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Techno-economic analysis of the novel solar power towers with unique solar selective coatings prescribed for the negative thermal-flux regions[#]

Qiliang Wang*, Zhicheng Shen, Yao Yao, Hongxing Yang*

Renewable Energy Research Group (RERG), Department of Building Environment and Energy Engineering, The Hong Kong Polytechnic University, Hong Kong, China, qiliang.wang@polyu.edu.hk hong-xing.yang@polyu.edu.hk

ABSTRACT

The solar power tower (SPT) is regarded as the most promising technology used for the next-generation concentrated solar-thermal power (CSP) plant. However, the degraded solar-thermal conversion performance of the solar tower receiver in the SPT system significantly reduces its power generation efficiency and capacity. In the previous study carried out by the authors, an unperceived negative thermal-flux phenomenon was discovered in the tower receiver, which is one of the main reasons for the degradation of the tower receiver's thermal performance. Aiming to eliminate the negative thermal-flux phenomenon, this study proposes a novel optimization method by depositing the unique solar selective-absorbing coatings on the negative thermal-flux regions to improve the solar-thermal conversion performance of these regions. Four kinds of solar selective-absorbing coatings (SSCs) with different spectral selectivities, namely, silver coating, black chrome coating, and ideal coatings with cutoff wavelengths of 2.5 μm and 1.5 μm, are employed to investigate the effects on the heat transfer characteristics of the negative thermal-flux region and overall thermal performance of the tower receiver. Besides, the economic metrics of the above four kinds of novel tower receivers with different solar selective coatings are also evaluated in this study. The results show that the optimization method by SSC substitution at negative thermal-flux regions exerts an excellent role in eliminating the adverse effects of the negative thermal-flux region. The efficiency of the novel tower receiver with an ideal coating could be significantly improved by 12.03 %. In addition, the annual power output of an SPT plant with the novel receiver is effectively improved by 5.0 %, and the levelized cost of energy is reduced by 4.9 %.

Keywords: Solar energy, Concentrated solar power, solar selective coating, tower receiver, techno-economic

NONMENCLATURE

Abbreviations	
SPT	Solar Power Tower
CSP	Concentrated Solar Power
SSC	Solar Selective-absorbing Coating

1. INTRODUCTION

Along with carbon-neutral strategies proposed by many countries, the development and utilization of renewable energy technologies are significant and urgent to realize the scheduled targets [1]. Concentrating solar power (CSP) is one of the dominant solar energy utilization technologies and has drawn much attention from the academic community and industrial sector due to its unique merits of cost-effective thermal storage and superior friendliness to electric grids. With the advancements in CSP technology, the CSP capacity has reached 6 GW as of 2019 [2], and its learning rate is exceptionally high, by above 20% [3]. In general, CSP technology forms mainly include parabolic trough collector, Fresnel collector, tower collector and dish collector. Among them, the solar power tower (SPT) is regarded as the most promising next-generation CSP technology owing to being the most efficient. Once the commercial development cost is reduced, a flourishing benefit will come to the SPT technology.

The SPT is generally composed of heliostats, a tower receiver, thermal storage tanks, power block, etc. The tower receiver is mounted on the top of a tower and has a compact structure, enabling it to have two salient features. The first is the extreme nonuniformity of the concentration ratios of solar irradiance projected on the tower receiver; the maximum and minimum concentration ratios simultaneously occurring on the receiver surface may span three orders of magnitude. The second is the high operating temperatures. Nowadays, for commercial SPT systems, the operating temperature of the tower receiver reaches around 560

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°C by using the binary molten nitrate salt as the heat transfer fluid (HTF) inside of the tower receiver. Furthermore, owing to the development of novel HTFs such as molten chlorine salt and supercritical carbon dioxide, the temperature of the tower receiver in the next-generation SPT system is highly promising to be enhanced to 700—800 °C for improving the generating efficiency of power block in the SPT system. According to Stefan-Boltzmann's law, the total power of radiation emitted across the entire spectrum of wavelengths from a surface at a given temperature is proportional to the fourth power of the Kelvin temperature of the radiating body. Therefore, the enhanced temperatures would conversely incur a sharp increase in radiation heat loss of the tower receiver. As the key component of the SPT system, the tower receiver is responsible for absorbing the concentrated solar irradiance and restricting the radiation heat loss by virtue of the solar selective-absorbing coating (SSC) deposited on the receiver surface. Conceivably, the characters of the SSC exert significantly crucial roles in the thermal performance of the tower receiver [4]. Generally, for the traditional tower receiver with an operating temperature of 560 °C, solar absorption is a higher priority than reducing the radiation heat loss because the radiation heat is one order of magnitude lower than the concentrated solar irradiance. Accordingly, the highest possible absorptance (α) is a proper choice for the conventional SSC, albeit with a high thermal emittance (ε) caused. The representative SSC popularly used in conventional tower receivers is black Pyromark 2500 paint (hereinafter referred to as Pyromark paint), the values of α and ε are around 0.95 and 0.88, respectively. However, for the next-generation SPT system with operating temperatures of 700—800 °C, the sharply increasing emissive heat loss in the tower receiver will appear. The amount of radiation heat loss becomes non-neglectable and even surpasses the solar absorption amount in partial regions of the receiver surface with low concentration ratios. This phenomenon will thereby result in severe thermal performance degradation of the tower receiver. Therefore, it is necessary and significant to reduce the massive radiation heat loss to obtain the most considerable heat gain for the tower receiver.

In the previous study [5], the author explored and investigated the heat transfer characteristics of each region of the tower receiver in detail, and discovered the negative thermal-flux phenomenon at the edge regions of the tower receiver surface. The reason for this phenomenon is that the edge regions of the tower receiver receive pretty low-concentration-ratio solar radiation but harvests high surface temperature. The radiation heat loss related to the temperature will thereby exceed the solar radiation absorption by an even two orders of magnitude, thus causing the negative net heat gain in such regions. The discovery of the negative thermal-flux region in the tower receiver inspires us that the optimization direction of such regions in the tower receiver should focus more on reducing the radiation heat loss rather than maximizing the absorption of the solar energy to obtain the largest heat gain.

In this context, four kinds of SSCs are proposed to cover the negative thermal-flux regions in the tower receiver. The different spectral selectivity characters (solar absorptance, thermal emittance) of four SSCs will exert crucial roles in regulating the heat transfer characteristics of the negative thermal-flux region. In this paper, the effects of different SSCs on the heat transfer characteristics and overall thermal performance of the tower receiver are evaluated and analyzed based on the established spectral heat transfer models. And the economic performance of the novel tower receiver is also investigated by adopting Dunhuang 10 MW SPT plant as the study. This work will further prove the importance of the negative thermal-flux region to the improvement of the overall performance of the tower receiver and SPT, and provide a unique optimization method by regional SSC substitution to improve the performance of the tower receiver. Furthermore, this work will contribute to verifying the applicability and economics of the novel receivers.

2. SPT SYSTEM, MODEL AND METHODOLOGY

2.1 Characteristics of Dunhuang 10 MW SPT system

The diagram of a commercial SPT system is shown in Fig. 1. As the key component of the SPT system, the collector field is responsible for solar absorption and energy conversion to supply thermal energy for the following power block.

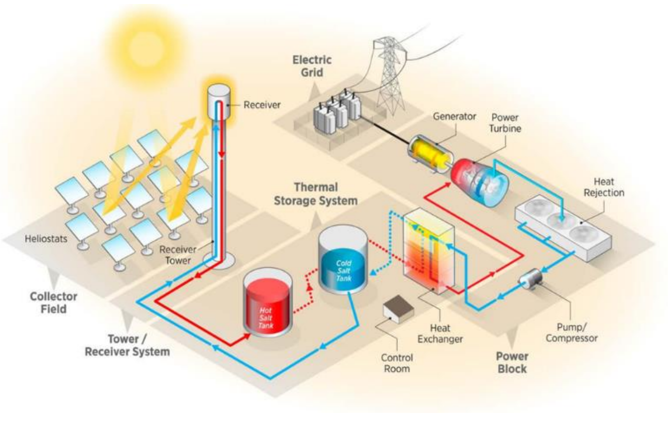

Fig. 1 Diagram of a commercial SPT system [6]

In this study, Dunhuang 10 MW SPT system is selected as the study objective to investigate the optimization method of regional SSC substitutions. The collector field of the Dunhuang 10 MW SPT is presented in Fig. 2 (a) and (b), and the configuration of the tower receiver is exhibited in Fig. 2 (c) and (d). The solar collector field covers 296 acres and consists of 1525 heliostats with a length and width of 10.95 m. The height and diameter of the tower receiver, which is mounted in the high-elevated tower, are 10.5 and 7.3 m, respectively. The key specifications of the SPT system are listed in Table 1.

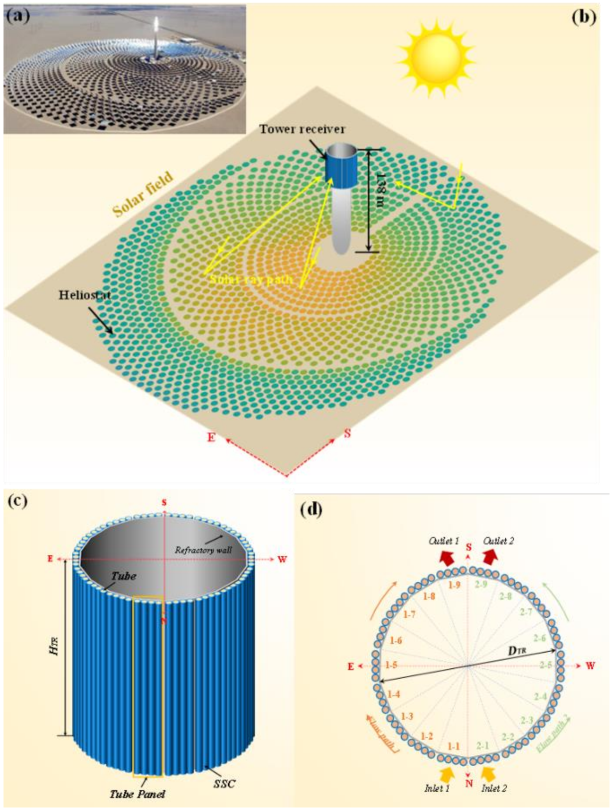

Fig. 2 Collector field of the Dunhuang 10 MW SPT system. (a) A realistic picture of the plant layout [7], (b) schematic diagram of the solar field of the plant, (c) three-dimensional view of the tower receiver, (d) aerial view of the tower receiver.

Table 1 The specifications of the Dunhuang 10 MW SPT system

Parameter	Specification	Parameter	Specification
Solar field	296 acres	Height of receiver	10.5 m
Length and width of heliostat	10.95 m	Diameter of receiver	7.3 m
Heliostat number	1525	Receiver area	240.8 m^2

2.2 *Solar selective-absorbing coatings (SSCs)*

Traditional SSC covered on the tower receiver surface is Pyromark paint, which has high solar absorptance and thermal emittance at the same time. Black chrome coating is a newly developed SSC by the National Renewable Energy Laboratory [8], which has a high solar absorptance but a relatively low thermal emittance compared to the Pyromark paint. Ag coating has an ultra-low spectral absorptance in the whole waveband. Besides the above three real coatings, two ideal coatings with cutoff wavelengths of 1.5 and 2.5 μm are also assumed to investigate their effects. In this study, the values of spectral absorptance (emittance) are assumed to be independent of the temperatures for faster calculations on the premise of sufficient accuracy. The values of spectral absorptance ($\alpha_{s,\lambda}$) of the assumed coating are expressed by the following equation. The spectral selectivity characters of SSCs involved in this study are exhibited in Fig. 3.

$$\alpha_{s,\lambda}(\varepsilon_{s,\lambda}) = \begin{cases} 0.99, \lambda \le \lambda_{cutoff} \\ 0.01, \lambda > \lambda_{cutoff} \end{cases} \tag{1}$$

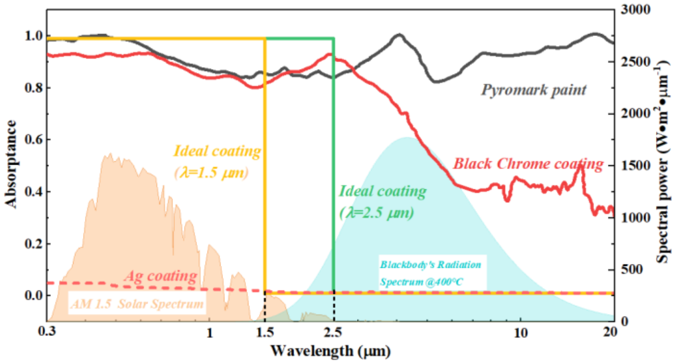

Fig. 3 Spectral selectivity characters of SSCs involved in this study

2.3 *Techno-economic model and methodology*

To investigate the effects of unique spectral characters of the proposed SSCs on the heat transfer characteristics of the tower receiver, a novel spectral heat transfer model is established. It is worth mentioning that the novel model is capable of capturing the spectral-level heat transfer process of the tower receiver, thus harvesting high precisions. In this study, the tower receiver surface is equally divided into 468 regions distributed as an array of 13 rows and 36 columns. The heat transfer processes occurring in each finite volume or divided region are exhibited in Fig. 4 (a). To calculate these heat transfer capacities, a spectral thermal resistance network is built for the finite volume at region (m, n), where m and n represent the row number (1~13) and column number (1~36), respectively, as shown in Fig. 4 (b).

At region (*m, n*), the spectral solar absorption amount ($q_{absorbed,\lambda}$, W/µm) by and spectral emissive radiation ($q_{rad,loss,\lambda}$, W/µm) from the region (*m*, *n*), can be figured out by Eq. (2) and (3).

$$q_{absorbed,\lambda}(m,n)=\alpha_{s,\lambda}A_{eff}E_{solar,\lambda}(m,n) \tag{2}$$

$$q_{rad,loss,\lambda}(m,n)=\frac{E_{b,s,\lambda}(m,n)-E_{b,amb,\lambda}(m,n)}{\frac{1-\varepsilon_{s,\lambda}}{\varepsilon_{s,\lambda}A_{ow}}+\frac{1}{A_{ow}}} \tag{3}$$

Then, the total heat fluxes of absorbed solar irradiance and radiation heat loss of a single region can be obtained by accumulating the spectral heat fluxes in Eqs. (2) and (3) from 0.3 to 100.0 µm:

$$q_{absorbed}(m,n)=\int_{0.3}^{100.0}q_{absorbed,\lambda}(m,n)d\lambda \tag{4}$$

$$q_{rad,loss}(m,n)=\int_{0.3}^{100.0}q_{rad,loss,\lambda}(m,n)d\lambda \tag{5}$$

The convective heat loss from the receiver surface can be calculated by:

$$q_{conv,loss}(m,n)=h_cA_{ow}(T_{ow}-T_{amb}) \tag{6}$$

And the receiver efficiency (*η*) can be obtained:

$$\eta=\frac{Q_{absorbed}-Q_{rad,loss}-Q_{conv,loss}}{Q_{received}} \tag{7}$$

where $Q_{received}$ represents the received solar radiation by the tower receiver surface. In the above equations, the thermal properties of the HTF of binary chlorine salt of $MgCl_2$-KCl varied with the different HTF temperatures can be calculated by the equations presented in [5].

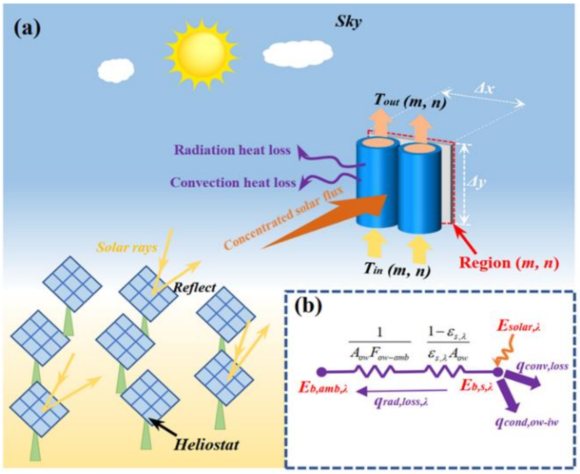

Fig. 4 Schematic diagrams of (a) heat transfer processes occurring in the region (m, n) of the receiver and (b) spectral thermal resistance network of the region (m, n)

Besides, in order to evaluate the economic performance of the novel tower receiver with different SSCs in negative thermal-flux regions, the initial investment costs involved in the SPT plant are presented in Table 2. Additionally, the cost difference between the receiver prototype with a single coating of Pyromark paint and the proposed novel receivers with regional SSC substitution is mainly reflected in the regional SSC. The estimated initial costs of pyromark paint and the other four kinds of novel SSCs are exhibited in Table 3.

***Table 2** Initial investment costs involved in the SPT plant*

Category	**Cost**
Site improvement cost of heliostats	16 $/m^2
Heliostat field	140 $/m^2
Tower	14,500,000 $

***Table 3** Estimated initial costs of five kinds of coatings*

Coatings	**Total costs ($)**
Pyromark paint	88,690
Black Chrome Coating	106,392
Ag coating	83,974
Ideal coating with λ_{cutoff}=2.5µm	110,000
Ideal coating with λ_{cutoff}=1.5µm	110,000

3. RESULTS AND DISCUSSIONS

3.1 Negative thermal-flux region (NTR) and radiation character of NTR after regional SSC substitution

To observe the heat transfer characteristics of the tower receiver in detail, the tower receiver surface is equally divided into 468 regions. Two-dimensional expansion of the tower receiver surface with divided 468 regions is presented in Fig. 5. The heat gain at each region of the tower receiver prototype with traditional Pyromark paint is calculated. It can be seen that the heat gains at the edge regions marked by the green slash line are below 0; the lowest value even reaches −85kW/m^2. This phenomenon occurring in such edge regions is called the negative thermal-flux phenomenon, and these edge regions are named negative thermal-flux regions (NTRs) [5]. The main reason for the negative thermal-flux phenomenon is that the massive radiation heat loss caused by the high surface temperature and high thermal emittance surpasses the absorption amount of the low-concentration-ratio solar radiation.

As exhibited in Fig. 6, the thermal emittance around the tower receiver's surface covered with Pyromark paint is generally up to above 0.9. Companying with high surface temperature, the radiation heat loss is considerably increasing. To reduce or even eliminate the adverse effects appearing in the negative thermal-flux region, four kinds of SSCs shown in Fig. 3 are proposed to substitute the Pyromark paint in NTRs. Of them, the thermal emittance map of the tower receiver with black chrome coating substituted in NTRs is illustrated in Fig. 7. Compared to Fig. 6, the NTRs' thermal emittance is significantly reduced to below 0.7 owing to lower spectral emittance in infrared wavelengths shown in Fig.

3. But simultaneously, the solar absorptance in NTRs would be accordingly reduced due to the lower spectral absorptance in the solar waveband. The detailed solar absorptance and thermal emittance are shown in *Fig. 8*.

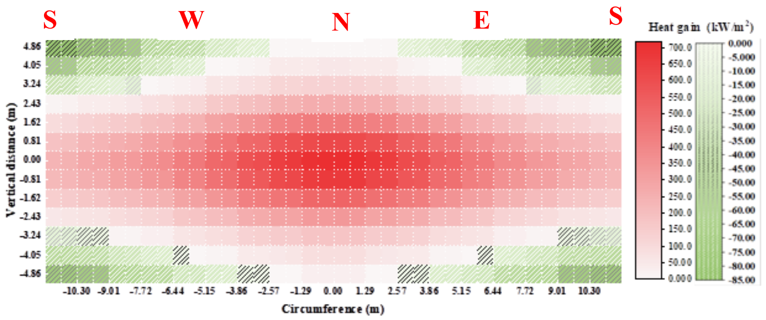

Fig. 5 Heat gain map distributed on the surface of the tower receiver prototype with Pyromark paint

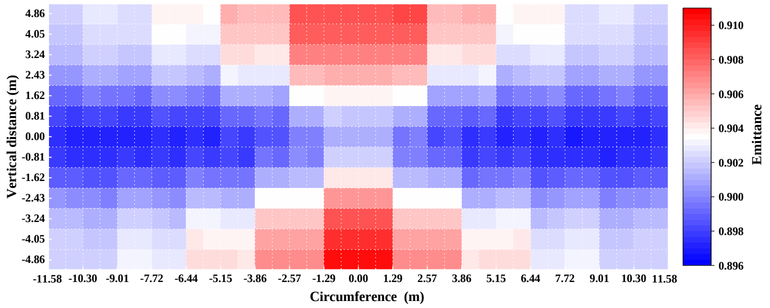

Fig. 6 Thermal emittance map distributed on the surface of the tower receiver prototype with Pyromark paint

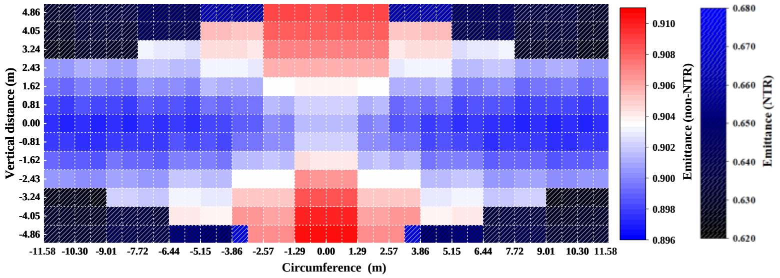

Fig. 7 Thermal emittance map distributed on the surface of the novel tower receiver with regional black chrome coating

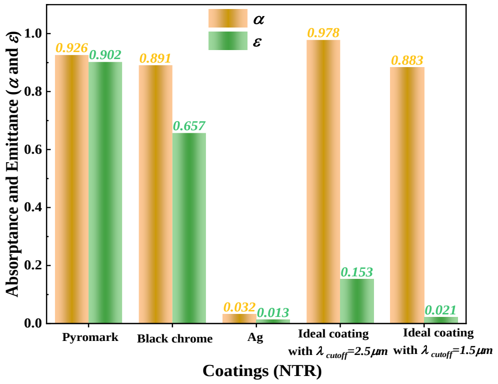

Fig. 8 Solar absorptance and thermal emittance of five kinds of SSCs

It can be seen that the Ag coating has the lowest thermal emittance as well as the solar absorptance. The ideal coating with a cutoff wavelength of 2.5 μm has a solar absorptance. By comparison, the ideal coating with a cutoff wavelength of 1.5 μm has a lower solar absorptance but much lower thermal emittance of around 0.021.

3.2 Heat transfer capacity and Receiver efficiency

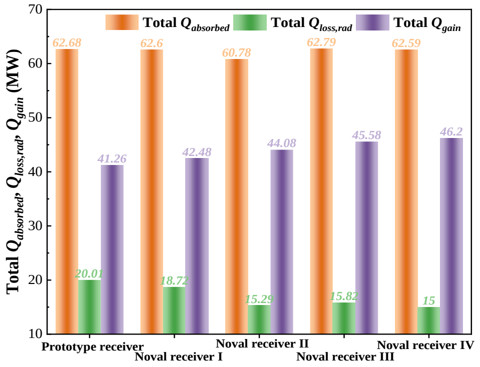

Fig. 9 Heat transfer capacities of the prototype and novel tower receivers

Through calculations, the amounts of solar absorption, radiation heat loss, and heat gain of the different tower receivers are shown in Fig. 9. It can be observed that novel receiver IV with an ideal coating with a cutoff wavelength of 1.5 µm has the smallest amounts of radiation heat loss and highest heat gain. Accordingly, the novel receiver IV harvests the best receiver efficiency up to 0.68 (Fig. 10), and the efficiency improvement rate reaches 12.03 %. Besides, the novel receiver I, II and III also possess superior performance to the prototype receiver, the efficiency improvement rates are 2.97, 6.92, and 10.54 %, respectively, demonstrating great effectiveness of the regional SSC substitutions.

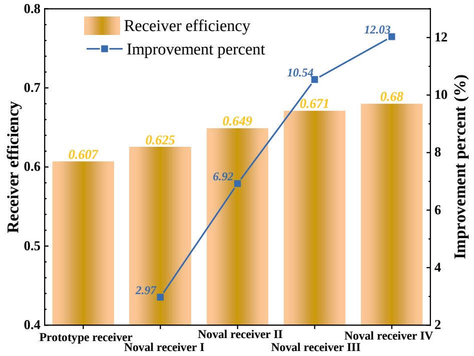

Fig. 10 Receiver efficiency and efficiency improvement rates of four novel tower receivers

Table 4 Techno-economic metrics of SPT plants with novel tower receivers

Items	Prototype receiver	Novel receiver I	Novel receiver II	Novel receiver III	Novel receiver IV
Annual power output (MWh)	52004.3	52598.5	53618.3	54090.5	54613.3
Capacity factor (%)	66.0	66.7	68.0	68.5	69.3
Net capital cost ($1m)	125.9	126.0	125.8	126.2	126.2
Real levelized COE (¢ /kWh)	**13.39**	**13.24**	**12.95**	**12.88**	**12.73**

3.3 Techno-economic metrics

The calculated techno-economic metrics of SPT plants with different tower receivers are shown in Table 4. The novel receiver IV has the best techno-economic performance. Its annual power output and capacity factor reach 54613.3 MWh and 69.3 %, respectively. Although the net capital cost of the novel receiver IV is a little higher than that of the prototype receiver due to the regional coating cost, the levelized cost of energy is significantly dropped to 12.73 ¢ /kWh from 13.39 ¢ /kWh in the prototype receiver. It is worth mentioning that the real coatings, such as Ag coating, also exert a positive role in improving the power output and reducing the levelized cost of energy.

4. CONCLUSIONS

Based on the discovery of negative thermal-flux regions (NTRs) in the tower receiver, a novel optimization method by substituting the conventional coating with the new solar selective coating (SSC) at NTRs is proposed in this study to eliminate the adverse effects caused by NTRs and thus improve the tower receiver's thermal performance. Four kinds of novel SSCs are adopted in this study, and their effects on the thermal performance of the tower receiver and techno-economic performance of the solar power tower plants are comprehensively investigated. The results are summarized as follows.

1) The high thermal emittance of the conventional Pyromark paint, up to 0.9, is the main reason causing the negative thermal-flux regions in the tower receiver.

2) The adopted SSC with low emittance significantly contributes to eliminating the adverse effects of NTRs, and effectively improves the receiver efficiency by up to 12.03 %.

3) The novel receiver with an ideal SSC with a cutoff wavelength of 2.5 µm can effectively improve the annual power output by 5.0 % and reduce the levelized cost of energy by 4.9 %.

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