

# Performance Analysis of Indirect Natural Circulation PVT System for Domestic Hot Water



Zhen Guo, Ruobing Liang, Jili Zhang and Ahmad Riaz

**Abstract** In this paper, the performance of an indirect natural circulation PVT system for domestic hot water with refrigerant as the circulating working medium was discussed and analyzed experimentally, including thermal performance, photovoltaic performance, overall efficiency, responding speed, heat exchange state, and temperature distribution at different positions. The influence of different five radiation intensities was tested. The results indicate that the performance is largely influenced by radiation intensity. The response speed of the system is greatly improved. It can complete the start-up within 5 min and maintain stable operation at relatively high efficiency. The superheat degree stays between 3 and 4 °C, which is not affected by the radiation intensity, but the sub-cooling degree of the liquid medium increases with the increasing of radiation intensity. Furthermore, the temperature of the panel all reaches the superheat range, but the superheat degree in the middle of the panel is the largest. The temperature distribution is not uniform, which needs to be optimized further.

**Keywords** Solar energy · PVT · Natural circulation · Domestic hot water

## 1 Introduction

The consumption of building energy accounts for about 20% of the country's total energy consumption since China entered the twenty-firsts century, which has huge energy-saving potential. Promoting the application of solar energy in the building area is of great significance for reducing energy consumption. The technology of PVT not only can generate electricity but also provide domestic hot water. Therefore, people have a great interest in the research and application of PVT in the field of building.

The current research for the PVT technology can be divided into forced circulation and natural circulation. The research on forced circulation is mainly for PVT heat pump system [1], which studies the system performance in different pump frequency,

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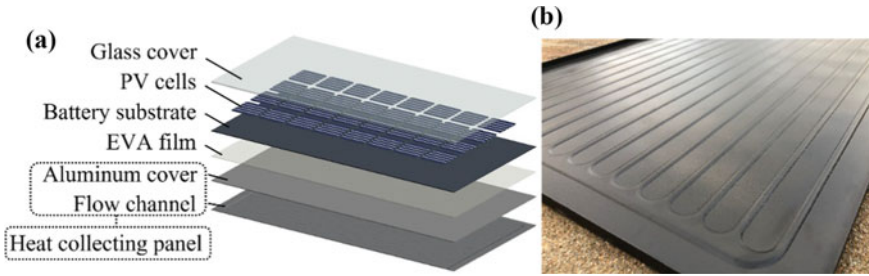
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different seasons, etc., but such system has high operating costs, complex forms, and generally consumes more electricity than their own generation, which is not suitable for small homes. The researches on the natural circulation for domestic hot water mainly use water as a circulating medium [2], which usually studies the circulation speed, system efficiency, primary energy-saving ratio, etc. Furthermore, to simulate the influence of different initial parameters on performance, many researchers study the theoretical model of the system [3]. However, according to the relevant references, for such a system, the layout is monotonous; the start-up performance is poor [4], and the water tube outside the room is easy to freeze. Experimental trials were made under same operating conditions and results were compared with plain tube V-trough (PVT) solar water heater and also with plain tube flat plate (PFP) solar water heater. Results show that PVT collector offers better thermal performances when compared to PFP collector [5]. Ziapour [6] etc. verified the new design of the photovoltaic (PV) panel combined with type of the wickless heat pipe solar water heater. Through the simulation results it is found that the optimal numbers of the wickless heat pipes may be five loops. Cao [7] etc. researched the behaviours of Controllable loop thermosyphon (CLT) with non-condensable gas (NCG) under active control. The CLT loses efficacy due to the excess NCG, and become entirely unacceptable when NCG reaches 0.47%. Herrando [8] etc. assessed the suitability of hybrid PVT systems for the provision of electricity and hot water in the UK. It is found that 51% of the total electricity demand and 36% of the total hot water demand over a year can be covered by a hybrid PVT system. The photovoltaic and thermal performances of a PVT collector with water heating in buildings are presented in given climate conditions [9]. The results indicated that the less series-connected PV modules, the lower inlet temperature of water and the higher mass flow rate of water resulted in the high photovoltaic efficiency.

Therefore, this paper designs an indirect natural circulation PVT system for domestic hot water with refrigerant as the circulating medium. In this system, the medium absorbs heat, the temperature rises and causes phase transformation, producing a density difference, driving the loop to run, and exchanges heat with water indirectly, rather than heating the water directly. The aim of this paper is to analyze the performance of indirect natural circulation PVT system in stable external environment, and mainly analyze its thermal performance, photovoltaic performance, overall efficiency, responding speed, heat exchange state, and temperature distribution at different positions.

## 2 Methods

The PVT experimental system with natural circulation is composed of PVT panel, hot water tank, gas tube, and liquid tube. The PVT panel consists of various layers as shown in Fig. 1a. The heat collecting panel is made up of aluminum plate with 16 longitudinal D-shape flow channels. The width of the upper and lower horizontal main channels is 25 mm. The diameter of the inlet and outlet is  $\varnothing 9.52$  and  $\varnothing 12.7$ ,

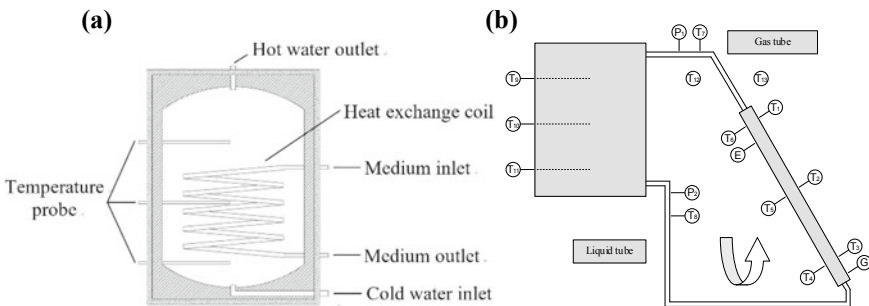


**Fig. 1** a Structure of PVT panel. b Heat collecting panel

respectively, just as shown in Fig. 1b. PV cells are laminated with the aluminum plate through the EVA film. The volume of the water tank is 60L with  $\varnothing 12.7$  stainless steel coil inside along  $\varnothing 9.52$  stainless port (Fig. 2a). To ensure the medium flows down smoothly, the slope of the coil descends strictly. The gas tube connects the outlet of the PVT panel with the inlet of the water tank while the liquid tube links outlet of the tank with the inlet of the panel. R134a is used as system medium.

The parameters measured for this study mainly include temperature, pressure, radiation intensity, and AC output power. To obtain the temperature distribution of the PVT panel, six Pt100 thermocouples labeled  $T_1 - T_3$  on the front side and  $T_4 - T_6$  on the back side are set on the panel, respectively (Fig. 2b). A couple of thermocouples labeled  $T_7 - T_8$  are set to record the temperature of the gas tube and liquid tube,  $T_9 - T_{11}$  to record the temperature inside the water tank,  $T_{12} - T_{13}$  to measure the ambient temperature, respectively. The pressure at both outlet and inlet of the PVT panel is also measured by two pressure transmitters. The radiation intensity is measured by a TBQ-2 solar pyranometer. AC output power is recorded by a EVT500 micro-inverter. All the measured parameters are connected to a Keithley 2700 data collector. All the measuring instruments mentioned above are shown in Table 1.

The output of PVT system based on natural circulation includes electrical energy and thermal energy. Considering the electricity means higher quality and value,



**Fig. 2** a Structure of water tank. b Schematic diagram

**Table 1** Specifications of measuring instruments

Items	Type	Range	Precision
PVT panel	Customized	1.56 × 0.78 m	–
Hot water tank	Customized	60 L	–
Thermocouple	Pt100	0–60 °C	±0.3 °C
Pressure transmitter	CYYZ11H15A110BG	0–2 MPa	±0.5%
Portable temperature recorder	ZDR-20	–40–100 °C	±0.5 °C
Micro-inverter	EVT500	24–42 V	–
Solar pyranometer	TBQ-2B	0.3–3 μm	±2%
Data collector	Keithley 2700	–	–
Solar simulator	TRM-PD4	400–1200 W/m <sup>2</sup>	±5%

Huang proposed another evaluation standard which is shown in Eq. (1).

$$\eta_{\text{overall}} = \left( \eta_{\text{thermal}} + \frac{\eta_{\text{electrical}}}{\eta_{\text{power}}} \right) \quad (1)$$

$$\eta_{\text{thermal}} = \frac{c_{\text{water}} m_{\text{water}} (T_{\text{water}_{n+1}} - T_{\text{water}_n})}{\int_{t_n}^{t_{n+1}} G \cdot A dt} \times 100\% \quad (2)$$

$$\eta_{\text{electrical}} = \frac{\int_{t_n}^{t_{n+1}} U \cdot I dt}{\int_{t_n}^{t_{n+1}} G \cdot A dt} \times 100\% \quad (3)$$

where  $\eta_{\text{overall}}$  is overall efficiency of system,  $\eta_{\text{thermal}}$  thermal efficiency,  $\eta_{\text{electrical}}$  electrical efficiency, and  $\eta_{\text{power}}$  is power generation efficiency of typical power plant which can take 0.38. Besides,  $c_{\text{water}}$  is specific heat capacity of water,  $m_{\text{water}}$  the mass of water in the tank,  $T_{\text{water}_{n+1}}$  and  $T_{\text{water}_n}$  are the temperature of water at  $t_{n+1}$  and  $t_n$ , respectively.  $G$  is the radiation intensity per unit area,  $A$  PVT panel area,  $U$  instantaneous voltage, and  $I$  instantaneous current.

The monitoring system mainly controls the stability of the ambient temperature and radiation intensity. Two split air conditioners are used to control the ambient temperature, which was maintained at 24 to 26.5 °C in Fig. 3a. Figure 3b shows the radiation intensity. It was set by the control system of the solar simulator, which was able to reach the design conditions with good stability.

To study the performance of the system at different radiation intensity, five different conditions are considered for this study (400 W/m<sup>2</sup>, 550 W/m<sup>2</sup>, 700 W/m<sup>2</sup>, 850 W/m<sup>2</sup>, and 1000 W/m<sup>2</sup>, respectively), which can cover most of the actual outdoor conditions of all parts across the country (including Dalian). The initial temperature of the system is 17.5 °C, equal to tap water temperature. The initial pressure is 0.5 MPa, the initial ambient temperature 20 °C. Additionally, the angle between the PVT panel and the ground is 60°. And the distance between the simulator and the panel is 1 m.

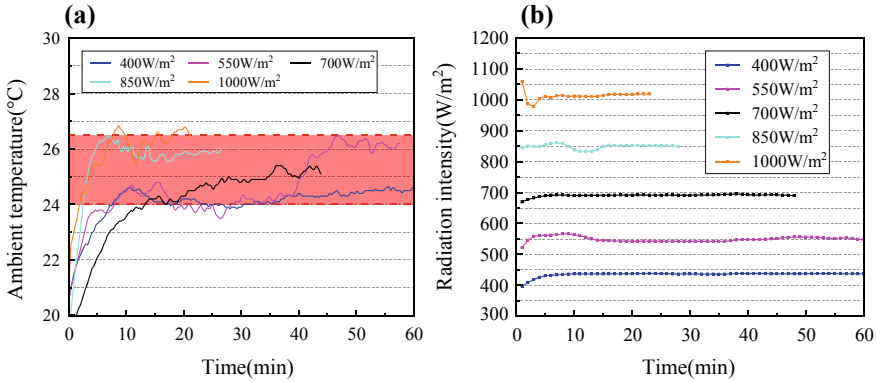


Fig. 3 a Stability of ambient temperature. b Stability of radiation intensity

### 3 Discussion and Results

In the start-up phase, the thermal power at 550 W/m<sup>2</sup> reaches the highest value of 365.8 W within 12 min with 53.9% thermal efficiency accordingly, just as shown in Fig. 4a. At 700 W/m<sup>2</sup>, the maximum thermal power 470.2 W appears at the 11th minute, with 55.8% corresponding efficiency. Compared with the former condition, the thermal power of 700 W/m<sup>2</sup> increases 28.5%, while the efficiency is not significantly improved. During the experiment, the thermal power shows a tendency that rises rapidly first then decreases and fluctuates slowly. There is no mechanical equipment and the diameter of the flow channel is too tiny to transfer the heat to the tank instantaneously after absorbing heat from the solar simulator, which causes intermittent air blockage and fluctuation of the curve. The thermal powers reduce to 209 and 261.3 W at the end of the test, which is 51.7% and 55.6% of the maximum, respectively. Meanwhile, the corresponding thermal efficiencies are 31.7% and 31.1%.

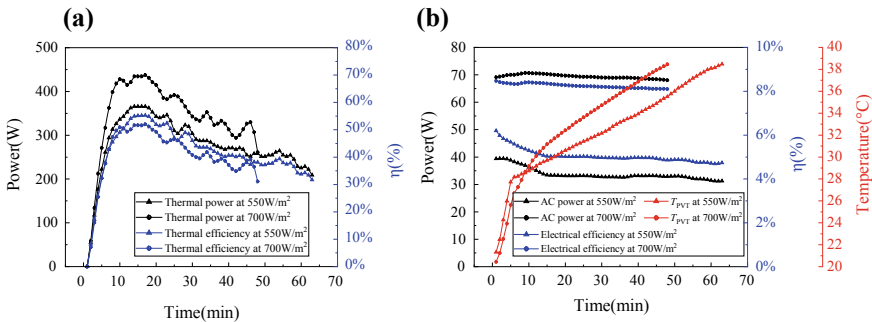


Fig. 4 a Thermal power and efficiency. b Electrical power and efficiency

The AC output power decreases from 39.4 to 31.25 W during 63 min at 550 W/m<sup>2</sup> in Fig. 4b, a relative decreasing of 20.69%. Meanwhile, the electrical efficiency dropped from the initial 6.2 to 4.47%. At 700 W/m<sup>2</sup>, the output power decreases from 69.1 to 68 W, with the efficiency declining from 8.48 to 8.10%. The PV performance is primarily dependent on the surface temperature of the cells, the higher temperature, the lower power and efficiency. Both conditions have higher AC output power in the start-up phase and then decline gradually. At 550 W/m<sup>2</sup>, increasing PV cells temperature by 10 °C decreases the electrical efficiency by 0.85%, which is 0.61% at 700 W/m<sup>2</sup>. This result is consistent with previous studies on the effect of temperature on the efficiency of crystalline silicon cells.

The trends of overall efficiency are basically consistent even though the radiation intensity is different (Fig. 5a). Comparing to direct PVT system with water as circulating medium in references, the start-up performance and response speed of an indirect system in this study are faster. It is able to start running in five minutes and achieve the maximum efficiency in 15 min. This is because the flowing of water depends on buoyancy which is generated by the temperature changing of the loop. The gravity differential pressure and density difference are too tiny to drive circulation in the initial period. Furthermore, when user consumes hot water and adds tap water, the direct system needs a long period to circulate once again.

Figure 5b shows the temperature difference between the gaseous medium and the upper part of water tank at 700 and 850 W/m<sup>2</sup>. The maximum temperature difference is up to 8 °C at 700 W/m<sup>2</sup>, which rises to 12.4 °C at 850 W/m<sup>2</sup>, with an increase of 55%. The time of maximum value is basically consistent at different conditions, concentrated between the 5th and 10th minute, but it increases with the ascending of radiation. The average temperature difference is 3.7 °C, 6.1 °C, 6.2 °C, 10.6 °C and 12.2 °C, respectively. Higher radiation intensity means higher AC output power and higher thermal power, but it cannot improve the thermal efficiency. The heat accumulates in the PVT panel cannot be timely transferred to the water, which results in the decreasing of AC output power. Therefore, for such kind of system, how to

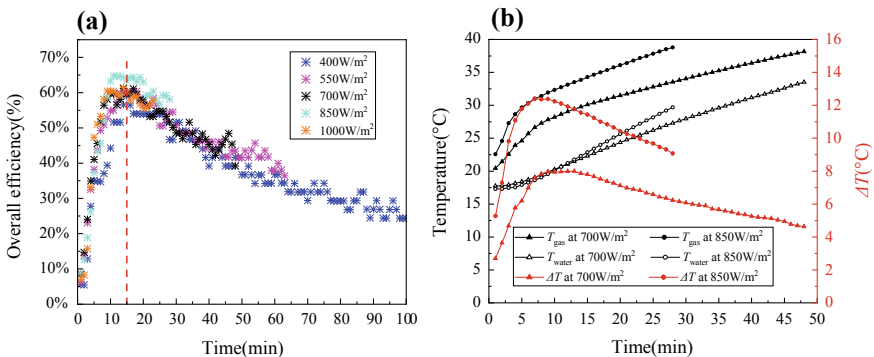


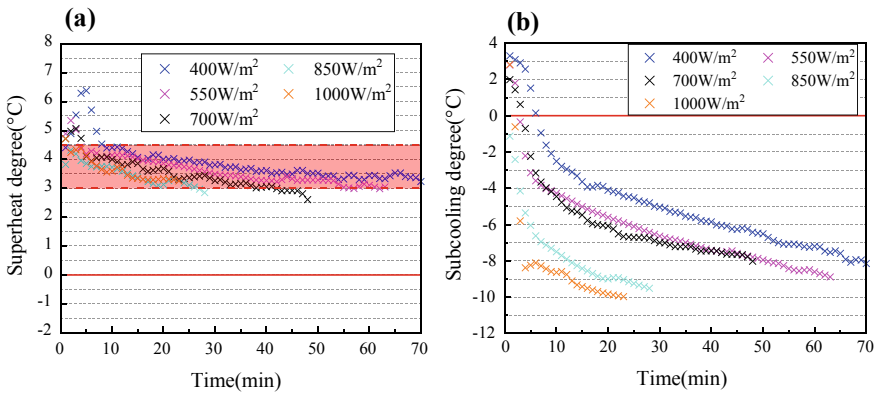
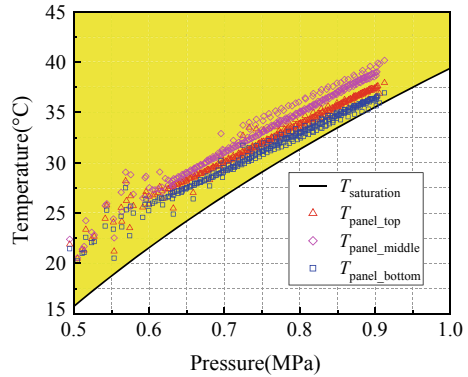
Fig. 5 a Overall efficiency. b Temperature difference between gaseous medium and tank

improve the thermal efficiency, especially in the case of high radiation intensity, is a key point for system optimization.

Figure 6 describes the distribution of pressure and average temperature at different points of PVT panel during the experiment. The yellow area above the black curve is superheated area and the white is subcooling. The thermal states of three points are all superheated. According to Fig. 7b, the medium remains in sub-cooling state after leaving the tank, so it can be judged that when the medium flows into the bottom of the panel, it absorbs heat immediately and start phase transformation to saturated state and then to superheat state. In addition, the superheat degree in the middle is higher than the top. This indicates that the flow situation in the middle is not ideal, resulting in heat accumulation in some part and unbalanced surface temperature.

The superheat degree of gas tube is demonstrated in Fig. 7a. The value is obtained by the difference between actual temperature and saturation temperature at certain system pressure. The medium remains in superheat state when leaving the PVT panel in all conditions. It reaches the highest level in the start-up phase and then decreases

**Fig. 6** Temperature distribution of PVT panel



**Fig. 7** a Superheat degree. b Sub-cooling degree

slightly, but the overall superheat degree is stable, which has no obvious relationship with radiation intensity. The average values are 3.51 °C, 3.63 °C, 3.54 °C, 3.49 °C, and 3.65 °C, respectively. In contrast, the degree of sub-cooling increases with increasing radiation intensity in Fig. 7b. This is because as the saturation temperature and pressure increase, the water and medium temperature in the bottom of the tank are relatively cold, which cause a larger difference with saturation temperature, that is sub-cooling degree.

## 4 Conclusions

This paper presents a performance experimental platform of indirect PVT system by natural circulation for domestic hot water. The performance at different radiation intensity was studied experimentally. The result shows that the response speed is high, and the running performance is stable. It can produce domestic hot water efficiently as well. Based on this study, some specific conclusions are drawn as follows.

1. For indirect natural circulation based on PVT system, the performance is largely influenced by radiation intensity. The maximum thermal power and electrical power is 313.5 W and 27.3 W at 400 W/m<sup>2</sup>, respectively. When the radiation intensity rises by 150% to 1000 W/m<sup>2</sup>, these two values are 731 and 98.5 W, which increases by 133.2 and 260.8%. The maximum efficiencies range from 65 to 75%.
2. Compared with the direct system with water as circulating medium in references, the response speed of the indirect system in this paper is greatly improved. It can complete the start-up within five minutes and reaches the maximum efficiency after about 15 min, and then maintains stable operation at relatively high efficiency. The experiment indicates that such a system form can obtain hot water in a timely and efficient way.
3. The superheat degree stays between 3 and 4 °C, which is not affected by the radiation intensity. However, due to the rapid increase of system pressure under high irradiance and the poor followability of water temperature, the sub-cooling degree of the liquid medium increases with the increasing of radiation intensity. In addition, the temperature of the panel all reaches superheat range, but the superheat degree in the middle is the largest. The temperature distribution is not uniform, which needs to be optimized further.

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