Theoretical Analysis of Photovoltaic Panels Using a Spray Cooling System with a Shallow Geothermal Energy Heat Exchanger

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Abstract

In this study, a cooling system integrated with a U-shape borehole heat exchanger (UBHE) is utilized to cool the PV panel. This cooling system sprays water on back of the panel, and a tank is used to reclaim cooling water. To enhance the cooling capacity, the recycle water is poured into the U-shaped borehole heat exchangers (UBHE) and dissipates heat to soil and groundwater. A theoretical model is built for evaluating the panel temperature and the cooling water temperature. This is model including three control volumes: the PV panel, the water tank, and the UBHE. Energy equation is used for each control volume, and this study applies the Euler method to calculated differential equations. Theoretical values and experimental results has same tendency. This study also carries out the analysis of economic feasibility. For a plant factory powered by 10 PV panels, for example, this cooling system can improve the efficiency of the panels about 14.3% compared with PV panels without cooling systems. Investment cost can be an be recovered in 8.7 years, meaning this cooling system is of great worth.

Keywords: PV panels, Spray Cooling System, Shallow Geothermal Energy, Borehole Heat Exchanger

1. Introduction

PV panels has been widely applied to generate electricity in the past decade, but the PV panel still has disadvantages, one of which is the high surface operating temperature causes the panel efficiency decline problem. Hence, there are many cooling systems has been developed to improve with this problem (Nižetić et al., 2018). The cooling systems can be mainly divided into active and passive forms. The active cooling systems are much effective than the passive cooling systems, but extra power is required to drive the fans or pumps. Consequently, the active cooling system must evaluate carefully economic feasibility. Among active cooling systems, water cooling methods, compared with air cooling methods, have better cooling capacity but require more power to drive pumps. Thus, water cooling methods are usually suitable for large area PV panels.

Shallow geothermal energy is a renewable resource, which is located at a depth of about 3-20m and has a feature of stable temperature for the whole year (Soni, et al., 2015; Luo, et al., 2018). Thus, shallow geothermal energy is commonly applied to air-conditioning systems (Soni, 2015), which transfer excess heat to the soil. Similarly, it is also suitable for cooling PV panels. In Taiwan, the soil temperatures at 3 m in depth below the earth’s surface are between 26 ^oC and 28 ^oC in summer and between 22 ^oC and 24 ^oC in winner. The soil temperature at 3m in depth is lower than the atmosphere temperature in summer and higher than the atmosphere temperature in winter. In addition, the soil temperature is not easily influenced by regions and weather, which means it is stable.

According to above reasons, in this study, a spray cooling system integrated with a UBHE is utilized to cool the PV panel, as shown in Fig. 1. Water is sprayed on the back of the PV panel, and the waste heat is transferred to water. Then, the high temperature water is collected in the tank. Water in the tank is pumped into a UBHE, which is installed in a well, and thus the high temperature water rejects heat to groundwater through a UBHE. Finally, water is spray again to cool the PV panel. The entire process is continuous, and the PV panel could be maintained appropriate operating temperatures.

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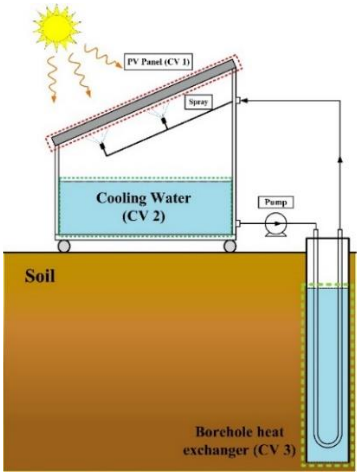

Fig. 1: The experimental setup of cooling system and the control volumes of theoretical model.

Jones and Underwood (2001) have used first-order differential equations to deduce the relationship between the panel temperature and the working time. In addition, a method for calculating the PV panel thermal capacity have been also proposed. Chen and Tsai (2011) further proved the correctness of the thermal model proposed by Jones and Underwood (2001). This model was used to analyze the panel temperature, and the model results were compared with experimental results. The results showed that this model has good agreement with experiment results. Moreover, Mihalakakou et al. (1997) has built a method based on energy conservation to predict the variation in the soil temperature. Ingersoll et al. (1951) has developed an infinite soil thermal model based on an infinitely long line heat source theory for calculating the temperature of soil. Furthermore, Pu et al. (2015) has applied simulation study to evaluate thermal performance of vertical U-tube heat exchangers for ground source heat pump system. The results showed that increasing the Reynolds number for laminar flow condition and enhancing the pipe diameter of UBHE can improve the cooling effect.

To the best of our knowledge, previous literatures only focus on the theoretical analysis of panel temperature or thermal performance of UBHEs. Consequently, this study aims to build a theoretical model for comprehensively evaluating the spray cooling system integrated with a UBHE. Moreover, investment costs and payback periods also be calculated and discussed.

2. Experimental processes

A 60-W PV panel (MSX-60) manufactured by SOLAREX is used in this study, and two nozzles installed in the tank are connected with pips and a diaphragm pump. The distance of nozzles from the panel is approximately 0.22 m. The diaphragm pump has the maximum volume flow rate of 1.2 LPM. The total flow rate of spraying water is 0.57 LPM, corresponding to 5W. The total weight of cooling water in the tank is 60 kg. The Solar Power Meter (Datalogging TES-132) has an operating range from 200 to 2000 W/m^2, and the accuracy is ±10 W/m^2. The UBHE system includes pipes and a borehole wall. Between the pipe and the borehole wall is groundwater, 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.

In this study, the PV panel without the cooling system is used as the base model, and its power output and temperature variation are measured. Then, the cooling system combined with a UBHE for improving the panel efficiency is applied. To reduce the power consumption of the pump, pump is switched on once the panel temperature reaches 45^{o}C and is switched off once the PV panel is cooled to 35^{o}C. Entire cooling processes are intermittent, which can maintain cooling water temperatures and can consume lower power. In Taiwan, the solar intensity is relatively stronger during summer (July) midday and relatively weaker during the afternoon. Thus, every experiment is carried out from 11:40 to 14:45. For each experiment, the power output and the temperature of the panel and cooling water are recorded through a data recorder (YOKOGAWA mv200). Apart from this, the solar radiation intensity, load voltage and load current are also measured.

3. Theoretical analysis

This study builds a theoretical model, as shown in Fig. 1,which contains three control volumes: the PV panel, the water tank, and the UBHE. Energy equation is utilized to predict temperatures for each control volume. Because these control volume are connected wih each other, the calcualted results of one control volume are inlet boundary conditions of another control volume. The following assumption are applied in this theoretical model:

(1) The temperature of the PV panel is distributed equally.
(2) The heat generated by the internal resistance of the PV panel is ignored.
(3) The temperature of the cooling water of the tank is distributed equally.
(4) The thermal insulation is an ideal thermal insulation; thus, the walls of the tank and the pipe are adiabatic.
(5) The ambient temperature is constant.
(6) Natural convection inside the tank during operation of the cooling system is ignored.
(7) All of the cooling water is sprayed onto the panel equally.
(8) Ambient wind velocity is 1 m/s.

Based on the energy conservation equation of the PV panel, as shown in Fig 2. The energy equation is expressed as follows:

$$C_{pv}\frac{dT_{pv}(t)}{dt} = A_{pv}\alpha\varphi - q_o - q_r - P_{pv} \quad \text{(eq. 1)}$$

where C_{pv} is the heat capacity of the PV panel, α is the absorption coefficient of the PV panel, φ is the solar radiation intensity, A_{pv} is the panel area, and $A_{pv}\alpha\varphi$ is the incoming solar radiation absorbed by the panel. Consulting the method by Jones and Underwood (2001), the thermal capacity C_{pv} can be calculated.

The convection coefficient q_o between the panel and fluid could be divided into two parts: q_{co} is the convection between the panel and outside air, and q_{ci} is the convection between the panel and the tank.

$$q_{co} = A_{pv}\cdot h_{co}\cdot[T_{pv}(t)-T_a] \quad \text{(eq. 2)}$$

where T_{pv} is the temperature of the PV panel, and T_a is the temperature of air. The force convection coefficient proposed by Stultz and Wen (1977) is written below:

$$h_{co}=1.247[(T_{pv}-T_a)\cos\theta]^{1/3}+2.658V,\ V = 1\ m/s \quad \text{(eq. 3)}$$

where V is the wind velocity.

Further, q_{ci} between the panel and the tank was predominantly based on natural convection of the air inside the tank before the cooling system initiated, and it could be expressed below:

$$q_{ci} = A_{pv}\cdot h_f\cdot[T_{pv}(t)-T_a] \quad \text{(eq. 4)}$$

According to Holman (1997), the natural convection coefficient h_f of the air in the tank could be expressed as follows:

$$h_f = \frac{k_a Nu}{l} \quad \text{(eq. 5)}$$

where k_a is the thermal conductivity of air, l is the length of the PV panel, Nu is the Nusselt number, and Gr is the Grashof number.

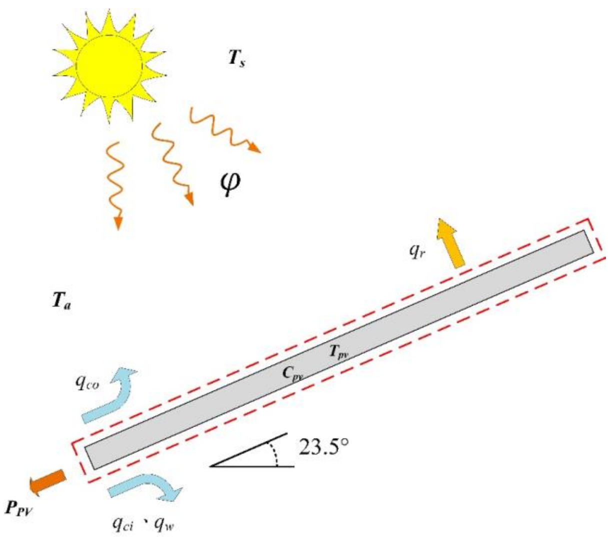

Fig. 2: The operation mechanism of the PV panel and the control volume of the PV panel.

$$Nu = 0.56[GrPr\cos(90^{\circ}-\theta)]^{1/4}, \theta > 2^{\circ} \quad \text{(eq. 6)}$$

$$Gr = \frac{g\beta(T_{pv}-T_a)l^3}{v_a^2} \quad \text{(eq. 7)}$$

where g is gravity, β is the coefficient of thermal expansion, and v_a is the kinematic viscosity of air.

After the cooling system is initiated, the force convection created by the spray is the main cooling mechanism, and internal natural convection could be ignored; thus, q_{ci} could be expressed as q_w. According to the empirical formula reported by Oliphant et al. (1998), the fore convection coefficient created by the spray could be derived as follows:

$$h_{sp} = \frac{k_w Nu}{D} \quad \text{(eq. 8)}$$

where k_w is the thermal conductivity of water, and D is the spray diameter of the nozzle.

$$Re^* = \frac{GD}{\mu_w} \quad \text{(eq. 9)}$$

$$G = \frac{\dot{m}}{A_{sp}} \quad \text{(eq. 10)}$$

$$D = 2H_{sp} \cdot \tan(0.5\gamma) \quad \text{(eq. 11)}$$

where Re^* is the Reynold number, G is the mass flux, $\dot{m}$ is the mass flow rate, H_{sp} is the distance between the nozzle and panel, and γ is the spray angle.

Thus, q_w could be derived as:

$$h_{sp} = \frac{k_w Nu}{D} \quad \text{(eq. 12)}$$

where A_{sp} is a spray area, $T_n(t)$ is the cooling water temperature (K) at the outlet of the nozzles.

The heat radiation of the panel absorbed from the environment could be expressed as:

$$q_r = A_{pv}\sigma[\varepsilon_{pv} \cdot T_{pv}(t)^4 - S_s\varepsilon_s \cdot T_s^4] \quad \text{(eq. 13)}$$

Consulting the formula by Liu and Jordan (1963), the shape factor between the sky and the panel could be expressed as:

$$S_s = \frac{1+\cos\theta}{2} \quad \text{(eq. 14)}$$

where ε_{pv}= 0.95, ε_s= 0.95, $T_s = T_a - 20K$ as demonstrated Schott (1985).

Based on Marion et al. (1999), the PV panel power output P_{pv} could be expressed below:

$$P_{pv} = \frac{\varphi_{inc}}{\varphi_{SRC}} P_{SRC} \{1+\gamma'[T_{pv}(t)-298K]\} \quad \text{(eq. 15)}$$

where φ_{SRC} is the solar intensity (1000 W/m^2, ambient temperature 25℃) and P_{SRC} is the maximum output power (60 W), both under standard reporting conditions (SRC); and γ' is the temperature correction factor (-0.0057).

The cooling system combined with the UBHE is shown in Fig 3. The heat from the panel is $\dot{E}_i$, and the heat that leaves from the tank is $\dot{E}_e$.

$$\dot{E}_i = \dot{m}_i e_{wi} \quad \text{(eq. 16)}$$

$$\dot{E}_e = \dot{m}_e e_w \quad \text{(eq. 17)}$$

where $\dot{m}_i$ is the mass flowrate of the cooling water into the tank from the PV panel, e_{wi} is the enthalpy of the cooling water into the tank from the PV panel, $\dot{m}_e$ is the mass flowrate that leaves from the tank, and e_w is the enthalpy of the tank water.

The mass conversation of the tank and nozzles can be expressed as:

$$\dot{m}_i = \dot{m}_e = 2\dot{m} \quad \text{(eq. 18)}$$

where $\dot{m}$ is the mass flowrate of one nozzel.

The energy balance equation for the inside of the tank in this case could be expressed as:

$$Mc_w \frac{dT_w(t)}{dt} = \dot{E}_i - \dot{E}_e = 2\dot{m}(e_{wi} - e_w) \quad \text{(eq. 19)}$$

where M is the mass of the cooling water, c_w is the specific capacity of the water, and T_w is the temperature of the cooling water.

Because the cooling system is combined with the UBHE, the cooling water temperature T_w is equal to the UBHE inlet water temperature T_{fi} and T_n is equal to the UBHE outlet water temperature T_{fo}. Thus, q_w could be expressed as follows:

$$2A_{sp} \cdot h_{sp} \cdot [T_{pv}(t) - T_{fo}(t)] = 2\dot{m}c'[T_{wi}(t) - T_{fo}(t)] \quad \text{(eq. 20)}$$

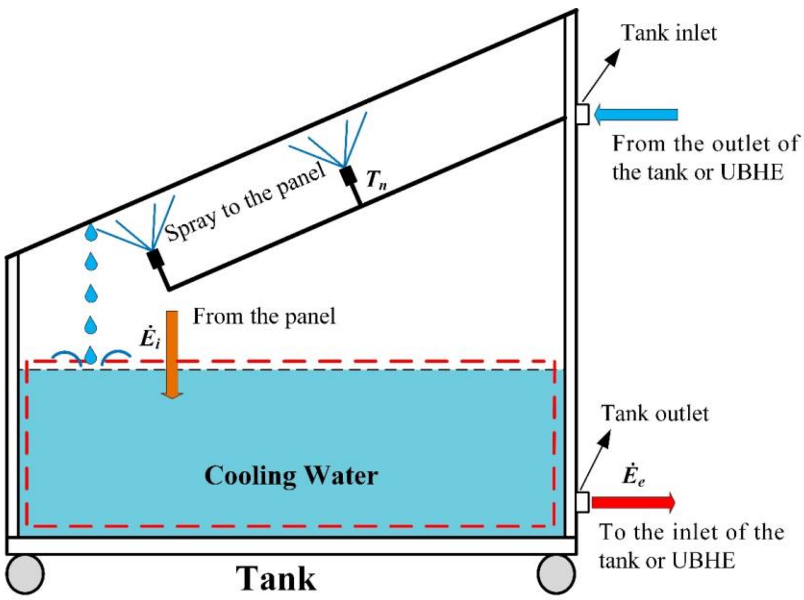

Fig. 3: The operation mechanism of the cooling system and the control volume of cooling water.

where c' is the specific heat of the tank water, T_{wi} is the temperature of the cooling water after cooling the panel and flowing into the tank. In addition, e_{wi} could be obtained from T_{wi}, which could be expressed as:

$$T_{wi}(t) = \frac{A_{sp} \cdot h_{sp} \cdot [T_{pv}(t) - T_{fo}(t)]}{\dot{m}c'} + T_{fo}(t) \quad \text{(eq. 21)}$$

The mathematical models of the UBHE assume the soil is a thermal reservoir that can effectively absorb all waste heat as demonstrated Ball et al. (1983) and Soni et al. (2015), and thus, the soil temperature T_{so} can be set as a constant temperature. The cooling water stays in the UBHE and discharges its heat while the pump rests, so the discharge relationship between the cooling water and the UBHE could be expressed as follows:

$$h_{bi}A_p\left[T_p(t)-T_{gw}(t)\right]=h_{bi}A_b\left[T_{gw}(t)-T_{so}\right] \quad \text{(eq. 22)}$$

where h_{bi} is the convection coefficient of the water in the borehole, A_p is the pipe area, A_b is the borehole area, T_p is the water temperature in the pipe, and T_{gw} is the ground water temperature.

According to DeWitt and Lavine (2007), natural convection in the borehole of the U-tube could be derived as follows:

$$h_{bi}=\frac{Nu_{bi}k_w}{D'} \quad \text{(eq. 23)}$$

$$Nu_{bi}=\frac{1}{24}Ra_{bi}\left(\frac{D'}{H_b}\right)\left\{1-exp\left[\frac{-35}{Ra_{bi}(\frac{D'}{H_b})}\right]\right\}^{3/4},\ 10^{-1}\le Ra_{bi}(\frac{D'}{H_b})\le 10^5 \quad \text{(eq. 24)}$$

$$Ra_{bi}=\frac{g\beta(T_{fi}-T_{fo})D'^3}{\alpha' \upsilon} \quad \text{(eq. 25)}$$

where D' is the distance between branch pipes, k_w is the water conductivity, Nu_{bi} is the Nusselt number of the water in the borehole, Ra_{bi} is the Rayleigh number of the water in the borehole, H_b is the borehole depth, β is the coefficient of thermal expansion, α' is Thermal diffusivity, and v is kinematic viscosity.

Then, the ground water temperature could be expressed as:

$$T_{gw}(t)=\frac{A_pT_p(t)+A_bT_{so}}{A_b+A_p} \quad \text{(eq. 26)}$$

Therefore, the energy balance equation between the UBHE and the ground water could be expressed as:

$$\int_t^{t+\Delta t} h_{bi}A_p\left[T_p(t)-T_{gw}(t)\right]dt = M_pc_w\left[T_p(t)-T_p(t+\Delta t)\right] \quad \text{(eq. 27)}$$

Thus, $h_{bi}A_p\left[\overline{T_p}(t)-T_{gw}\right]\Delta t=M_pc_w\left[T_p(t)-T_p(t+\Delta t)\right]$, and by means of estimate, average $\overline{T_p}(t)$ is $\frac{T_p(t)+T_p(t+\Delta t)}{2}$, and M_p is the mass of the cooling water that in the pipe. eq. (27) could be reworded as follows:

$$h_{bi}A_p\left[\frac{T_p(t)+T_p(t+\Delta t)}{2}-T_{gw}(t)\right]\Delta t=M_pc_w\left[T_p(t)-T_p(t+\Delta t)\right] \quad \text{(eq. 28)}$$

where $T_p(t+\Delta t)$ is the temperature of the UBHE outlet water T_{fo}. From eq. (26) and eq. (28), T_{fo} could be derived as follows:

$$T_{fo}=\frac{-2}{2M_pc_w+h_{bi}A_p\Delta t}\left\{h_{bi}A_p\Delta t\left[\frac{T_p(t)}{2}-\frac{A_pT_p(t)+A_bT_{so}}{A_b+A_p}\right]-M_pc_wT_p(t)\right\} \quad \text{(eq. 29)}$$

When the pump is working, the high-temperature cooling water in the tank will flow into the UBHE again, and it will affect the low-temperature cooling water in the UBHE. Thus, the mixed water temperature in the pipe could be expressed as $T_{p'}$:

$$T_{p'}=T_{fi}\frac{\sigma' t_{ope}}{t_{tot}}+T_p\frac{t_{tot}-\sigma' t_{ope}}{t_{tot}} \quad \text{(eq. 30)}$$

where t_{tot} is the total time for the cooling water to pass through the UBHE, t_{ope} is the total operating time of the cooling system, and σ' is a correction factor that is considered an effective thermal ratio for the axial and radial parts of U-shape pipe.

From eq. (30) into eq. (29), T_{fo} can be obtained; then, by substituting T_{fo} into eq. (20), q_w can be obtained; then, q_w can be substituted into eq. (1). Finally, eq. (1), (19), (29), and eq. (30) represent a mathematical model for the cooling period of the PV panel system, which is cooled by the spray cooling system with UBHE. Governing equations of a cooling system combined with UBHE for PV panels are listed in Tab. 1. Then, the Euler method is applied to calculate the differential equations. In this study, theoretical analysis and experimental results are compared. In addition, the difference between them are also discussed.

Tab. 1: Governing equations of a cooling system combined with UBHE for PV panels.

	State of pump	Governing Equation
	off	$C_{pv}\frac{dT_{pv}(t)}{dt}=A_{pv}\alpha\Phi-\dot{Q}_{co}-\dot{Q}_{ci}-\dot{Q}_{rad}-P_{pv}$
Cooling system combined with UBHE	on	$C_{pv}\frac{dT_{pv}(t)}{dt}=A_{pv}\alpha\Phi-\dot{Q}_{co}-\dot{Q}_{ci}-\dot{Q}_{rad}-P_{pv}$ $Mc_w\frac{dT_w(t)}{dt}=\dot{m}(e_{wi}-e_w)$ $T_{fo}=\frac{-2}{2M_{wp}c_w+h_{bi}A_p\Delta t}\left\{h_{bi}A_p\Delta t\left[\frac{T_p(t)}{2}-\frac{A_pT_p(t)+A_bT_{so}}{A_b+A_p}\right]-M_{wp}c_wT_p(t)\right\}$ $T_{p'}=T_{fi}\frac{xt_{ot}}{t_{to}}+T_p\frac{t_{to}-xt_{ot}}{t_{to}}$

4. Results and discussion

First, this study investigated characteristics of the PV panel without the cooling system and discussed the effect of high PV panel temperatures on the PV efficiency. Experimental results were applied as the basic model for comparison. Fig. 4 shows the relationship of experimental and theoretical PV panel temperatures. The experiment was conducted from 11:40 to 14:45, and the theoretical PV temperature can be obtained through eq. (1). The initial temperature of the PV panel is 52 ℃, and the highest temperature in both the theoretical and experimental results are above 65 ℃. Moreover, the average error between the theoretical and experimental result is about 1.49%. Fig. 5 shows the relationship between the solar intensity and the power output. The average solar intensity and the average power output during experimental periods are 946.5 W/m^2 and 34.5 W, respectively. The energy conversion efficiency of the PV panel is about 6.56%. In accordance with Fig. 4 and Fig. 5, the solar intensity and panel temperature are main factors, which influence the power output. As shown in 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. The temperature of the panel at t = 180 min is higher than that at t = 0 min, thus the power output is lower at t = 180 min. The results show that the power output decreases as the PV panel temperature increases.

Second, to decrease PV panel temperatures, this study applies a spray cooling system combined with UBHEs. In addition, the spray cooling system is intermittent operating, which can reduce power consumption of a pump and maintain the cooling capacity. Pump is switched on once the panel temperature reaches 45ºC and is switched off once the PV panel is cooled to 35ºC. The experimental results and theoretical predictions are shown in Fig. 6. The experiment was executed continuously for 3 hours 5 minutes. Theoretical results were calculated from eq. (1), (19), (29), and eq. (30). Because the tank could not be completely insulated in the experiment, the experimental tank water temperature was higher than the theoretical ones. The water temperature increase from the initial temperature in the experiment was about 3.5 ℃ and, theoretically, was 2.4 ℃. Moreover, since soil cannot cool the cooling water completely in a short time, the increment of experimental cooling water temperature

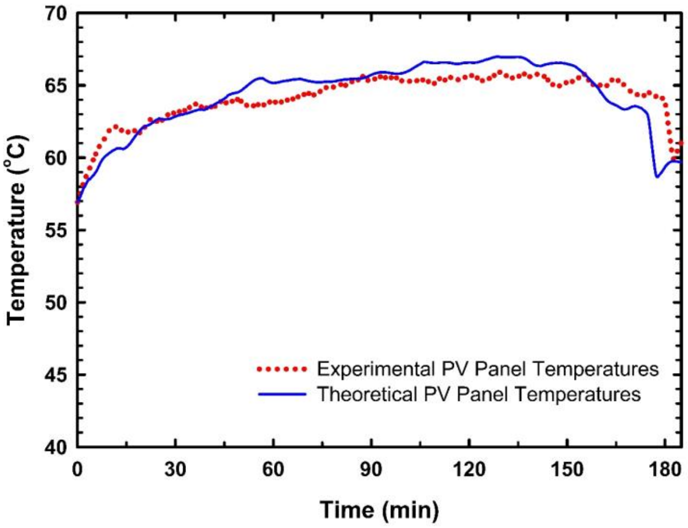

Fig. 4: Relationship between experimental and theoretical PV panel temperatures.

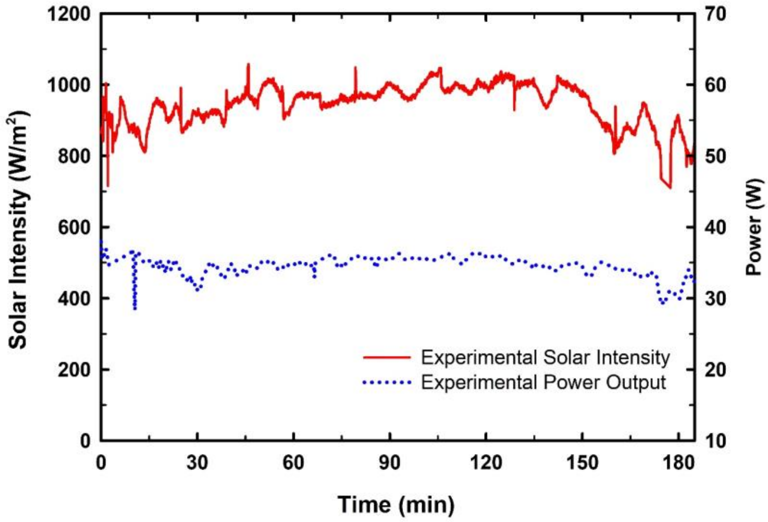

Fig. 5: Relationship between solar intensity and power output.

was higher than the theoretical temperature (1.9 ℃). Thus, for the theoretical analysis, more cooling cycles than experimental results are observed because of the lower cooling water temperatures and the better cooling capacity. The number times of cooling cycles for theoretical predictions are 52, while the experimental results are 50. Fig. 7 shows the relationship between solar intensity and power output. The average solar intensity and the average power output are 777.1 W/m^2 and 30.7 W, respectively. The energy conversion efficiency of the PV panel is about 7.5%. However, the power consumption of a pump must be considered, so the actual energy conversion efficiency of the PV panel is 7.1%. Fig. 7 shows the relationship between solar intensity and power output for the PV panel with the spray cooling system combined with UBHEs. Predictably, the power output is propotional to the solar intensity. 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.

Based on above experimental results and theoretical analyses, the spray cooling system combined with a UBHE can improve the energy conversion efficiency of the PV panel. To analyze further economic feasibility, the theoretical model is utilized to calculated the power output under different solar intensity. The solar intensity adopted in the theoretical model is 800, 900, and 1,000 W/m^2, respectively. Moreover, this analysis fixes the ambient temperature at 32℃ and the initial PV panel temperature at 45℃. The results presented in Tab. 2 show that solar intensities are 800, 900, and 1,000 W/m^2, and the PV panels without any cooling systems have efficiencies of 8.72%, 8.41%, and 8.31% respectively. With the increase of solar intensity and the increase of the

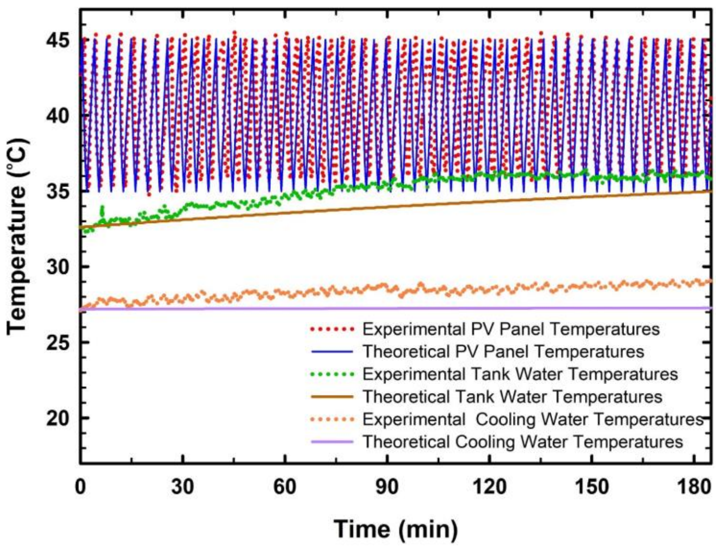

Fig. 6: Relationship between the PV panel temperatures, tank water temperatures and the cooling water temperatures in the experimental results and theoretical predictions.

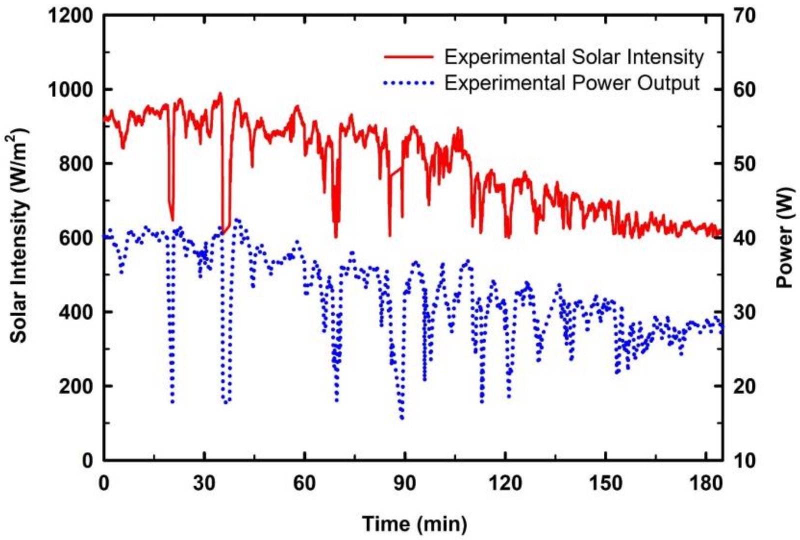

Fig. 7: Relationship between solar intensity and power output for the PV panel with the spray cooling system combined with UBHEs.

panel temperature, the efficiency declines. However, after this PV panel system utilized the UBHE system to cool its cooling water, the efficiency could be improved to 9.17%, 13.08%, and 14.32%, respectively. Those results indicate that the panel temperature or the solar intensity is higher, and the benefits of the UBHE system more obvious.

According to the calculated results in Tab. 2, because only a 60 W PV panel is used in this study, the increment of output power is slight. However, for a large-scale solar farm or plant factory utilizing solar electricity, the cooling system could effectively improve the efficiency of the PV panels. This study executes a further analysis by applying a theoretical model developed for the cooling system. Take a plant factory powered by 10 PV panels, for example; the UBHE cooling system can use the existing irrigation wells, so only investment in pumps and pipes is considered. Furthermore, the requirement of the cooling system applied in this example is an 85 W diaphragm pump (the head is 35m, and flow rate is 6LPM), and thus, an appropriately sized well is sufficient for the cooling demand, and its equipment costs can be recovered in 8.7 years in a sunny area (with an average solar intensity of 1,000W/m^2). The economic analysis is presented in Tab. 3. This results shows that the spray cooling system combined with a UBHE has the economic feasibility and can be suitable for a large-scale solar farm or plant factory.

Tab. 2: Theoretical power output for a fixed ambient temperature of 32°C, with an initial panel temperature of 45°C.

Solar intensity (W/m^2)	Cooling system	Pump working time (s)	Average power output (W)	Average net power output (W)	Conversion efficiency (%)	Increment (%)
800	No	-	38.8	38.8	8.72	-
	Yes	3,750	44.0	42.4	9.52	9.17
900	No	-	42.1	42.1	8.41	-
	Yes	4,390	49.6	47.6	9.51	13.08
1,000	No	-	46.2	46.2	8.31	-
	Yes	5,110	55.2	52.9	9.50	14.32

Tab. 3: Economic analysis for a plant factory powered by 10 PV panels; 1 USD = 30 NTD.

Construction	Cost (NTD)	Price per kWh (NTD/kWh)	Solar intensity (W/m^2)	Net electricity generation (kWh/year)	Payback period (year)
Pump	1,150		800	28.32	18.5
Pipes and other	2,000	6	900	49.30	10.7
Total	3,150		1,000	60.44	8.7

5. Conclusions

This study used a cooling system integrated with a U-shape borehole heat exchanger (UBHE) to cool the PV panel. Moreover, a theoretical model for the cooling system was built. In addition, the theoretical model was utilized to evaluate the further economic feasibility. The results of the present research give the following conclusions:

(1) The spray cooling system combined with a UBHE can improve the energy conversion efficiency of the PV panel. The panel temperature or the solar intensity is higher, and the benefits of the UBHE cooling system more obvious.

(2) A theoretical model for estimation of the PV panel temperature and conversion efficiency under was developed, and the theoretical and experimental results had the same trend. This mathematical model is helpful for preliminary design and analysis of the PV panel systems with the UBHE.

(3) For a large-scale solar farm or plant factory utilizing solar electricity, the cooling system can effectively benefit the efficiency of the PV panels. Take a plant factory powered by 10 panels, for example, with a solar intensity of 1,000 W/m^2; this cooling system can improve the efficiency of the panels about 14.3%, and its equipment costs can be recovered in 8.7 years. This results shows that the spray cooling system combined with a UBHE has the economic feasibility

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