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ORIGINAL RESEARCH ARTICLE

Research on optimization of collector module of new flat plate heat pipe PV/T heat pump system

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ABSTRACT

The mathematical model of a new flat plate heat pipe PV/T heat pump system is established. The experimental data of the system under various working conditions are obtained through experimental measurement, and the accuracy and reliability of the model are verified. Based on the verified mathematical model, the thermal performance, electrical performance and the performance of the heat pump system are simulated. The results show that under winter conditions, the daily average thermal power, electrical power and COP of the system are 274.5 W, 93.5 W and 2.7 W respectively. Due to the low outdoor ambient temperature in winter, during winter operation, the heat collection system will lose a lot of heat to the surrounding environment through the photovoltaic panel surface, resulting in the heat collection of the system cannot meet the heat demand of the heat pump side, which is intuitively shown as the water temperature of the heat collection tank on the evaporation side shows a downward trend throughout the day. Therefore, the collector module of the system is optimized by adding a collector. After optimization, the daily average thermal power of the system is increased to 654.2 W and the COP is increased to 6.9.

Keywords: Flat Plate Heat Pipe; PV/T; Heat Pump; Numerical Simulation; Performance Optimization

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1. Introduction

As a kind of renewable energy, solar energy has the characteristics of rich reserves, clean and pollution-free, and has gradually been paid attention to and widely used[1]. The solar photovoltaic photothermal comprehensive utilization system combines photovoltaic technology and photothermal technology, and uses the circulating fluid of the photovoltaic panel backplane to take away and collect the heat generated by the photovoltaic panel. While collecting heat, it can also reduce the temperature of the photovoltaic panel to improve the photoelectric conversion efficiency of the system[2]. Compared with the separate photovoltaic system and solar collector system, the solar photovoltaic solar thermal comprehensive utilization system can share system components, reduce system costs, and save building area[3]. Therefore, the comprehensive utilization system of solar photovoltaic light and heat has broad application prospects.

Many scholars at home and abroad have simulated PV/T (photovoltaic/thermal) system. As early as 1979, Hendrie[4] proposed the mathematical theoretical model of PV/T collector based on the traditional solar collector. In 1981, Raghuraman established a mathematical model to simulate and analyze the thermoelectric performance of water-cooled PV/T collector[5], and in 1985, he simulated and studied the air-cooled PV/T system[6].

Chow[7] established the dynamic mathematical model of water-cooled PV/T collector, simulated and analyzed the energy transfer process between different components in the system, and obtained the instantaneous characteristics of the system. As the water-cooled PV/T system is easy to freeze in winter when used in high latitude areas, some scholars proposed to apply heat pipe to PV/T system, and many scholars have carried out simulation research on circular heat pipe PV/T system. Ren *et al.*[8] established the mathematical model of the circular heat pipe PV/T system, and analyzed the influence of the heat pipe spacing, the presence or absence of the air layer and the thickness of the air layer on the performance of the whole system. The results showed that with the increase of the heat pipe spacing, the photoelectric and photothermal output of the system would decrease. In order to make better use of the low-grade heat energy collected by the heat pipe PV/T collector system, some scholars proposed to apply the heat pump to the heat pipe PV/T system. Zhang and Li[9] established the mathematical model of the photovoltaic solar heat pump/ring heat pipe composite system, and used the verified mathematical model to compare and simulate the performance of the system under the two working modes of heat pump operation alone and heat pump and ring heat pipe combined operation. The simulation results show that the working mode of heat pump and ring heat pipe combined operation should be adopted when the solar radiation intensity is high. In winter or when the solar radiation intensity is low, the working mode of independent operation of heat pump should be adopted.

In the traditional circular heat pipe PV/T heat pump system, the contact part between the circular heat pipe and the photovoltaic panel backplane is linear, resulting in less contact area, which affects the heat absorption efficiency of the heat pipe. Applying the new flat plate heat pipe to the heat pipe PV/T system can greatly increase the contact area between the heat pipe and the back plate of the photovoltaic panel and enhance the heat exchange efficiency of the heat pipe. However, there is little research about this part. In order to further study the impact of the new flat plate heat pipe on the operating performance of the heat pipe PV/T heat pump system, this paper has built an experimental device of the new flat plate heat pipe PV/T heat pump system, established the mathematical model of the system, verified the accuracy of the established mathematical model using the previously measured experimental data, and simulated the typical working conditions in winter according to the verified mathematical model. According to the simulation results, the heat collection part of the system is optimized.

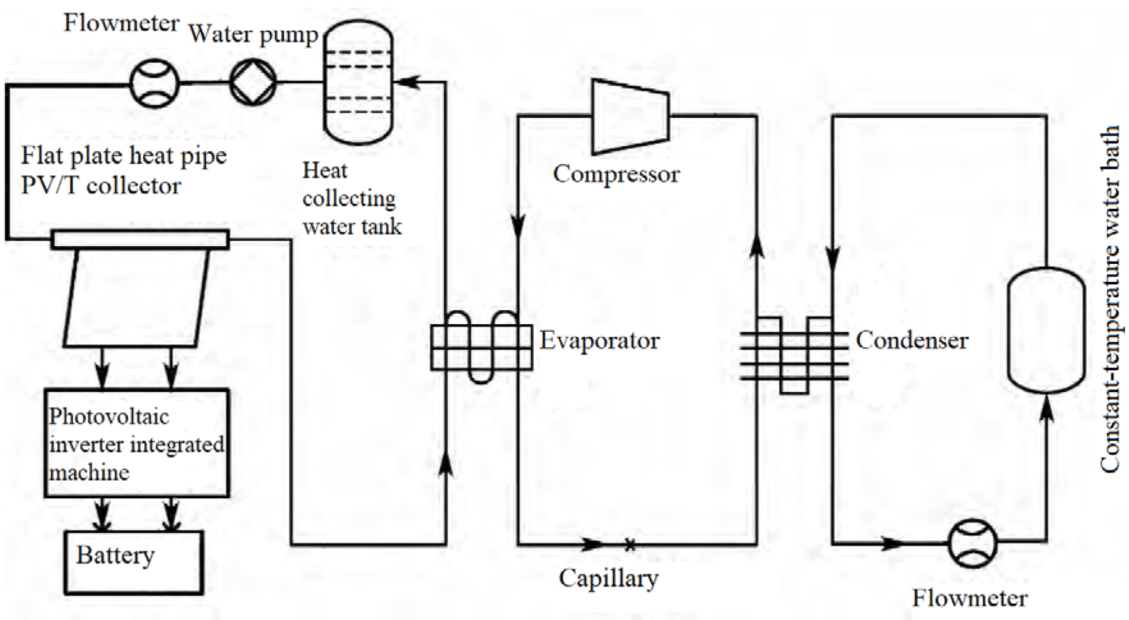

Figure 1. Schematic of the overall system.

2. Mathematical model of flat plate heat pipe PV/T heat pump system

2.1 System composition

Figure 1 is the schematic diagram of the new flat plate heat pipe PV/T heat pump system. The system is mainly composed of flat plate heat pipe PV/T heat collection system and heat pump system[10]. The main devices of the flat panel heat pipe PV/T heat collection system include: new flat panel heat pipe PV/T heat collector, heat collection water tank, expansion water tank, photovoltaic inverter control integrated machine, battery, electromagnetic flowmeter and water pump[11]. The heat pump device is mainly composed of evaporator, condenser, compressor and capillary tube[12]. The condenser and evaporator of the heat pump are plate heat exchangers, the evaporator is connected to the water tank on the evaporation side, and the constant temperature water bath is connected to the condensation side of the heat pump. The refrigerant filled in the heat pump system is R134a.

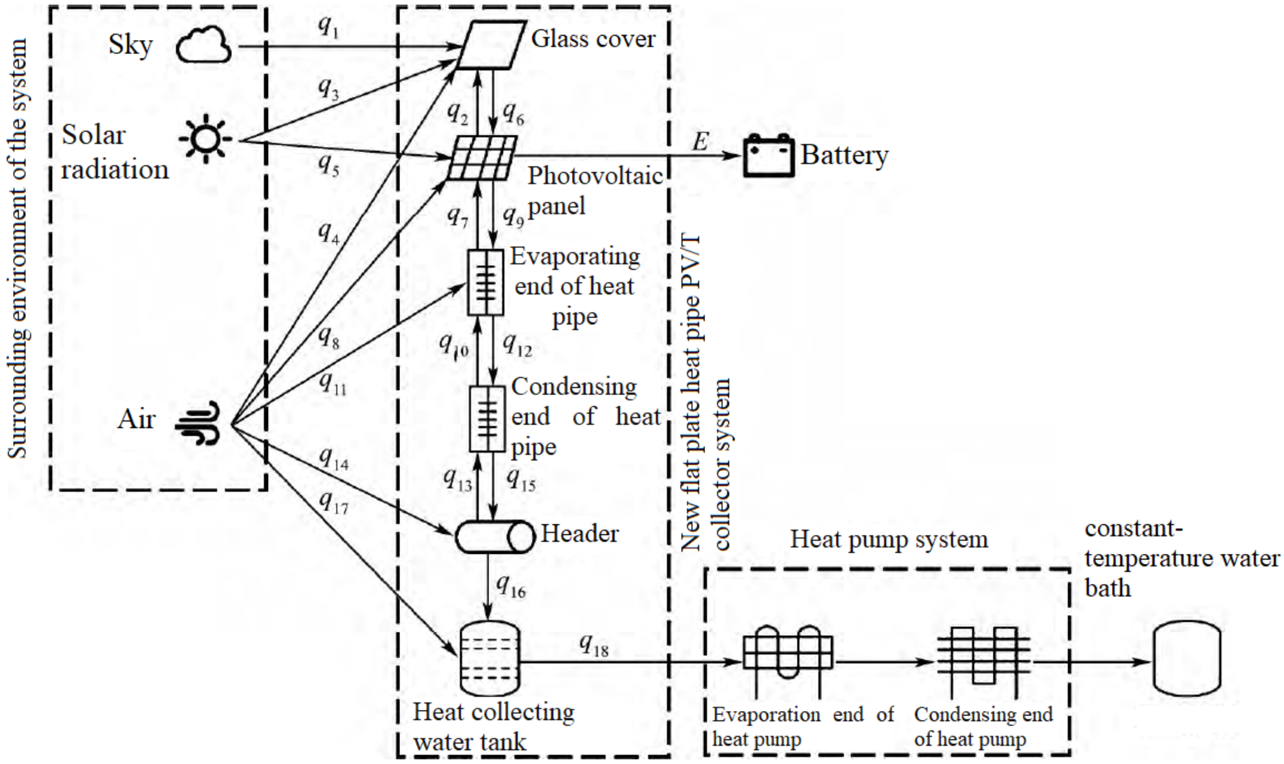

Figure 2. Energy transfer model diagram of a new flat heat pipe type PV/T heat pump system.

2.2 Establishment of system mathematical model

The energy transfer model of the new flat plate heat pipe PV/T heat pump system is shown in **Figure 2**. The sunlight shines on the photovoltaic panel through the glass cover plate, and the short-wave radiation is converted into electric energy, which is converted into AC through the photovoltaic reverse control device and stored in the battery. The long wave radiation is absorbed by the photovoltaic panel to generate heat, which is transmitted to the flat plate heat pipe on the photovoltaic panel back plate through the glass cover plate and the photovoltaic panel respectively. The liquid acetone in the evaporation end of the flat heat pipe is converted into vapor acetone after endothermic evaporation, and the acetone rises to the condensing end of the flat heat pipe after vaporization. After that, the circulating water in the header absorbs the heat at the condensing end of the flat heat pipe and the temperature rises. Under the power provided by the circulating water pump, the high-temperature water in the header is transmitted to the heat exchange coil in the heat collection tank, and the heat is released to the water in the heat collection tank through the heat exchange coil. As the low-temperature heat source of the heat pump, the heat of the heat collecting water tank is absorbed by the evaporation end of the heat pump, and then released to the constant temperature water bath pot by the condensation end of the heat pump.

Table 1. The physical meaning and formula of q_i

q_i	**Physical meaning**	**Formula**	**Physical meaning of parameters in formula**
q_1	Radiant heat transfer between glass cover and environment	$q_1 = h_{\mathrm{sky}}(t_{\mathrm{sky}} - t_{\mathrm{g}})$	h_{sky} is the radiant heat transfer coefficient between the glass cover plate and the environment, W/(m^2·°C); t_{sky} is the effective temperature, °C; t_{g} is the temperature of the glass cover plate, °C
q_2 q_6	Integrated heat transfer between glass cover and PV panel	$q_2 = h_{\mathrm{g,PV}}(t_{\mathrm{pv}} - t_{\mathrm{g}})$ $q_6 = h_{g,PV}(t_g - t_{\mathrm{pv}})$	$h_{\mathrm{g,pv}}$ are the comprehensive heat transfer coefficients between the glass cover plate and the photovoltaic panel; t_{pv} is the temperature of photovoltaic panel, °C
q_3	Solar radiation energy absorbed by glass cover plate	$q_3 = G\alpha_{\mathrm{g}}$	G is solar radiation intensity, W/m^2; α_{g} absorption rate of glass cover plate
q_4	Convection heat transfer between glass cover plate and surrounding environment	$q_4 = h_{\mathrm{a}}(t_{\mathrm{a}} - t_{\mathrm{g}})$	h_{a} is the convective heat transfer coefficient between the glass cover plate and the surrounding environment, W/(m^2·°C); t_{a} is the temperature of air, °C
q_5	Solar radiation energy absorbed by photovoltaic panels	$q_5 = G(\tau\alpha)_{\mathrm{pv}}$	$(\tau\alpha)_{\mathrm{pv}}$ is the effective absorption rate of photovoltaic panels
q_7	Heat exchange between photovoltaic panels and heat pipes	$q_7 = n\lambda \frac{1}{R_{\mathrm{ei}}}(t_{\mathrm{hpeva}} - t_{\mathrm{pv}})$	n is the total number of flat plate heat pipes on the back plate of photovoltaic panel; λ is the coverage rate of heat pipe; R_{ei} is the thermal resistance of heat conducting silica gel, (m^2·K)/W; t_{hpeva} is the temperature at the evaporation end of heat pipe, °C
q_8	Heat exchange between photovoltaic panels and the environment	$q_8 = (1 - n\lambda)h_{\mathrm{pv,a}}(t_a - t_{\mathrm{pv}})$	$h_{\mathrm{pv,a}}$ is the total heat transfer coefficient between the photovoltaic panel backplane and the surrounding environment, W/(m^2·K)
q_9	Heat absorbed by evaporation end of heat pipe	$q_9 = (t_{\mathrm{pv}} - t_{\mathrm{hpeva}})\frac{A_{\mathrm{hp,PV}}}{R_{\mathrm{ei}}}$	$A_{\mathrm{hp,\,pv}}$ is the contact area between each heat pipe and photovoltaic panel, m^2
q_{10} q_{12}	Evaporation end and cold end of heat pipe Heat exchange between condensing ends	$q_{10} = \frac{t_{\mathrm{hpcon}} - t_{\mathrm{hpeva}}}{R_{\mathrm{eva,con}}}$ $q_{12} = \frac{t_{\mathrm{hpeva}} - t_{\mathrm{hpcon}}}{R_{\mathrm{eva,con}}}$	t_{hPcon} is the temperature at the condensing end of the heat pipe, °C; $R_{\mathrm{eva,con}}$ is the thermal resistance between the evaporating end and condensing end of the heat pipe, (m^2·K)/W
q_{11}	Heat exchange between evaporation end of heat pipe and environment	$q_{11} = h_{\mathrm{hpeva}}A_{\mathrm{hp,pv}}(t_a - t_{\mathrm{hpeva}})$	h_{hpeva} is the heat transfer coefficient at the evaporation end of the heat pipe, W/(m^2·K)
q_{13} q_{15}	Condensation end and circulation of heat pipe Heat exchange of circulating water	$q_{13} = A_{\mathrm{w}}h_{\mathrm{w,con}}(t_{\mathrm{w}} - t_{\mathrm{hpcon}})$ $q_{15} = A_w h_{w,con}(t_{\mathrm{hpcon}} - t_w)$	A_{w} is the heat exchange area between condensing end and circulating water, m^2; $h_{\mathrm{w,con}}$ is the convective heat transfer coefficient between the condensing end and the circulating water, W/(m^2·K); t_{w} is the average temperature of circulating water in the header, °C
q_{14}	Heat exchange between circulating water and environment in header	$q_{14} = \frac{t_{\mathrm{a}} - t_{\mathrm{w}}}{R_{\mathrm{a,w}}}$	$R_{\mathrm{a,w}}$ is the thermal resistance between the circulating water in the header and the environment, (m^2·K)/W
q_{16}	Heat collection of header	$q_{16} = q_{m_{\mathrm{w}}}c_{\mathrm{w}}(t_{\mathrm{w,o}} - t_{\mathrm{w,i}})$	c_{w} is the specific heat capacity of water in the header, J/ (kg·°C); $q_{m_{\mathrm{w}}}$ is the mass flow of water in the header, kg/s; $t_{\mathrm{w,i}}$ and $t_{\mathrm{w,o}}$ are the inlet and outlet temperatures of water in the header respectively, °C
q_{17}	Heat exchange between collector tank and environment	$q_{17} = \frac{t_{\mathrm{a}} - t_{\mathrm{w,t}}}{R_{\mathrm{a,wt}}}$	$t_{\mathrm{w,t}}$ is the average temperature of water in the heat collection tank, °C; $R_{\mathrm{a,wt}}$ is the heat transfer resistance between the collector tank and the environment, (m^2·K)/W
q_{18}	Heat collection of heat pump	$q_{18} = q_{m_{\mathrm{r}}}(h_{\mathrm{r2}} - h_{\mathrm{r1}})$	$q_{m_{\mathrm{r}}}$ is the mass flow of refrigerant in the heat exchange element, kg/s; h_{r1} and h_{r2} are the specific enthalpy of inlet and outlet of refrigerant in the heat exchange element, J/kg

According to the energy transfer model diagram of the system, the mathematical model of the system can be established. The mathematical model of the new flat plate heat pipe PV/T heat pump system is divided into two parts, namely, the mathematical model of the new flat plate heat pipe PV/T heat collection system and the mathematical model of the heat pump system.

2.3 Verification of system mathematical model

Based on the experimental data measured before, this paper verifies the mathematical model of the new flat plate heat pipe PV/T heat pump system.

Figure 3 shows the meteorological data on the day of the test. As shown in **Figure 3**, the average solar radiation intensity of the day is 778.9 W/m^2, and the average outdoor air temperature is 31.4 ℃.

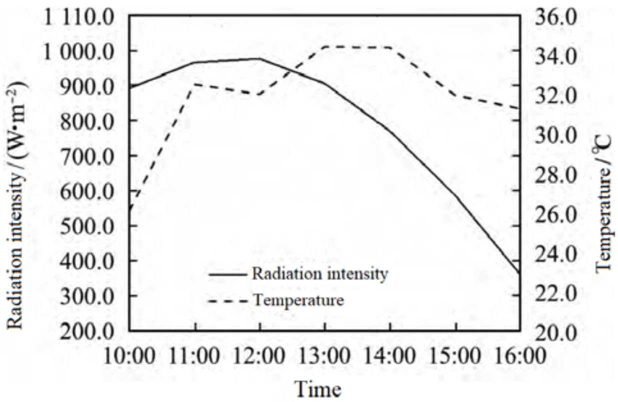

Figure 3. Variation of solar radiation and ambient temperature.

Figures 4, **5** and **6** show the comparison of measured and simulated values of the thermal performance, electrical performance and relevant parameters of the heat pump system. It can be seen from **Figure 4** that the simulated value of the system thermal power is lower than the measured value before 12:00, but higher than the measured value after 12:00, with a deviation of -1.3%–10.2%; the simulated value of the thermal efficiency of the system has been slightly higher than the measured value, and the deviation between the two is -1.0%–9.5%. It can be seen from **Figure 5** that the deviation between the simulated value and the measured value of the electric power of the system is -3.1%–2.4%; the deviation between the simulated value and the measured value of the electrical efficiency of the system is -2.1%–5.4%. It can be seen from **Figure 6** that the accuracy of the mathematical model of the heat pump system is high, and the deviation between the simulated and measured values of relevant parameters is very small. The deviation between the simulated and measured values of *COP* is only -0.4%–0.5%, and the deviation between the simulated and measured values of condensation heat exchange and compressor power is -2.4%–5.1% and 1.4%–3.3% respectively. The deviation between the simulated value and the measured value of the mathematical model of the system is within a reasonable range, and the model is more accurate.

3. System performance simulation and optimization

3.1 System performance simulation

Based on the verified mathematical model of the new flat plate heat pipe PV/T heat pump system, this paper simulates and analyzes the operation performance of the system. The meteorological data used in the simulation analysis is the previously collected measured data on December 13, 2019. In winter, generally, 40.0 ℃ domestic hot water can meet the daily needs of heat users[15], so the temperature of constant temperature water bath is set to 40.0 ℃ during simulation.

Figure 7 shows the meteorological data on the day of the test. It can be seen from **Figure 7** that the overall solar radiation intensity shows a trend of rising first and then declining, with an average of 492.5 W/m^2 and an average ambient temperature of 4.8 ℃.

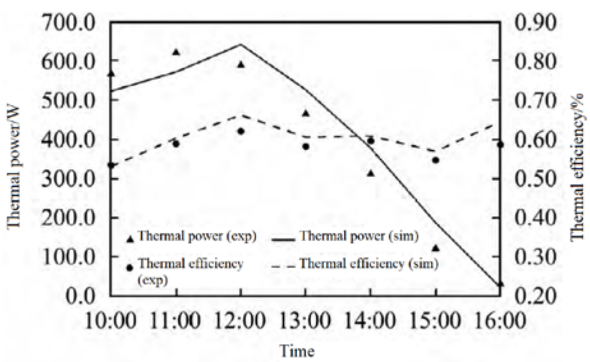

Figure 4. Comparison of measured and simulated values of thermal performance.

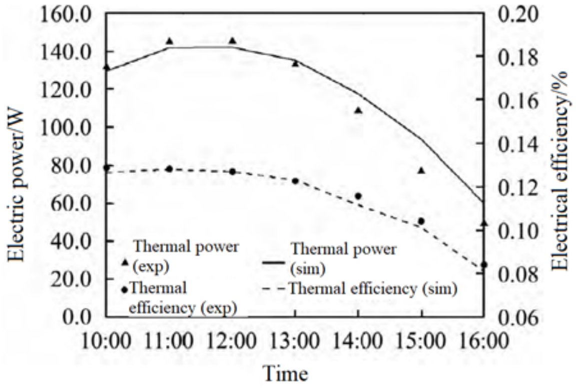

Figure 5. Comparison of measured and simulated values of electrical performance.

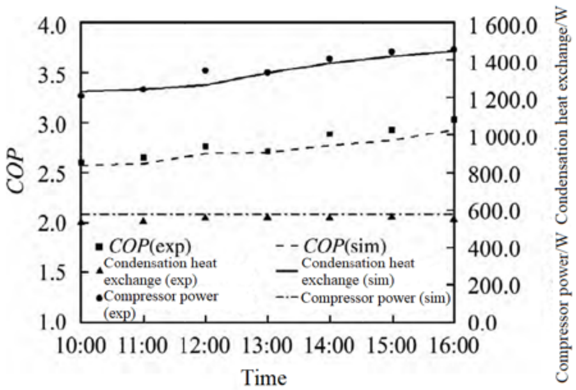

Figure 6. Comparison of measured and simulated values of the performance of heat pump system.

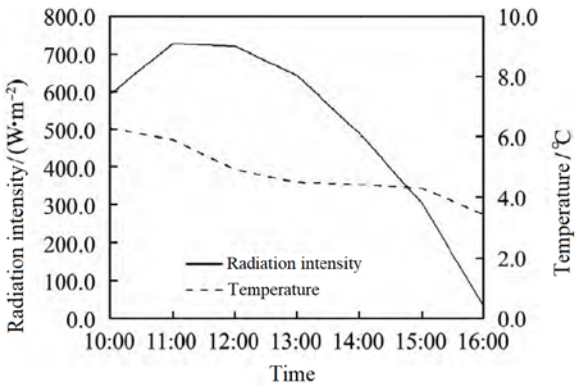

Figure 7. Variation of solar radiation and ambient temperature.

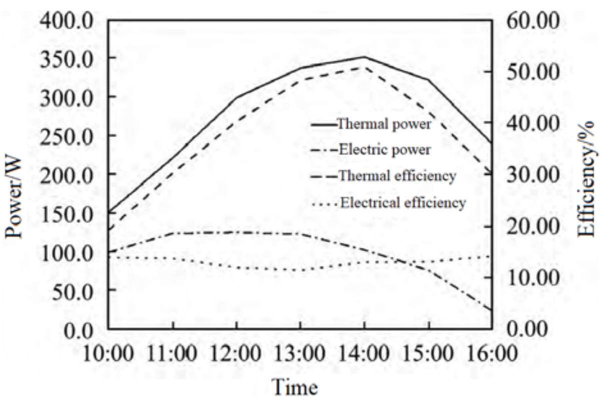

Figure 8. Variation of the thermoelectric performance.

Figure 8 shows the thermoelectric performance simulation results of the system. It can be seen from **Figure 8** that the change trend of thermal power and thermal efficiency is similar to that of solar irradiation intensity, both of which show a trend of rising first and then declining. The maximum value of thermal power appeared at 14:00, which was 351.4 W, and the daily average thermal power was 274.5 W; the maximum thermal efficiency is 48.10%, and the daily average thermal efficiency is 36.30%. It can also be seen from **Figure 8** that the overall change trend of electric power also increases first and then decreases, but the change range is small compared with thermal power and thermal efficiency. The maximum value of electric power is 123.3 W, and the daily average value is 93.5 W. Due to the high temperature of photovoltaic panels at noon, the electrical efficiency is at the lowest value, so the change of electrical efficiency shows a downward trend first and then an upward trend, but the overall change is relatively gentle, the maximum value of electrical efficiency is 14.10%, and the daily average value is 12.10%.

Figure 9 shows the simulation results of relevant parameters of the heat pump system. It can be seen from **Figure 9** that the overall change trend of *COP*, condensation heat exchange and compressor power is relatively flat. The daily average value of *COP* is 2.7, the daily average value of condensation heat exchange is 1,215.1 W, and the daily average value of compressor power is 577.9 W. It can be seen that the operation of heat pump in the whole day is relatively stable. The temperature of the heat collection tank at the evaporation side tends to decrease throughout the day. The initial temperature is set at 6.0 ℃, and the water temperature drops to the lowest value of 2.9 ℃ at the end of the simulation. It can be seen that the heat collected by the flat plate heat pipe PV/T heat collection system throughout the day does not meet the requirements of 40.0 ℃ constant temperature of water bath. This is because the capacity of the heat pump does not match the heat collection, resulting in insufficient heat collection of the flat plate heat pipe PV/T heat collection system. The heat pump needs to absorb heat from the hot water, so the water temperature will be lower and lower. Therefore, under winter conditions, the new flat plate heat pipe PV/T heat collection system using a collector cannot meet the requirements of 40.0 ℃ constant temperature of water bath, and the heat collection system needs to be optimized.

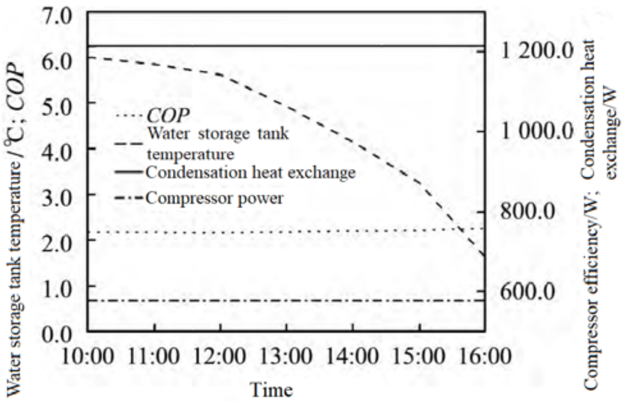

Figure 9. Variation of the performance of heat pump system.

3.2 System performance optimization

This paper aims to make the new flat plate heat pipe PV/T heat pump system designed to meet the domestic heat demand of heat users. In general, 40.0 ℃ domestic hot water can meet the daily needs of heat users in winter. Therefore, the heat collection of the optimized system should make the temperature of the constant temperature of water bath reach 40.0 ℃. Through the simulation and analysis of the system in winter, it can be seen that the system has not reached the expected requirements, so it is necessary to optimize the heat collection module of the system.

When designing a new flat plate heat pipe PV/T heat pump system, the factors such as heat pipe spacing, circulating water flow and photovoltaic cell coverage were simulated and optimized. This paper optimizes the performance of the system by changing the number of collectors. In the optimization, first increase the number of collectors to two, but through the simulation study, it is found that the results do not meet the expected goal, and then add another collector, using three collectors in series, the simulation shows that the results can meet the requirements.

Therefore, the optimization measure in this paper is to add two collectors in the heat collection system and adopt the mode of three collectors in series. The optimized simulation results are shown in **Figure 10**.

Figure 10 shows the change curve of the thermoelectric performance of the optimized system. It can be seen from **Figure 10** that the overall change trend of thermal power and thermal efficiency after optimization is similar, both rising first and then declining. The maximum value of thermal power is 882.2 W, and the daily average value is 654.2 W. The maximum value of thermal efficiency is 55.90%, and the daily average value is 35.90%. After optimization, compared with that before optimization, the thermal power is increased by 2.4 times, and the thermal efficiency remains basically unchanged. It can also be seen from the figure that the overall trend of the optimized electric power is to rise first and then decline. The maximum electric power is 340.5 W and the daily average is 252.2 W. The overall trend of electric efficiency after optimization is to decrease first and then increase. Contrary to the change trend of electric power, the lowest value of electric efficiency is 11.90%, and the daily average value is 13.00%. After optimization, the electric power is increased by 2.7 times, and the electric efficiency is basically unchanged.

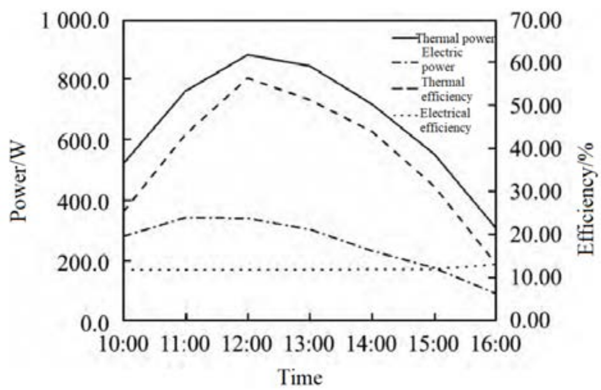

Figure 10. Variation of thermoelectric performance after optimization.

Figure 11 shows the change curve of relevant parameters of the heat pump system after optimization. It can be seen from **Figure 11** that the change trends of compressor power, *COP* and condensation heat exchange are relatively flat. The daily average value of compressor power is 581.1 W, *COP* is 6.9, and the daily average value of condensation heat exchange is 2,432.7 W. It can be seen that the performance of the heat pump has been greatly improved compared with that before optimization. The water temperature of the heat collection tank on the evaporation side generally shows a trend of rising first and then declining. At noon, the water temperature reaches the maximum value of 9.0 ℃. During the period from 10:00 to 15:30, the temperature of the heat collection tank is higher than the initial temperature. It shows that the heat collection of the new flat plate heat pipe PV/T heat collection system can meet the requirements of constant temperature of water bath at 40.0 ℃.

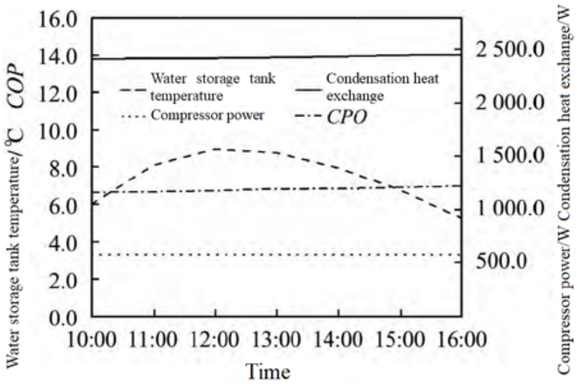

Figure 11. Variation of the performance of heat pump system after optimization.

4. Conclusion

In this paper, the mathematical model of a new flat plate heat pipe PV/T heat pump system is established, and the model is verified by experimental data. Based on the verified model, the system performance is simulated and optimized, and the conclusion is obtained.

(1) By comparing the experimental data with the simulation results, the error is -3.1%–10.2%. The mathematical model of the new flat plate heat pipe PV/T heat pump system has good reliability and accuracy.

(2) Under sunny conditions in winter, the daily average thermal power and thermal efficiency of the new flat plate heat pipe PV/T heat pump system are 274.5 W and 36.30% respectively, and the daily average electric power and electric efficiency are 93.5 W and 12.10% respectively. The average *COP* of the system is 2.7.

(3) After the optimization of the system, the daily average thermal power and electric power were increased to 654.2 W and 252.2 W respectively. At the same time, the performance of the heat pump system was also greatly improved, and its average *COP* reached 6.9.

Conflict of interest

The authors declared no conflict of interest.

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