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An efficient hybrid system integrated concentrated parabolic trough solar collector with solar photovoltaics

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ABSTRACT

The concentrated parabolic trough solar power is regarded as a promising renewable alternative expected to exert a vital role in supplying green and sustainable electricity and thermal energy for the human race in the future. However, the parabolic trough collector (PTC) system still encounters a knotty problem of considerable radiation heat loss caused by its high operating temperature (generally above 400 °C), which significantly degrades the thermal performance of the PTC system and thus power generation performance of the PTC power plant. In this work, a novel PTC system integrated with solar photovoltaics (PTC-PV) is proposed. The PV panels have a narrow width which is the same as the diameter of the parabolic trough receiver (PTR), and are placed above the PTRs at a certain distance. In addition, the rear surfaces of the PV panels are covered with a high-reflective coating used to block the radiation heat loss from the PTR. The unique configuration of PV panels in the PTC-PV system is expected to reduce the radiation heat loss of PTRs and simultaneously generate electricity in an efficient manner due to the sun tracking mechanism of the PTC system. In this research, a test rig of the proposed PTC-PV system was established in the Hong Kong Polytechnic University. The comprehensive experiments were carried out. In the experiments, PV efficiency under different PTR's operating temperatures and solar irradiances were explored. Moreover, the overall performance of the PTC-PV system was also evaluated and compared with the traditional PTC system. The experimental results showed that the PV panels in the PTC-PV system maintained superior photoelectric efficiency compared to the traditional PV system without sun tracking. The high-reflective coating covered on the rear surface of the PV panel can effectively reduce the PV temperature when the temperature of the glass tube in the PTR is above 75 °C. And the electricity capacity of the PTC-PV based concentrated solar power plant is effectively improved by 1.1 % compared to the traditional PTC based concentrated solar power plant.

Keywords: Solar Energy, Concentrated Parabolic Trough Collector, Photovoltaic, Solar Power, Integrated system

NONMENCLATURE

Abbreviations	
PTC	Parabolic Trough Collector
PTR	Parabolic Trough Receiver
PV	Photovoltaic
CSP	Concentrated Solar-thermal Power

1. INTRODUCTION

As carbon neutrality strategies were proposed in many countries, the research and development of renewable energy technologies have been paid much attention in the whole world. Solar energy is regarded as the most promising renewable alternative in the future owing to its easy accessibility and massive abundance on the Earth. Besides the well-known solar photovoltaic (PV) technology [1], concentrated solar-thermal power (CSP) is another dominant solar energy technology that generally realizes power generation [2]. Different from the direct solar-electricity conversion in the PV system, CSP system firstly employs the solar collector to harvest the solar energy and convert it into thermal energy, then converted into electricity by the thermal power generation system. Compared to the PV system, CSP system has the advantages of efficient thermal storage and high electricity generation flexibility, thus causing the research interest from worldwide researchers.

At present, the implementation forms of solar-thermal conversion in the CSP technology mainly include parabolic trough collector (PTC) [3], tower collector [4], dish collector [5] and Fresnel collector [6]. As the most widely used technology, PTC system is expected to exert a crucial role in the development of CSP system in the future. PTC system is mainly composed of mirrors, parabolic trough receiver (PTR), solar tracking system. As the sole site of solar receiving, absorbing, conversion, the PTR is responsible for a key role of thermal collection in the PTC system and CSP system. To date, the PTR's operating temperature is generally around 400 °C by using the oil as the heat transfer fluid (HTF) and is expected to be raised to 550 °C by using the molten salt as the HTF [7] in the next-generation PTC system. However, the solar-thermal conversion performance of the PTR encounters a significant degradation at high operating temperatures. This knotty problem results in a substantial reduction of power generation output for a CSP plant.

Many researchers have investigated the heat transfer characteristics of the PTR and proposed a number of methods to improve the solar-thermal conversion efficiency of the PTR [8, 9, 10]. Among the proposed theories and methods proposed in the previous literature, an interesting phenomenon named "negative thermal-flux phenomenon" was discovered and studied by the authors [11]. In normal commercial PTC systems, the PTR receives an extremely uneven distribution of solar radiation in circumference. In a commercial EuroTrough collector, the lower part and upper part of the PTR receive one and more than 70 solar radiations, respectively. But the circumferential temperature of the PTR reaches approximately 400 °C, which causes massive radiation heat loss from the PTR. In the upper part of PTR, the radiative heat is larger than the absorbed solar radiation, thus leading to a negative heat gain in such a part. This work revealed a new understanding of the heat transfer characteristic in the PTR and pioneered a novel design strategy, that is, reducing the radiation heat loss should be the priority of the design, even compromising the absorption of the solar radiation. In such context, the authors proposed many methods, such as introducing the radiation shield into the upper part of the annular vacuum space [12]. Though the radiation shield blocked the one solar radiation, it was capable of effectively reducing the radiation heat loss, the net heat gain of upper part of the PTR still had a dramatic increase.

The studies mentioned above demonstrate that only one solar radiation projected on the upper part of the PTR hardly benefits the heat gain of the PTR, and the current approaches such as radiation shield do not reuse the blocked the upper one solar radiation and thus largely waste the solar radiation. In this paper, a novel hybrid system integrated PTC system with solar PVs was proposed. The Solar PV panels were mounted on the PTC system and positioned above the PTR. The PV panels could receive and convert the upper one solar radiation into electricity. Moreover, because of the sun-tracking mechanism of the PTC system, the PV is highly expected to possess high photoelectrical efficiency. Therefore, the proposed hybrid system would harvest more electricity output than the traditional PTC system. It is worth mentioning that this newly designed system combining PTC and PV was not reported by the previous research.

In this paper, the structure and configuration of the hybrid system are designed and the comprehensive performance is evaluated by experiments. Due to high operating temperature of the PTR up to 400 °C, the rear surface of PV panels will receive massive radiation heat from the PTR and thus have an elevated temperature. This phenomenon will lead to the reduction of the photoelectricity performance. In order to reduce the radiation heat from the PTR and decrease the PV's temperature, a high-reflectivity coating is proposed to cover the rear surface of PV panels. In this work, the temperatures of PV panels with and without a high-reflectivity coating are observed under different PTR's temperatures through experiments. And the estimated electricity output of the traditional parabolic trough power plant and novel PTC-PV power plant are exhibited and analyzed.

2. EXPERIMENTS AND METHODOLOGY

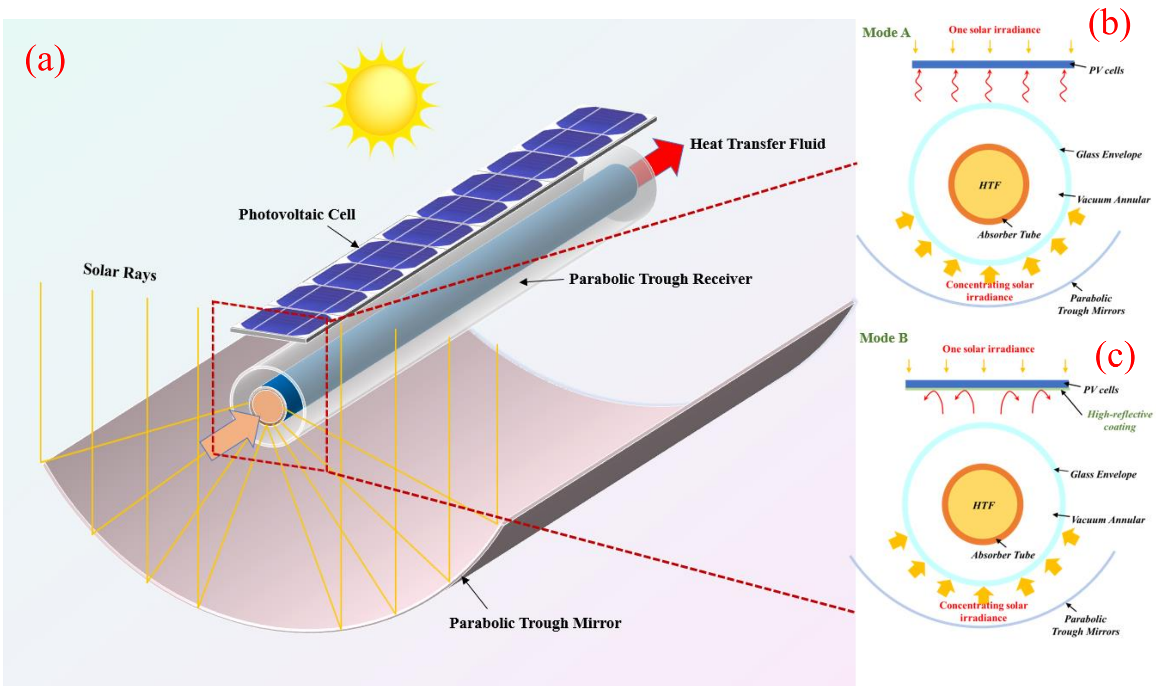

Fig. 1 (a) Schematic digram of hybrid PTC-PV system and two modes of PV panels: (b) PV panels without high-reflective coating and (c) PV panels with high-reflective coating

2.1 Hybrid PTC-PV system

The schematic diagram of the hybrid PTC-PV system is presented in Fig. 1(a). It can be observed that the concentrated solar radiation mainly projects on the lower part of the PTR, and the upper part only receives one solar radiation. This unique characteristic of the PTC system provides the possibility of PV integration, that is, positioning the PV panels above the PTRs. It is worth mentioning that the width of the PV panel is set as the same dimension as the diameter of the PTR in order not to intercept unnecessary solar radiation, which should be concentrated to the lower part of the PTR. Schott's 2008 PTR70 receiver and EuroTrough collector are selected as the PTC system investigated in this work. Besides, a monocrystalline silicon PV (m-PV) panel is designed and customized. The detailed dimensions are shown in Table 1.

Table 1 Dimensions of 2008 PTR70, EuroTrough collector and PV panel

Parameter	Dimension	Parameter	Dimension
Diameter of PTR's outer tube	125 mm	Distance between the PTR and PV panel	80 mm
Diameter of PTR's inner tube	70 mm	Width of m-PV panel	125 mm
Aperature width of the mirror	5.67 m	Length of single m-PV panel	50 mm

As explained in the Introduction part, the rear surface of the m-PV panel is also covered by a high-reflective coating for reducing the radiation from the PTR. The coating adopts polished aluminum, which has a reflectivity of 0.96.

2.2 Experiments and methodology

The overall experiments were carried out in the indoor laboratory at the Hong Kong Polytechnic University. The test rig is exhibited in Fig. 2. Firstly, the temperature and I-V curve of the m-PV panel without a high-reflective coating was tested under different solar radiances and outer tube's temperatures. Then, the temperature and I-V curve of the m-PV panel with high-reflective coating was tested under almost the same experimental conditions as the PV panel without coating. After the testing, the temperatures and maximum powers of PV panels with and without high-reflective coating were evaluated and compared.

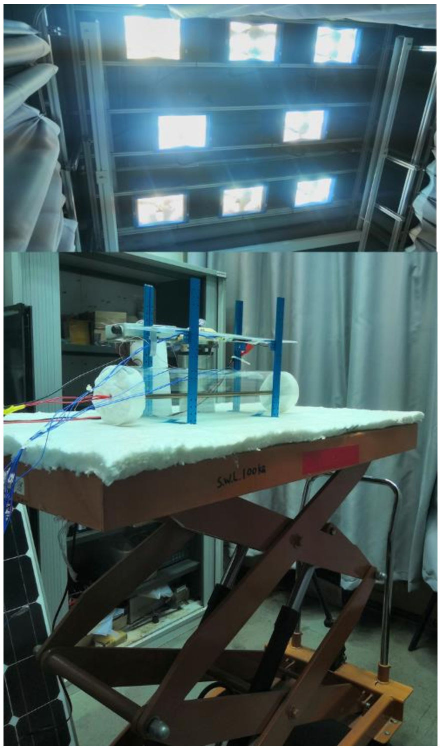

Fig. 2 Test rig in an indoor laboratory at the Hong Kong Polytechnic University

3. RESULTS AND DISCUSSIONS

3.1 I-V curve of m-PV panel

Under the solar irradiance of 1066 W/m^2, m-PV temperature of 35.9 °C, the I-V curve of m-PV panel is tested and exhibited in Fig. 3. It is observed that short-circuit current and open-circuit voltage are 3.84 A and 3.78 V. The maximum power point locates at the voltage of 2.93 V and current of 3.56 A, and the maximum power reaches 10.45 W. In this context, the photoelectric efficiency is 16.45 %.

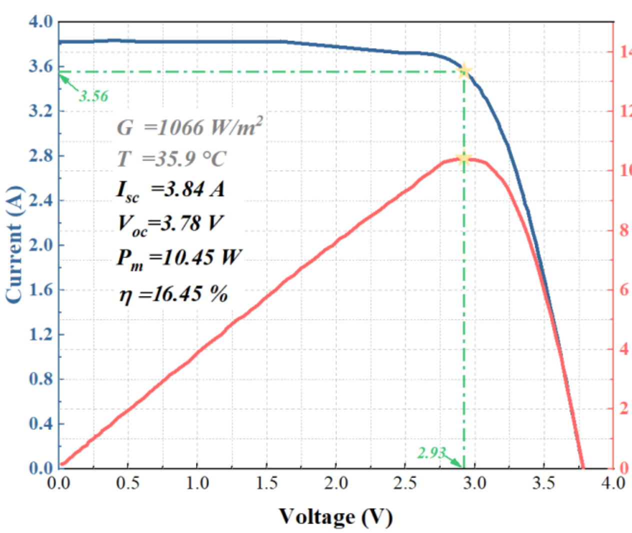

Fig. 3 I-V curve of PV panel

3.2 Performance of m-PV panels with and without high-reflective coating

To evaluate the effectiveness of the high-reflective coating in reducing the PV's temperature, the PV panels with and without high reflective coating (Mode A and mode B, respectively) are tested. The experimental results are exhibited in Figs. 4 and 5. It can be observed that, at a lower outer tube temperature (glass temperature) below 75 °C, the PV's temperature in mode B is higher than that in mode A; but with increasing glass temperature, the latter surpasses the former. In addition, the PV temperature in Mode A increases in a much more rapid manner compared to that in Mode B. This demonstrates that the high-reflective coating is capable of exerting an effective role in reducing the temperature by blocking the radiation heat from the PTR at higher glass temperatures.

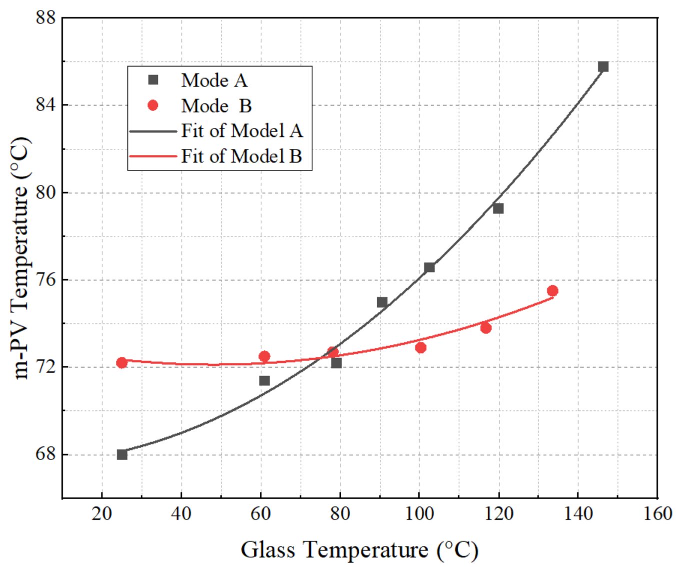

Fig. 4 Comparisons of temperatures of m-PV panels with and without high-reflective coating

Accordingly, the photoelectric efficiencies of PV panels in Mode A and Mode B are calculated and presented in Fig. 5. It can be seen that the photoelectric efficiency of the PV panels decreases with the increasing glass temperature because of the increasing PV temperature caused. For the PTC system, it is thereby necessary to cover the high-reflective coating on the rear surface of the PV panel to improve its photoelectric efficiency.

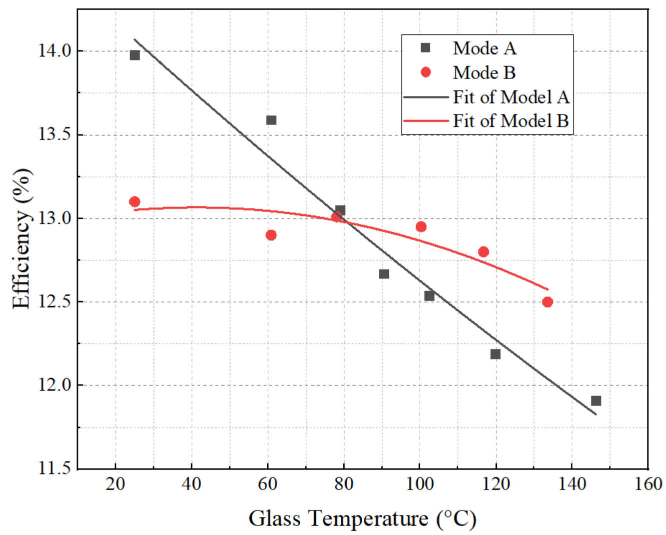

Fig. 5 Comparisons of photoelectric efficiencies of m-PV panels with and without high-reflective coating

3.3 Overall performance of hybrid PTC-PV system

Considering the intercepted one solar radiation by the PV panel, the optical efficiency of the PTC will be slightly reduced. Assuming that the optical efficiency of the traditional PTC system is 0.736, its value will be reduced to 0.724 for the proposed PTC-PV system. However, the one solar radiation blocked is efficiently used by the PV panel. Taking a traditional 100 MW PTC CSP plant as an example, the electricity capacities of PTC-PV (Mode A and Mode B) based CSP plants reach 100.5 and 101.1 MW, and the improvement rates are 0.5 and 1.1 %, respectively. The detailed results and discussions will be introduced later.

4. CONCLUSIONS

In this work, a novel hybrid PTC-PV system is proposed to reduce radiation heat loss from the PTR and improve the power capacity of the concentrated solar power plant. In addition, the PV panels with and without a high-reflective coating on the rear surface are customized and tested in an indoor laboratory at the Hong Kong Polytechnic University. Through the experimental data, the electricity capacity of the CSP plant based on the proposed PTC-PV is evaluated and compared to that based on traditional PTC. The results are summarized as follows.

(1) The novel design of the PV panel integrated PTC system could significantly contribute to reusing upper one solar radiation in the negative thermal-flux region and improving the solar uitilization efficiency.

(2) The high-reflective coating covered on the rear surface of the PV panel can effectively reduce the PV temperature when the temperature of the glass tube in the PTR is above 75 °C.

(3) The electricity capacity of the PTC-PV based CSP plant is effectively improved by 1.1 % compared to the traditional PTC based CSP plant.

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REFERENCE

[1] Shubbak M H. Advances in solar photovoltaics: Technology review and patent trends[J]. Renewable and Sustainable Energy Reviews, 2019, 115: 109383.
[2] Fuqiang W, Ziming C, Jianyu T, et al. Progress in concentrated solar power technology with parabolic trough collector system: A comprehensive review[J]. Renewable and Sustainable Energy Reviews, 2017, 79: 1314-1328.
[3] Wang Q, Yang H, Zhong S, et al. Comprehensive experimental testing and analysis on parabolic trough solar receiver integrated with radiation shield[J]. Applied Energy, 2020, 268: 115004.
[4] He Y L, Wang K, Qiu Y, et al. Review of the solar flux distribution in concentrated solar power: non-uniform features, challenges, and solutions[J]. Applied Thermal Engineering, 2019, 149: 448-474.
[5] Kumar K H, Daabo A M, Karmakar M K, et al. Solar parabolic dish collector for concentrated solar thermal systems: a review and recommendations[J]. Environmental Science and Pollution Research, 2022: 1-33.
[6] Rungasamy A E, Craig K J, Meyer J P. A review of linear Fresnel primary optical design methodologies[J]. Solar Energy, 2021, 224: 833-854.
[7] Bellos E, Tzivanidis C, Tsimpoukis D. Thermal, hydraulic and exergetic evaluation of a parabolic trough collector operating with thermal oil and molten salt based nanofluids[J]. Energy Conversion and Management, 2018, 156: 388-402.
[8] Wang Q, Hu M, Yang H, et al. Energetic and exergetic analyses on structural optimized parabolic trough solar receivers in a concentrated solar–thermal collector system[J]. Energy, 2019, 171: 611-623.
[9] Liu P, Dong Z, Xiao H, et al. A novel parabolic trough receiver by inserting an inner tube with a wing-like fringe

for solar cascade heat collection[J]. Renewable Energy, 2021, 170: 327-340.
[10] Cheng Z D, Men J J, Zhao X R, et al. A comprehensive study on parabolic trough solar receiver-reactors of methanol-steam reforming reaction for hydrogen production[J]. Energy Conversion and Management, 2019, 186: 278-292.
[11] Wang Q, Yang H, Hu M, et al. Optimization strategies and verifications of negative thermal-flux region occurring in parabolic trough solar receiver[J]. Journal of Cleaner Production, 2021, 278: 123407.
[12] Wang Q, Li J, Yang H, et al. Performance analysis on a high-temperature solar evacuated receiver with an inner radiation shield[J]. Energy, 2017, 139: 447-458.