Experimental investigation on direct expansion solar assisted heat pump system employing a novel PVT module

Jian Yao [1,2], Wenjie Liu [1,2], Junjie Zhu [3], Vojislav Novakovic [4], Yanjun Dai [1,2,*]

[1] Institute of Refrigeration and Cryogenics, Shanghai Jiao Tong University, Shanghai 200240, China

[2] Engineering Research Center of Solar Energy and Refrigeration, MOE, China

[3] Solar Energy Department, Institute for Energy Technology, Kjeller, Norway

[4] Department of Energy and Process Engineering, Norwegian University of Science and Technology, Trondheim NO-7491, Norway

*: Corresponding author: E-mail address: yjdai@sjtu.edu.cn (Yanjun Dai); Tel.: +86-21-34204358; fax: +86-21-34206814

Abstract

The system performance of the solar assisted PVT (photovoltaic-thermal) heat pump (SA-PVT-HP) system was experimentally investigated on a typical winter day in Shanghai. A novel PVT module with optimized fluid channel pattern and manufacture approach was employed as a solar collector/evaporator, and it showed great ability in temperature control of solar cells compared with a single PV module. The results indicated that the COP (Coefficient of Performance) of the SA-PVT-HP system could reach its maximum value of 11.2 which is 180% higher than that of the conventional air source heat pump system, while its average value was 7.1 during the operation under the solar radiation intensity of 585.3 W/m^2, ambient temperature of 28.0 ℃. To be noted, the referenced COP of the air-source heat pump system is 4.0 on an annual average in Shanghai. Moreover, the solar cells' working temperature of the PVT module could be reduced from 36.0 ℃ to 23.5 ℃, and the electrical efficiency could be improved from 17.24% to 18.16% compared with a single PV module.

Keywords: PVT; solar assisted, heat pump, temperature control, comparative study

1. Introduction

The temperature effect of the solar cells is unavoidable during the operation and it would deteriorate its electrical efficiency and service life. The PVT technology is proposed by Wolf et al. (Wolf, 1976) to reduce the working temperature of the PV module, and increase its electrical efficiency. The thermal absorber attached backside of the PV module could extract the waste heat of solar cells through different working fluids like air, water, refrigerant, etc. Among these, the refrigerant-based PVT module has better performance in heat absorption capacity due to the evaporation process. Moreover, the grade of the thermal energy could be improved effectively through the heat pump cycle, and then the useful heat could be used for the domestic hot water supply of residential heating.

The sheet-and-tube type PVT module is one type of refrigerant-based PVT module and it is easy to manufacture. Thus, it is used wildly in earlier studies of solar assisted PVT heat pump systems. For instance, Ji et al. (Ji et al., 2009) conducted experiments to evaluate the performance of the sheet-and-tube PVT collector/evaporator. They found that a 1.01 m*0.73 m PVT evaporator could reach 12% of electrical efficiency and 50% of thermal efficiency. Tsai (Tsai, 2015) presents a model of the sheet-and-tube PVT assisted heat pump water heater, and the proposed model could well simulate the system operation status under real-time conditions.

However, the roll-bond type PVT module is more efficient in the heat transfer process due to the larger heat exchange area. Therefore, the roll-bond type PVT module is applied in the heat pump system recently and it has a great improvement in system performance. Del Col et al. (Del Col et al., 2013) comparatively studied the performance of sheet-and-tube type PVT modules and roll-bond type PVT modules, the results indicated that the roll-bond type PVT module performs better in the heat pump system. Zhou et al. (Zhou et al., 2019) tested the roll-bond type PVT module in the solar assisted heat pump system and the electrical efficiency of the PVT module was 11.8% while the system COP was 6.16.

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Nevertheless, temperature uniformity is another important issue that should be considered in the structure design of the PVT module because it would cause heat spots and shorten its life. Therefore, a novel roll-bond type PVT module is employed to form a solar assisted heat pump system to realize temperature control of solar cells in this paper. In addition, the PV system is also established as a control group to compare the situation of the solar cells with the PVT module. The objective of this paper is to evaluate the thermal and electrical performance of the novel PVT module experimentally as well as the performance of the solar assisted PVT heat pump system.

2. System description

The schematic diagrams of the solar assisted PVT heat pump (SA-PVT-HP) system and PV system have shown in Fig. 1. The PVT module employed in the SA-PVT-HP system is a combination of a roll-bond collector/evaporator and a conventional PV module, and these two components are attached through EVA grease. The SA-PVT-HP system consists of the PVT modules, gas-liquid separator, compressor, water tank (condenser), expansion valve, MPPT controller, accumulator, and DC load. The PV system consists of the PV modules, MPPT controller, accumulator, and DC load. The field tests of both systems were conducted under the same conditions to reveal the temperature control ability of the PVT module compared with a single PV module. Moreover, the heat pump performance of the SA-PVT-HP system was also investigated in this study.

The solar power units of these two systems were composed of the MPPT controller, the accumulator, and the DC load. Moreover, the specific parameters of the solar cells were the same as the PVT module and the PV module. In the SA-PVT-HP system, the PVT module was adopted as the evaporator which uses the refrigerant as a working fluid to absorb heat from the solar cells. The PVT collector/evaporator, compressor, condenser (which is encapsulated in the water tank), and expansion valve formed the thermodynamic cycle of the PVT heat pump system. To be noted, the PV system was set as a control group in comparison to the electrical performance of the PVT module and the PV module.

In the PV system, the solar energy was converted to electricity through the photovoltaic effect and the electrical energy was controlled by the MPPT controller. Meanwhile, a portion of the solar radiation which could not excite electron transitions would be absorbed by the solar cells and then rise its operating temperature. Subsequently, the high operating temperature has adversely impacted the PV module due to the temperature effect and caused a reduction in the electrical efficiency of the solar cells ultimately.

In contrast, the PVT module in the solar assisted PVT heat pump system would reduce the operating temperature of the solar cells prominently through the evaporating process. The low-quality refrigerant would extract heat from the solar cells and gradually vaporize to the high-quality refrigerant in the PVT collector/evaporator. The refrigerant vapor would be compressed to a high-temperature and high-pressure state through the compressor and then condensed in the water tank. The thermal energy released by the refrigerant would heat the water in the tank for domestic hot water usage or residential heating. Thus, the solar assisted PVT heat pump system could realize co-generation during the operation.

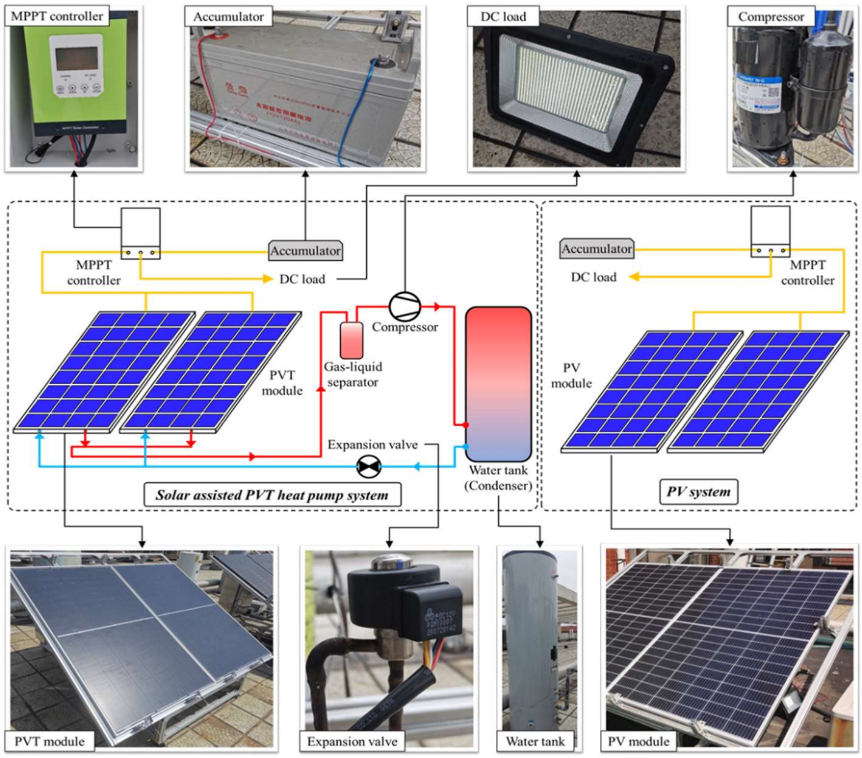


Fig. 1: The schematic diagrams of the solar assisted PVT heat pump system and PV system

3. Experimental setup

Fig. 2 presents the front view of the solar assisted PVT heat pump system and the PV system. The tilt angle of the modules is 30 degrees (considered the latitude of Shanghai). In the SA-PVT-HP system, two PVT modules are used as an evaporator that could absorb heat from the solar cells. Furthermore, the working fluid in the evaporator could reduce the working temperature of the PV module and then increase its electrical efficiency. The PV system is arranged as a control group to compare the PV module's electrical efficiency in two systems.

Fig. 2: Front view of the experimental rigs

The back view of the experimental rigs as shown in Fig. 3 presents the components' arrangement position in the workbench. For the PV system, the PV modules generate electricity and are controlled by the MPPT controller which is connected to an accumulator. The DC load is applied to consume the electricity powered by the PV modules. For solar assisted PVT heat pump system, it could be divided into two sub-units: the solar power unit and the heat pump unit. The solar power unit has the same system components as the PV system. In the heat pump cycle, the working fluid absorbs heat from the solar cells through the evaporation process and it would be turned into vapor with high enthalpy. Subsequently, the outlet vapor would be compressed to a high-temperature and high-pressure state through the compressor, and then it would be condensed in the water tank. The condensation heat released by the refrigerant vapor would heat the water to meet the requirement of the domestic hot water supply. The working fluid would flow into the PVT collector/evaporator for another thermodynamic cycle after expansion through the expansion valve.

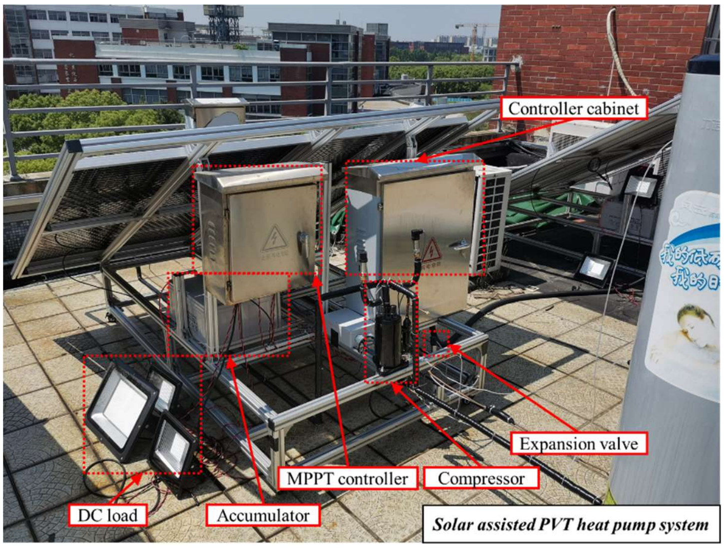


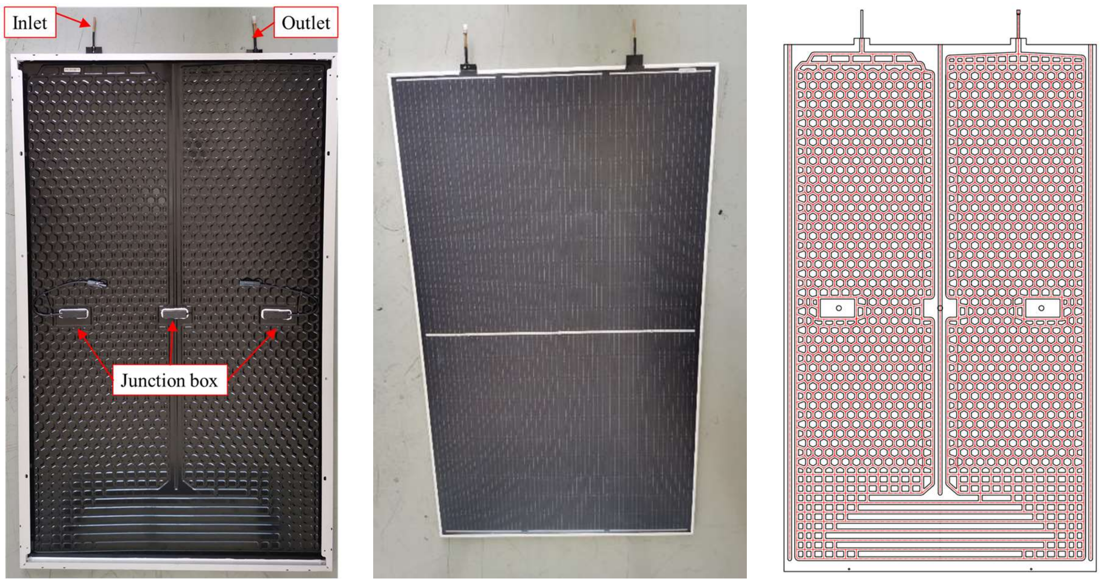
Fig. 3: Back view of the experimental rigs

As shown in Table. 1, the specific characteristics of each component are listed. The areas of the PVT module and PV module are 1.14 m^2 and 1.01 m^2, respectively. A 150L water tank is used as a condenser to heat the water. Both the PVT module and PV module are arranged with 30 degrees angle facing south for higher solar irradiation.

Tab. 1: System configurations of the SA-PVT-HP system and PV system

Parameters	**Nomenclature**	**Value**	**Unit**
Volume of the water tank	V_{water}	150	L
Rated power of the compressor	P_{com}	565	W
Length of the PVT module	L_{PVT}	1680	mm
Width of the PVT module	W_{PVT}	1000	mm
Area of the PVT module	A_{PVT}	1.68	m^2
Length of the PV module	L_{PV}	1680	mm
Width of the PV module	W_{PV}	1000	mm
Area of the PV module	A_{PV}	1.68	m^2
Standard solar cells' electrical efficiency	η_e	19.94	%
Temperature coefficient of the solar cell's electrical efficiency	β_e	-0.39	%/°C
Tilt angle	Θ	30	degree
Refrigerant type	*ref*	R134a	[-]

Fig. 4 shows the photograph of the novel PVT module. The rear side of the PVT module shows the fluid channel pattern of the roll-bond panel. This structure considers the thermal performance, temperature uniformity, and hydraulic performance simultaneously. The fluid channel pattern consists of hexagon, grid, and linear type fluid channel units. The fluid channel patent design is based on the authors' previous work (Yao et al., 2020; Yao et al., 2022; Yao et al., 2021), and for this novel structure proposed in this paper, the arrangement of the grid and linear type units ensure the flow of working fluid in the corners of the PVT module, in this regard, the corner temperature uniformity could be improved. Furthermore, the junction box of this type of PVT module is smaller and therefore the hole in the roll-bond panel could be smaller to improve the heat exchanging performance. The rear side of the PVT module is painted black to absorb heat from the reflective solar irradiation of the ground. In this way, the thermal efficiency of the PVT module could be further improved.



(a) (b) (c)

Fig. 4: Photograph of the novel PVT module

4. Results and discussion

The field tests of the solar assisted PVT heat pump system and the PV system were conducted on a typical cloudy day in Shanghai. The PVT module's thermal and electrical performance, as well as the solar assisted heat pump system's performance, were experimentally investigated compared with a single PV module. Additionally, the temperature distributions of the PVT module and PV module were compared through the infrared camera to further indicate the temperature situation of the solar cells in these two systems.

Table.1 presents the boundary conditions of the field test of the SA-PVT-HP system and PV system. The average ambient temperature is 28 ℃ while the average solar radiation intensity is 585.3 W/m^2, and the initial water tank temperature is 33.7 ℃.

Tab. 2: Boundary conditions of the field test

Parameters	**Value**	**Unit**
Date	2021.05.31	[-]
Operating period	10:10~11:35	[-]
Average ambient temperature	28	℃
Average solar radiation intensity	585.3	W/m^2
Wind speed	0~3	m^2
Refrigerant charge	800	g
Tilt angle	30	degree
Initial water tank temperature	33.7	℃

The experimental results of the SA-PVT-HP system have shown in Table. 3. The average COP of the system could reach 7.1 which is 77.5% higher than the conventional air-source heat pump system. To be noted, the referenced COP of the air-source heat pump system is 4.0 on an annual average in Shanghai (China, 2008). The peak value of the COP is 11.2 which shows the remarkable performance of the heat pump system. The final water tank temperature is 60.4 ℃ which could meet the heat demand of the domestic hot water usage or residential heating. During the 1.4 hours of operating time, the total energy consumption of the compressor is

0.7 kWh while the average compressor power is 490.8 W, this value is lower than the rated power of the compressor which means the compressor performance could be further improved through the better arrangement of the system configuration. From the aspect of the PVT module, the inlet temperature is around 22.0 ℃ and the superheat degree is 8.5 ℃. The PVT module has a mild pressure loss due to the optimized fluid channel pattern, and its dimensionless pressure loss is only 0.078. The condensing pressure is 1.438 MPa while the inlet pressure of the compressor is 0.496 MPa, thus, the compression ratio of the compressor could be calculated as 2.9.

Tab. 3: Experimental results of the SA-PVT-HP system

Parameters	Value	Unit
Average COP	7.1	[-]
Maximum COP	11.2	[-]
Initial water tank temperature	33.7	℃
Final water tank temperature	60.4	℃
Running time	1.4	hours
Total energy consumption of the compressor	0.7	kWh
Average compressor power	490.8	W
Inlet temperature of the PVT module	22.0	℃
Outlet temperature of the PVT module	30.5	℃
Temperature difference between inlet and outlet of the PVT module	8.5	℃
Inlet pressure of the PVT module	0.562	MPa
Outlet pressure of the PVT module	0.520	MPa
Pressure loss of the PVT module	0.042	MPa
Dimensionless pressure loss of the PVT module	0.078	[-]
Inlet pressure of the compressor	0.496	MPa
Condensing pressure	1.438	MPa
Compression ratio	2.9	[-]

Table. 4 shows the comparison results of the electrical performance of the PVT module and the PV module. The operating temperature of the solar cells could reduce from 36.0 ℃ to 23.5 ℃ of the PVT module due to the evaporating process of the cooling panel. In this regard, the electrical efficiency of the solar cells could be improved from 17.24% to 18.16% due to the low working temperature.

Tab. 4: Comparison of results of the electrical performance of the PVT and PV modules

Parameters	PVT module	PV module
Output current	6.65 A	6.22 A
Output voltage	68.6 V	69.6 V
Output power of one piece	228.1 W	216.5 W
Electrical efficiency	18.16%	17.24%
Efficiency improvement	5.38%	[-]
Operating temperature	23.5 ℃	36.0 ℃
Temperature reduction	12.5 ℃	[-]

The temperature uniformity is another indicator to evaluate the performance of the module. Fig. 5 presents the infrared images of the PVT module and PV module during the operation. It could be found that the temperature difference of the PVT module could be controlled within 2.4 ℃ while the temperature difference of the PV module is around 4.2 ℃. In this regard, the temperature uniformity of the PVT module is better than the PV module. The temperature difference of the existing PVT module (Buonomano et al., 2016) is around 5 ℃ and the temperature of the PV cells is between 29.4~34.4 ℃, thus, compared to the existing PVT module, The proposed PVT modules have better temperature uniformity and lower working temperature of the PV cells. Moreover, the low operating temperature of the PVT module would also benefit the electrical performance and service life of the solar cells.

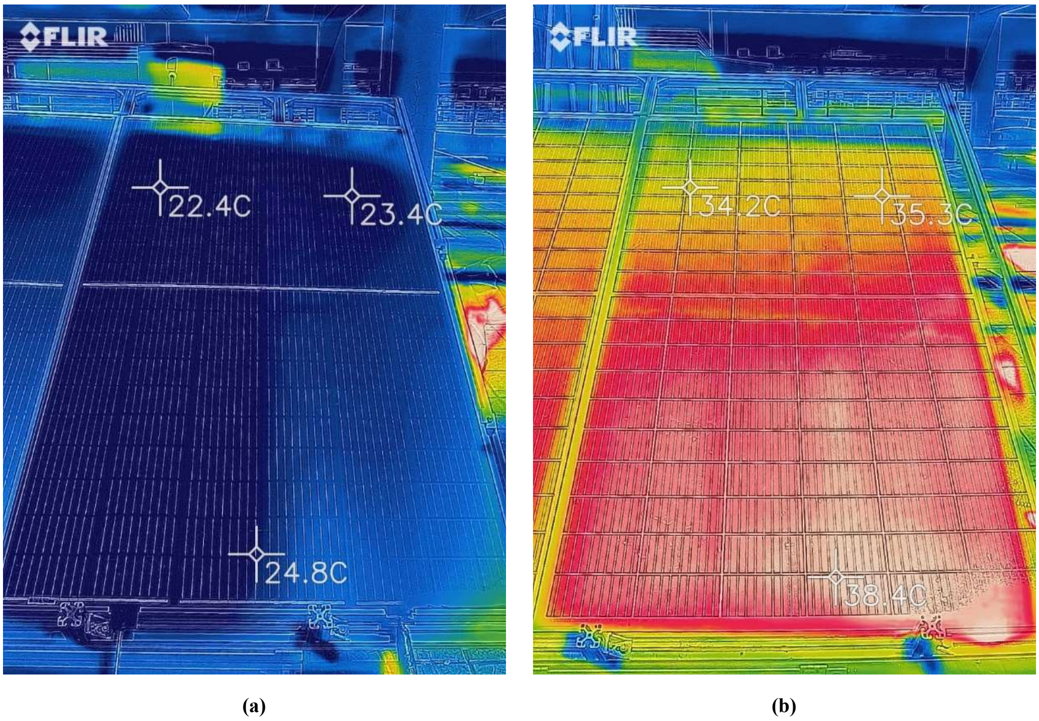


Fig. 5: Infrared images of the PVT module and PV module during operation

5. Conclusions

In this paper, a novel PVT module was manufactured and employed in the solar assisted PVT heat pump system, and then evaluated its performance compared with a single PV module. The results revealed that the PVT module shows the remarkable temperature control ability of solar cells and improves its electrical efficiency significantly. Furthermore, the solar assisted PVT heat pump system was found high-efficiency compared with conventional air source heat pump system which shows great potential in building solar energy utilization. The long-term operation test would be done in a future study to ensure the system's stability.

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