

Simulation Study on The Influencing Factors of MHPA-PV/T Module Performance in High-altitude and High-altitude Cold Regions

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Abstract

This article uses Fluent simulation software to establish a three-dimensional steady-state model of MHPA-PVIT, and verifies the reliability of the model. The simulation results are in good agreement with the experimental results. Taking into account thermal efficiency, electrical efficiency, and losses caused by increasing flow rate, the optimal operating flow rate for MHPA-PVT components should be $0.15 \text{ kg}/(\text{m}^2 \cdot \text{s})$. The thermal efficiency decreases with increasing wind speed, while the electrical efficiency increases with increasing wind speed. And when the inlet temperature is low, the difference in thermal efficiency and electrical efficiency is small, but as the inlet temperature increases, the difference in thermal and electrical efficiency becomes more significant. The solar irradiance has a significant impact on the heat collection efficiency, and the heat collection efficiency of the components increases significantly with the increase of irradiance.

Keywords

High altitude and cold regions; MHPA-PV/T components; Influencing factors; Simulation study.

1. Introduction

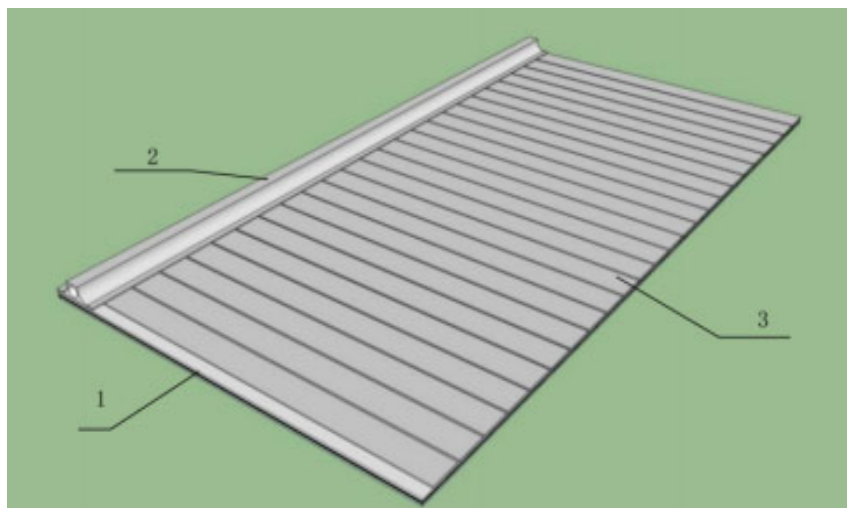
The decrease in solar photovoltaic conversion efficiency is mainly due to the decrease in open circuit voltage with the increase of photovoltaic module temperature. For every $1 \text{ }^\circ\text{C}$ increase in module temperature, the photovoltaic conversion efficiency decreases by about 0.5% [1]. How to utilize these waste heat resources of photovoltaic modules and achieve the recovery and utilization of waste heat is a meaningful research topic. PV/T modules are a combination of solar photovoltaic cell modules and collectors. The cell modules act as the heat absorbing body of the collectors, producing both electrical and thermal energy to improve the overall utilization efficiency of solar energy [2]. Domestic and foreign scholars' research on improving the efficiency of PV/T devices mainly focuses on the form of cover plate heat transfer structures, the application of heat pipes, and the efficient utilization of heat pumps. There is still a gap in research on the efficient coupling and utilization of flat plate micro heat pipe array technology and heat pump technology [3]. Therefore, this article proposes a micro heat pipe array solar PV/T heat pump system suitable for high-altitude areas. On the basis of further reducing the temperature of photovoltaic modules and improving the photoelectric conversion efficiency, it achieves efficient and stable output of electric heating. Through the indirect heat exchange method of antifreeze, it increases the heat exchange area, reduces the risk of working medium leakage and freezing, and improves the comprehensive utilization efficiency of solar energy in PV/T devices in high-altitude and high-altitude areas [4].

This article uses Fluent simulation software to establish a three-dimensional steady-state model of MHPA-PVIT, and uses this model to simulate and study the factors affecting the

instantaneous performance of components, providing theoretical basis for component optimization.

2. Instantaneous Model of MHPA-PV/T

This article establishes a model based on the actual dimensions of MHPA-PV/T components, as shown in Figure 1. The actual MHPA has bends at the battery junction box, but this has almost no impact on the component performance, so it will be ignored in the modeling.



1-Photovoltaic cell modules (including glass, EVA, solar cells, TPT panels, and frames);
2-Water tube heat exchanger; 3-MHPA

Figure 1. The schematic of MHPA-PV/T component model

In Fluent Gabbit software, a grid is generated for the calculation area and encrypted at the water tube heat exchanger. The finite volume method is used to discretize the general control equations, and the pressure interpolation scheme adopts the Body Force Weighted format; The pressure velocity coupling equation adopts the SIMPLE algorithm; The momentum, energy, and turbulence equations adopt a second-order upwind format. The known parameters are input into the model to start the calculation. When the relevant residuals are less than the set values, the calculation is considered to have converged. The outlet water temperature, glass temperature, and battery temperature of the output component are input into the corresponding calculation formulas to calculate the instantaneous thermal efficiency and electrical efficiency. When the calculated electrical efficiency matches the initial set values, the calculation ends. If there is a difference, adjust the set electrical efficiency value and calculate again until the calculated value matches the initial set values [5].

3. Verification Model

By simulating the experimental data on December 20, 2024, the results show that the simulation results of thermal efficiency are in good agreement with the experimental results, as shown in Table 1. The relative error of the largest set of data points is 6.4%, while the error of electrical efficiency is slightly larger, with a relative error of 8.0%.

Table 1. Error of experimental and simulated values

Inlet temperature/°C	Temperature difference experimental value/°C	Temperature difference simulation value	Error	Experimental value of electrical efficiency	Simulated value of electrical efficiency	Error
19.823	0.636	0.677	0.064	0.12	0.123	0.027
24.881	0.65	0.692	0.064	0.112	0.119	0.06
30.065	0.637	0.656	0.029	0.108	0.116	0.08
35.16	0.587	0.566	-0.037	0.107	0.114	0.066
40.138	0.511	0.53	0.037	0.11	0.111	0.013

Experimental results of instantaneous efficiency:

$$\eta = 0.414 - 3.95 \frac{T_i - T_a}{G} \tag{1}$$

Simulation results of instantaneous efficiency:

$$\eta = 0.428 - 3.99 \frac{T_i - T_a}{G} \tag{2}$$

The fitting results and electrical efficiency results are shown in Figures 2 and 3. It can be observed that the relative error of intercept is -3.38% and the relative error of slope is -1.00%, indicating a high degree of agreement. Therefore, this model can be used for analysis and research.

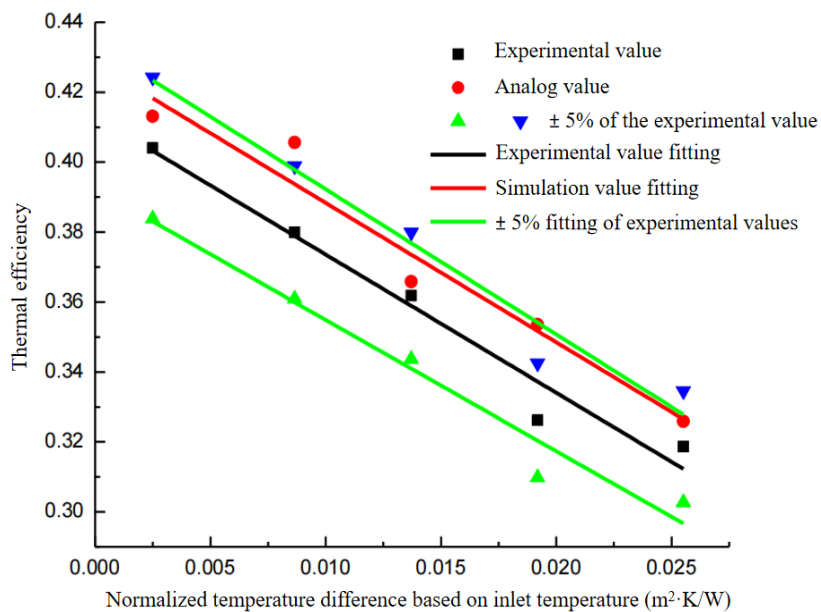


Figure 2. The comparison chart of component’s instantaneous thermal efficiency and simulation results

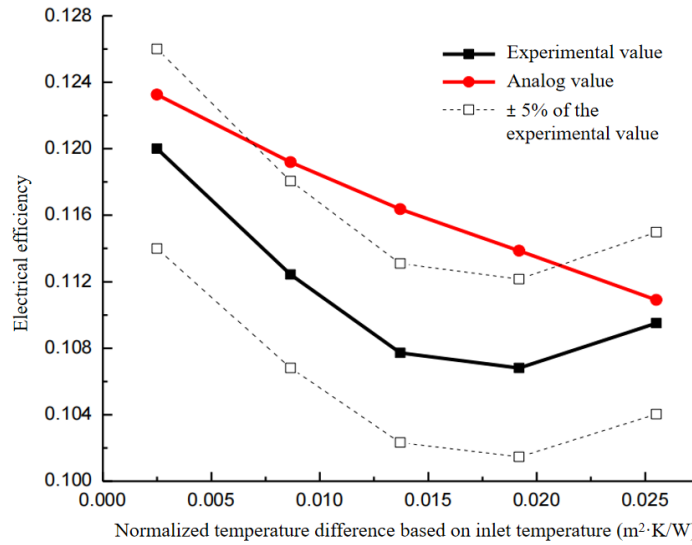


Figure 3. The comparison chart of component’s instantaneous power generation efficiency and simulation results

4. Simulation Study on Performance Influencing Factors

There are many factors that affect the performance of MHPA-PV/T modules, including environmental temperature, wind speed, solar irradiance, operating parameters, and other factors. It is difficult to systematically grasp the impact of these factors on the optoelectronic and thermal performance of modules solely through experiments [6]. This article uses the model established and validated above to explore the effects of circulating water flow rate, environmental wind speed, and solar irradiance on the performance of MHPA-PV/T modules, providing theoretical basis for their application in different environmental conditions and obtaining optimal operating parameters.

4.1. The impact of running traffic on performance

Under the existing model, set the total solar irradiance $G=800W/m^2$, ambient temperature $t_a=20\text{ }^\circ\text{C}$, instantaneous wind speed $u=0.5m/s$, and adjust the inlet flow rates of MHPA-PV/T components to 0.05, 0.10, 0.15, 0.20, respectively 0.25kg/(m²·s), respectively, are used for solving. The results of thermal efficiency are presented in the form of instantaneous efficiency regression curves, as shown in Figure 4, while electrical efficiency and total efficiency are presented in the form of scattered points, as shown in Figures 5 and 6.

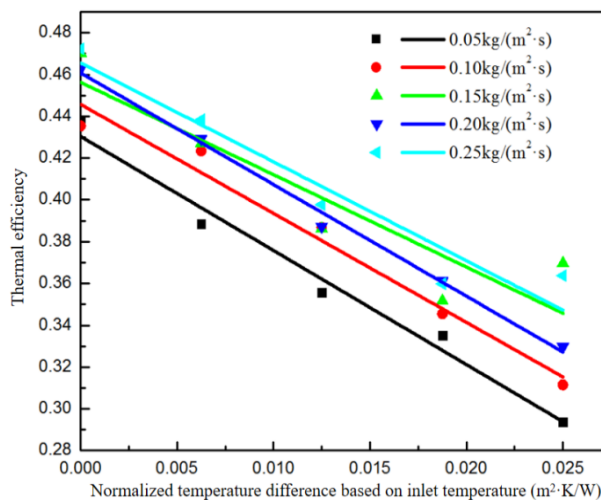


Figure 4. Instantaneous thermal efficiency curves under different flow rate

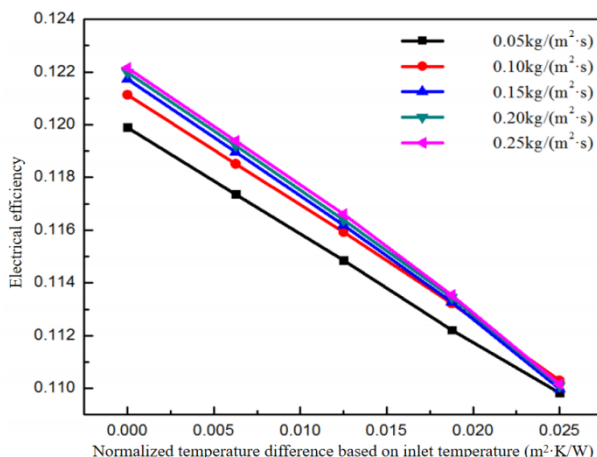


Figure 5. Electrical efficiency under different flow rates

From Figure 4, it can be seen that during the process of increasing the flow rate from $0.05\text{kg}/(\text{m}^2\cdot\text{s})$ to $0.15\text{kg}/(\text{m}^2\cdot\text{s})$, the instantaneous thermal efficiency increases significantly. After further increasing to $0.20\text{kg}/(\text{m}^2\cdot\text{s})$ until $0.25\text{kg}/(\text{m}^2\cdot\text{s})$, the increase in thermal efficiency is not significant. From Figure 5, it can be seen that at the same inlet temperature, the higher the flow rate, the higher the electrical efficiency, and the increase is similar to the thermal efficiency. It is more significant before $0.15\text{kg}/(\text{m}^2\cdot\text{s})$, but not significant afterwards.

Therefore, as shown in Figure 6, taking into account thermal efficiency, electrical efficiency, and losses caused by increasing flow rate, the optimal operating flow rate for MHPA-PV/T components should be $0.15\text{ kg}/(\text{m}^2\cdot\text{s})$.

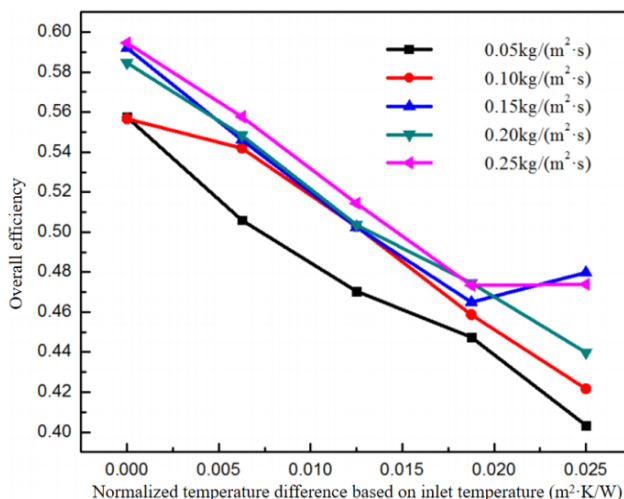


Figure 6. Total efficiency under different flow rates

4.2. The impact of environmental wind speed on performance

At the optimized flow rate of $0.15\text{kg}/(\text{m}^2\cdot\text{s})$, $G=800\text{W}/\text{m}^2$, and $t_a=30\text{ }^\circ\text{C}$ calculated in the previous text, the heat collection efficiency, power generation efficiency, and overall efficiency of MHPA-PV/T components were calculated at different wind speeds (0-4m/s) and inlet temperatures, as shown in Figures 7 to 9. It can be seen that thermal efficiency and overall efficiency decrease with increasing wind speed, while electrical efficiency increases with increasing wind speed. And when the inlet temperature is low, the differences in thermal efficiency, electrical efficiency, and total efficiency are small. At an inlet temperature of $10\text{ }^\circ\text{C}$, the thermal and electrical efficiencies are almost equal at different wind speeds. However, as the inlet temperature increases, the differences in thermal and electrical efficiencies become

more significant, especially when the wind speed changes from 0 to 1m/s, the decrease in thermal efficiency and the increase in electrical efficiency are greater. At an inlet temperature of 40 °C, the absolute value of electrical efficiency increased by 0.6% when the wind speed was 4m/s compared to no wind, but the absolute value of thermal efficiency decreased by 26.0%, a relative decrease of 55.2%.

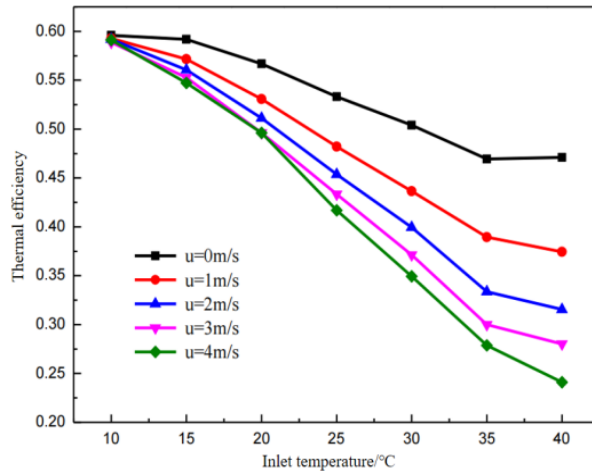


Figure 7. The curve of environmental wind speed effects on component’s thermal efficiency

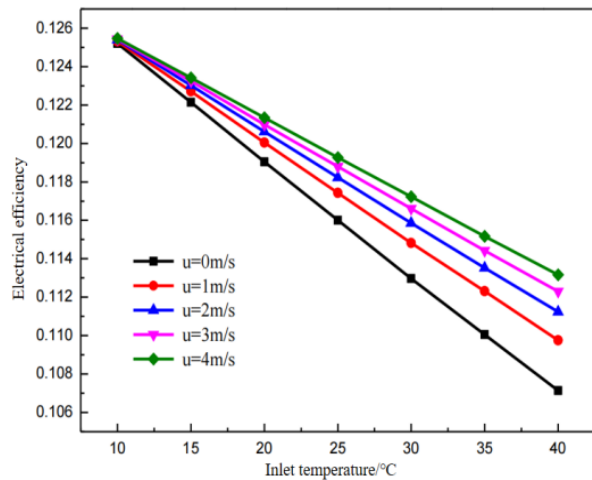


Figure 8. The curve of environmental wind speed effects on component’s power generation efficiency

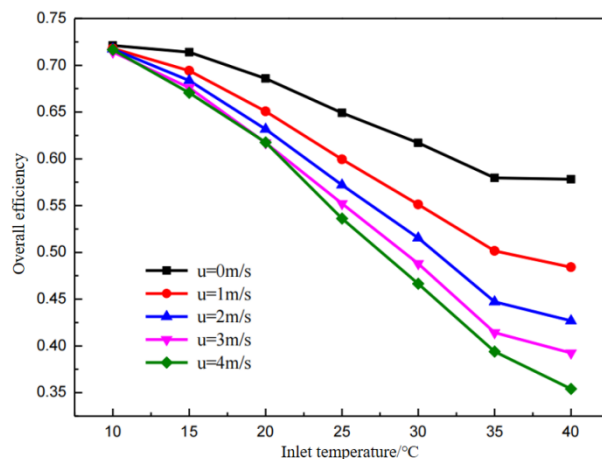


Figure 9. The curve of environmental wind speed effects on component’s total efficiency

From the above, it can be seen that the environmental wind speed has a relatively small impact on the power generation efficiency of MHPA-PV/T modules, but has a significant impact on thermal efficiency, which is related to the structural form of the modules, that is, the heat loss is mainly concentrated on the upper surface. Can we refer to a flat solar collector and add a certain height of air layer on the upper surface to achieve insulation effect, but it will affect the power generation efficiency and increase the cost, but it will definitely improve the heat collection effect. This is also an area that needs to be further studied in the later stage of the project.

4.3. The impact of solar irradiance on performance

The solar irradiance is also a key factor affecting the photovoltaic and photothermal conversion efficiency of the MHPA-PV/T module, and this variable cannot be controlled during the experimental process. Through a model, the heat collection efficiency, power generation efficiency, and total efficiency of the MHPA-PV/T module were calculated at different irradiance ($G=1000, 800, 600, 400, 200\text{W/m}^2$) and inlet temperatures under optimized flow rate of $0.15\text{kg}/(\text{m}^2\cdot\text{s})$, ambient temperature t_a of $20\text{ }^\circ\text{C}$, and instantaneous wind speed u of 0.5m/s . The simulation results are summarized in Figures 10 to 12.

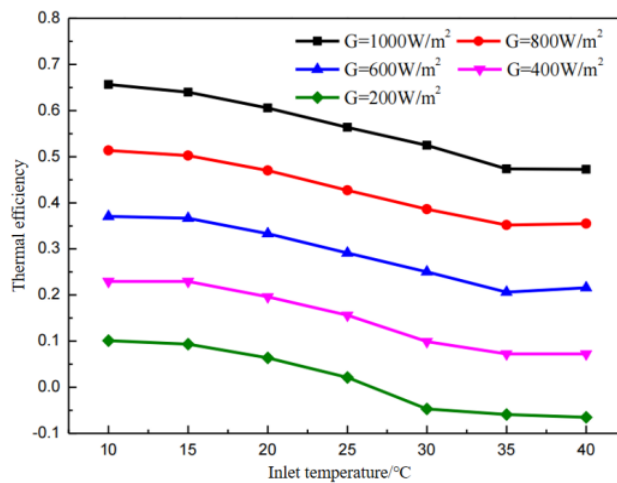


Figure 10. The curve of irradiance effects on component's thermal efficiency

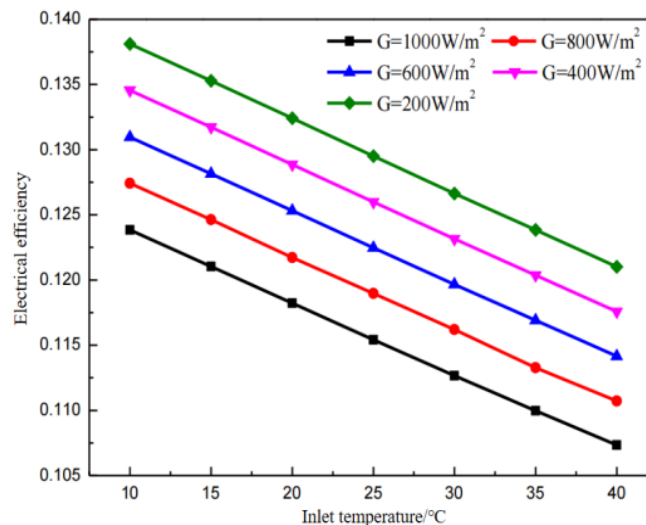


Figure 11. The curve of irradiance effects on component's power generation efficiency

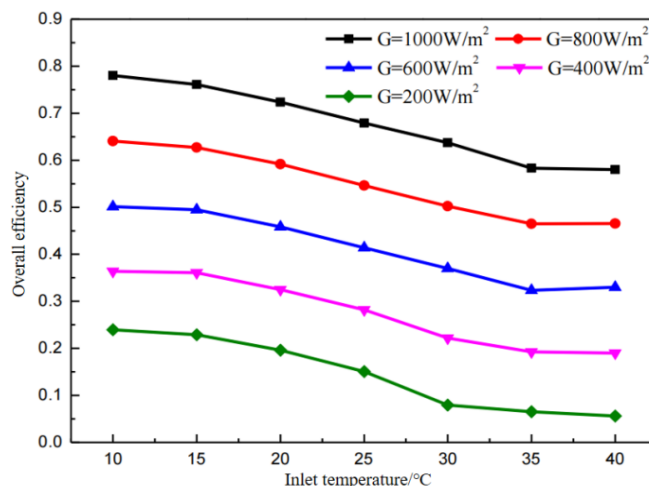


Figure 12. The curve of irradiance effects on component's total efficiency

It can be seen that the solar irradiance has a significant impact on the heat collection efficiency. As the irradiance increases, the heat collection efficiency of the components increases significantly. When the inlet temperature is 20°C and the irradiance is 1000W/m², the instantaneous efficiency reaches 72.4%. When the irradiance drops to 600W/m², the instantaneous efficiency is only 33.3%. This is because when the irradiance is high, the temperature of the battery is high, resulting in a large temperature difference between the components and the cooling water, and the heat transfer effect is good. It should be noted that when the irradiance is 200W/m² and the inlet temperature exceeds 30 °C, the heat collection efficiency is already negative. This means that the temperature of the battery is already lower than the water temperature, and the water no longer has the effect of cooling the battery. Instead, it releases heat to the battery. During the operation of the system, around 15:00-17:00, the solar irradiance is already weak, and the water temperature in the water tank is high. At this time, it is necessary to notify the automatic control or manual control to disconnect the circulating water pump. This can reduce the heat loss of the collected hot water and also reduce the power consumption of the water pump.

Similarly, changes in irradiance cause changes in battery temperature, resulting in changes in battery power generation efficiency. As shown in Figure 12, an increase in irradiance leads to a decrease in power generation efficiency, which explains why in the system experiment, the daily power generation efficiency presents a curve similar to an *M*-shape, that is, at noon, the power generation efficiency will first decrease and then increase. Although the power generation efficiency may decrease when the irradiance is high, the power generation at this time is still much higher than other time periods. Considering the overall situation, it is still applied in areas with a large total irradiance, and the total benefits of power generation and heat collection are relatively large.

5. Conclusions

(a) This article establishes a three-dimensional model of a micro heat pipe array solar cogeneration module and verifies its reliability. The simulation results are in good agreement with the experimental results. Taking into account thermal efficiency, electrical efficiency, and losses caused by increasing flow rate, the optimal operating flow rate for MHPA-PVT components should be 0.15 kg/(m²·s).

(b) The thermal efficiency decreases with increasing wind speed, while the electrical efficiency increases with increasing wind speed. And when the inlet temperature is low, the difference between thermal efficiency and electrical efficiency is small, but as the inlet temperature

increases, the difference between thermal and electrical efficiency becomes more obvious, especially when the wind speed changes from 0 to 1m/s, the decrease in thermal efficiency and the increase in electrical efficiency are greater. At an inlet temperature of 40 °C, the absolute value of electrical efficiency increased by 0.6% when the wind speed was 4m/s compared to no wind, but the absolute value of thermal efficiency decreased by 26.0%, a relative decrease of 55.2%.

(c) The solar irradiance has a significant impact on the heat collection efficiency. The heat collection efficiency of the component increases significantly with the increase of irradiance. When the inlet temperature is 20 °C and the irradiance is 1000 W/m², the instantaneous thermal efficiency reaches 72.4%. When the irradiance drops to 600 W/m², the instantaneous thermal efficiency is only 33.3%. Although the power generation efficiency may decrease when the irradiance is high, the power generation at this time is still much higher than other time periods.

Supported Project Name

“Experimental Study on the Performance of MHPA-PV/T Heat Pump System Suitable for High Altitude” (XZ202501ZR0067)

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