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A mechanism study of optimal spectral selectivity of solar absorbing coating and thermal performance potential of solar power tower

Qiliang Wang [1, *], Guiqiang Li [2], Gang Pei [2], Hongxing Yang [1]

1 Renewable Energy Research Group (RERG), Department of Building Environment and Energy Engineering, The Hong Kong Polytechnic University, Hong Kong, China

2 Department of Thermal Science and Energy Engineering, University of Science and Technology of China, Hefei 230027, China

ABSTRACT

The solar power tower (SPT) is one of the most common applications of concentrating solar power technology. The tower receiver is the core component in a SPT system, responsible for solar absorption and solar conversion by depositing one single solar selective-absorbing coating (SSC), which usually has a fixed spectral selectivity characteristic. Owing to highly non-uniform optical distribution on the receiver surface, the tower receiver is riddled with complex physics coupled with optical, thermal and mechanical problems. The SSC exerts crucial roles in the activity in the physical process of optical-thermal conversion. However, given the complex physics on the surface of the tower receiver, the common SSCs used in the tower receiver are far from the optimal design of SSC in terms of spectral selectivity, which leads to the less efficient solar-thermal conversion in the tower receiver. In this paper, a comprehensive spectral heat transfer model of the tower receiver was first established and verified. The calculation accuracy of the proposed model was significantly improved by 10% compared with the conventional model. In this context, the mechanism of optimal spectral selectivity of SSC in response to the different concentration ratios and service temperatures was fully revealed. Dunhuang 10 MW SPT was selected as a study case, and the tower receiver covered with a variety of SSCs with optimal spectral selectivity was analyzed. The potential performance in the solar-thermal conversion of the tower receiver was analyzed as well. The results showed that the optimal spectral selectivity of SSC varied dramatically with the solar irradiance density and receiver surface's temperature, revealing the mismatches problem of the current SSC on the next-generation SPT system. The tower receiver with optimal SSCs exhibited the largest improvement potential in receiver efficiency and pointed out the development direction for the next-generation tower receiver.

Keywords: Concentrating solar power, Solar power tower, Solar absorbing coating, Spectral selectivity, Solar energy conversion, Spectral heat transfer.

1. INTRODUCTION

Along with carbon-neutral strategies proposed by many countries, the development and utilizations of renewable energy technologies are significant and urgent to realize the scheduled targets. 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 advancement of CSP technology, the CSP capacity has reached 6 GW as of 2019 [1], and its learning rate is exceptionally high, by above 20%. In general, CSP technology forms include parabolic trough collector, Fresnel collector, tower collector and dish collector [2-5]. Among them, the solar power tower (SPT), composed of tower collectors, is regarded as the most promising next-generation CSP technology owing to its much higher operating temperature and compact receiver compared to the mature parabolic trough collector. The tower receiver is the sole equipment in the SPT system responsible for receiving, absorbing, converting the incoming solar irradiance concentrated from the around heliostats on the ground, which is thereby the key component in the solar heliostat field of the SPT system. Nowadays, the outlet temperature of the tower receiver reaches around 560 °C by using the binary molten nitrate salt as the heat transfer fluid (HTF) inside of tower receiver [6]. And its temperature is highly promising to be enhanced to 700-800 °C in the future owing to the development of novel HTFs, such as molten chlorine salt and supercritical carbon dioxide, which will much contribute to improving the generating efficiency of power block in the SPT system. In such a context, the tower receiver will encounter the challenge of thermal

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performance degradation due to the high operating temperature.

According to the experimental Stephan's law [7], the total power of radiation emitted across the entire spectrum of wavelengths at a given temperature is proportional to the fourth power of the Kelvin temperature of the radiating body. Generally, for the traditional SPT system with 560 °C operating temperature, the highest possible absorption of solar energy is the priority for the design of the tower receiver regardless of emissive heat from the receiver surface since the emissive heat from the tower receiver is one order of magnitude lower than the solar radiation absorption. Accordingly, the receiver surface is usually covered with a solar absorbing coating which has high solar absorptivity (α) but simultaneously high infrared emissivity (ε), such as popularly used black Pyromark paint (α=0.94, ε=0.88) [8]. However, for the next-generation SPT system with 700-800 °C operating temperature, the sharply increasing emissive heat occurring in the tower receiver may surpass the solar absorption amount in partial regions of the receiver surface and thus result in severe thermal performance degradation of the tower receiver at high operating temperatures. Therefore, the infrared emissivity of solar absorbing coating should be fully considered in the next-generation SPT system other than the solar absorptivity, which has long been focused.

Nowadays, many efforts have been made to develop the advanced solar selective-absorbing coatings (SSCs), which have much lower infrared emissivity compared to the traditional Pyromark paint [9]. However, it can be observed from the above literature that the most of advanced SSCs are developed still following the rule of first design priority of high absorptivity in the solar spectrum of 0.3-2.5 μm for the premise of the most considerable solar absorption. Then, the second design priority of low emissivity in the band above 2.5 μm is considered for the reduction of infrared radiation heat. This design idea results in a tradeoff between solar absorptivity and infrared emissivity, i.e., a high solar absorptivity above 0.9 and a medium infrared emissivity of 0.4-0.8. Given the highly nonuniform concentrating solar flux distribution and high temperature on the surface of the next-generation tower receiver, it is significant to verify the correctness of such a tradeoff for the SSC. There are no relative reports about the calculation method and analysis on the optimal tradeoff of the selectivity SSC in the external-type tower receiver.

In this paper, a novel spectral heat transfer model was established. In general, the traditional heat transfer model of the tower receiver [10] only considers the average radiation property parameters (i.e., absorptivity, emissivity, reflectivity) and total radiant powers of tower receiver, surroundings, and received solar energy. Different from such traditional heat transfer model, the newly established one adopted the spectral radiation property parameters and spectral radiant powers, enabling it to capture and analyze the impacts of the spectrum profile of SSC on the thermal performance of tower receiver with more robust prediction ability. In consideration of highly non-uniform solar flux and temperature at different regions of the receiver surface, the cylinder surface of the receiver was equally divided into 468 regions for the ease of observing and analyzing their optimal spectral selectivity characters. In this study, the Dunhuang 10 MW SPT plant was selected as the study case. With an objective of the maximum heat gain obtained by the receiver, the optimal tradeoff between the absorptivity and emissivity for the SSC at each region was investigated by regulating the cutoff wavelength of SSC, a key parameter indicating the spectral selectivity propagation. Additionally, the thermal performance potential of the tower receiver under optimally regional tradeoff of radiation properties of SSC was also studied in detail. The research will contribute to filling in gaps of spectral selectivity profiles of SSC in the next-generation SPT system and providing the scientific reference for the optimization direction of advanced SSC.

2. GEOMETRY AND MODEL

2.1 Dunhuang 10MW SPT plant and tower receiver

Dunhuang 10 MW SPT plant is located in Dunhuang (40.15°N, 94.68°E), northwest of China. The external-type central receiver is mounted on the top of the tower with a height of 138 m. The surrounding heliostats concentrate the incoming solar rays to the surface of the tower receiver. It is worth mentioning that the Dunhuang 10 MW SPT plant is renovating from a conventional steam Rankin cycle into a supercritical CO_2 Brayton cycle, demonstrating a fitting case for this study about the next-generation SPT technology. The tower receiver, as shown in Fig. 1 (a), is the key component of the SPT system for realizing the solar-thermal conversion and thus providing the high-temperature heat for the subsequent power block. The tower receiver has a height (H_{CR}) of 10.5 m and a diameter (D_{CR}) of 7.3 m. As shown in Fig. 2(a) and (b), the tower receiver is composed of 18 tube panels in the circumferential. A single tube panel has a width (W_{panel}) around 1.29 m and consists of 31 tubes. The outer and inner diameters of a single tube are 40 and 37.5 mm, respectively. Black Pyromark paint, generally regarded as a graybody with a diffuse surface, deposits on the outer surface of tubes.

According to the setup of the commercial SPT plant [11], 18 tube panels are divided into symmetrical two flow paths (flow path 1 and flow path 2), as shown in Fig. 1 (b). Two inlets (inlet-1 and inlet-2) and outlets (outlet-1 and outlet-2) are located on the north and south sides of the tower receiver, respectively. The binary molten chlorine salt ($MgCl_2$-KCl, 38-62 wt%) is selected as the HTF in this study.

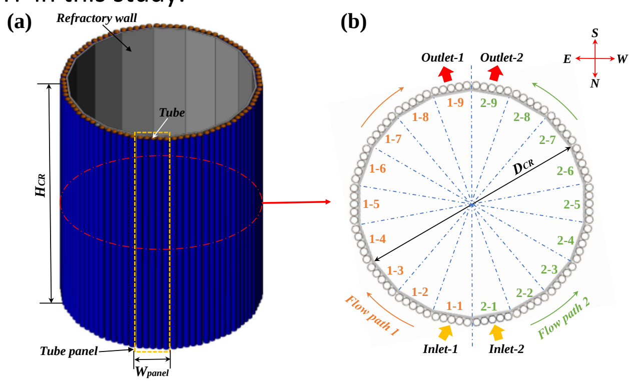

Fig. 1 Schematic diagram of the tower receiver: (a) Three-dimensional view, (b) Aerial view.

2.2 Assumptions, model and method

2.2.1 Principle and Assumptions

In order to obtain universal and scientific rules of the tradeoff of radiation property parameters of the SSC deposited on the receiver surface, ideal values of spectral selectivity characters were adopted in this study. That is, the spectral absorptivities ($\alpha_{s,\lambda}$) of the SSC at the wavebands shorter and longer than the cutoff wavelength (λ_{cutoff}) are determined as 0.99 and 0.01, respectively.

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

It is worth explaining that the cutoff wavelength (λ_{cutoff}) is defined as the maximum wavelength at which the radiation property parameters such as absorptivity will propagate. As shown in Fig. 2, the radiation power from the receiver surface sharply increase with the elevated temperature, and the radiation spectrum has an increasing overlap with the solar spectrum with growing receiver temperature. These facts lead to the explosive radiation heat loss from the receiver covered by the SSC with a cutoff wavelength of around 2.5-3 μm. For the receiver surface's partial regions only receiving low concentration-ratio solar irradiance but possessing high temperature, the radiation heat loss probably exceeds the absorbed solar irradiance. Thus, the heat gains at such regions are of high probability to be negative. Therefore, it is necessary and significant to analyze the tradeoff of absorptivity.

In theory, the spectral absorptivity is equal to the spectral emissivity, and their values would slightly vary with the temperature. In this study, the values of spectral absorptivity (emissivity) are assumed to be independent of the temperatures for faster calculations on the premise of sufficient accuracy.

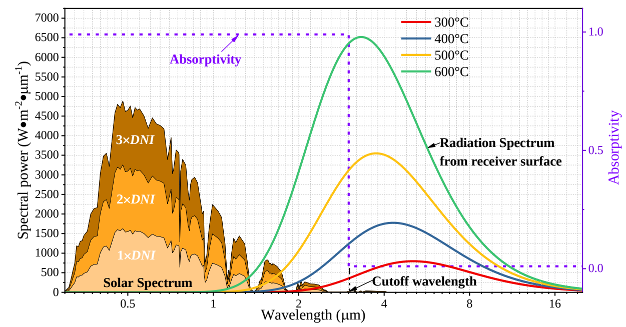

Fig. 2 Spectral radiation powers of solar irradiance (DNI=1000W/m^2, AM 1.5) and receiver surface as well as the cutoff wavelength of the ideal SSC

2.2.2 Model and method

In this study, an optical model of FluxSPT relying on the MCRT method was employed to calculate the optical property of the solar field, i.e., detailed solar flux and concentration ration (C) distributions projected on each region of the receiver surface. In this section, a detailed spectral heat transfer model of the tower receiver is established, relying on the finite volume method. The total receiver is equally divided into 468 control volumes distributed as an array of 13 rows and 36 columns, simultaneously corresponding to the divided regions, as shown in Fig. 3.

As mentioned above, the built model employs spectral radiation property parameters and spectral radiation powers, namely, spectral absorptivity or emissivity ($\alpha_{s,\lambda}$ or $\varepsilon_{s,\lambda}$, values of both are equal), blackbody's spectral radiation power of the receiver surface ($E_{b,s,\lambda}$), blackbody's spectral radiation power of the ambient ($E_{b,amb,\lambda}$), spectral radiation power of received solar irradiance ($E_{solar,\lambda}$). The values of $E_{b,s,\lambda}$ and $E_{b,sky,\lambda}$ can be calculated by the formula:

$$E_{b,\lambda}(T,\lambda) = 3.742\times10^{8} \Big/ \lambda^{5}\{\exp[1.439\times10^{4}/(\lambda T)]-1\} \quad (2)$$

where T refers to the receiver's outer wall temperature and sky temperatures (T_{ow} and T_{amb}) respectively when used to calculate $E_{b,s,\lambda}$ and $E_{b,amb,\lambda}$ for the specific control volume at position (i, j). i and j represent the row number (1~13) and column number (1~36), respectively. With achieved values of $E_{b,s,\lambda}$, $E_{b,amb,\lambda}$, and $E_{solar,\lambda}$ as exhibited in Fig. 2, the spectral heat fluxes of solar absorption ($q_{absorbed,\lambda}$) by and emissive radiation ($q_{rad,loss,\lambda}$) from the receiver surface at position (i, j) can be figured out.

$$q_{absorbed,\lambda}(i,j)=\alpha_{s,\lambda}A_{eff}E_{solar,\lambda}(i,j) \quad (3)$$

$$q_{rad,loss,\lambda}(i,j)=\frac{E_{b,s,\lambda}(i,j)-E_{b,amb,\lambda}(i,j)}{\dfrac{1-\varepsilon_{s,\lambda}}{\varepsilon_{s,\lambda}A_{ow}}+\dfrac{1}{A_{ow}}} \quad (4)$$

where A_{eff} and A_{ow} represent the effective area to receive the incoming solar energy and outer wall area of a single region on the receiver surface, m^2. It is worth mentioning that the value of $\alpha_{s,\lambda}$ ($\varepsilon_{s,\lambda}$) will vary at the determined cutoff wavelength as shown in Eq. (1). In subsequent, the total heat fluxes of absorbed solar energy and radiation loss of a single region will be obtained by accumulating the spectral heat fluxes from 0.3 to 100.0 µm:

$$q_{absorbed}(i,j)=\int_{0.3}^{100.0}q_{absorbed,\lambda}(i,j)d\lambda \quad (5)$$

$$q_{rad,loss}(i,j)=\int_{0.3}^{100.0}q_{rad,loss,\lambda}(i,j)d\lambda \quad (6)$$

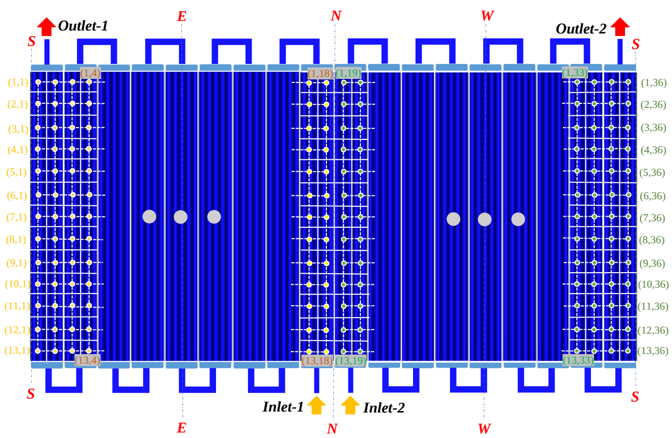

Fig. 3 468 regions and control volumes divided equally

Besides the radiation heat loss, the convective and conductive heat losses between the receiver and ambient are the essential parts of the total heat loss occurring on the receiver surface. The conductive heat loss is negligible in this study due to its much less amount than the radiation and convective heat loss. The convective heat loss from the receiver surface can be calculated by:

$$q_{conv,loss}(i,j)=h_c A_{ow}(T_{ow}-T_{amb}), \quad (7)$$

where h_c represents the comprehensive convective heat transfer coefficient, W/(m^2·K).

The absorbed solar energy $q_{absorbed}$ *(i,j)* will be partially transmitted into the inside of the tube by conduction mode and then converted to the thermal energy of HTF mainly by convection mode. The conductive heat transfer from the outer wall to the inner wall of the tube ($q_{cond,ow\text{-}iw}$) and convective heat transfer from the inner wall to the HTF ($q_{conv,iw\text{-}HTF}$) are presented as the following formulas:

$$q_{cond,ow-iw}(i,j)=\frac{2\pi\Delta y k_{tube}(T_{ow}-T_{iw})}{\ln\left(D_{tube,iw}/D_{tube,ow}\right)}\times 15.5 \quad (8)$$

$$q_{conv,iw-HTF}(i,j)=\pi D_{tube,iw}\Delta y h_f(T_{iw}-T_f)\times 15.5 \quad (9)$$

where Δy is the height of a single region divided, m; k_{tube} is the thermal conductivity of the tube, W/(m·K); and the value of 15.5 represents the tube number in a single region *(i,j)*.

In the calculation process of the above finite volumes, two iteratively calculated parameters of T_{ow} and T_{iw} in every region can be determined based on two energy balance equations as follows:

$$\begin{cases} q_{absorbed,\lambda}(i,j)=q_{rad,loss,\lambda}(i,j)+q_{conv,loss}(i,j)+q_{cond,ow-iw}(i,j) \\ q_{cond,ow-iw}(i,j)=q_{conv,iw-HTF}(i,j) \end{cases} \quad (10)$$

Subsequently, the heat gain of the HTF ($q_{gain,HTF}$) in a specific region *(i, j)* can be expressed:

$$\begin{cases} q_{gain,HTF}(i,j)=c_{p,f}m_f(T_{out}(i,j)-T_{in}(i,j))\times 15.5 \\ q_{gain,HTF}(i,j)=q_{conv,iw-HTF}(i,j) \end{cases} \quad (11)$$

where $c_{p,f}$ is the specific heat of the HTF, J/(kg·K); m_f is the mass flow rate of HTF in a single tube, kg. It should be noted that the values of m_f in flow paths 1 and 2, depending on the actual solar flux and environmental conditions, are different. T_{out} and T_{in} represent the outlet and inlet temperatures of the region *(i, j)*. In the iterative calculations of the model, the T_{in} *(i, j)* is the outlet temperature of the previous region.

As a result, the total solar irradiance absorbed, total radiation heat loss, total convective heat loss and total heat gain by the HTF in the whole receiver can be calculated by the expressions:

$$Q_{absorbed}=\sum_{i=1}^{i=13}\sum_{j=1}^{j=36}q_{absorbed}(i,j), \quad (12)$$

$$Q_{rad,loss}=\sum_{i=1}^{i=13}\sum_{j=1}^{j=36}q_{rad,loss}(i,j), \quad (13)$$

$$Q_{conv,loss}=\sum_{i=1}^{i=13}\sum_{j=1}^{j=36}q_{conv,loss}(i,j), \quad (14)$$

$$Q_{gain,HTF}=\sum_{i=1}^{i=13}\sum_{j=1}^{j=36}q_{gain,HTF}(i,j). \quad (15)$$

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

$$\eta=\frac{Q_{gain,HTF}}{Q_{received}}, \quad (16)$$

where $Q_{received}$ represents the total received solar irradiance by the receiver surface, W.

3. RESULTS AND DISCUSSIONS

3.1 Regulations of cutoff wavelength with varied concentration-ratios and temperatures

The cutoff wavelength is a crucial parameter determining the radiation properties of the SSC, i.e., solar absorptivity and infrared emissivity. A shorter cutoff wavelength demonstrates a lower solar absorptivity and a lower infrared emissivity. The tradeoff between absorptivity and emissivity is of high significance for the tower receiver with extremely uneven solar fluxes and high operating temperatures. To verify the correctness of the traditional tradeoff, the universal selection rules of optimal cutoff wavelength along with different concentration ratios and temperatures are investigated.

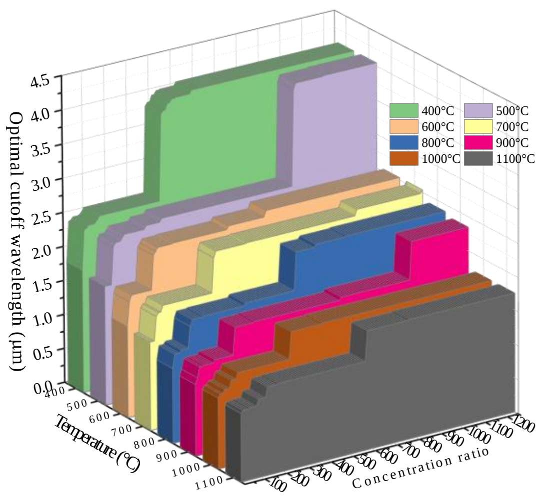

Fig. 4 Regulations of optimal cutoff wavelength with varied concentration ratios and temperatures

In this section, the direct normal irradiance (DNI), wind speed, ambient temperature used in the model are set as 800W/m^2, 1.0 m/s, and 25 °C, respectively. It is demonstrated from Fig. 4 that the optimal cutoff wavelength of ideal SSC regulates to a lower value with response to smaller concentration ratios and higher temperatures for pursuing the most considerable heat gain. The smaller concentration ratios lead to low-intensity solar irradiance capable of being received by the surface. When the surface possesses an increasing temperature, the cutoff wavelength of ideal SSC shifts to a shorter spectrum for harvesting a lower infrared emissivity and thus obtaining much lower radiation heat loss. Though the solar absorption amount is decreased due to the reduced solar absorptivity, the decrement of radiation heat loss is larger than that of the solar absorption amount, which will contribute to capturing the most significant heat gain. On the contrary, the higher concentration ratio and lower temperature prompt the cutoff wavelength to move to the longer spectrum for achieving higher solar absorptivity and thus harvesting more solar absorption amount. As exhibited in Fig. 4, the cutoff wavelength is up to around 4.0 μm in the case of $C > 350$ and $T = 400$ °C and the case of $C > 850$ and $T = 500$ °C. Meanwhile, the shortest cutoff wavelength of around 1.0 μm occurs in the case of $C = 10$ and $T = 1100$ °C.

Additionally, the regulation of cutoff wavelength with the varied *DNIs* under the determined surface temperature of 700 °C is also investigated in this section. Similar to the conclusion above, when the *DNI* is higher, the cutoff wavelength jumps to a higher position at a lower concentration ratio, as exhibited in Fig. 5.

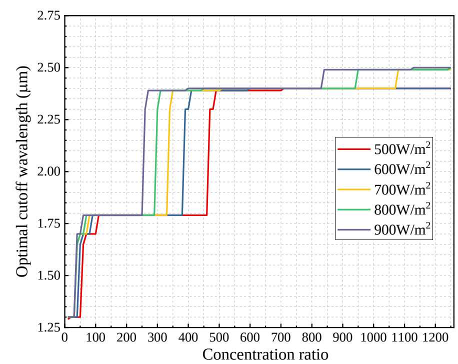

Fig. 5 Regulations of optimal cutoff wavelength with varied concentration ratios and DNIs

3.2 Distribution of optimal cutoff wavelength in the tower receiver

In this section, the regionally optimal cutoff wavelengths of the tower receiver in Dunhuang 10 MW SPT plant were calculated relying on the built spectral heat transfer model. To focus on the thermal performance of next-generation SPT technology, the HTF used the binary chlorine salt ($MgCl_2$-KCl, 38-62 wt%) which is regarded as a promising high-performance next-generation fluid. The mass flow rate of HTF and inlet temperature of the tower receiver were set as 520 °C. Relying on the tool of FluxSPT and annual weather data in Dunhuang, the yearly average solar flux distribution on the receiver surface is achieved and shown in Fig. 6. In this context, the optimal cutoff wavelength of the ideal SSC at each region is calculated and exhibited in Fig. 7. It is observed that there are three distinct areas with different cutoff wavelength ranges. Long, medium, and short cutoff wavelengths in the ranges of 2.0~2.5, 1.7~2.0, and 1.0~1.7μm focus on the central, external ring, and edge regions on the receiver surface, respectively. The reason for this distribution is that the central regions have high-intensity solar irradiance and low operating temperature, while the edge regions have low-intensity solar irradiance and high operating temperature, thus longer and shorter cutoff wavelengths with response to the above two regions contribute to harvesting the largest heat gains.

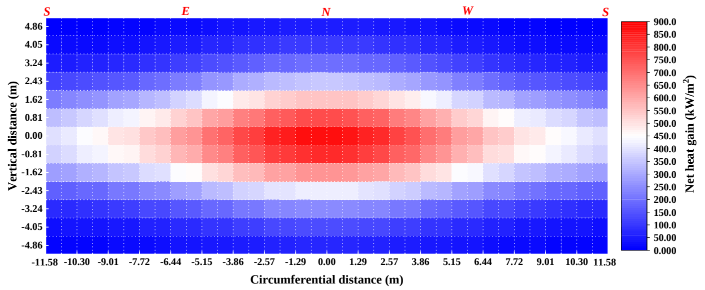

Fig. 6 Distribution of solar flux on the receiver surface

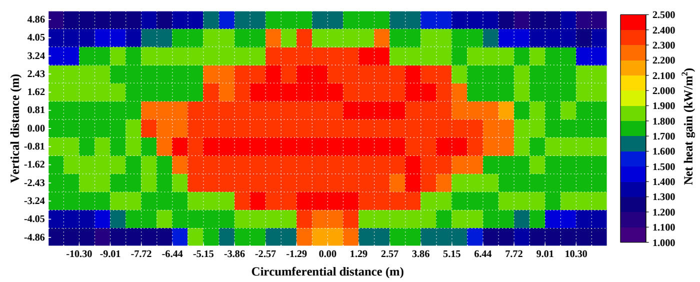

Fig. 7 Reginal optimal cutoff wavelength of the ideal SSC on the receiver surface

3.3 Thermal performance potential of novel receiver

Table 1 Operating parameters and heat transfer metrics of prototype and novel receivers

Item	Prototype Receiver	Novel Receiver	Improvement value
Inlet-1 and 2 temperatures	520.0 °C		\
m in flow paths 1 and 2	100 kg/s		\
Outlet-1 temperature	702.11 °C	804.98 °C	+102.87 °C
Outlet-2 temperature	699.77 °C	801.72 °C	+101.95 °C
Total solar absorption amount	63.83 MW	64.94 MW	+ 1.74 %
Total radiation heat loss	15.47 MW	1.95 MW	- 87.39%
Total heat gain	46.98 MW	61.61 MW	+31.34%
Receiver efficiency	0.691	0.907	+31.34%

As presented in Table 1, the novel receiver with the ideal SSC demonstrates the most immense potential of thermal performance of the tower receiver. Compared with the prototype tower receiver covered with Pyromark paint, the novel receiver with the ideal SSC harvests almost the same solar absorption amount but is capable of reducing the radiation heat loss by 87.39%. Therefore, the heat gain and receiver efficiency of the latter can be significantly enhanced by 31.34 %.

4. CONCLUSIONS

In order to explore the largest potential of thermal performance of the tower receiver, the optimal cutoff wavelengths of the ideal solar selective-absorbing coating at different regions were investigated to achieve the best tradeoff of the solar absorption amount and radiation heat loss. Based on the established novel spectral heat transfer model, the universal mechanism of the optimal cutoff wavelength varied with the solar irradiance and temperature was studied. By taking the Dunhuang 10MW SPT plant as the case, the largest potential of thermal performance of the tower receiver was studied.

The results showed that the optimal cutoff wavelength shifted to a longer spectrum at the higher solar irradiance and lower temperature. The receiver efficiency of the novel receiver with the ideal SSC can be significantly enhanced by 31.34 % compared with the conventional receiver, pointing out the optimization direction of the SSC and next-generation SPT system.

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