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An operating characteristics study on a small-scale CPV-ORC power generating system in summer typical day

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ABSTRACT

This study concerns a hybrid CPV (Concentrator Photovoltaic) system coupled with an Organic Rankine Cycle (ORC), which mainly contains CPV modules and cooling subsystem. The cooling fluid driven by pump is evaporated in tubes under the CPV modules. The superheated vapor of working fluid is generated for additional electric power generation with an ORC. Through the study of the impact of different parameters on the system, the efficiency of CPV-ORC combined system is compared with that of single CPV system. When the temperature of CPV cells increases, the combined system can effectively cooling the CPV and increase the additional energy generation.

Keywords: hybrid system, CPV-ORC, heat dissipation, combination efficiency

NONMENCLATURE

Symbols	
A	*Area*
C	*Concentration ratio*
G	*Direct solar radiation*
P	*Power*
Q	*Energy*
T	*Temperature*
β	*temperature coefficient*
η	*Efficiency*
Subscripts	
cell	*PV cell*
con	*Concentrator*
conv	*Convection*
e	*Variable PV parameter*
inv	*Inverter*
opt	*Optical*

1. INTRODUCTION

CPV is a technology that concentrates solar radiation into a small area of a solar photovoltaic cell through a concentrator, replacing the expensive cell area with an optical device. Using concentrated solar photovoltaic system has the advantage of reducing the cost of solar photovoltaic system. However, concentrating solar photovoltaic cells could generate more heat than non-concentrating solar panels, and the heat could increase the temperature of photovoltaic cells rapidly, which may cause aberrant operation of the cells at high temperature, causing irreversible damage, and reducing the efficiency of the cells as the temperature drop coefficient is 0.4-0.5%/K, thus harmful to the efficiency and lifetime of solar cells. Presently, the optimal efficiency of photovoltaic cells occurs usually with the surface temperature of no more than 100°C.[1] In order to overcome the effects of the increasing photovoltaic temperature, it is necessary to remove the heat from the photovoltaic by appropriate cooling methods. Typical CPV thermoelectric systems, which consists of solar cells and heat utilization subsystems, can be divided into two different approaches: one is to capture the heat emitted by a cooling system installed under the solar cells, which can be considered a photovoltaic-topping approach. The coolant is heated to higher temperature for domestic use and local heating, absorption cooling, seawater desalination, power generation, etc., provided that the solar cells operates at the appropriate temperature.

To solve this problem many researchers deployed their experimental and theoretical studies. Royne et al.[2] examined several nozzle array designs to optimize high-concentrated photovoltaic (HCPV) cooling using impinging jets. Han et al.[3] presented a novel solar concentrating photovoltaic/concentrating solar power (CPV/CSP) hybrid system contained thermal receiver and ORC cycle to sufficiently use the peripheral low-concentration solar radiation. Kermani et al.[4] researched microchannels and carried out experiments applying the same principles used for electronics cooling to cool HCPV cells. Kribus et al.[5] proposed and analyzed a miniature CPV/T system that uses a simple coaxial parabolic antenna as a concentrator. The three-junction solar cell is installed on the cooling plate from which the coolant is injected.

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An innovative technique for cooling cells under concentrated light is the use of organic refrigerants. The advantage of this method is that the evaporated refrigerant can be used to generate excess power using the organic Rankine cycle (ORCs) for combination system. G.Kosmadakis et al. [6] proposed a CPV/T system coupled with an ORC for additional electricity and heat dissipation. They used R245fa as working fluid along with the optimization of some system parameters. but they didn't inspect whether the chosen fluid was the optimal type for this novel combination system. Rahim Moltames et al.[7] found the optimal temperature of CPV cells when the combined system produced the maximum power, aiming at CPV panels with different efficiency respectively. But they didn't inspect whether the chosen fluid was the optimal type for this novel combination system. Zhang and Wang[8] designed a high-concentration photovoltaic system combined with a small ORC. They also developed a complete microchannel flow boiling model based on the laws of mass, energy and momentum conservation. Zhao et al.[9] conducted thermodynamic evaluation on an ORC and a system, and their system optimization showed that 130°C was an appropriate evaporation temperature.

In order to overcome the effect of PV temperature increase on the cell power generation efficiency, it is necessary to remove the heat from the PV by appropriate cooling methods and, at the same time, it is necessary to reuse its waste heat considering that the mere heat dissipation causes huge energy waste. There are two main problems faced in designing a CPV-ORC system: one is to simulate and calculate the actual waste heat generated by the CPV module at the corresponding direct solar irradiation value; and the other is how to couple the CPV module with the ORC system. Therefore, the research in this paper is carried out in two aspects: first, the calculation of heat production of CPV module based on numerical simulation, and second, the secondary utilization of waste heat for power generation using ORC.

In this paper, a micro-scale CPV-ORC hybrid system was proposed, in order to effectively cooling the CPV cells, meanwhile to utilize the exhaust heat of CPV to generate electricity through ORC cycle. The impact of different parameters on the system was investigated, and then the applicability of CPV-ORC in different climate zones were compared with different operating mode.

2. NUMERICAL METHOD

2.1 Description of the system

In this study, a CPV-ORC coupled system was firstly designed. The CPV module and the ORC system was then simulated under different parameter conditions. Finally, the operating performance of the CPV-ORC system was further evaluated and analyzed. The following is the detailed methodology of this study.

Fig. 1 shows the detailed layout of CPV-ORC system including a CPV modules and an ORC cycle. To enhance the heat dissipation from PV panel caused by the concentrator, a small-scale heat exchanger with organic working fluid was embedded inside the PV panel to absorb the exhausted thermal energy. To utilize this thermal energy, a low temperature ORC was designed, including two expander, one condenser, one pump and one evaporator embedded inside the CPV module, as shown in Fig. 1. In the evaporator, the working fluid is heated from a subcooled liquid to a saturated vapor at high temperature and pressure by recovering heat from a heat source. After leaving the evaporator, the saturated steam expands through the turbine to generate power, changing from the state of high temperature and high pressure to state of high temperature and low pressure. The steam discharged from the turbine is then condensed and heat exchanged through the condenser, condensing the steam into a saturated liquid. Finally, the condensed liquid driven by pump back to the evaporator continues the circulation. Hence, in this CPV-ORC system, part of the concentrated solar radiation is converted directly into electricity by PV panel, and the left thermal energy, except from which emitting by convective heat and radiation from the system to the surrounding environment, is recovered through the ORC system. The CPV module and the ORC system was coupled through the evaporator inside the CPV module, which was used for heat exchange. The CPV module would be simulated through MATLAB, and the waste heat from PV panel would be calculated as the thermal driving of ORC and input parameter to ORC system. The simulation of ORC system was established in Aspen plus v10.

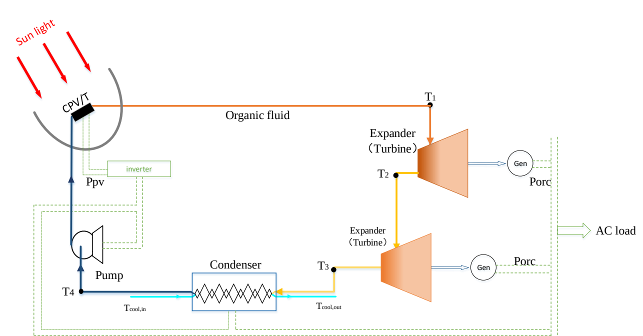

Fig. 1 Schematic diagram of CPV system combined with ORC

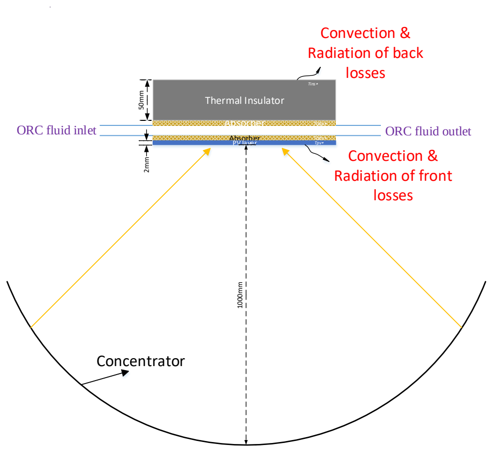

Fig.2 Simplified configuration of the PV component

2.2 Concentrated photovoltaic modeling

The structure of CPV module is shown in Fig. 2. As shown in Fig. 2, the CPV module is composed of a flat panel photovoltaic, which was positioned at the focal point of the concentrator, and a parabolic trough concentrator which was used to increase the radiation intensity.

The CPV module investigated in this study was a small-scale one with the kilowatt power level. The PV panel area was assumed to be 1 m^2, with length of 3.162m and width of 0.3162m. The length of the concentrator was also 3.162 m, and the aperture of the concentrator was 1m in diameter.

$$A_{con} = A_{pv} \times C \tag{1}$$

where, A_{con} is concentrator area, A_{pv} is PV module area, and C is concentration ratio, with the value of 10.

The electric efficiency of the photovoltaic module is related to the temperature of the panel, which is given by the following equation:

$$\eta_{pv} = \eta_{T_{ref}}[1 - \beta_{ref}(T_e - T_{ref})] \tag{2}$$

where, η_{pv} is module's efficiency; $\eta_{T_{ref}}$ is PV module's efficiency at reference conditions; T_c is PV temperature as variable parameter; T_{ref} is cell's reference temperature in this work that is equal to 25°C and the module efficiency($\eta_{T_{ref}}$) under the reference condition is 12% at this reference temperature. For this initial design, the concentration ratio and the designed cell temperature were selected to be 100°C. β_{ref} is temperature coefficient, 0.004/°C.

The net incident concentrated solar radiation on the photovoltaic panel is given by the following equation, which is the premise of calculating the power generated by the photovoltaic panel:

$$Q_{pv} = GC\eta_{opt}A_{pv} \tag{3}$$

In equation (3), G direct solar radiation and the value of G is 1000W/m^2; Q_{pv} is net incident concentrated solar radiation on the PV module; η_{opt} is optical efficiency, 0.85.

The electricity generated by the photovoltaic panels is calculated as follows:

$$P_{pv} = Q_{pv}\eta_{pv}\eta_{inv} \tag{4}$$

P_{pv} is electric power produced by the CPV. And η_{inv} is inverter efficiency, 0.9.

When the net incident concentrated solar radiation already was calculated, a part of which directly converted to electricity as equation (4), and the remnant dissipated as thermal power, that can be reckoned in following equation:

$$Q_{Th} = Q_{pv}(1 - \eta_{pv}) \tag{5}$$

The waste heat produced by the CPV system is partially exhausted by radiation and convective heat transfer from the system to the surrounding environment (Fig.2). The remaining part of energy transfers into ORC system. Thus, the thermal power transferred from PV panel to ORC can be written as follows:

$$Q_{Th} = Q_{ORC} + Q_{conv} + Q_{rad} \tag{6}$$

2.3 ORC modeling

The ORC process is simulated in Aspen plus V10, while the calculation of the CPV module will be done by MATLAB, and the connection between MATLAB and Aspen Plus would be done by Excel Link.

With the waste heat from CPV calculated as one of input parameters of the ORC system, other parameters of the ORC are set as well. According to reference, the conditions are as follow Table

Table 1 The initial setup about specifications, and constraints in ORC mode

Parameters	Value
The working fluid	R22
The discharge pressure of pump	10bar
Direct solar radiation	1000/W/m^2
Ambient temperature	25°C
Thermal energy utilization rate of heat exchanger	90%
Evaporating pressure	10bar
The discharge pressure of expander	5/1.75bar
Condensing pressure	2bar
Condensing temperature	30°C

3. RESULTS AND DISCUSSION

3.1 The effect of mass flow of working fluid

With simulated calculation by Aspen plus, The waste heat recovery efficiency (WHRE) of CPV, the Exergy destruction (ED) of each component of the system, the efficiency of CPV-ORC combined system (CE) and the power of the pump (PP) were selected as the evaluation indexes of the CPV-ORC combined system.

The sensitivity analysis of Aspen plus was used to find the optimal mass flow rate of R22 at 20bar and 90% waste heat utilization rate. Under this optimal mass flow rate, the combined efficiency, waste heat utilization rate and combined work of the system reached the maximum value. When the optimal mass flow rate increased by 0.05kg/s compared with the original flow rate, the system power output was increased by 8.42%, the system waste heat utilization rate was increased by 2.9%, and the combined efficiency was increased by 3.25%. At this time, the power consumption of the pump also increased by 83.35%, exergy loss increased by 6.85%. With the increase of mass flow, both the water pump consumption and exergy loss of the system increased, among which the water pump power consumption increased the most, but the utilization rate and combined efficiency of waste heat both reached the maximum under the waste heat input. When the flow rate increased, the waste heat utilization rate and combined efficiency of the system decreased successively.

Table 2 R22 operating results at optimal flow rate of 20bar and 90% waste heat utilization rate

Mass flow	Wn (W)	ED (W)	PP (W)	WHRE (%)	CE (%)
0.012 kg/s	1240.49	377.82	63.11	18.27	21.18
0.022 kg/s	1344.92	403.68	115.71	19.80	21.79

3.2 The effect of direct solar radiation

After selecting the optimal R22 mass flow of the combined system, the performance of the system in all aspects was optimized. The energy input to the system is determined by the direct solar radiation, and the concentration ratio of the CPV determines the energy absorbed by the panels. Different suns affect the solar radiation on the photovoltaic module, and then affect the waste heat generated by photovoltaic; The amount of electricity produced by the combined system was calculated by calculating the waste heat generated by different suns.

When the temperature of the PV cell changes, the thermal cycle of the system alters subsequently. As the temperature of a PV cell rises, its efficiency decreases. At this time, the waste heat generated will increase, and the power generation of ORC would also increase, so the change of the power generation of the system needs to be studied. The change of CPV efficiency under high temperature with the improvement of ORC could protect CPV from being destroyed by high temperature. According to the literature, the equation of cell temperature changes with direct radiation can be obtained:

$$T_{cell} = 0.5 \times 10^{-5} G + 0.025G + 30 \quad (7)$$

When G, the solar radiation, changes, the cell temperature of CPV changes accordingly, and the residual heat generated by CPV can be obtained through iterative calculation. At this point, CPV efficiency decreases with the increase of temperature, which is calculated by equation (2). After the efficiency of the CPV is obtained, the power generation of the CPV can be calculated, and the power generation of the ORC can be calculated using Aspen Plus.

According to the influence of PV temperature on the efficiency, as the result of simulation shown in Table 3, the optimal power generation efficiency of PV cells is below 100°C. Therefore, the upper limit of CPV plate temperature is set as 70°C when the variable solar radiation simulation is performed. That is, when the temperature exceeds this set value, the CPV-ORC system will operate under variable conditions to reduce the CPV plate temperature. The calculation was repeated until the CPV temperature error was within 5%, and then the heat value carried by ORC was calculated.

Table 3 Result of CPV simulation

G(W/m^2)	Q_{pv} (W)	Set T_{cell}(°C)	Q_{Th} (W)	Q_{rad}+Q_{cond}(W)	T_{cell}(°C)	Residual(%)	Q_{ORC}
390	1657.5	70	1494.40	494.40	69.67	-0.47	1000
440	1870	70	1685.09	485.09	68.92	-0.11	1200
490	2082.5	70	1877.58	497.58	70.03	0.05	1380
540	2295	70	2069.17	499.17	70.21	0.30	1570
590	2507.5	70	2260.76	490.76	69.26	-1.06	1770
640	2720	70	2452.35	502.35	70.57	0.82	1950
690	2932.5	70	2643.94	493.94	69.62	-0.54	2150
740	3145	70	2835.53	500.53	70.37	0.53	2335
790	3357.5	70	3027.12	497.12	69.98	-0.03	2530
840	3570	70	3218.71	498.71	70.16	0.23	2720

$G(W/m^2)$	Q_{pv} (W)	Set T_{cell}(°C)	Q_{Th} (W)	$Q_{rad}+Q_{cond}$(W)	T_{cell}(°C)	Residual(%)	Q_{ORC}
890	3782.5	70	3410.30	500.30	70.34	0.49	2910
940	3995	70	3601.89	501.89	70.52	0.75	3100
990	4207.5	70	3793.48	498.48	70.13	0.19	3295
1040	4420	70	3985.07	500.07	70.32	0.45	3485
1090	4632.5	70	4176.66	501.66	70.50	0.71	3675
1140	4845	70	4368.25	498.25	70.11	0.16	3870
1190	5057.5	70	4559.84	499.84	70.29	0.41	4060
1240	5270	70	4751.43	501.43	70.47	0.67	4250

As can be seen from Table 3, when the solar radiation increases gradually, the heat taken away by ORC should also increase gradually to keep the temperature of PV cell at 70°C. At this time, the mass flow rate of working medium increases with the increase of waste heat input to ORC, and the output work also increases with the increase of mass flow rate.

3.3 Applicability of CPV-ORC system in different climate zones

The hourly solar radiation values of five cities with typical climate zones (Beijing, Shanghai, Kunming, Guangzhou and Harbin) in summer on July 15 are queried according to the special meteorological dataset for building thermal environment analysis in China, as shown in Fig.3. Considering that the heat generated by too low solar radiation will not cause high temperature damage to CPV batteries, The minimum solar radiation to start ORC was set as $300W/m^2$. According to the variable solar irradiation operating state characteristics of CPV-ORC coupling system, the hourly solar irradiation values of five typical cities in summer sunny days were input to obtain the PV typical daily hourly temperature values of different cities, as shown in Fig.4.

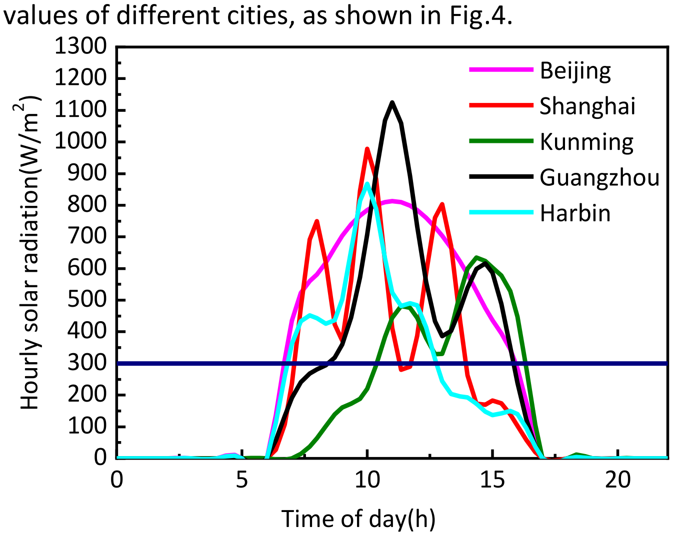

Fig.3 Typical hourly solar radiation on sunny days in summer in five cities

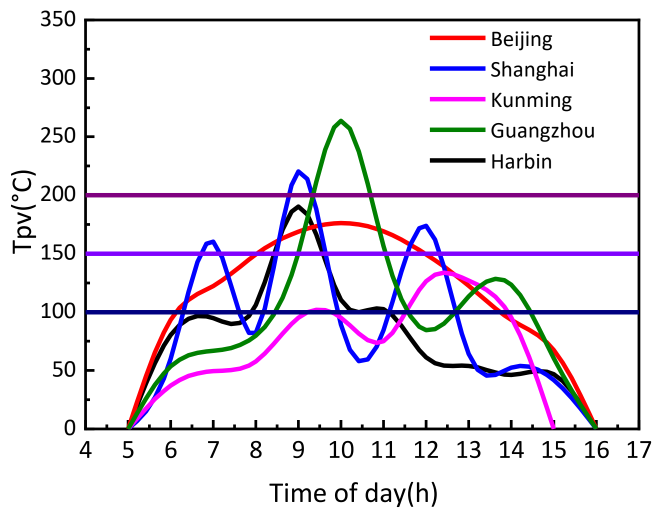

Fig.4 Hourly PV panel temperature in five cities

The high temperature CPV caused by the changing solar radiation can be maintained at 70°C after being cooled by ORC, and the additional power generation of ORC system can be obtained while keeping the PV efficiency stable, and the hourly output power of the coupling system can be obtained. In order to more intuitively compare the power generation of CPV without heat dissipation(N-CPV), CPV with heat dissipation(O-CPV) and CPV-ORC coupling system, the hourly power generation of typical summer days is counted, as shown in Fig. 5.

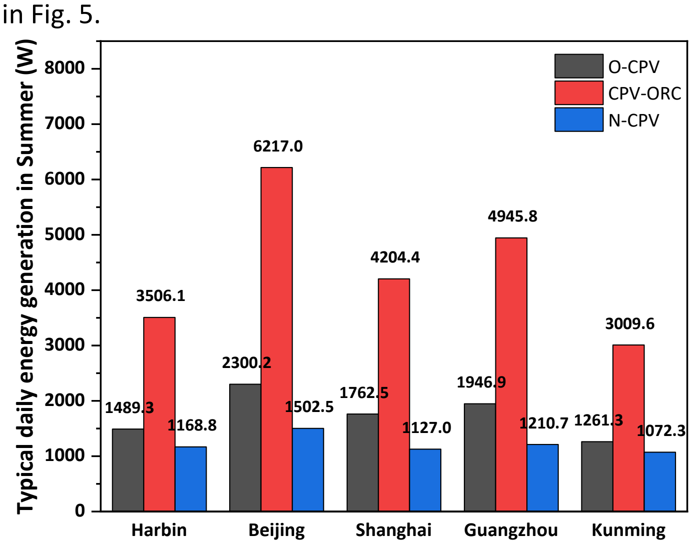

Fig.5 Typical daily hourly electricity generation statistics in summer

4. CONCLUSIONS

By Aspen Plus sensitivity analysis, the optimal mass flow rate of refrigerant R22 in CPV-ORC was found to be 0.018kg/s. The optimized mass flow rate improved the waste heat utilization rate and combined efficiency of the system: WHRE increased from 18.27% to 21.17%. CE increased from 21.18% to 24.43%.

The direct solar radiation and the temperature curve of CPV board were fitted. The mass flow rate of working medium was obtained by ASPEN PLUS simulation, and the combined efficiency of output power and system and waste heat utilization rate were obtained. Compared with the single CPV system, the efficiency of the combined system increased by more than 12% and the battery temperature remained stable.

At the set cooling temperature (70°C) and under the variable solar irradiation input, the power generation of the coupled CPV-ORC system increased by about 90% compared with the N-CPV system alone. The average daily power generation efficiency of CPV-ORC coupling system in summer was 20.2%, which was 9.5% higher than that of N-CPV, which was 10.7%.

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