it is sunny, in order to ensure the water temperature quality, the working mode of parallel operation of two sets of PVT module is adopted. In summer, when the ambient temperature is above 20°C. Only one set of PVT module is opened for independent operation. Whether two sets of PVT module are operated at the same time or a single set of PVT module is determined by the actual situation of the test site climate environment. Its purpose is to ensure that the water temperature after secondary heat exchange meets the design requirements. When the solar irradiance is poor in cloudy days in winter or other seasons, such as when the solar irradiation value is continuously lower than 300W/m^2, the system stops running.

3.4. System Test Results

The purpose of this verification and test system is to detect the operation status of PVT components; the second is to detect whether the electrical and thermal conversion efficiency of PVT components meets the design requirements in different seasons.

After testing, in winter, in sunny weather with an ambient temperature of -10°C, tap water of about 10°C is injected, and two sets of PVT module are connected in parallel. After 6 hours of sunlight, the temperature of the water tank is between 44°C- 49°C; It is sunny in summer, and the ambient temperature can reach more than 20°C. On sunny days in summer, the ambient temperature is above 20°C. When tap water of about 15°C is injected, only a single PVT module is used. After 6 hours, the water tank temperature is generally between 53°C-58°C. In the steady-state efficiency experiment, four working medium inlet temperatures with uniform intervals are selected within the working range of PVT components, and the detection time interval of each instantaneous efficiency point is not less than 3 minutes, so the comprehensive efficiency test results of PVT components under four working conditions are obtained (see Table 2). Through a series of tests, the comprehensive electro-thermal conversion efficiency of this photovoltaic photo-thermal integrated PVT module operating under high temperature conditions is greater than 67%, which basically meets the design requirements.

Table 2. *Comprehensive efficiency test results of PVT module under 4 working conditions.*

Working condition	**1**	**2**	**3**	**4**
Irradiance (W/m^2)	1009	1019	1017	1003
Ambient temperature (°C)	25.6	24.2	23.3	22.2
Inlet temperature (°C)	22.0	34.5	45.7	60.6
Outlet temperature (°C)	25.6	39.1	49.0	61.5
Heat gain (W)	1039.17	763.58	526.82	130.42
Heat collection efficiency (%)	53.08	38.64	26.70	6.70
Generating voltage (V)	24.34	23.98	23.56	23.30
Generating current (A)	8.99	8.91	8.86	8.79
Generating power (W)	218.77	213.57	208.67	204.86
Efficiency of electricity generation (%)	14.17	13.70	13.41	13.35
Heat collection efficiency + power generation efficiency (%)	67.25	52.34	40.11	20.05

Figure 3 shows the fitted instantaneous thermal efficiency curve of the PVT module.

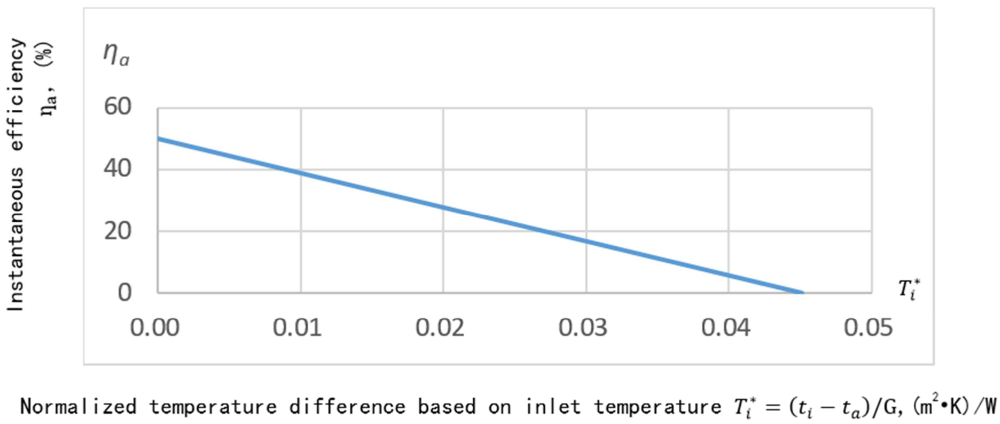

Figure 3. *Instantaneous efficiency curve based on daylighting area A_g and collector inlet temperature T_i (η_G =0.498-11.033T_i^*).*

4. Conclusion

After two-and-a-half of design, processing and testing, through the post-test evaluation of this PVT components operating under high temperature conditions, the conclusion is:

1) The packaging material used in the power generation and heat conduction layer of the PVT module has a great impact on its comprehensive electrothermal output efficiency. It is advisable to consider the heat conduction and insulation material with high-cost performance and good heat absorption characteristics, which is helpful to improve its overall efficiency.
2) Photovoltaic cell screening of PVT module is very important. The best choice for photovoltaic cells is crystalline silicon photovoltaic cells that can operate in full spectrum. In addition, the preferred photovoltaic cells should have better temperature characteristics.
3) Increasing the contact area between the heat transfer tube plates can improve the heat transfer efficiency. Worldwide, researchers have also studied and improved this problem by improving materials, innovating processing technology, changing heat transfer structure and so on.
4) As a new force in the field of solar energy application at present, PVT module has the advantages of photovoltaic power generation and photo-thermal utilization. Under the same scenario, its photoelectric photo-thermal comprehensive efficiency conversion per unit area is high, and the potential for promotion and utilization is huge.

In the future, PVT module will play an irreplaceable role in energy conservation, environmental protection, carbon reduction and sustainable development of energy.

5. Recommendation

For the field of large-scale use of PVT components as solar electric heating integrated utilization system, such as centralized heating, industry process, etc., it is recommended that the combination of PVT system and heat pump technology can achieve maximum energy saving and reduce operating costs. However, for the field of single-household, multi-household and small-scale PVT systems, it is recommended to directly use the PVT module researched in this paper that can operate under high temperature conditions, which has more cost advantages while saving energy.

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