Experimental Investigation on A Novel Flat-Plate Water-Based Photovoltaic-Thermal Module

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Abstract

The performance of a novel flat-plate water-based PVT (photovoltaic-thermal) module was experimentally investigated under different environmental conditions in Shanghai. A novel PVT module was. An experimental bed was implemented to investigated the performance of the module on heat collection, benefit for electricity generation, and pressure drop. Additionally, the temperature unevenness of the module was discussed. The results revealed that the PVT module can contribute a 12% benefit for electricity generation compared with PV module. Additionally, the intercept efficiency factor of the module could reach over 0.8, and the heat efficiency can reach over 45%. Meanwhile, the relation between temperature unevenness and dimensionless temperature was fit.

Keywords: PVT, water-based, experimental investigation, temperature unevenness.

1. Introduction

Buildings, which offer indispensable facilities for human beings, consume about 40% of the global energy (Lin et al., 2021) and emit more than 30% of the global carbon dioxide (Costa et al., 2013). Meanwhile, the energy consumption and the carbon emission of the building section is expected to keep growing in the future (Ibn-Mohammed et al., 2013). Renewable and sustainable energy, especially solar energy, is increasingly widely applied to buildings as a more energy-saving and low-carbon approaches to face with the energy crisis and the global warming.

Solar energy technology can be roughly categorized into photovoltaic (PV) technology and solar thermal technology (Vassiliades et al., 2022). Thereinto, PV technology is widely accepted and applied in recent years due to the rapid progress in electrical efficiency (Gao et al., 2019; Zhao et al., 2008) and the reduction in the power generation costs (IRENA, 2018).

The PV modules transfer solar irradiation received into heat in addition to electricity during operation, leading to the rising modules temperature and worsening electricity efficiency due to temperature effect (Dubey et al., 2013). As some research reported, every 1 ºC temperature increase will lead to 0.45-0.50% drop in relative efficiency (Siecker et al., 2017). Meanwhile, a high working temperature can also shorten the life span of PV modules. The PVT technology, which was first conceptualized by Wolf et al. (Wolf, 1976) in 1976, can serve to extract and reuse the waste heat and to lower the working temperature of PV modules by implementing a thermal absorber in the back side of the modules.

After decades of research, the PVT technology has witnessed profound progresses, including innovation on designs and working fluids. The PVT modules can be mainly categorized into the following types with respect to different working fluid: air-based (Solanki et al., 2009), water-based (Shyam et al., 2015) and refrigerant-based (Jouhana et al., 2016). Among these, the water-based PVT presents a satisfactory heat efficiency, better adaptability to large-scale system, and lower system complexity, resulting in its wide application. Aste et al. (Aste et al., 2015) reported a simulation, showing that the glazed water-cooling PVT could offer a thermal efficiency of 42% with an electrical efficiency of 13.2%.

As a heat collector, the performance of the water-based PVT module can be evaluated from the aspect of heat efficiency, which is depended on the climate conditions (ambient temperature, irradiation intensity), the operation parameters (flow rate, inlet temperature), and the design parameters. UI Abdin et al. (UI Abdin et al., 2021) conducted a simulation on a parallel-shape sheet-and-tube water-based PVT module, reporting a

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thermal efficiency varying from 32%~70% under different flow rates. Saeed et al. (Saeed et al., 2021) developed a water based PVT module, achieving a thermal efficiency varying from 38.8–43.1%.

However, the temperature unevenness of water-based PVT modules is also an important factor. Yu et al. (Yu et al., 2019) reported a temperature difference above 20 ºC for a roll-bond water-based PVT collector. Uneven temperature distribution in the solar cells (which is unavoidable because water is sensible-heat working fluid), like hot spot, will undermine the electrical performance and shorten the life span. Thus, the research on water-based PVT should consider the temperature unevenness (or uniformity) as an essential factor. The object of this paper is to experimentally investigated the temperature uniformity besides other important electrical and thermal parameters of a novel water-based PVT module.

2. System description and experimental setup

Fig. 1 briefly illustrated the structure of the water-based PVT module investigated. The working fluid inside the tube absorbs waste heat generated in the PV cells through the tube-plate heat transfer structure behind the white plate. The insulation in the backside is made of foamed polyurethane, preventing the fluid from the heat dissipation.

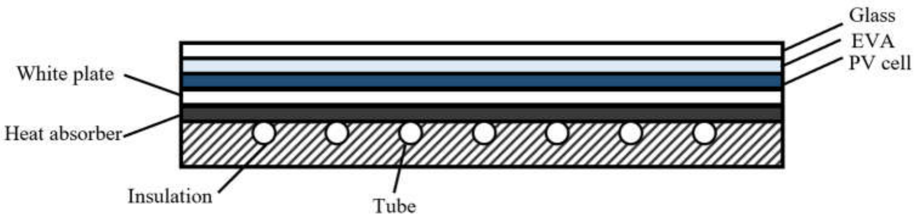
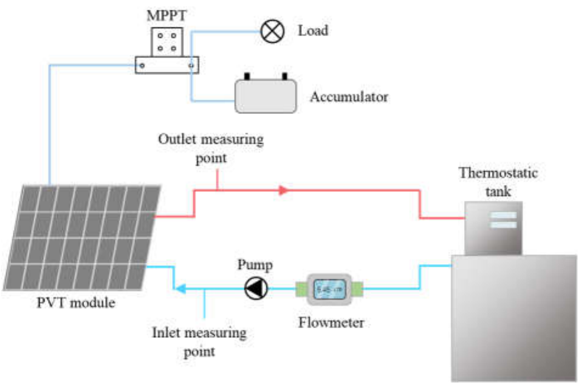
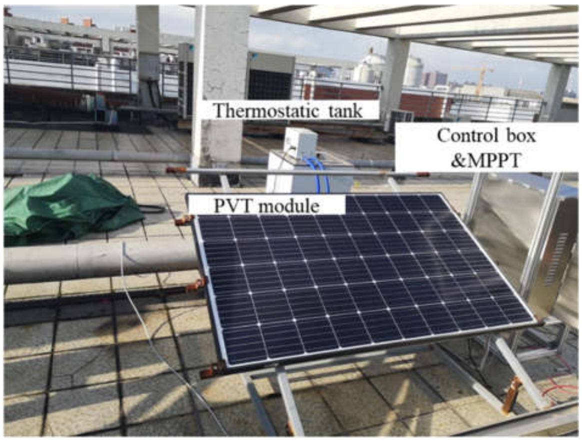


Fig. 1: The schematic diagram of the structure of the water-based PVT module.

Fig. 2(a) presented the schematic diagram of the experimental rig testing the PVT module. Two different measuring points are set at the inlet and outlet of the PVT module to measure the temperature rise and pressure drops of the module. Thermostatic tank is used to keep the inlet temperature constant. The electricity sector, including MPPT (maximum power point tracer), accumulator, and load, is used to measure and to consume the electricity power. Additionally, five temperature sensors were distributed in different position between the thermal absorber and the insulation to measure the temperature difference of the PVT module (shown in Fig. 3). The front view of the experiment rig was shown in Fig. 4.



(a) The schematic diagram



(b) The front view

Fig. 2: The experiment rig.

Fig. 3: The locations of five temperature sensors.

The field tests of the water-based PVT experiment system were conducted in a series of days from Oct. to Jan. in Shanghai. Besides the PVT module's thermal performance, its electrical performance was also experimentally investigated in comparison with a single PV module to estimate its benefit on electricity generation.

3. Results and discussion

3.1 Mathematical model

Apart from the electricity output, the PV cells convert part of the solar irradiation into heat:

$$Q_{abs} = (\tau\alpha)I_R(1-\eta_e) \quad \text{(eq. 1)}$$

The heat dissipation from the PVT module to the ambient can be expressed by the following equation:

$$Q_L = U_L(T_p - T_a) \quad \text{(eq. 2)}$$

where T_p, T_a refer to the temperature of the PV cells and the ambient air; U_L, the heat loss coefficient, can be expressed by:

$$U_L = \frac{1}{\frac{1}{h_{cv}+h_{rd}}+\frac{L_g}{k_g}} + \frac{1}{R_{pb}+\frac{L_b}{k_b}} \quad \text{(eq. 3)}$$

where h_{cv}, h_{rd} refer to the heat transfer coefficient of the convection and radiation processes; R_{pb} is the thermal resistance between the PV cells and the heat absorber; L, k refer to the thickness and the thermal conductivity; the subscript g, b represent the glass cover and the back insulation, respectively.

The heat absorbed by the working fluid (water) is:

$$Q = Q_{abs} - Q_L \qquad \text{(eq. 4)}$$

The thermal efficiency is defined as:

$$\eta = \frac{Q}{I_R A} \qquad \text{(eq.5)}$$

Besides the thermal efficiency, two other parameters, efficiency factor and the heat removal factors were defined and calculated to evaluate the thermal performance:

Efficiency factor F' and heat removal factor F_R are defined as:

$$F' = \frac{A[(\tau\alpha)I_R(1-\eta_e)-U_L(T_f-T_a)]}{Q} \qquad \text{(eq. 6)}$$

$$F_R = \frac{A[(\tau\alpha)I_R(1-\eta_e)-U_L(T_{in}-T_a)]}{Q} \qquad \text{(eq. 7)}$$

where T_f is the average temperature of the working fluid, T_{in} is the inlet temperature; τ,α are the transmittance of the glass and the absorptivity of the PV cells, respectively.

An excess temperature was proposed to comprehensively consider the module temperature and the irradiation:

$$\theta = \frac{T_f-T_a}{\tau\alpha(1-\eta_e)I} \qquad \text{(eq. 8)}$$

Another excess temperature, θ_f, was proposed as the ratio of the temperature rise of the fluid to the irradiation:

$$\theta_f = \frac{T_o-T_i}{\tau\alpha(1-\eta_e)I} \qquad \text{(eq. 9)}$$

The temperature unevenness is defined as:

$$\Delta = T_5 - T_1 \qquad \text{(eq. 10)}$$

where T_1, T_5 refer to the lowest and the highest temperature recorded by the five temperature sensors.

3.2 Comprehensive performance

The field tests were conducted under two different levels of the mass flow rate of the water (1.3 kg/min and 0.25 kg/min) in different days.

Fig. 4 presents three different experiments in Nov. 26th, Jan. 1st, and Dec. 31st, respectively.

(1) The experiment in Nov. 26th (Flow rate:1.3 L/min)

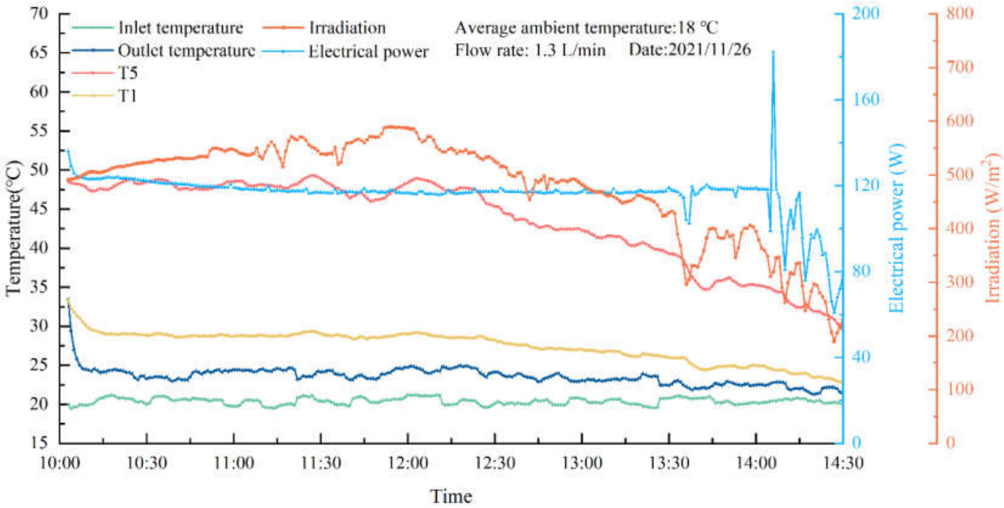
As shown in Fig. 4(a), the experiment lasted from 10:03 to 14:30, within which the average ambient temperature was 18 ℃, and the average irradiation is 477 W/m^2. During the experiment, the average temperature rise of the circulating water is 3.16 ℃, and the average electrical/thermal/overall efficiency were 14.27%/35.24%/49.51%, respectively. Besides, the average module temperature is 34.9 ℃. The maximum value of the temperature unevenness during the experiment was 19.9 ℃, while the average value of that was 16.0 ℃.

(2) The experiment in Jan. 1st (Flow rate: 0.25 L/min)

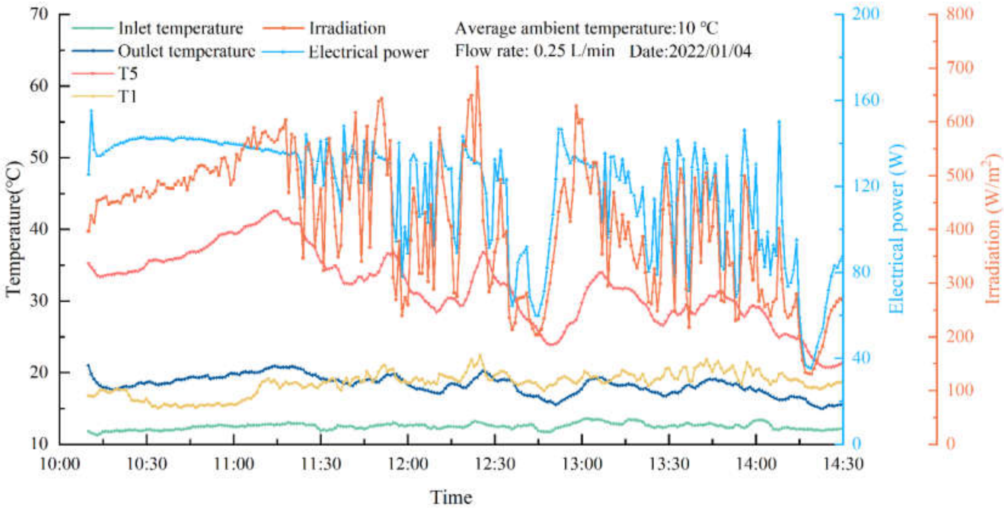
As shown in Fig. 4(b), the experiment lasted from 10:10 to 14:30, within which the average ambient temperature/solar irradiation was 10 ℃/414 W/m^2. Compared with the experiment in Nov. 26th, the average temperature rise of the circulating water improved due to the smaller flow rate (from 3.16 ℃ to 5.77 ℃). However, the convective heat transfer within the tube was undermined by the decreasing flow velocity, which leads to lower thermal efficiency. The average electrical/thermal/overall efficiency of the PVT module were 16.75%/14.29%/31.04%, respectively. Compared with the thermal efficiency of the PVT module with a flow rate of 1.3 L/min, that of the PVT module with a flow rate of 0.25 L/min decreased by 59.45%. Additionally, the maximum value of the temperature unevenness was 20.0 ℃, while the average value of that was 13.2 ℃, showed little difference from that of the PVT module with a flow rate of 1.3 L/min.

(3) The experiment in Dec. 31st (Pure PV module)

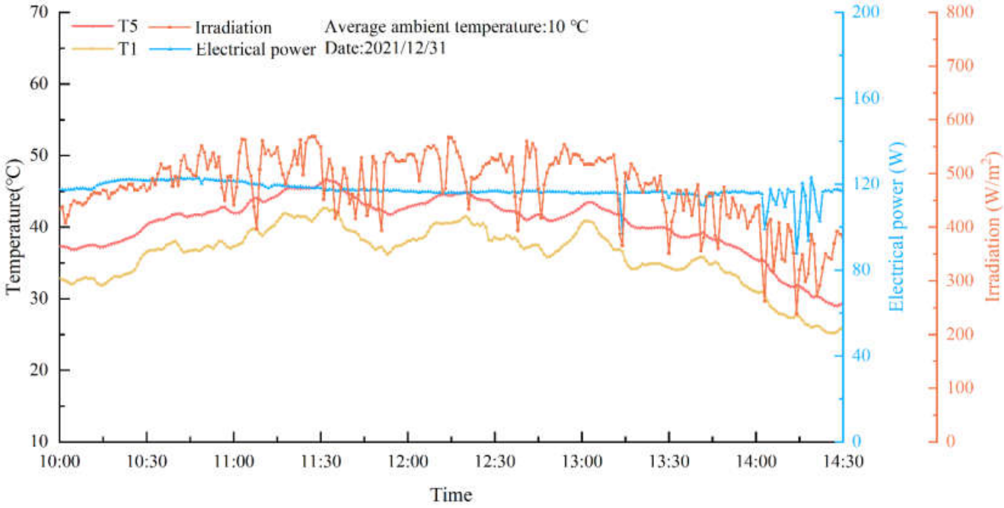
As shown in Fig. 4(c), the experiment lasted from 10:00 to 14:30, within which the average temperature is the same as that on Jan. 1st. During the experiment, the average electrical efficiency of the PV module is 14.90%, 12.4% lower than the electrical efficiency of the PVT module on Jan. 1st, proving the electricity generation benefit of the PVT module.



(a) Experiment in Nov. 26th



(b) Experiment in 2022/01/04



(c) Experiment in 2021/12/31

Fig. 4: The experiment results.

3.3 Thermal performance

Besides the comprehensive performance, the thermal performance of the PVT module was specifically analyzed with reference to the flat-plate collector. Some important coefficients, such as efficiency factor, heat removal factor, and thermal efficiency were investigated to reveal their relation to heat loss coefficient or excess temperature based on a series of experiment results. Meanwhile, the relation of the temperature unevenness to the excess temperature was also investigated.

Fig. 5(a) presents the relation between F' of the PVT module and U_L under different flow rate. The efficient factor decreases with the increasing heat loss coefficient to similar extend under different flow rate. The PVT module with a flow rate of 1.3 L/min has higher intercept efficiency factor (0.974) than that with a flow rate of 0.25 L/min (0.833), indicating higher flow rates leads to higher heat collection potential of the PVT modules. Fig. 5(b) presents the fitting results of F_R-U_L curves under different flow rate. These two curves present similar trend to the F'-U_L curves. The intercept heat removal factors of the PVT module were estimated to be 0.939 and 0.680 when the flow rate is 1.3 L/min and 0.25 L/min, respectively.

Fig. 5(c) illustrates the relation between thermal efficiency and the excess temperature. The experimental results showed that, the thermal efficiency varied from 20% to 45% under different climate and operating conditions with the flow rate of 1.3 kg/min, while varied from 9% to 18% with the flow rate of 0.25 kg/s. The intercept thermal efficiency were expected to be 52.57% and 21.42% for PVT modules with flow rates of 1.3 L/min and 0.25 L/min, respectively.

Fig. 5(d) shows the relation between the temperature unevenness and the excess temperature. With the increasing excess temperature, the temperature unevenness increases. In a series of experiments, the temperature unevenness varied from 12 to 21 ºC. The PVT modules with higher flow rate is estimated to have higher temperature unevenness.

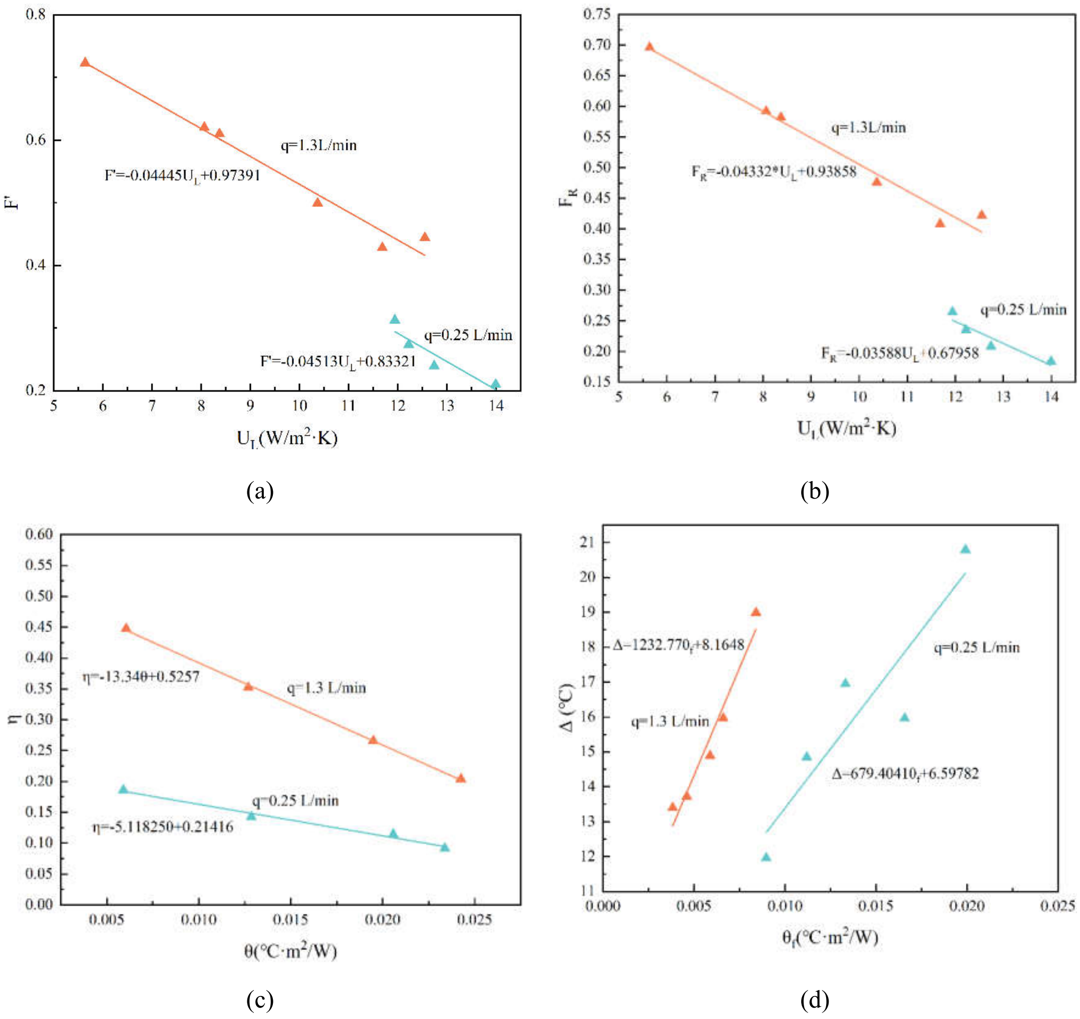


Fig. 4: The thermal performance of the PVT modules.

4. Conclusions

In this paper, a novel water-based PVT module was manufactured and experimentally investigated. The thermal and electrical of the module was evaluated. The results suggested that the PVT module has satisfactory thermal efficiency and benefit on electricity generation. The relation between efficiency/heat removal factors and heat loss coefficient was fitted to comprehensively present its thermal performance. Meanwhile, the relation between temperature unevenness and excess temperature was also discussed.

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