Research and Analysis of Solar Heat Pump Performance

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Abstract: Solar energy is a kind of inexhaustible, clean energy and the heat pump has high efficiency in energy utilization. If solar energy and heat pumps are combined and developed into a solar heat pump system, it will produce greater economic and social benefits. This experiment develops and designs three different solar heat pump water heater systems: solar direct-expansion heat pump water heater, solar and air dual-source heat pump water heater, and PVT heat pump water heater. Moreover, the performance of three kinds of solar heat pump water heater systems is preliminarily tested and verified under different solar irradiation. The problems found in the testing process are analyzed and demonstrated, which lays a foundation for the future commercial development of solar heat pump water heater systems.

*Keywords**:** solar heat pump water heater; solar direct-expansion heat pump water heater; solar and air dual-source heat pump water heater; PVT heat pump water heater; overall COP*

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1. Introduction

Solar energy is a kind of inexhaustible and clean energy. The most comprehensive application of solar heat utilization is using the solar collector to convert the solar energy into the internal energy of the water or other medium to increase the temperature of the medium [1], which is used in water heating, heating supply, and industrial fields [2]. While air energy is used through the reverse Carnot cycle. The consumption of a share of energy in the air will transfer more than one share of heat to water or other media, which is an efficient way of using energy [3]. Air energy can also be used in water heating, heating supply, and industrial fields [4]. If solar and air energy are combined and developed into a solar heat pump system, it will produce greater economic and social benefits [5]. This research explores three innovative solar heat pump water heater systems: solar direct-expansion heat pump water heater, solar and air dual-source heat pump water heater, and PVT heat pump water heater.

2. Principle of solar heat pump water heater systems

The first system is the solar direct-expansion heat pump water heater system, and the operating principle is shown in Figure 1. The characteristics of the system are that the solar collector is the only heat source. The refrigerant becomes a high-temperature and high-pressure gas refrigerant after being compressed by the compressor. The high-temperature and high-pressure gas refrigerant heats the water in the hot water storage tank through the heat exchanger. The heat exchanger condenses the high-temperature and high-pressure gas refrigerant into the high-pressure and low-temperature liquid refrigerant. The high-pressure and low-temperature liquid refrigerant is depressurized by the electronic expansion valve to the low-pressure and low-temperature liquid refrigerant. The low-temperature and low-pressure liquid refrigerant flows through the solar collector. When there is solar radiation, the front of the solar collector absorbs the heat from the solar energy, and the back of the solar collector absorbs heat from the air, vaporizing the low-temperature and low-pressure

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liquid refrigerant into the low-temperature and low-pressure gas refrigerant. After being compressed by the compressor, it becomes a high-temperature and high-pressure gas refrigerant to heat the heat storage tank. This cycle will continue until the water in the heat storage tank reaches the target temperature. Without solar radiation, the solar collector will absorb heat from the air through the front and back.

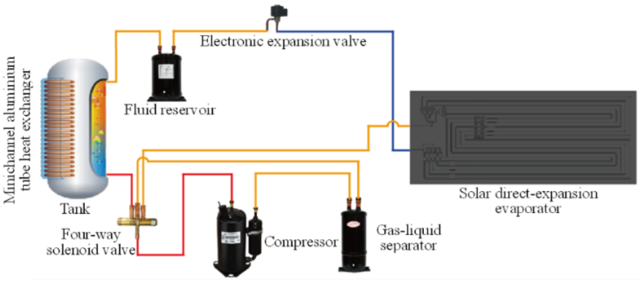

Fig. 1: Solar direct expansion heat pump water heater system

The second system is the solar and air dual-source heat pump water heater system, which is shown in Figure 2. The feature of the system is that the solar collector and the finned heat exchanger are in parallel and serve as the evaporator of the heat pump to provide thermal energy for the heat pump water heater system. The refrigerant becomes a high-temperature and high-pressure gas refrigerant after being compressed by the compressor. The high-temperature and high-pressure gas refrigerant heats the water in the heat storage box through the heat exchanger. The high-temperature and high-pressure gas refrigerant is condensed into the high-pressure and low-temperature liquid refrigerant through the heat exchanger. Low-temperature liquid refrigerant flows through the solar collector and the finned heat exchanger. When there is solar radiation, the front of the solar collector absorbs the heat from the solar energy. At the same time, the back of the solar collector absorbs heat from the air and vaporizes the low-temperature and low-pressure liquid refrigerant flowing through the solar collector into the low-temperature and low-pressure gas refrigerant. At the same time, the finned heat exchanger will also absorb heat from the air, and the low-temperature and low-pressure liquid refrigerant flowing through the finned heat exchanger is vaporized into low-temperature and low-pressure gas refrigerant. After being compressed by the compressor, it becomes a high-temperature and high-pressure gas refrigerant to heat the heat storage tank. This cycle will continue until the water in the heat storage tank reaches the target temperature. Without solar radiation, the solar collector will absorb heat from the air through the front and back, while the finned heat exchanger will also absorb heat from the air.

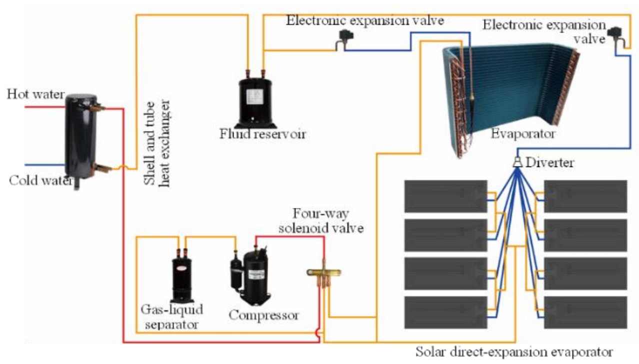

Fig. 2: Solar and air dual-source heat pump water heater

The third system is the PVT heat pump water heater system, which is shown in Figure 3. The characteristics of the system are that the heat absorbent part of the integrated photovoltaic module (PVT) is used as the evaporator of the heat pump to provide thermal energy for the heat pump water heater system, and the photovoltaic part can generate electricity at the same time, which can be used to drive the DC load and grid-tie inverter, and charge the battery. The refrigerant becomes a high-temperature and high-pressure gas refrigerant after being compressed by the compressor. The high temperature and high-pressure gas refrigerant heats the water in the heat storage box through the heat exchanger. The high-temperature and high-pressure gas refrigerant is condensed into the high-pressure and low-temperature liquid refrigerant through the heat exchanger. The low-temperature and low-pressure liquid refrigerant flows through the back channel of the solar photovoltaic thermal integrated module. When there is solar radiation, the front side can absorb the heat generated by the photovoltaic panel while generating electricity. At the same time, the back side of the PVT will absorb heat from the air, which will vaporize the low-temperature and low-pressure liquid refrigerant flowing through the PVT channel into the low-temperature and low-pressure gas refrigerant. After being compressed by the compressor, it becomes a high-temperature and high-pressure gas refrigerant to heat the heat storage tank. This cycle will continue until the water in the heat storage tank reaches the target temperature. Without solar radiation, the solar collector will absorb heat from the air through the front and back.

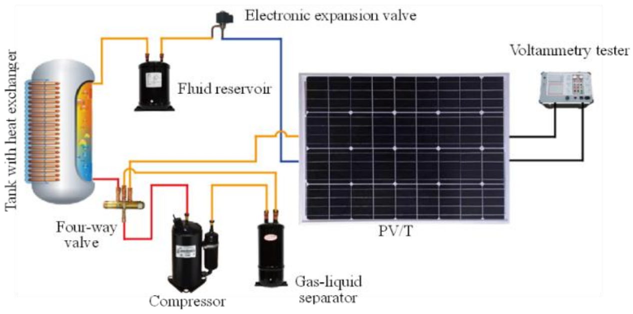

Fig. 3: PVT heat pump water heater

3. Testing method

The testing method for system 1 is illustrated below.

Fig. 4: Prototype of the solar direct-expansion heat pump water heater system

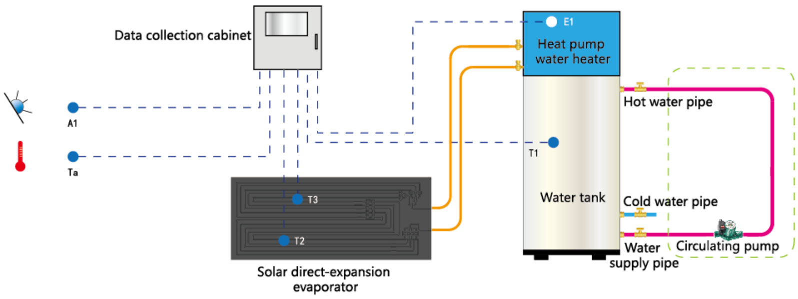

Fig. 5: Schematic diagram of the solar direct-expansion heat pump water heater system

Tab 1: Testing parameters of the solar direct-expansion heat pump water heater

	Testing parameters	**Instrument for testing**	**Note**
1	Tank temperature T1	PT100 sensor	
2	Heat pump power consumption E	Digital electricity meter	
3	Water tank capacity M	Scale of electron	Measuring water tank capacity by weighing method
4	Irradiation intensity H	Irradiation meter	Same angle as solar heat absorption panel (75°)
5	Ambient temperature	PT100 sensor	
6	Ambient humidity	Humidity meter	
7	Ambient wind speed	Wind speed instrument	
8	Rainfall	Rain gauge	

1. Testing Preparation

1) Fill the tank with water, circulate the pump to mix water, and record the starting temperature T1.

2) Record the initial electricity quantity E1 of the electricity meter.

2. Testing Process

1) Start the heat pump system and set the final temperature at 55 degrees Celsius. During the experiment, the data acquisition system will automatically record the parameters of irradiation, water tank temperature, wind speed, and real-time electricity.

2) After the heat pump reaches the temperature and stops, start the external mixed water pump until the water temperature from the mixed water to the tank does not change, then record the water temperature T2 as the final water temperature.

3) Record the final reading of the digital electricity meter: E2. C is the specific heat capacity of water; M is the mass of water, COP is the Coefficient of Performance.

3. Data Processing

1) Heat gain of the water tank:

$$Q = CM(T2 - T1) \qquad \text{(Eq. 1)}$$

2) Power consumption of heat pump system:

$$E = E2 - E1 \qquad \text{(Eq. 2)}$$

3) For the heat pump system:

$$COP = Q/E \qquad \text{(Eq. 3)}$$

The testing method for system 2 is illustrated below.

Fig. 6: Prototype of the solar and air dual-source heat pump water heater system

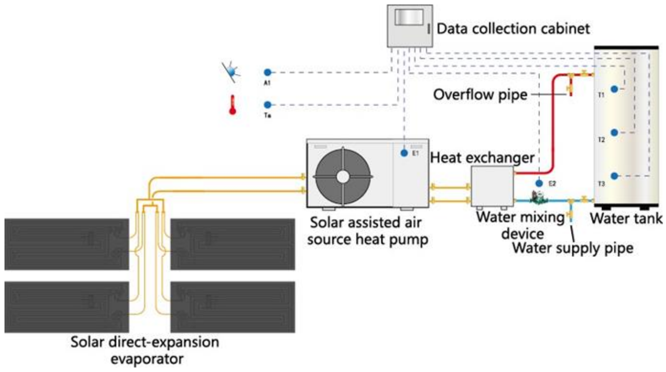

Fig. 7: Schematic diagram of the solar and air dual-source heat pump water heater system

Tab 2: Testing parameters of the solar and air dual-source heat pump water heater system

	Testing parameters	**Instrument for testing**	**Note**
1	Tank temperature T1	PT100 sensor	
2	Heat pump power consumption E	Digital electricity meter	
3	Water tank capacity M	Scale of electron	Measuring water tank capacity by weighing method
4	Irradiation intensity H	Irradiation meter	Same angle as solar heat absorption panel (75°)
5	Ambient temperature	PT100 sensor	
6	Ambient humidity	Humidity meter	
7	Ambient wind speed	Wind speed instrument	
8	Rain	Rain Gauge	

The testing steps, testing process, and data processing of system 2 are same with system 1.

The testing method for system 3 is illustrated below.

Fig. 8: Prototype of the PVT heat pump water heater system

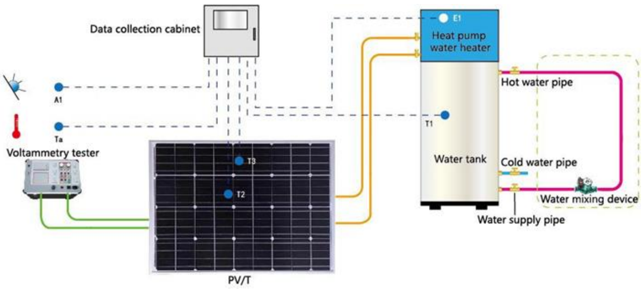

Fig. 9: Schematic diagram of the PVT heat pump water heater system

Tab 3: Testing parameters of the PVT heat pump water heater system

	Testing parameters	Instrument for testing	Note
1	Tank temperature T1	PT100 sensor	
2	Heat pump power consumption E	Digital electricity meter	
3	Water tank capacity M	Scale of electron	Measuring water tank capacity by weighing method
4	Irradiation intensity H	Irradiation meter	Same angle as solar heat absorption panel (75°)
5	Ambient temperature	PT100 sensor	
6	Ambient humidity	Humidity meter	
7	Ambient wind speed	Wind speed instrument	
8	Rain	Rain Gauge	

For system 3, we record the electricity generation of PVT as E3, and we can use Equation 4 to calculate the COP of the photothermal heat pump system. For the PVT heat pump system:

$$COP = Q/(E - E3) \qquad \text{(Eq. 4)}$$

4. Testing results and analysis

Similar external conditions are selected during the test for three systems. For solar direct-expansion heat pump water heaters and solar and air dual-source heat pump water heaters, the COP of the system is tested respectively with and without solar irradiation.

For the PVT heat pump water heater, the test includes the heat pump COP with solar irradiation and the power generation of the photovoltaic panel. The testing results of three solar heat pump water heater systems are shown below. The followings are the results and analysis for the first system: solar direct-expansion heat pump water heater system.

Tab 4: Testing results of the solar direct-expansion heat pump water heater

Test Date	Time	Inclined plane irradiation (W/m^2)	Horizontal plane irradiation (W/m^2)	Ambient temp. (℃)	Wind speed (m/s)	Heat gain of water tank (kWh)	Power consumption of heat pump (kWh)	COP
2022/6/14	21:06	0	0	20.9	0.27	6.44	2.04	3.16
2022/6/15	19:23	0	0	24.2	1.79	6.19	1.66	3.73
2022/6/14	14:56	64	122	27.4	1.02	6.08	1.75	3.47
2022/6/15	14:02	184	470	32.8	2.12	5.78	1.43	4.04
2022/6/17	13:45	212	551	39.9	1.62	5.84	1.26	4.63
2022/6/16	13:46	231	565	33.7	2.35	6.02	1.31	4.6
2022/6/17	8:39	459	744	32	2.08	6.2	1.32	4.7
2022/6/18	11:50	466	898	38.9	1.86	5.82	1.21	4.81
2022/6/16	8:33	475	778	33.3	1.12	6.52	1.35	4.83
2022/6/21	9:23	518	870	32.5	1.46	5.77	1.23	4.69
2022/6/15	9:21	524	891	33.1	1.52	6.24	1.4	4.46
2022/6/20	10:42	532	912	33.4	2.37	5.91	1.21	4.89

It can be seen from the testing results that the COP of the solar direct-expansion heat pump water heater is about 3.16 when the average ambient temperature is 21°C without irradiation. At this time, the heat obtained by the tank is mainly achieved by the heat exchange between the evaporator and the surrounding air and heat absorption and work done by the compressor.

With the increase of ambient temperature and irradiation, the COP of the system increases significantly. When the irradiation of the inclined plane reaches 532 W/m^2, the COP of the system reaches 4.89. It can be seen that the irradiation has an obvious effect on the heating performance of solar direct-expansion heat pump water heaters. The average COP of the solar direct-expansion heat pump water heater is 4.33 throughout the testing period.

In order to study the effect of rain on the performance of the solar direct-expansion heat pump water heater system, the difference of COP between the system in the rain and no rain is tested, as shown in Table 5.

Tab 5: Effect of rain on COP of solar direct-expansion heat pump water heater

Ambient temperature（℃）	COP without rain or irradiation	COP in the rain but no irradiation (Average rainfall: 4 mm/h, heavy rain)	Improvement of COP caused by rain
22.3	3.58	4.05	13.13%

With the other environmental conditions being the same, the COP of the system is 4.05 when it rains, while the COP is only 3.58 when there is no rain. The COP of the solar direct-expansion heat pump water heater increases by 13.13% due to rain. Solar heat pump water heater systems can obtain heat from the sun, air, and rain with a diverse energy source. The COP is higher during the daytime. And the system does not depend on a fan to run, which is required by traditional air heat exchangers, thus reducing the operating noise. This system needs to absorb heat from sunlight and air through solar panels, which needs enough area to install the panels. For civil high-rise buildings, this system can be installed with balconies.

The followings are the results and analysis for the second system: solar and air dual-source heat pump water heater system.

Tab 6: Testing results of the solar and air dual-source heat pump water heater

Testing date	Time	Inclined plane irradiation (W/m^2)	Horizontal plane irradiation (W/m^2)	Ambient temp. (℃)	Wind speed (m/s)	Heat gain of water tank (kWh)	Power consumption of heat pump (kWh)	COP
2022/6/14	19:58	0	0	23	0.66	11.52	3.07	3.75
2022/6/14	23:25	0	0	20.7	0.32	11.84	3.21	3.69
2022/6/15	19:32	0	0	24.9	1.77	11.38	2.66	4.28
2022/6/15	23:30	0	0	22.5	1.73	11.56	2.8	4.13
2022/6/14	15:03	137	151	31.1	1.22	10.91	2.6	4.19
2022/6/13	13:40	217	282	32.8	1.27	10.58	2.33	4.54
2022/6/12	14:37	249	324	31.1	2.04	11.26	2.47	4.56
2022/6/17	13:22	336	608	38.9	1.83	11.27	2.32	4.86
2022/6/17	8:47	342	557	28.7	1.99	11.4	2.39	4.77
2022/6/14	9:17	355	597	27	0.92	11.8	2.82	4.18
2022/6/20	14:07	357	760	34.2	2.58	9.66	2.02	4.78
2022/6/12	9:43	431	711	30	1.68	11.26	2.56	4.4
2022/6/16	13:03	435	765	35	1.92	11.05	2.19	5.04
2022/6/16	8:46	448	770	31.2	1.11	11.72	2.8	4.19
2022/6/13	10:35	466	769	33.1	1.29	11.49	2.49	4.61
2022/6/15	9:20	480	792	32	1.63	11.67	2.52	4.63
2022/6/15	12:37	525	893	35.5	1.23	12.03	2.38	5.05
2022/6/18	11:28	559	916	35.2	2.08	11.07	2.09	5.30

Compared with the solar heat pump water heater, the solar and air dual-source heat pump has two kinds of evaporator: solar heat collector and finned heat exchanger, so the dual-source heat pump can operate more efficiently when there is no irradiation. According to the testing data, the average COP reaches 3.96 during the testing period without irradiation. With the increase of ambient temperature and irradiation, the COP of the system increases significantly. When the irradiation of the inclined plane reaches 559 W/m^2, the COP of the system reaches 5.30. The average COP of the solar heat pump water heater is 4.50 throughout the testing period.

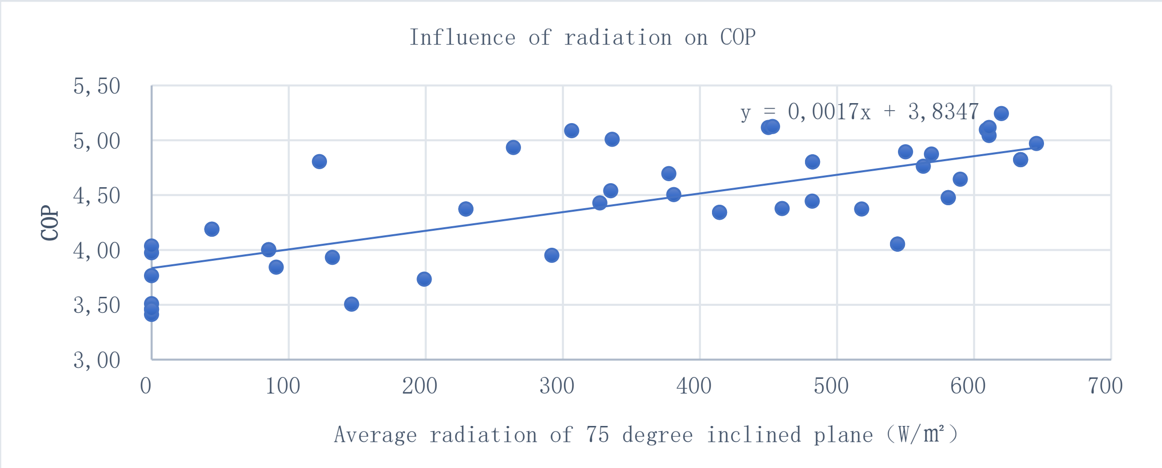

Fig. 10: Effect of irradiation on the performance of the solar and air dual-source heat pump

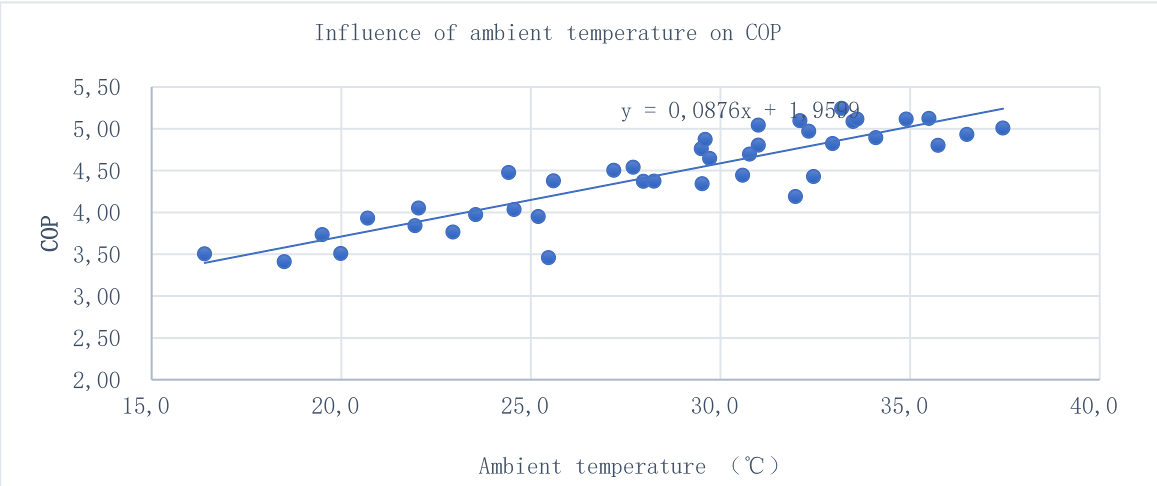

Fig. 11: Effect of temperature on the performance of the solar and air dual-source heat pump

According to the testing data, the linear regression equation of COP with irradiation and temperature during the testing period is obtained by using mathematical statistics theory:

$$COP = 2.164119 + 0.000649\, G + 0.074948\, T \qquad \text{(Eq. 5)}$$

Where G is the solar irradiation intensity (W/m^2), T is the ambient temperature (°C). The ratio of the ambient temperature coefficient (0.074948) to the irradiation coefficient (0.000649) is about 115. Under this system configuration and the external environmental conditions during the testing period, the influence of the ambient temperature increment of 1°C is basically close to that of the COP increment caused by the irradiation increment of 115W/m^2. For the solar and air dual-source heat pump water heater, there is a distinct influence of ambient temperature and irradiation on COP. However, the influence of temperature is more obvious.

To study the influence of the solar heat transfer side and air heat transfer side on the system performance at night, the COP of the system at different ambient temperatures with and without a solar heat collector evaporator is tested separately. The testing results are as follows: ambient dry bulb temperature during the test: 35°C, 30°C, 25°C, 20°C, 15°C, 10°C, 5°C, 0°C, -5°C, -10°C; System operating water temperature: 41°C.

Tab 7: Testing results of COP for solar and air dual-source heat pump water heater with/without solar heat collector evaporator

Ambient temperature (°C)	COP with a solar heat collector	COP without solar heat inflator
-10	0.637	1.597
-5	1.071	1.912
0	1.582	2.589
5	2.054	2.908
10	2.526	3.236
15	2.988	3.521
20	3.458	3.776
25	3.989	4.171
30	4.394	4.663
35	4.83	5.206

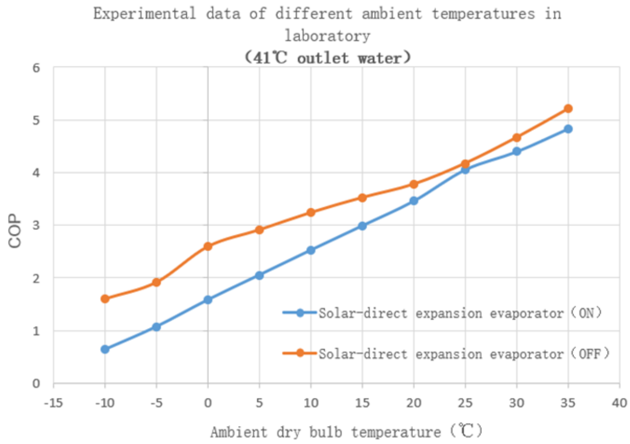

Fig. 12: COP for solar and air dual-source heat pump water heater with/without solar heat collector evaporator

The testing results show that the COP of the system is higher when the solar collector is turned off than when the solar collector is turned on. Under normal circumstances, it is believed that when the solar collector panel is turned on, the area of the evaporator for the heat pump system increases. Even without irradiation, the solar side can absorb heat from the air, thus playing a positive role in increasing the energy efficiency of the heat pump system. However, the experimental results indicate the opposite. The possible reasons are as follows. The control logic does not reach the optimal, and the electronic expansion valve fails to adjust the two refrigerants to the appropriate flow rate according to the overheating, resulting in excessive refrigerant retained in the inflator plate. Moreover, the air evaporator refrigerant quantity is small, resulting in a decrease in heat exchange efficiency, thus affecting the COP. Optimizing the control logic and adjusting the distribution of refrigerant in different working conditions is the key to optimizing the performance of the solar and air dual-source heat pump water heater system. The followings are the results and analysis for the third system: the PVT heat pump water heater system.

Tab 8: Testing results of the COP for the PVT heat pump water heater system

	Inclined plane irradiation (W/m^2)	Horizontal plane irradiation (W/m^2)	Average temp. (°C)	Average wind speed (m/s)	COP of the heat pump	Power generation of the PVT (kWh)	Power consumption of the PVT (kWh)	Overall power consumption of the PVT system (kWh)	Overall COP of the heat pump system
1	527	783	35.9	1.7	3.54	0.791	1.83	1.039	6.23
2	568	832	36.9	1.3	4.01	0.665	1.46	0.795	7.36
3	450	678	35.6	1.6	3.79	0.759	1.63	0.759	7.1

This test only studies the system operating during the daytime with solar irradiation. From the results, when the irradiation of the PVT heat pump water heater is installed at an angle of 45° and the inclined plane irradiation of 515 W/m^2, the COP of the heat pump system is about 3.78 without considering the photovoltaic power generation. However, the PVT heat pump water heater differs from the other two systems. During the heat pump heating stage, the PVT module can on average generate 0.738 kWh of electricity. If the heat pump offsets this part of electricity, the average COP of the PVT heat pump water heater system is 6.90.

5. Conclusion

Under similar working conditions, the testing results of the three systems are summarized in Table 9.

Tab 9: Summarized testing results of the COP for three heat pump water heater system

System	Average COP during the test	Note
Solar direct-expansion heat pump water heater	4.33	
Solar and air dual-source heat pump water heater	4.50	
PVT heat pump water heater	6.90	Overall COP

The comparison results show that the solar direct-expansion heat pump water heaters use solar panels as the evaporator, and the energy efficiency is affected by solar radiation. It is more suitable for collecting heat during the daytime and using heat at night. At the same time, the capacity of the water tank is generally 100-300 Liters. The installation of the heat collection plate requires a particular plane or building facade, so it is more practical to provide rural and urban domestic households with hot water.

The solar and air dual-source heat pump water heater has high energy efficiency, whether under irradiation or not. However, under different working conditions, the two evaporators will directly interfere with each other. Therefore, it is necessary to optimize the refrigerant charging amount and operation logic and further improve the system's adaptability under different working conditions. Similarly, installing heat collection plates and units requires a specific surface. The system can work with a single machine or multiple machines in series and parallel. The volume of the system can be both large and small. It is usually suitable for domestic and commercial usage to get hot water, heating, and drying under various working conditions in solar-rich areas.

PVT solar heat pump water heaters can combine photothermal and photovoltaic to achieve a higher solar energy utilization rate. In the process of heat pump heating, PVT solar heat pump water heater can also reduce the temperature of photovoltaic panels and improve the efficiency of photovoltaic power generation. However, the industrialization of PVT photovoltaic thermal modules is not mature, the structure is complex, and the initial investment is high. It is not widely used in some areas.

The emission coating on the backside of the solar panel can significantly improve efficiency. Meanwhile, the coating can improve the anti-corrosion performance of the panel and extend the system's service life. Using selective solar absorption coating on the front of the solar panel helps to improve the solar heating efficiency of the system. However, there are some problems such as complex processing technology, poor weather resistance, and high cost, which should be further studied.

More projects of this solar fresh air system should be built to conduct a more comprehensive study on the solar heating efficiency of the system, the economy of actual use, and the improvement of indoor air quality to get better guidance on the development and utilization of this solar fresh air system.

6. Acknowledgments

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7. References

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