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Operational performance of a novel heat pump coupled with mini-channel PV/T and thermal panel in low solar radiation

Jinzhi Zhou [a,b], Xudong Zhao [b,*], Yanping Yuan [a], Jing Li [b], Min Yu [b], Yi Fan [b]

[a] School of Mechanical Engineering, Southwest Jiaotong University, Chengdu, Sichuan, PR China
[b] School of Engineering and Computer Science, University of Hull, Hull, HU6 7RX, UK

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ABSTRACT

Here we describe a heat pump system coupled with novel PV/T and thermal panels for space heating in low solar radiation conditions. Existing solar indirect-expansion systems connect the solar panels and evaporator of the heat pump in parallel with the heat storage tank. For our system these three components are instead connected in series, which can stabilize the temperature at the inlet of the evaporator and decrease the inlet temperature of the solar panels, leading to improved energy efficiency and the production of much more thermal energy. The experimental results of this system show that the average electrical, thermal and overall efficiency of the PV/T panels are 15.9%, 33.4% and 49.3%, respectively. The average thermal efficiency of the thermal panels is 60.4%, the COP of heat pump is 4.7 and the room temperature is constantly over 18 °C. Based on the experimental results, some improvements are analyzed. We conclude that this operating model can meet the requirement of space heating in low solar radiation environments.

1. Introduction

Space heating requires the greatest proportion of energy used within buildings, after air-conditioning, lighting and hot water [1]. In the EU space heating accounts for 67% of total residential consumption, whilst in China it is 54%. In the EU and China, the amount of renewable energy used in buildings is 10% [2] and 2.6% [3] respectively, representing a very small proportion of the total energy consumed. Hence there is a significant potential for the application of renewable energy technologies within buildings.

Solar energy is an abundant energy source which is potentially able to cover a great part of the energy consumption of buildings including hot water, space heating and electricity. Existing techniques used to tap into this potential involve photovoltaic panels, thermal collectors and photovoltaic/thermal panels [4,5]. Heat pump systems are another way to transfer energy effectively. Combining the solar energy system and heat pump technology together can significantly enhance the energy efficiency of the solar energy system and COP of the heat pump [6]. The solar assisted heat pump system (SAHP) can be classified as a solar direct-expansion or indirect-expansion heat pump system. For the direct SAHP system, the solar thermal collector serves as the evaporator of the heat pump. The heat transfer fluids flowing through the solar thermal collector would be the refrigerant of the heat pump units [7]. For indirect SAHP systems the energy from the solar energy system is transferred to the heat pump via a working fluid. Most of the indirect SAHP systems have multiple energy sources, such as air source, ground source or water source [8].

The air source is generally very convenient, however when the ambient air temperature decreases in winter the COP of the air-source heat pump reduces because less energy is absorbed by the evaporator [9–12]. Whilst the soil can provide a stable energy source, the installation cost of the heat exchanger underground is very high, which is unacceptable for most families [13–15]. Taking these factors into account, a water-source heat pump system is best for use in buildings. Wang [16] designed a multiple function solar heat pump system which can provide space heating in winter, cooling in summer and hot water throughout the year/seasons. It was shown that the overall efficiency of the PV/T system is more than 50%, and the PV/T-WSHP heating mode provides the largest COP of 3.18. Besagni et al. [17] also investigated a multiple function solar assisted heat pump system and found that the use of a water-source evaporator significantly increased the performance of the system and helped to avoid defrost cycles. Bellos and Tzivanidis [18] used PV/T panels as the energy source to drive a heat pump system. With several days' test in winter (January) it was shown that the daily heating and electricity production was 34.9 kWh and 5.13 kWh respectively. It was also shown that the mean daily energy efficiency was 60.53% and that the exergy was 9.26% for the month. Del Amo et al. [19] theoretically and experimentally investigated a solar-assisted heat pump

* Corresponding author.
E-mail address: Xudong.Zhao@hull.ac.uk (X. Zhao).

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Nomenclature

A	area, m^2
COP	coefficient of performance,
C_p	specific heat capacity, kJ/(kg·K)
E	output power, W
G	solar radiation, W/m^2
I	output current, A
M	mass flow rate of working fluid, kg/s
P	input power, W
SAHP	solar assisted heat pump system
T	temperature, °C
U	output voltage, V
η	efficiency,

Subscripts

com	compressor,
che	condenser of heat pump,
che.o	outlet of condenser of heat pump,
che.i	inlet of condenser of heat pump,
ehe	evaporator of heat pump,
ehe.o	outlet of evaporator of heat pump,
ehe.i	inlet of evaporator of heat pump,
pvt	PV/T panel,
pvt.e	electrical efficiency of PV/T panels,
pvt.i	inlet of PV/T panel,
pvt.o	outlet of PV/T panel,
pvt.oa	overall efficiency of the PV/T panels,
pvt.t	thermal efficiency of PV/T panels,
pvt.total	all of the PV/T panels,
th	thermal panels,
th.o	outlet of thermal panel,
th.i	inlet of thermal panel,

fed by photovoltaic-thermal collectors. It was shown that the working cold temperature ranges from 10 °C to 20 °C and that the seasonal COP rose to 4.62, from 2.96 when working between 7 °C and 10 °C. The PV/T can provide 67.6% of the electricity demanded by the heat pump. Zhua et al. [20] simulated the performance of a solar heat pump system in three different cities. It was found that in severely cold regions the system has the best feasibility and energy saving properties, whilst in hot summer and cold winter regions the system has the best economy. For existing solar heat pump systems, it is common for the solar panel and heat pump evaporator to be connected in parallel with the heat storage tank. However, this restricts the potential to strengthen the function of the heat pump system and improve the operating performance of the solar panels [21–23].

In order to obtain more energy under low solar radiation conditions, a new connection method between the solar panels, water tank and heat pump evaporator is presented for our system here. The three components are connected in series, rather than parallel, which helps to stabilize the temperature of working fluid at the inlet of evaporator. As the energy is absorbed by the heat pump, the working fluid has a much lower temperature at the inlet of the solar panels, which improves their energy efficiency.

2. System description

2.1. Operational principle

The schematic of our novel heat pump coupled mini-channel PV/T and thermal panel system is shown in Fig. 1. The solar heat pump system is composed of a solar panel circulation system, a heat pump system and a terminal thermal dissipation system. The solar circulation system includes mini-channel PV/T, thermal panels and water tank. There are two working modes based on the weather condition.

When solar radiation is high the working fluid travels through the PV/T and thermal panels, where it is heated. One part of the high temperature working fluid enters the testing room directly to provide thermal energy for space heating, whilst the other part travels through the water tank and releases the surplus energy to the water, which can act as the energy source of the heat pump during the night.

When solar radiation is low, the heated working fluid travels through the water tank first and then enters the evaporator of the heat pump. If the temperature of the working fluid is too low, it will absorb energy and be heated by the water in the tank. If it is too high, it will release energy and be cooled by the water in the tank. The water tank acts as a stabilizer to make sure that the working fluid travels through the evaporator at a stable temperature. When the heat exchange is completed in the evaporator, the low temperature working fluid travels back to the PV/T and thermal panel, improving their energy efficiency. By transferring energy from the solar panels, the heat pump system can provide energy for the building constantly. The heat pump continues to work for one out of every two hours, providing energy for building. When the heat pump stops, the solar panels heat the water in the tank to store energy continually.

Table 1
Sizes and description of the components.

No	Components	Size	Description
1	PV/T	2000 × 1000 × 80 mm	Effective area:1.85 m^2 Maximum output power: 310 W Electrical efficiency: 17%
2	Thermal panel	2000 × 1000 × 80 mm	Effective area:1.85 m^2
3	Heat storage tank	1 m^3	Heigh:1180 mm Diameter:1190 mm Thickness of insulation: 50 mm
4	Coil-type-heat-exchanger	1.32 m^2	Quantity: 2 Diameter:15 mm Thickness:1 mm Length:14 m
5	Heat pump	880 × 660 × 1470 mm	Refrigerant: R-22 Cooling capacity: 9.9KW Input power: 2.1KW Heating capacity: 12 KW
6	Inverter	400 × 850 × 850 mm	Output power: 4 kW Input direct voltage: 24 V Output alternating voltage: 220 V

2.2. System components and set up

As shown in Figs. 2 and 3, the PV/T panel consists a glass cover, PV cell layer, absorber, mini-channel heat exchanger, an air vent, insulation layer and frame. The glass cover, PV cell, EVA and TPT are laminated together, then the absorber is attached to the backplane of the PV panel. The mini-channel heat exchanger tubes are welded with two head tubes in parallel, and then connected to the absorber by thermal adhesive glue.

The structure of the mini-channel thermal panel is shown in Fig. 4, which is similar to the mini-channel PV/T panel. The difference is the addition of an air gap between the glass cover and absorber, removing the need for an air vent behind the mini-channel heat exchanger. The sizes and material of each component is shown in Table 1.

A photograph of the experimental set up for the heat pump coupled mini-channel PV/T and thermal panel system is shown in Fig. 5. The system was constructed in Lüliang city China. The solar panel circulation system is located outdoors, whilst the heat pump is placed indoors. There are 10 PV/T and 10 thermal panels, both types connected in series and installed with an angle of 36° facing south. The area of each panel is 2 m^2, with an effective area of 1.85 m^2. The volume of the water tank is 1000 L, with two steel heat exchangers inside.

The water-source heat pump is from Gree, with a rated compressor input power of 2.1 kW. High and low voltage switches were installed at

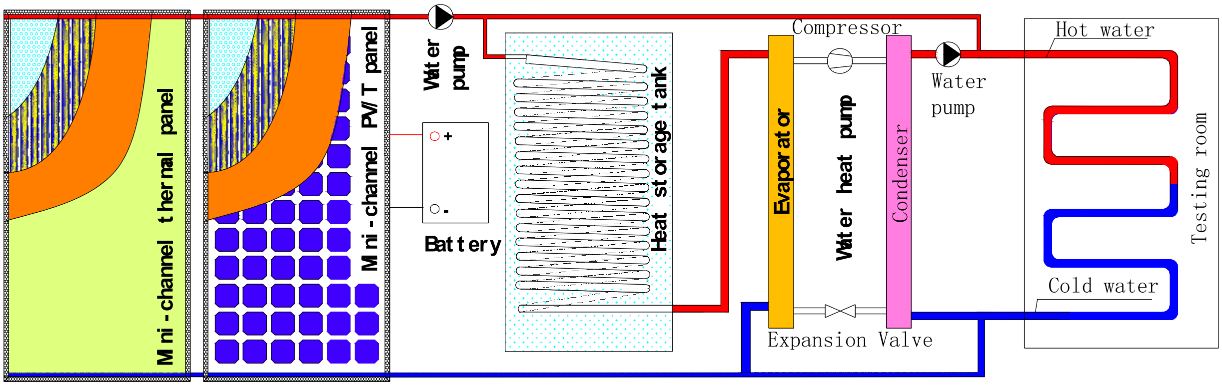

Fig. 1. Schematic of design of heat pump coupled mini-channel PV/T and thermal panel system.

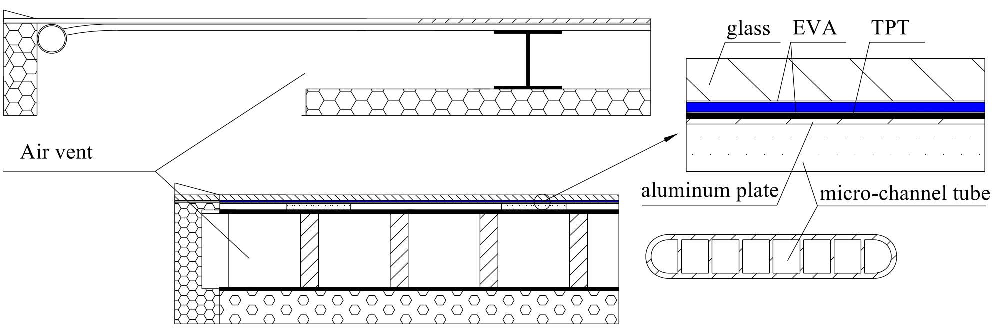

Fig. 2. The structure of the mini-channel PV/T panel.

Fig. 3. Picture of the mini-channel PV/T panel.

the import and export of the compressor to ensure a secure environment during the system operation. The system uses two double-tube heat exchangers for absorbing and releasing energy. The rated heat exchange amount of the double-tube heat exchanger is 12 kW, which is suitable for meeting the room heating demand.

The terminal thermal dissipation system was inserted in the floor of the testing room, which has an area of 150 m^2. Four solar batteries are used in this system, each having a voltage of 12 V and a capacity of 200Ah. The PV/T panel and solar batteries are connected to a solar control inverter in parallel, which ensures that the PV/T panel generates electricity at the maximum point and converts DC to AC.

3. Experimental description

3.1. Measurement parameters

Thermocouples were used to measure the temperatures of ambient air, solar panel, working fluid at the inlet and outlet of the panel, evaporator and condenser of heat pump and water in the tank. The flow meter was used to measure the flow rate of working fluid in the PV/T panel, thermal panel, evaporator and condenser of the heat pump. Power sensors were used to measure the output power of the PV/T panel and input power of the heat pump. A pyranometer was used to measure the solar radiation. Two pressure gauges were installed to measure the pressure variation of the pipe. Two computer and data loggers were used to record the testing data.

3.2. Performance evaluation

The heat product of the PV/T panels can be expressed as:

$$Q_{pvt} = C_p M_{pvt} \left(T_{pvt.0} - T_{pvt.i} \right) \tag{1}$$

Where Q_{pvt} is the heat product by the PV/T panels (W), C_p is the specific heat capacity of the working fluid (kJ/(kg·K), M_{pvt} is the mass flow rate of working fluid in PV/T panel (kg/s), $T_{pvt.0}$ and $T_{pvt.i}$ is the temperature at the outlet and inlet of the PV/T panel (°C), respectively.

The thermal efficiency of the PV/T panels can be given as:

$$\eta_{pvt.t} = \frac{Q_{pvt}}{G A_{pvt.total}} \tag{2}$$

Where $\eta_{pvt.t}$ is the thermal efficiency of the PV/T panel, G is the solar radiation (W/m^2) and $A_{pvt.total}$ is the total effective area of the PV/T panels (m^2).

The power output of the PV/T panels can be described as:

$$E_{pvt} = U_{pvt} I_{pvt.total} \tag{3}$$

Where E_{pvt} is the total output power of the PV/T panels (W), U_{pvt} is the output voltage of PV/T panels (V) and $I_{pvt.total}$ is the total output current of the PV/T panels (A).

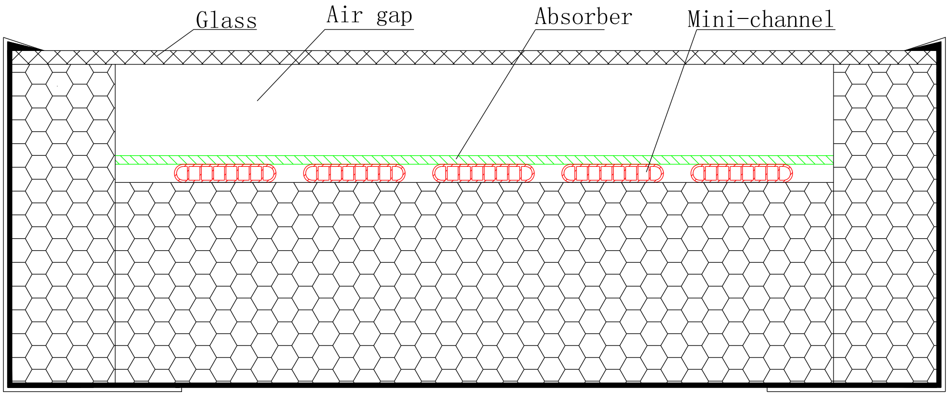

Fig. 4. Sectional view of the mini-channel solar thermal panel.

Fig. 5. Set up of the system.

The electrical efficiency of the PV/T panel ($\eta_{pvt.e}$) can be given as:

$$\eta_{pvt.e} = \frac{E_{pvt}}{GA_{pvt.total}} \tag{4}$$

The overall efficiency of the PV/T panels ($\eta_{pvt.oa}$) can be expressed as:

$$\eta_{pvt.oa} = \eta_{pvt.e} + \eta_{pvt.t} \tag{5}$$

The thermal efficiency of the thermal panel ($\eta_{th.t}$) can be given as:

$$\eta_{th.t} = \frac{C_p M_{th}(T_{th.0} - T_{th.i})}{GA_{th.total}} \tag{6}$$

Where M_{th} is the mass flow rate of working fluid in thermal panel (kg/s), $T_{th.0}$ and $T_{th.i}$ is the temperature at the outlet and inlet of the thermal panel (°C), respectively.

The heat absorbed by the evaporator can be described as:

$$Q_{ehe} = C_p M_{ehe}(T_{ehe.0} - T_{ehe.i}) \tag{7}$$

Where Q_{ehe} is the heat absorbed of the evaporator (W), M_{ehe} is the mass flow rate of working fluid in the evaporator (kg/s), $T_{ehe.0}$ and $T_{ehe.i}$ are the temperatures at the outlet and inlet of the evaporator (°C), respectively.

The heat released by the condenser can be described as:

$$Q_{che} = C_p M_{che}(T_{che.0} - T_{che.i}) \tag{8}$$

Where Q_{che} is the heat released of the condenser (W), M_{che} is the mass flow rate of working fluid in the condenser (kg/s), $T_{che.0}$ and $T_{che.i}$ are the temperatures at the outlet and inlet of the condenser (°C), respectively.

The COP of the heat pump system can be expressed as:

$$COP = \frac{Q_{che}}{P_{com}} \tag{9}$$

Where P_{com} is the input power of the compressor (W).

4. Experiment results and analysis

The experimental test was carried out from 15th to 19th and 21st to 22nd December 2016. The testing time of the system was from 9:30 to 16:00 each day. The results for these days are shown in Table 2 and one typical day's results were selected to show the performance of the system.

The variation of the solar radiation and ambient temperature on a typical day is shown in Fig. 6. The solar radiation increases from 200 W/m^2 to 525 W/m^2 in the morning (9:30–12:30), then drops to

Table 2
Testing results at the selected dates.

Date	Radiation(W/m2)	Temperature °C			System performance (%)				
2016	G	T_a	T^i_{wt}	T^f_{wt}	$\eta_{th.t}$	$\eta_{e.PVT}$	$\eta_{pvt.t}$	$\eta_{pvt.o}$	COP
15/12	421.4	2.2	15.2	30.5	59.4	15.6	31.4	47.0	4.7
16/12	380.2	3.3	15.5	28.3	57.1	16.2	33.1	49.3	4.6
17/12	410.2	4.5	14.8	29.9	58.8	15.3	33.7	49.0	4.8
18/12	431.3	5.1	15.3	30.4	60.8	15.1	31.4	46.5	4.9
19/12	354.9	2.4	14.1	27.2	56.5	15.4	32.2	47.6	4.5
21/12	368.6	2.7	14.7	28.8	57.3	16.0	32.8	48.8	4.6
22/12	413.6	1.8	15.2	29.7	60.4	15.9	33.4	49.3	4.8

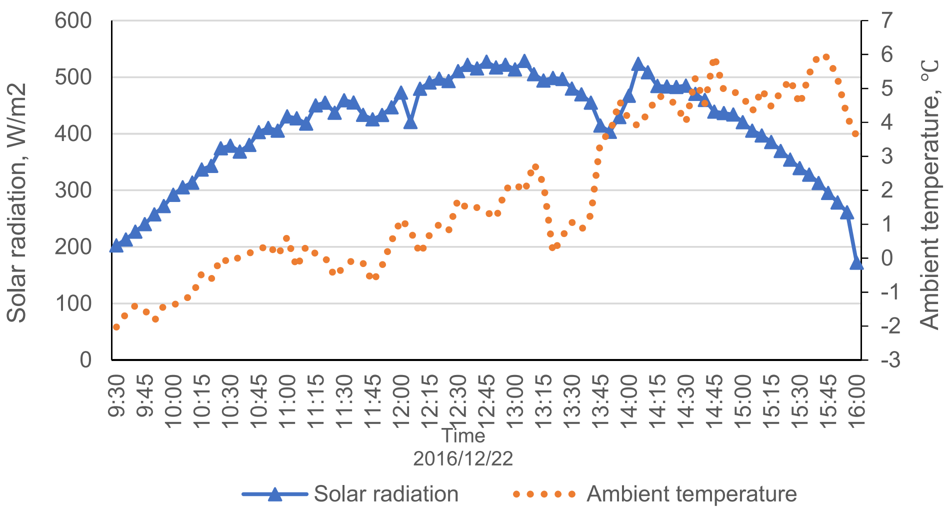

Fig. 6. Solar radiation and ambient temperature on a typical day in December.

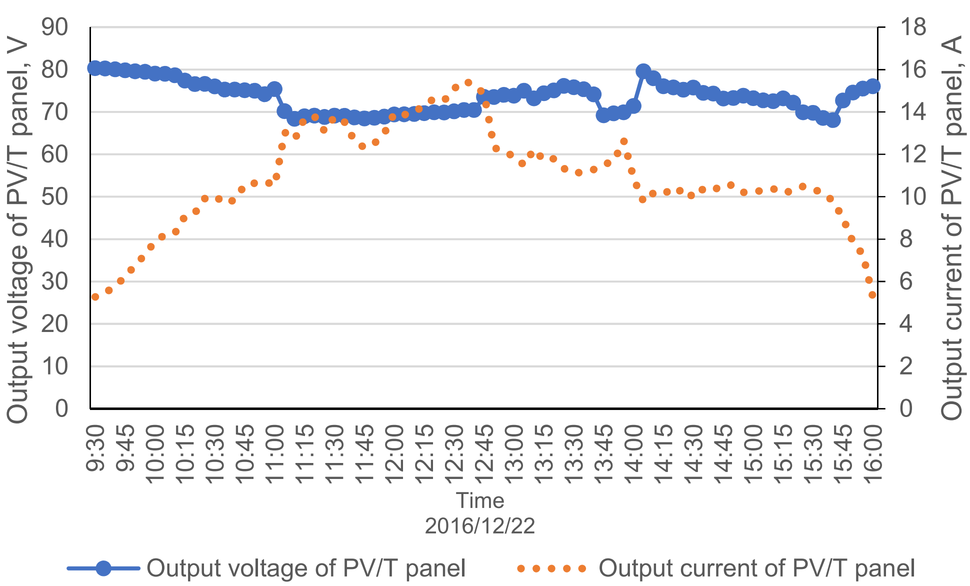

Fig. 7. Output voltage and current of the PV/T panels.

175 W/m^2 by 16:00. The average solar radiation is around 413 W/m^2, which is low compared with the figure for March (average value: above 700 W/m^2 [6]). The ambient temperature increases slowly from −2 °C to 6 °C during the testing process.

Fig. 7 shows the variation of output voltage and current for the PV/T panels throughout the day. The voltage and current are impacted by the solar radiation, solar control and inverter. The output voltage varies inversely with solar radiation, decreasing from 80 V to 70 V then fluctuating between 70 and 80 V. The output current varies with solar radiation, increasing from 5.3A to 15.3A, then drops to 5.3A again. Maximum power production is achieved around 12:45 when the system produces 72 V and 15.3A, giving an output power of around 1100 W.

Fig. 8 shows the variation of the electrical efficiency throughout the day. It shows an opposite trend to the solar radiation, as a higher temperature leads to a lower efficiency. The average electrical efficiency of the PV/T is 15.9% during the testing process.

Fig. 9 shows the variation of the temperature at the inlet/outlet of the PV/T panel and the average absorber temperature. All 3 measured temperatures show a similar trend; when the heat pump is operating, the temperatures decrease slowly and when the heat pump is not operating the temperatures show a similar trend to the incident solar radiation. This is due to the energy produced by the solar panels being lower than the total energy released to the tank and absorbed by the heat pump whilst the pump is operating.

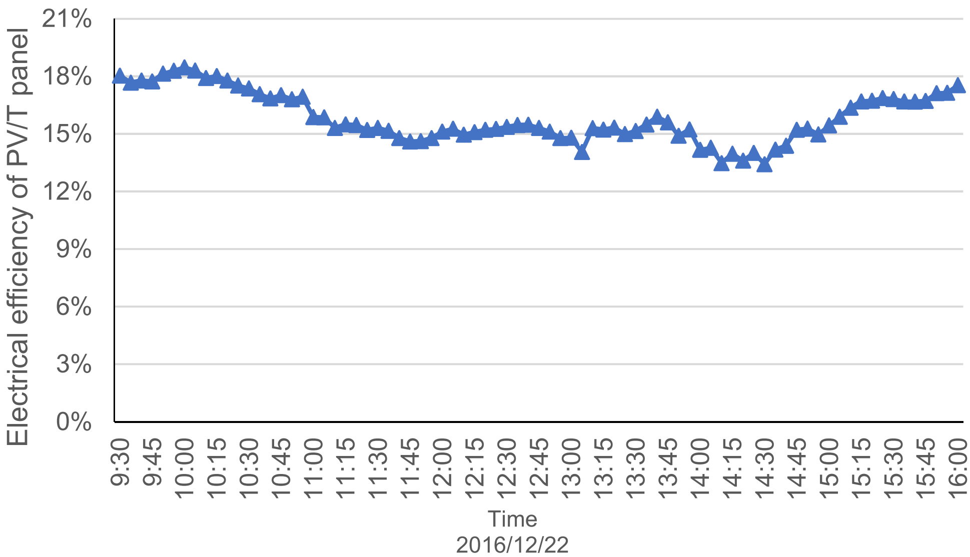

Fig. 8. Variation of the electrical efficiency of the PV/T panels.

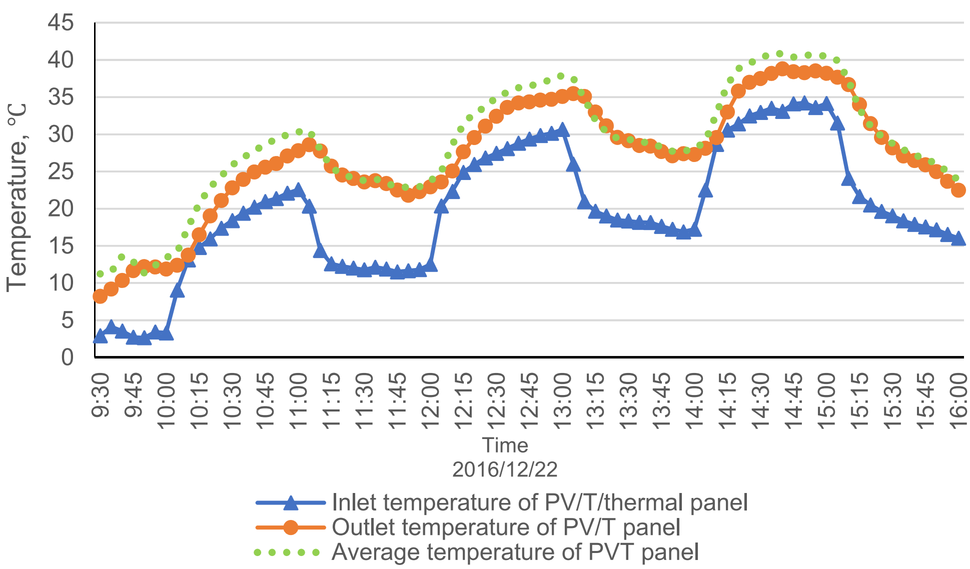

Fig. 9. Variation of the temperature at the inlet/outlet of the PV/T panels and average absorber temperature.

The heat product and thermal efficiency of the PV/T panels are shown in Fig. 10. When the heat pump operates, the working fluid temperature at the inlet of panels is very low which can improve the thermal efficiency. As the heat pump operates, its cooling capacity decreases, leading to the energy absorbed from the solar panel decreasing too. Therefore, during this process, the thermal efficiency decreases slowly. When the heat pump stops, the thermal efficiency and heat product of the PV/T panels show a similar trend as the incident solar radiation. The average thermal efficiency of PV/T panels was 33.4% during the testing process.

Fig. 11 shows the variation of the temperature at the inlet/outlet and the average absorber temperature in the thermal panel. Being impacted by the heat pump and solar radiation, it shows a similar variation trend as the PV/T panels.

The heat product and thermal efficiency of the thermal panels is shown in Fig. 12. We see the same variation trend as for the PV/T panels. The average thermal efficiency of the PV/T panels was 60.4% during the testing process.

Fig. 13 shows the variation of the mixed outlet temperature of the PV/T and thermal panels, the water temperature in the tank and the outlet temperature of the tank. Between 9:30 to 10:00 and 15:00 to 16:00, the inlet temperature of the tank is lower than the outlet temperature. This is due to the solar radiation being too low, whilst the working fluid is being heated by the water in the tank.

Fig. 14 shows the variation of the temperature at the inlet/outlet and the heat gain of the evaporator. When the heat pump is operating the temperature difference between the inlet and outlet of the evaporator ranges from 8 °C to 11 °C. The heat gain of the evaporator ranges from 6000 W to 11,000 W, which is impacted by the temperature difference and changing flow rate of the working fluid.

Fig. 15 shows the flow rate of the working fluid in the PV/T, thermal panel, evaporator and condenser. The working fluid is anti-freezing liquid, composed of a mixture of water and ethylene glycol. The lower the temperature, the higher of the viscosity, which means that the flow rate is inversely proportional to the temperature.

The variation of the temperature at the inlet/outlet and the heat gain of the condenser is shown in Fig. 16. They have a similar trend as that of the evaporator. The temperature difference between the inlet and outlet ranges from 4 °C to 6 °C, whilst the energy released by the condenser ranges from 7200 W to 12,000 W.

Fig. 17 shows the variation of the input power and COP of the heat pump system. As the temperature at the outlet of the condenser

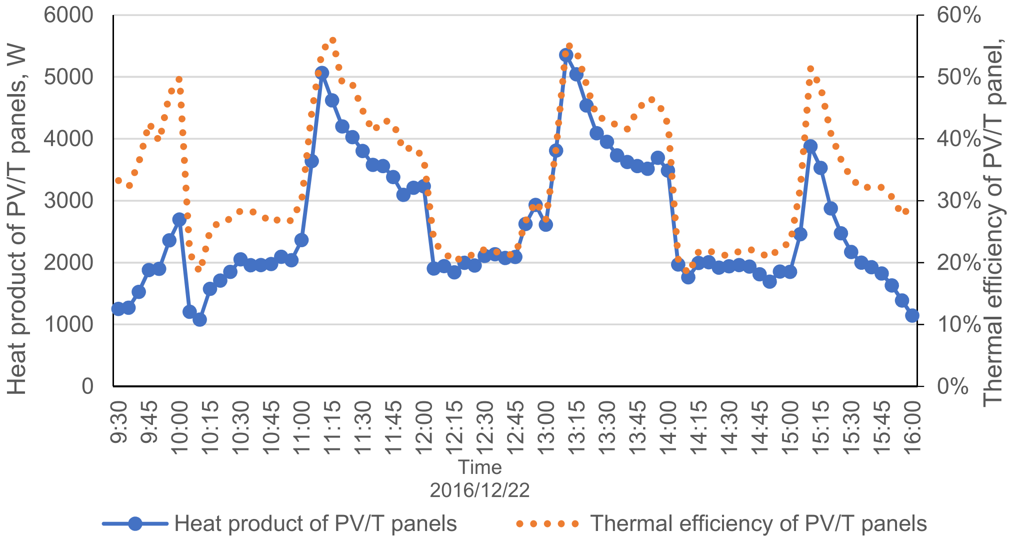

Fig. 10. Heat product and thermal efficiency of the PV/T panels.

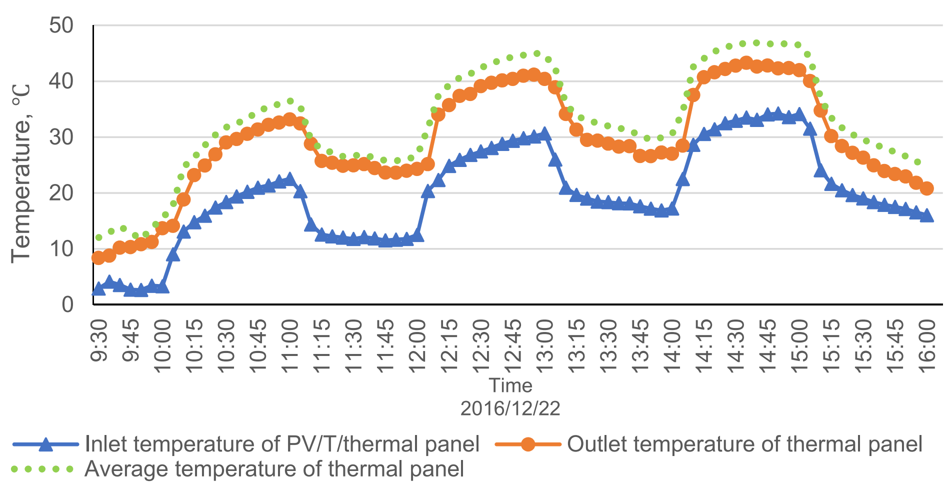

Fig. 11. Variation of the temperature at inlet/outlet of the thermal panels and average absorber temperature.

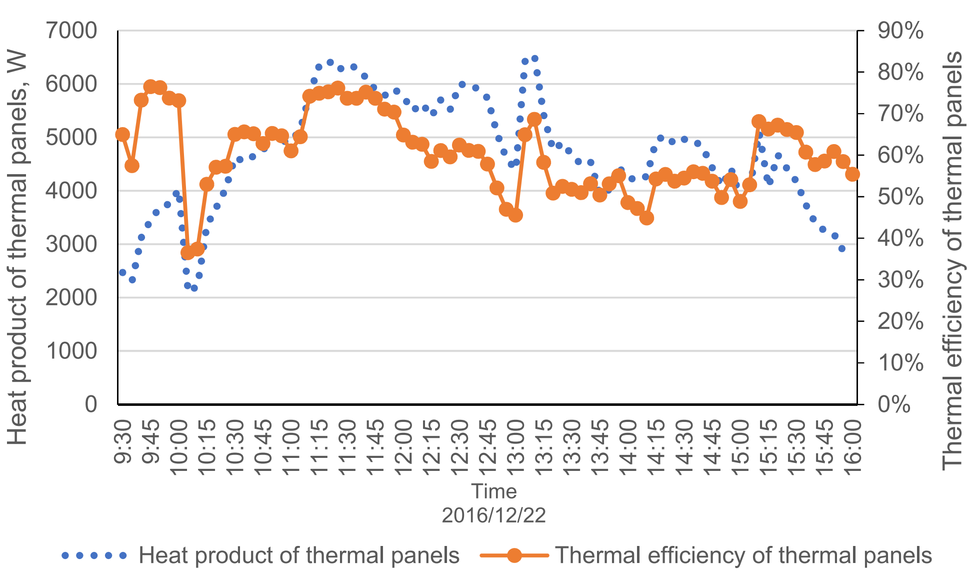

Fig. 12. Heat product and thermal efficiency of the thermal panels.

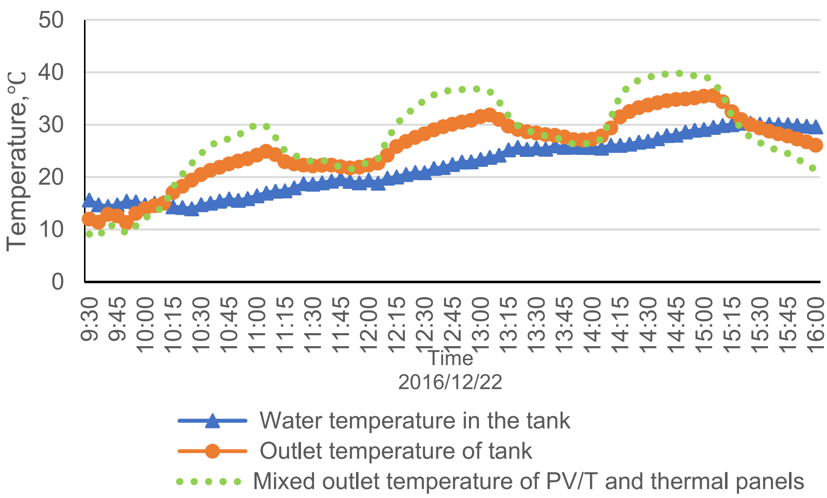

Fig. 13. water temperature in the tank, outlet temperature of tank and mixed outlet temperature of PV/T and thermal panels.

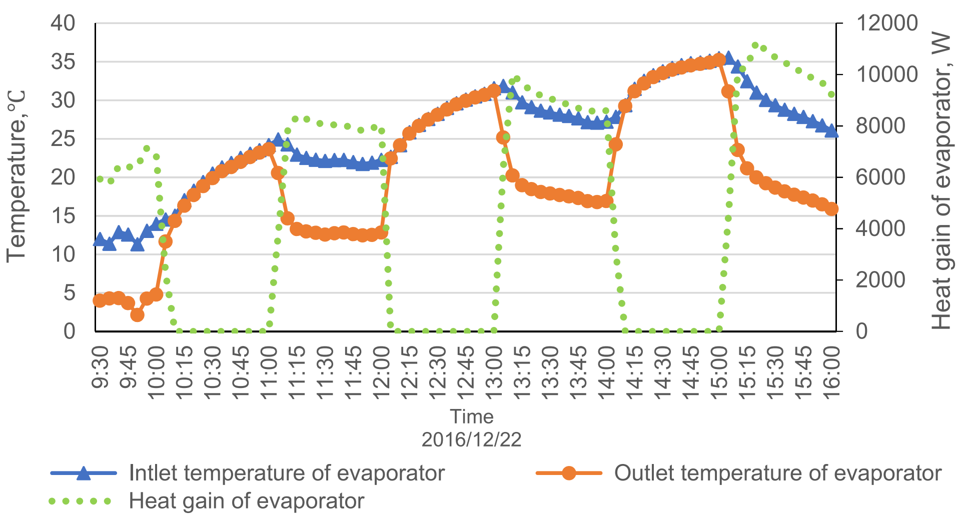

Fig. 14. Variation of the temperature at the inlet/outlet and heat gain of evaporator.

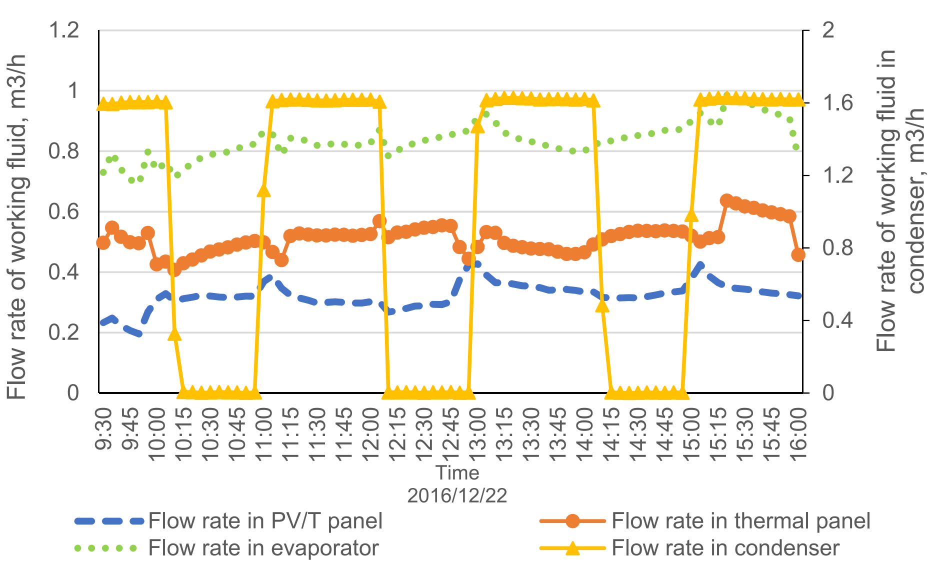

Fig. 15. Flow rate of the working fluid in the PV/T, thermal panel, evaporator and condenser.

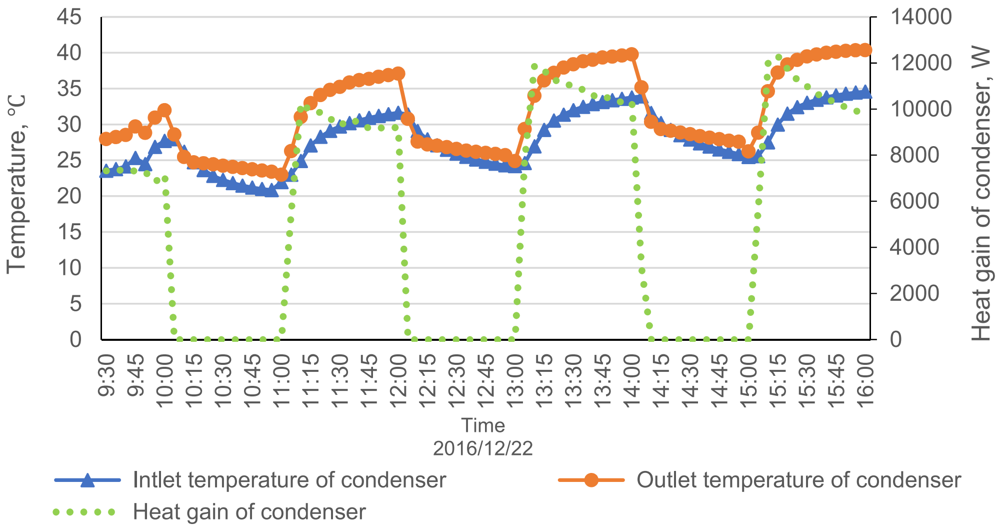

Fig. 16. Variation of the temperature at the inlet/outlet and heat gain of condenser.

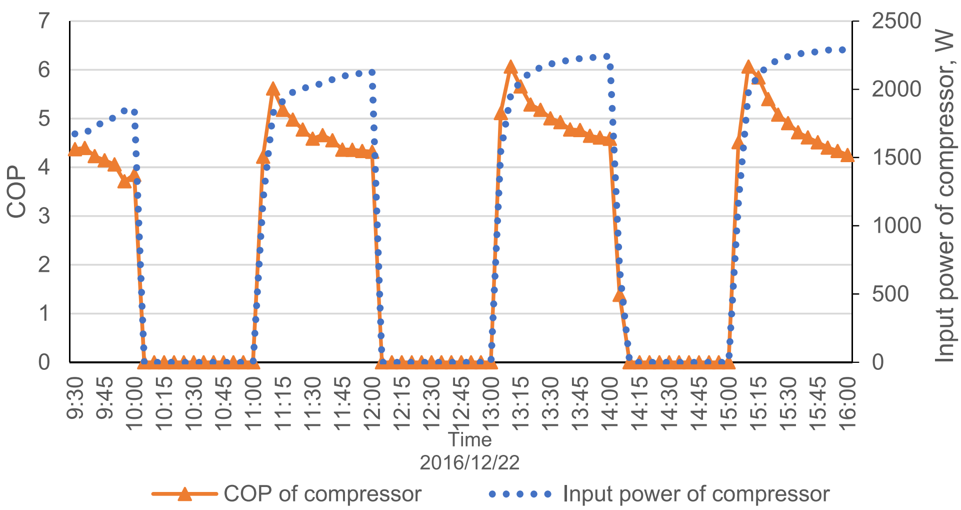

Fig. 17. Variation of the input power and COP of the heat pump system.

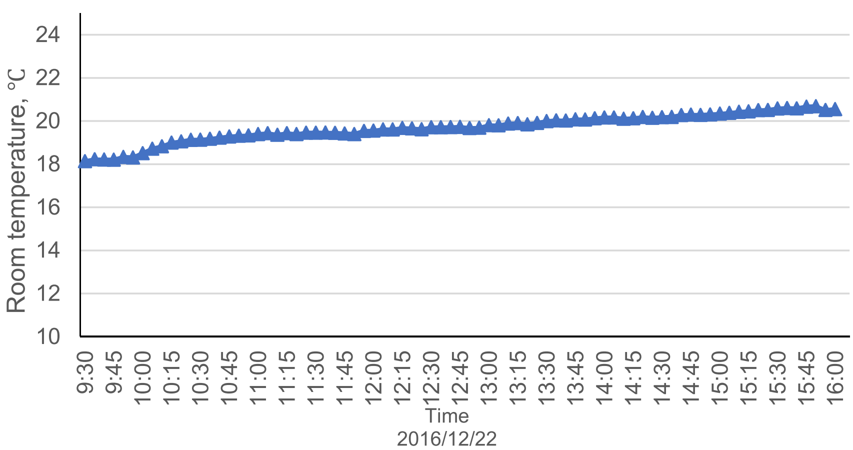

Fig. 18. Variation of the room temperature on the testing day.

increases, the input power of the heat pump also increases. As the heat released by the condenser decreases and the input power of heat pump increases, the COP of the heat pump decreases. The average COP of the heat pump was 4.7.

The variation of the room temperature is shown in Fig. 18. As the ambient temperature and heat released by the condenser are increasing, the room temperature also gradually increases from 18 °C to 20.6 °C. This shows that the energy provided by the system can meet the heat demand of the building.

5. Suggested routes for system simplification and reconfiguration

The energy source of this system contains solar thermal panels, PV/T panels, heat pump. Each number of the thermal and PV/T panels are 10 which is high costing and needs large installation space. While the water-source heat pump just can absorb energy from solar system which has a limited energy source. From the above experimental testing and result analysis, the following measures are suggested:

(1) Replace the water-source heat pump with double-source heat pump (water and air): The water-source heat pump is limited to operate in the night (2 h) and low solar radiation condition which has a short working time. Hence, the double-source heat pump has a much longer operating time which can provide energy for building in the night, rainy and snow days.
(2) Minimised use of the PV/T and thermal panels: Use of the two types of panels should be minimised owing to relatively high cost and large space. The logic of the design is to achieve equalisation between the year-round PV electrical generation and the electrical demand for the winter heating.
(3) Removal of batteries: It is proposed to feed the PV electricity directly into the local grid without the use of batteries that are for electrical storage. While the electricity needed for winter heating could be imported from the local grid. This will greatly simplify the electrical system and lower its cost.

By implementing one or more of the above measures, the configuration of the system can be significantly simplified and the cost of the system is expected to be significantly reduced.

6. Conclusion

We presented a novel system for space heating and electricity generation which combined a heat pump with mini-channel PV/T and thermal panels. The performance of the system was examined on a daily basis during the winter at low solar radiation in Lüliang city. To obtain more energy the solar panels, water tank and evaporator of the heat pump are connected in series, reducing the inlet temperature of solar panels and hence improve the energy efficiency. The results show that the average electrical, thermal and overall efficiency of the PV/T panels are 15.9%, 33.4% and 49.3%, respectively. The average thermal efficiency of the thermal panels is 60.4% and the COP of heat pump is 4.7. The room temperature stays above 18 °C during the testing process. With the improvements presented on this system, its initial cost can be reduced and its features will be more prefect. Therefore, this paper provides an acceptable working model for a solar assisted heat pump system under low solar radiation conditions.

Declaration of Competing Interest

None.

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