Improvents on the Efficiency of the Photovoltaic Panel by Integrating a Spray Cooling System with Shallow Geothermal Energy Heat Exchanger

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Abstract

A spray cooling system with shallow geothermal energy is experimentally investigated to mitigate the photovoltaic (PV) panel efficiency decline problem, which is due to high temperatures. This cooling system is utilized to cool PV panels by spraying water on the back of the panel, and a tank is used to reclaim the cooling water. To enhance the cooling capacity, the recycled water is poured into U-shaped borehole heat exchanger (UBHE), which is installed in existing well, and the water exchanges heat with the shallow geothermal energy. Finally, the recycled cooling water is sprayed again to cool the panel. The experiments contain three parts: The first is the PV panel operation without any cooling system. The second is the panel operation with the cooling system but without the UBHE. The third is the cooling system operation with the UBHE. The results of experiments show that this cooling system can improve the efficiency of PV panels about 8.2%.

Keywords: PV Panel Cooling, Spray Cooling, Shallow Geothermal Energy, Borehole Heat Exchanger.

1. Introduction

Solar energy is the major factor in renewable energy development, but the energy conversion efficiency of photovoltaic (PV) panels is too low. Most of the solar energy is transferred into waste heat. This waste heat can cause the panel temperature to increase, and high temperature reduces the efficiency of the panel, with the efficiency dropping by about 0.5% for every 1 ℃ increase in temperature (Kane et al., 2017). Thus, PV panels require an effective cooling system to maintain a suitable working temperature.

The commonly used cooling methods are divided into air and water cooling methods. Air cooling requires lesser energy than water cooling, but its cooling ability is also mediocre. Conversely, water cooling has better cooling capability than air cooling, and its equipment costs are usually higher than air cooling. Kaiser et al. (2014) set a large air fan under the PV panel for cooling and discussed the influence of the air-channel size and the flow velocity on the efficiency of the PV panel. The results showed that the power output of a PV panel can be improved with air cooling. Water cooling methods include sprinkling water on the panel top or the use of channels for a working fluid to cool the panel (Bigorajski, 2018; Abdolzadeh, 2009; Chandrasekar, 2015). Moharram et al. (2013) found that the cooling system should be turned on when the panel temperature reaches 45 ℃ or more and the PV panel has the optimum power output. Nižetić, et al. (2016) indicated that a water spray cooling technique is more efficient than other already analyzed cooling techniques except for the water submersion method (when the PV panel is completely flooded with water). Zhu and Si (2012) has found that the amount of solar energy accepted by the panel is decreased when using water spray cooling on front of the panel, and the amount of cooling water is also decreased quickly. Thus, it is preferable to spray water on the back of the PV panel when the panel temperature achieves 45 ℃ and to reuse the cooling water. However, the cooling water temperature will increase as the water is reused, and its cooling capacity decreases as the water temperature increases. Thus, the cooling water requires an extra cooling source to maintain its low-temperature state.

Shallow geothermal energy is a stable low-temperature geothermal resource that is distributed on the earth’s surface (3–50 m) soil, and it has some advantages, including renewability, ease of use, stable temperature, and wide distribution; it is a clean energy (Chen et al., 2015; Soni, 2015). In this study, a full year period of soil temperatures in Taiwan had been measured, and the results are shown in Fig. 1. According to these results, the temperatures of the soil 5 m below the earth’s surface at Taiwan were about 24 to 27 ℃ for a full year, which are lower than the PV panel temperature. Moreover, this temperature of the soil is not constrained by weather and region; i.e., it is relatively steady (Soni, et al., 2015; Luo, et al., 2018). Thus, this characteristic could be employed through heat exchange methods for cooling the PV panel. Jakhar et al. (2017) placed the water channels at the

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rear of the panel and used cooling water to cool the PV panel, then utilized an earth water heat exchanger (EWHE), which is a horizontal-type borehole heat exchanger, to cool the water. The results showed that this system can improve the PV panel efficiency. Horizontal-type borehole heat exchangers were used in early periods, but such systems were influenced by atmospheric temperature (Chen et al., 2015) and need large spaces for installation. By comparison, a U-shaped borehole heat exchanger (UBHE) is only minimally influenced by ambient temperature (Chen et al., 2015); moreover, the UBHE requires little space for installation (Schiel, et al., 2016)**,** and it can thus save most initial costs (Gemelli, et al., 2011). The cooling water of UBHE is first used to cool the equipment, and then, the waste heat from the water is transferred to the soil. Finally, the cooled water is used for cooling the equipment again, and the cycle is completed.

As a result of all the above reasons, in this study, spray water was used to cool the back of a PV panel. The waste heat was discharged into the well with the cooling water that continually flowed through the UBHE, and continuous recycling was used to improve the capacity of the cooling system. The PV panel cannot function at night, but the soil can discharge heat during that time. Then, the soil could cool the cooling water during the daytime, and hence, the cooling system could be combined with UBHE. Thus, the system can maintain a suitable working temperature for the panel and improve its efficiency.

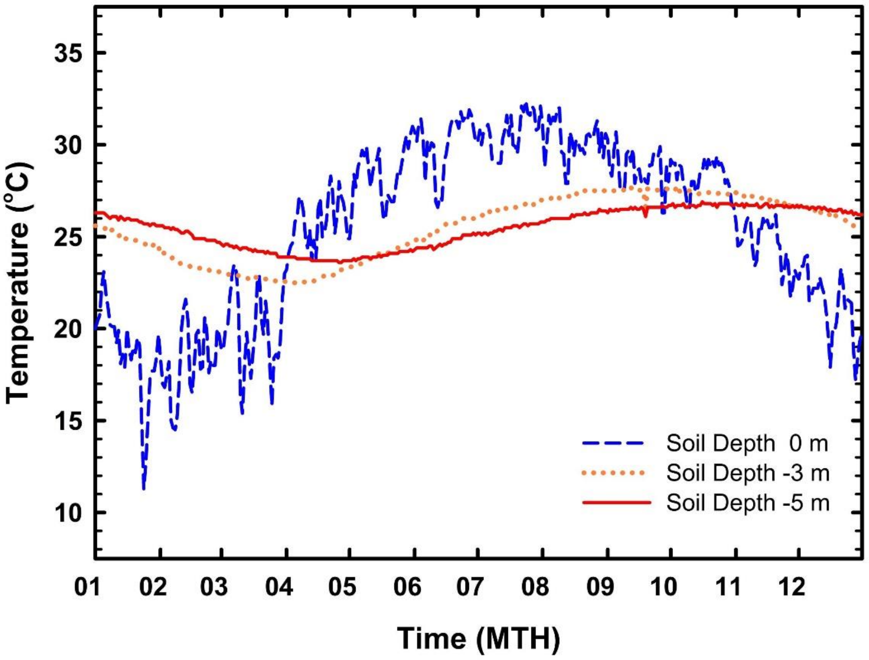

Fig. 1: Soil temperature in Taichung, Taiwan over a one-year period

2. Experimental Investigation

2.1. Experimental processes and configuration

The schematic diagram of the system, equipment setup, and photographic view are shown in **Fig.2** and **Fig. 3**. A 60-W PV panel (MSX-60) manufactured by SOLAREX was used in the experiments, and the spray cooling system was combined with the UBHE. The water in this cooling system first cools the PV panel, and then the shallow geothermal energy through the UBHE is used to cool the cooling water and to maintain the cooling capacity of this cooling system. Temperature variation of this system would be observed during the experimental process. This experimental investigation includes three experiments, as explained below: First, the differences between the PV panels with and without the cooling system are investigated; second, the influence of shallow geothermal energy on the cooling system is determined by changing the experimental control method. Because the solar intensity is relatively stronger during summer (July) midday and relatively weaker during the afternoon, every experiment is carried out from 11:40 to 14:45. In the experimental process, the power output and the temperature variations of this system are measured.

In the first experiment, the system without the cooling system is constructed as the base model for all experiments, and its power output and temperature variation are observed during the process. In the second experiment, a common cooling system is used, in which pipes are used to link the pump to propel the fluid flow and recycling. The cooling water for cooling the PV panels is sprayed through nozzles. The initial temperature of the cooling water is 31.5 ℃. The cooling system is switched on once the panel temperature reaches 45 ℃. Because the cooling capacity decreases after the cooling water cools the panel, the working time according to the experiment control was set as 240 s. The panel temperature increases again after the cooling system is switched off until it reaches 45 ℃, after which the cooling system is switched on again and the entire process is repeated. In the third experiment, the cooling system combined with the UBHE is used. The cooling water cools the PV panel, and then, the UBHE cools the cooling water using ground water and soil. Because the cooling water is cooled through the UBHE, its cooling capacity can be maintained, and thus, the experimental control differs from that in the previous experiment. The pump is switched on once the panel temperature reaches 45 ℃ and is switched off once the panel temperature is cooled to 35 ℃. The panel temperature increases again after the cooling system is switched off until the temperature reaches 45 ℃, after which the cooling system is switched on again and the entire process is repeated.

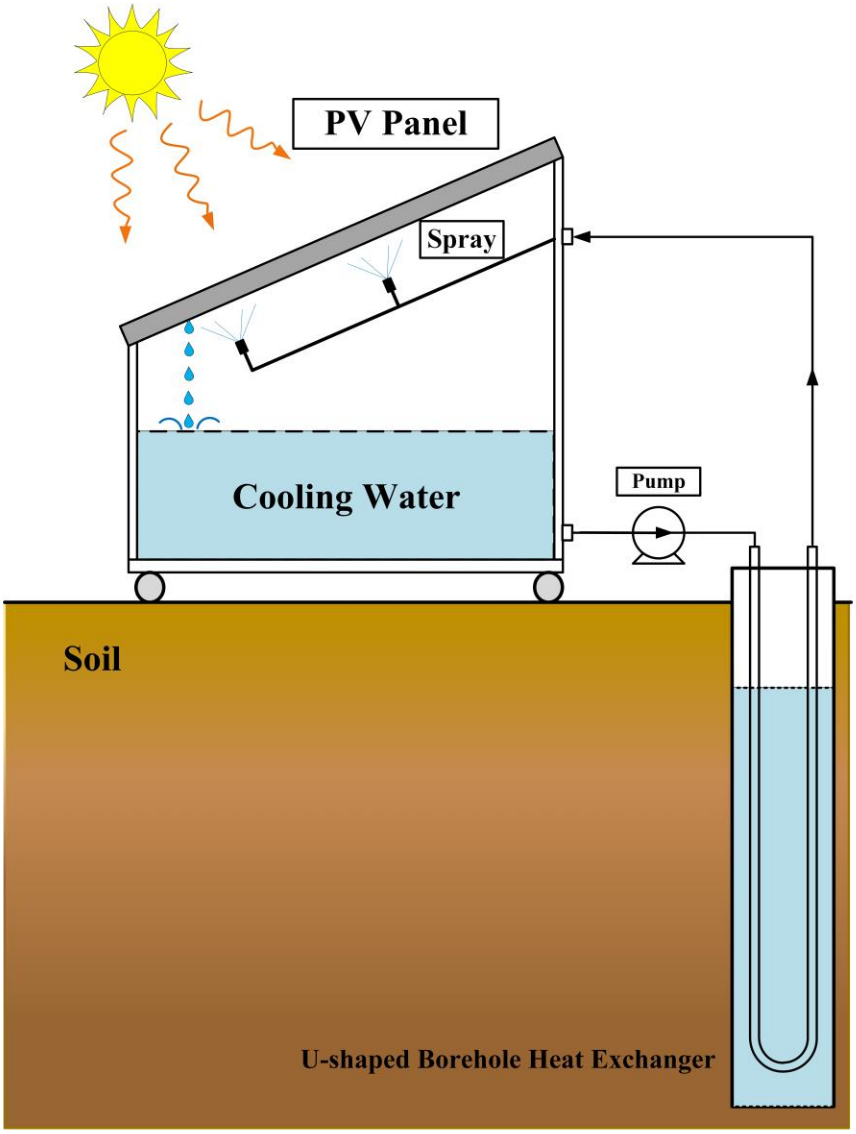

Fig. 2: System scheme

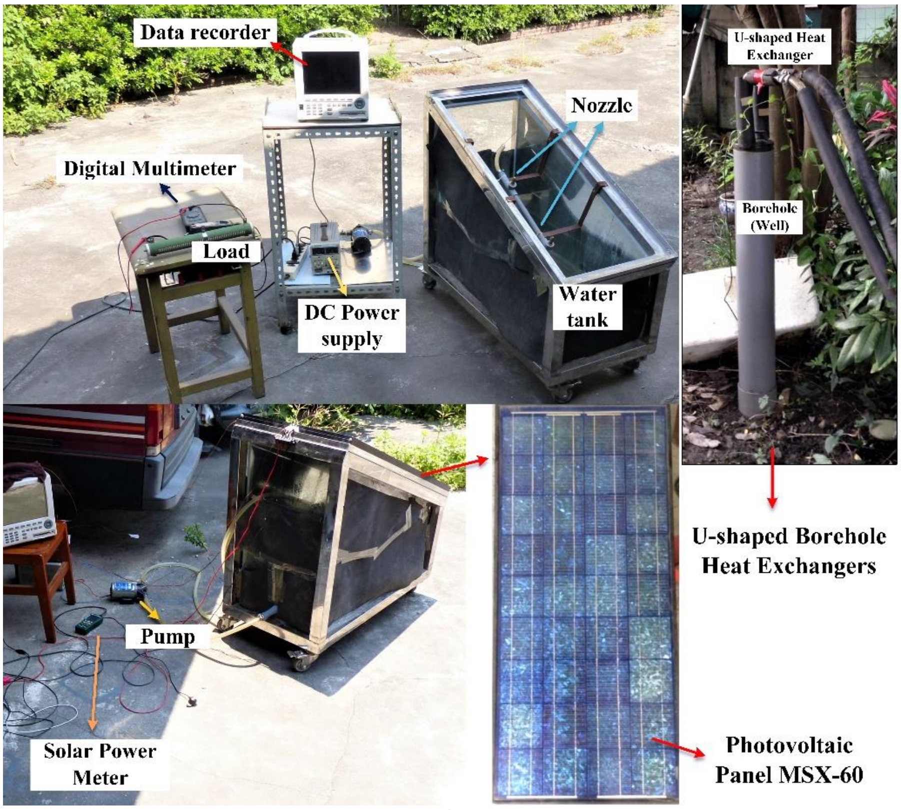

Fig. 3: Photographic view of the experimental equipment

2.2. Experimental equipment

The specifications of the PV panel are listed in Tab. 1; the maximum output power under the standard test condition is 60 W, the maximum conversion efficiency is 10.9%, the size is 1.1 m × 0.5 m × 0.05 m, and the weight is 7.8kg. The Solar Power Meter (Datalogging TES-132) used for measuring the solar radiation has an operating range from 200 to 2000 W/m^2, and the accuracy is ±10 W/m^2. The walls of the cooling water tank are made of glass, and two nozzles installed in the tank are linked with the outside pump (DC Diaphragm pump HF-8367) through pipes. The total weight of cooling water in the tank is 60 kg. The caliber of nozzles is 0.8 mm; the total flow rate is 0.57 LPM; the distance of the nozzles from the panel is approximately 0.22 m, and the spray angle is 68.5°. The UBHE system includes pipes and a borehole wall. Groundwater is placed between the pipe and the borehole wall, and the groundwater level distance from the earth's surface is about 2 m. The external and internal diameter of the well are 0.135 m and 0.125 m, respectively. The pipe is made from stainless steel. It is located at a depth of 5 m, its length, external diameter, and internal diameter are 10.3 m, 0.018 m, 0.016 m. The working fluid is water. The rated voltage of the pump is DC 24 V, the working current is 0.21–0.85 A, and the maximum volume flow rate is 1.2 LPM. This study applies a DC power supplier to adjust the pump flow rate and power consumption by controlling the supplied voltage. The total flow rate is 0.57 LPM, corresponding to 5W. A T-type thermocouple is used to measure temperature. The error range of T-type thermocouples is ±0.5°C for a temperature range of "$0°C \leq T \leq 200°C$", and the accuracy is ±0.2°C after correction.

2.3. Efficiency evaluation

Because the experiments could not be carried out under the same solar strength every time, the average energy conversion efficiency was applied to assess the performance of the system in order to avoid errors caused by different solar strengths. Moreover, the average conversion efficiency (η_{ori}) before cooling could be calculated as follows:

$$\eta_{ori} = \frac{\int_0^{t_t} P_{pv} dt}{A \varphi t_t} \qquad \text{(eq. 1)}$$

where P_{pv} is the output power of the PV panel, A is the panel area, φ is solar radiation intensity, and t_t is the total operating time.

The average conversion efficiency (η_{sp}) after cooling and inclusion of the energy consumption of the pump could be expressed as follows:

$$\eta_{sp} = \frac{\int_0^{t_t} P_{pv} dt - P_{pp} t_{ot}}{A \varphi t_t} \qquad \text{(eq. 2)}$$

The enhanced effect of the average conversion efficiency could be expressed as:

$$\delta = \frac{\eta_{sp} - \eta_{ori}}{\eta_{ori}} \qquad \text{(eq. 3)}$$

Tab. 1: Experimental specifications of PV Panel (MSX-60)

Area (m^2)		0.556	**Pmax Voltage (Volt)**	17.7
Length (m)		1.108	**Pmax Current (Ampere)**	3.5
Absorption, α'		0.7	**Open-circuit voltage (Volt)**	21.1
Emissivity, ε		0.9	**Short-circuit current (Ampere)**	3.8
slope angle, θ (˚)		23.5	**Temperature coefficient of power (%/°C)**	-(0.5±0.05)
Maximum Power (W)		60	**Nominal Operating Cell Temperature, NOCT (°C)**	47±2

3. Results and discussion

3.1. The system without any cooling system

The purpose of the first experiment is to investigate the working characteristics of the PV panel and to build a base model for comparison in all analyses. Following is a discussion of the high PV panel temperature effect on the PV efficiency. During the experimental period, the PV panel worked from 11:40 to 14:45. As t = 20–170 min, the period for the experiment is about 12:00–14:30. During this period, the solar intensity is the strongest and relatively steady. Fig. 4 shows the PV panel temperatures. The initial temperature of the PV panel is 52 °C, and the highest temperature in experimental results is above 65 °C. Fig. 5 shows the relationship between the solar intensity and the power output. According to Fig. 4 and Fig. 5, the factors that affect the power output are solar intensity as well as panel temperature. According to Fig. 5, the solar intensity at t = 0 min is approximately the same as that at t = 180 min, i.e., about 850 W/m^2, but the temperatures of the panels are different. Because the temperature of the panel at t = 180 min is higher than that at t = 0 min, the power output is lower at t = 180 min. The results show that the power decreases as the temperature increases, and that the output power of the PV panel without the cooling system decreases as the temperature increases. This experiment measured the relationship between the power output and the temperature of the panel, and the energy conversion efficiency η_{ori} of the PV panel without the cooling system calculated from eq. 1 is about 6.56%. The experimental results are presented in Tab. 2.

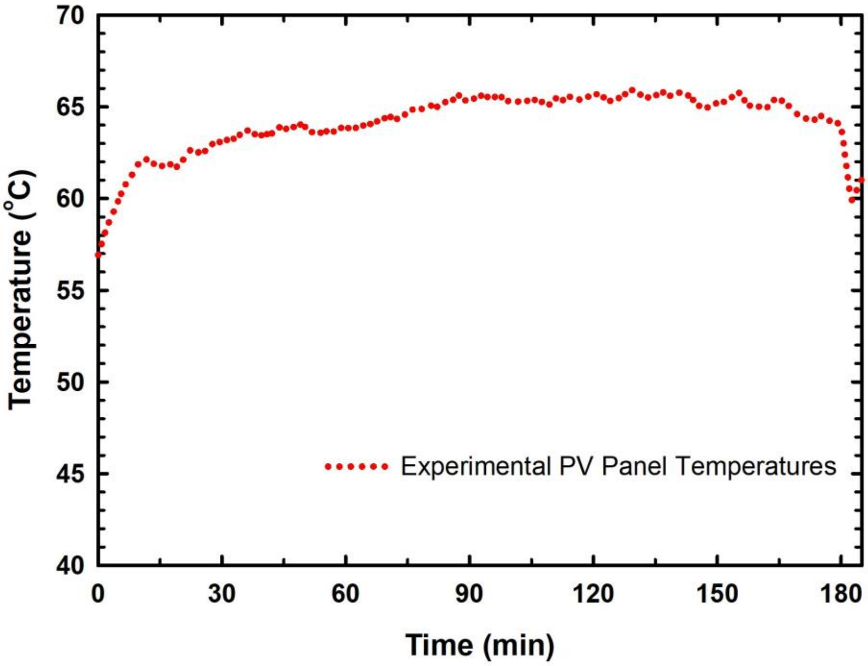

Fig. 4: Experimental PV panel temperatures

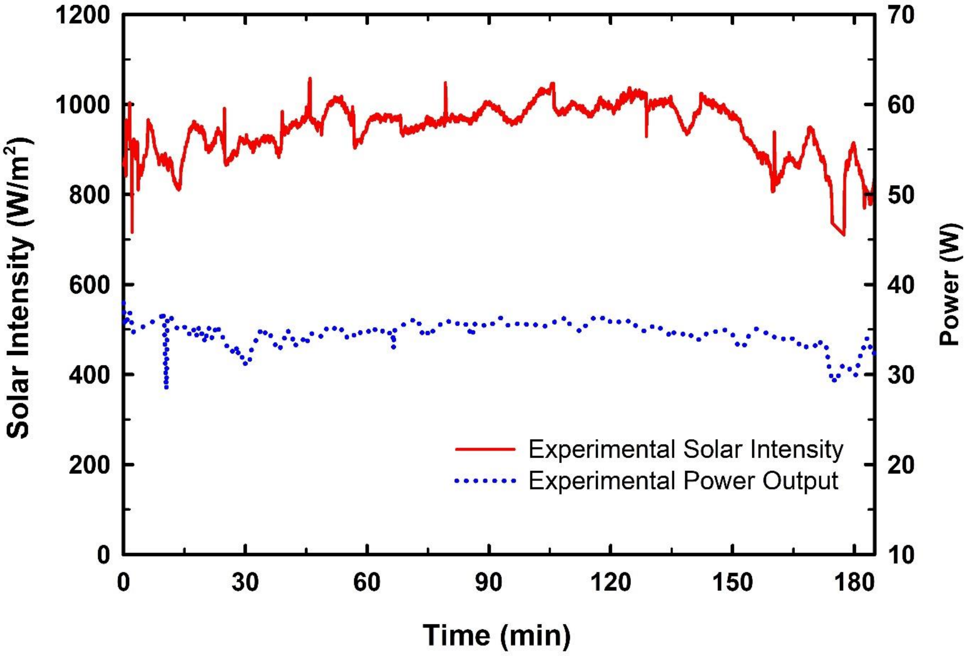

Fig. 5: Relationship between solar intensity and power output

3.2. The system with the cooling system without UBHE

In the second experiment, the PV panel was cooled using a cooling system without the UBHE. The output and the average conversion efficiency of this system were observed during the working period. The cooling water was sprayed onto the PV panel through two nozzles, and the total flow rate of the nozzles was 0.57 LPM; and the temperatures of the nozzles and the tank were equal. In this experiment, the cooling system was switched on for 240 s when the panel temperature reached 45 °C, and then, it was switched off until the temperature reached 45 °C again. The above steps were repeated for a total operational time of 3 hours 5 minutes.

The experimental results are shown in Fig. 6 and Tab. 2. After the cooling system was switched off, the panel temperature increased, and each cooling cycle caused the cooling water's temperature to increase from 31.3 to 40.2 °C, which represents an increase of about 8.9 °C, and as a result, the cooling effect of the cooling system deteriorated. In the first cooling cycle, the cooling water could cool the PV panel temperature to 35 °C, but in the final cooling cycle, the PV panel temperature was only cooled to 43 °C. The cooling capacity decreased because of the increase in the temperature of the cooling water temperature. Further, as shown in Fig. 6 and Fig. 7, after a working time of t = 150 min, the solar intensity decreased gradually, and hence, the temperature increase of the cooling water was not obvious. To compare Fig. 7 with Fig. 4, Fig. 5 and Fig. 6, when the solar intensity was approximately 900 W/m^2, the power output of the panel with cooling system was enhanced by 4 W. This indicates that the temperature increase considerably affects the output efficiency, and thus, the cooling system can improve the efficiency of the panel, but the pump also needs additional energy. The average conversion efficiency after cooling could be obtained through eq. 2, and the average conversion efficiency is calculated to be about 6.64% after the pump energy consumption is included. For improving the cooling capacity and reducing the energy consumption. Moreover, the results in Fig. 9 show that as the cooling system operates for a longer period, the cooling capacity decreases as the water temperature of the tank rises. Thus, the cooling water needs to be cooled to maintain its capability, and UBHE is used to cool the cooling water in the next experiment.

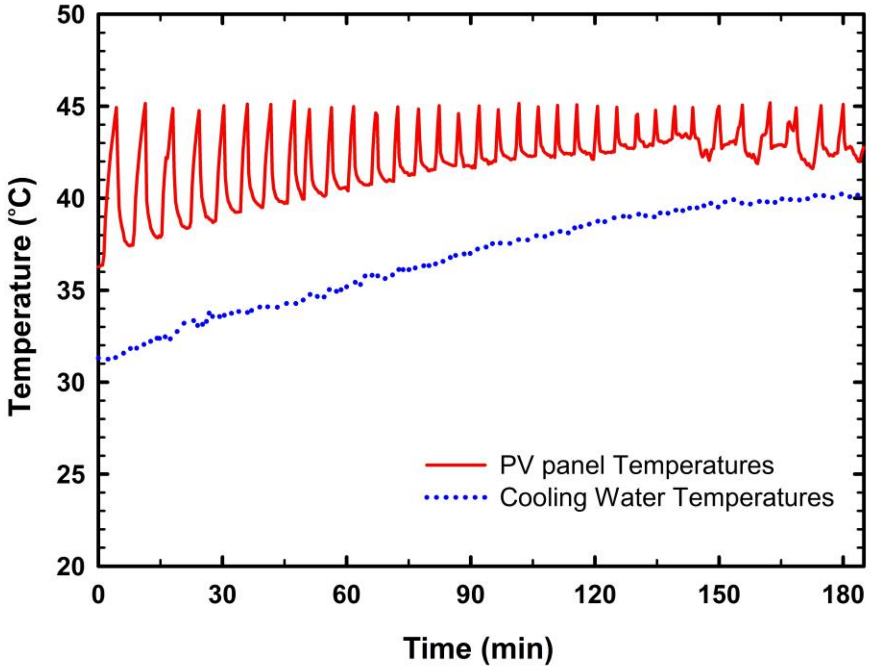

Fig. 6: Relationship between the PV panel temperatures and the cooling water temperatures in the experimental results

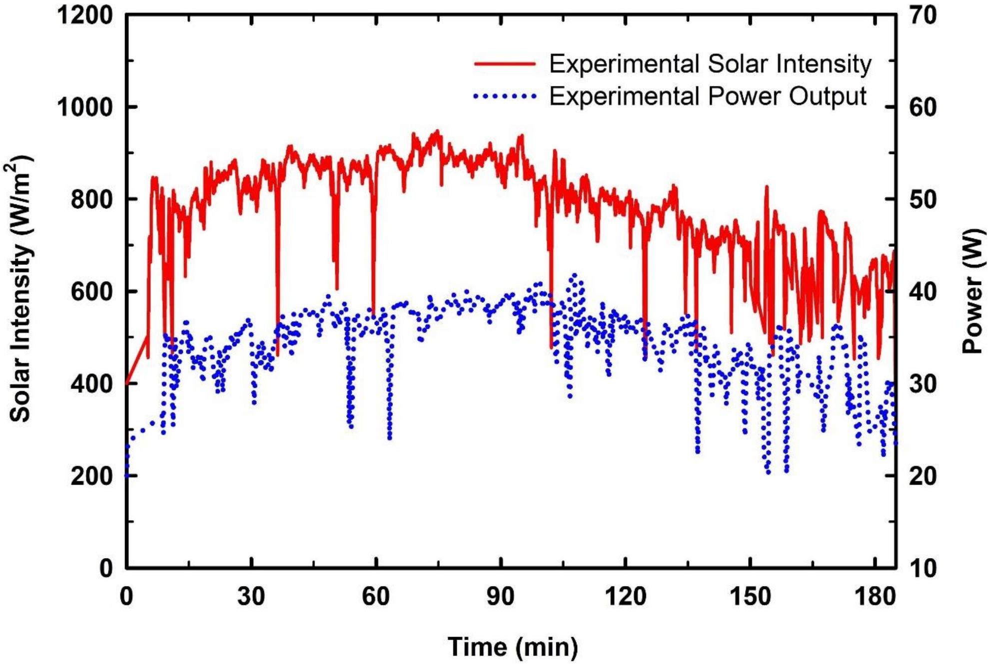

Fig. 7: Relationship between solar intensity and power output

3.3 The system with the UBHE cooling system

According to the above experimental results, the cooling capacity of the cooling system decreased as the temperature increased, and thus, this experiment combined the UBHE with the cooling system to enhance its cooling capacity and efficiency.

The cooling water total flow rate of this experiment was 0.57 LPM, the nozzle temperature was equal to the UBHE outlet temperature, and the cooling system was switched on to cool the PV panel once the temperature reached 45 ℃. Through a test conducted before this experiment, it was found that the cooling system combined with the UBHE can maintain its cooling capacity for cooling the PV panel to 35 ℃ over time, and thus, the experimental control method differs from that in the previous experiment on the system without the UBHE. In this experiment, once the PV panel was cooled to 35 ℃, the cooling system was switched off, and it was switched on once the panel temperature reached 45 ℃ again. Then, this operational cycle was repeated throughout the working period of 3 hours 5 minutes. The experimental results are shown in Fig. 8 and Tab. 2. The cooling water temperature increase from the initial temperature in the experiment was about 3.5 ℃.

A comparison of the experimental results between the cases with and without the UBHE shows that the increase in the cooling water temperature is clearly moderated in the case with the UBHE. Because the cooling water temperature could be maintained at about 27 to 29 ℃ effectively, the cooling capacity of this system is considerably improved. Thus, the cooling capacity of every cooling cycle in this experiment was equivalent to that in the first cooling cycle. Fig. 9 shows the relationship between solar intensity and power output. During midday, the solar intensity is the highest in a day, and the solar intensity decreases in the afternoon. At t = 170 min, because the solar intensity is lower, the output of the PV panel is also lower. The cooling water temperature increased during the working period; the temperature increased from 27 to 29 ℃ because of the increase in the groundwater temperature. The final temperature difference between the outlet and the inlet of the borehole was about 7 ℃, and this result displayed that the UBHE had enough cooling capacity until the end of the experiment. The experimental results shown in Fig. 10 indicate the relationship among the groundwater temperature, tank water temperature, cooling water temperature, and soil temperature. Because the water in the borehole exchanges its heat with the U-shaped heat exchangers, the water temperature increases as the working time increases, but the variation in the soil temperature is small. During the working period, the soil temperature maintained at about 28 ℃. The results show that the soil temperature variation is small in the heat exchange period, so the soil could be used to cool the UBHE. The average conversion efficiency after cooling could be obtained through eq. 2, and the average conversion efficiency is calculated to be about 7.1% after the pump energy consumption is included.

According to the previous experiment, because the temperature of the tank increases continually, the cooling capacity decreases continually, and the pump working time also increases as the cooling capacity decreases, so more energy is consumed. The results of the third experiment indicate that the cooling system combined with the UBHE can provide lower temperature cooling water for the system. Until the experiment completed, the nozzle temperature only increased to 29 ℃, whereas that in the second experiment increased to 40.4 ℃. This shows an obvious improvement in the final experiment, and thus, the cooling capacity in the last experiment is better than that in the second experiment. Further, the pump working time in the third experiment is also decreased owing to the improvement of the cooling capacity, and thus, the energy consumption is decreased. After the PV panel is combined with the UBHE, its efficiency could be improved.

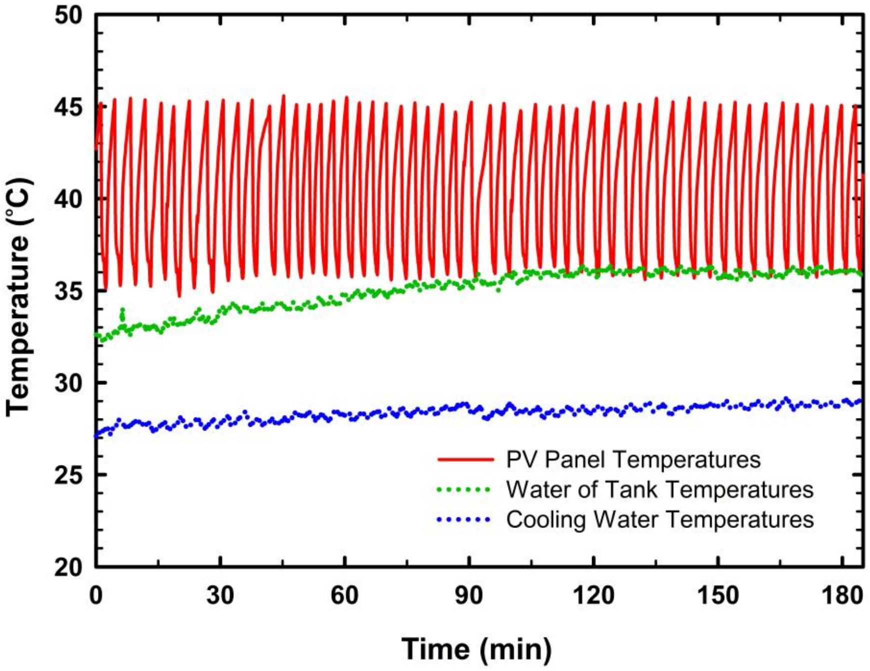

Fig. 8: Relationship between the PV panel temperatures and the cooling water temperatures in the experimental results

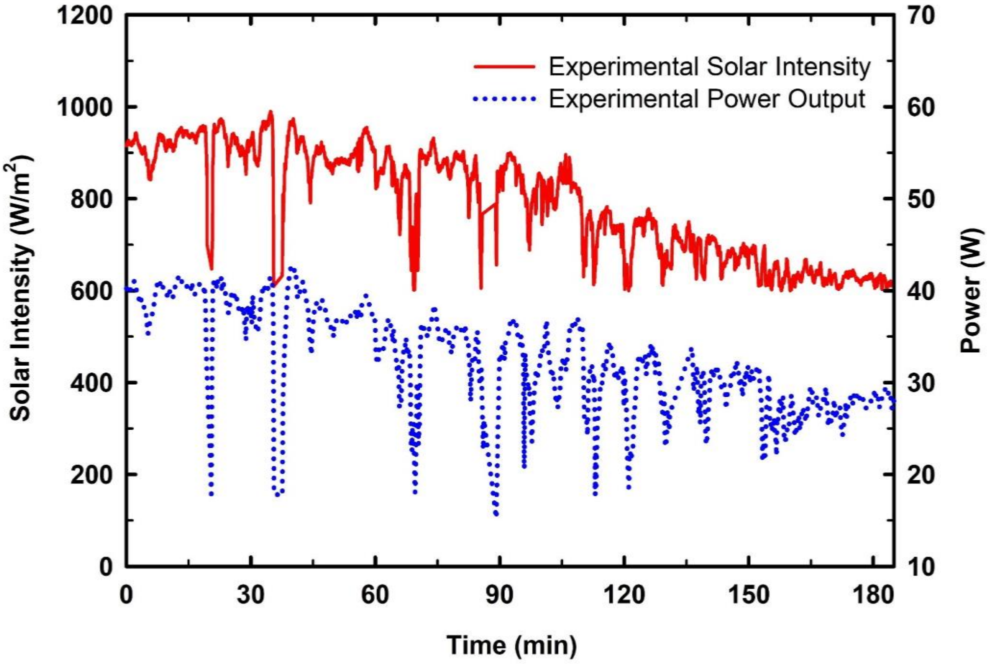

Fig. 9: Relationship between solar intensity and power output

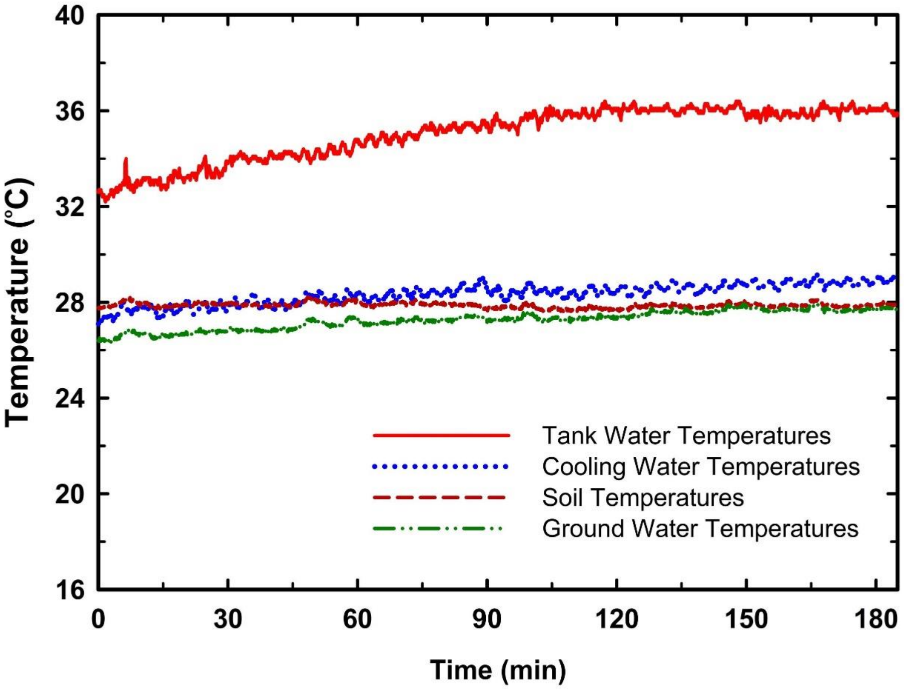

Fig. 10: Relationship among tank water temperatures, cooling water temperatures, soil temperatures, and groundwater temperatures

Tab. 2: Results of experiment; Case1: Without cooling system, Case 2: Cooling system without UBHE, and Case 3: Cooling system with UBHE

Case	Average solar intensity (W/m^2)	Maximal solar intensity (W/m2)	Pump working time (s)	Average power output (W)	Average net power output (W)	Conversion efficiency (%)
Case 1	946.5	1,058	-	34.5	34.5	6.56
Case 2	729.3	948	8,400	30.7	27.0	6.64
Case 3	777.1	990	3,605	32.3	30.7	7.10

4. Conclusions

According to the experimental results, the factors mainly affecting PV panel power output are solar intensity and panel temperature. However, solar intensity cannot be easily controlled, and a method that improves efficiency by reducing the PV panel working temperature is more feasible. This paper presents such a method to mitigate the PV panel efficiency decline problem, which is due to high temperatures. Cooling capacity of the cooling system is further improved through combination with a UBHE. To compare with the cooling system without UBHE, the UBHE system also reduces the energy consumption of the cooling system. The following conclusions can be obtained:

(1) The water temperature of the nozzle outlet could be maintained at 27–29 °C after the cooling water passes through the UBHE, and the cooling water temperature increased to 29°C until the experiment ended. However, for the cooling system without UBHE, its cooling water temperature would increase to 40.4°C; thus, the system with UBHE can cool the PV panel more effectively than the system without UBHE.

(2) The UBHE system can reduce the pump operating time; thus, the pump energy consumption can decrease. The result indicates that the cooling capacity of the cooling system with the UBHE is better than that of the system without the UBHE, and this cooling system can improve the efficiency of PV panels about 8.2%; moreover, as the temperatures and the number of panels increase, the benefit is more obvious.

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