Assessment of Performance Enhancement Potential of a High-Temperature Parabolic Trough Collector System Combining the Optimized IR-Reflectors

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Abstract: Heat collecting elements (HCEs) are the core components in the parabolic trough collector (PTC) system because photothermal conversion of the whole system occurs in the HCEs. However, considerable heat loss from the HCEs at high operating temperature exerts seriously negative impact on the photothermal conversion efficiency of the PTC system and subsequent application systems. To effectively reduce the heat loss and thus enhance the overall performance of the PTC system, in our previous work, we proposed three kinds of novel HCEs by partially depositing different IR-reflector coatings on the inner and outer surfaces of the glass envelope. The infrared (IR)-reflector of actual transparent conductive oxide (TCO) film, IR-reflector with a fixed cutoff wavelength of 2.5 μm, and the IR-reflector with optimal cutoff wavelength showed extremely effective roles in the reduction of heat loss in HCEs. In this paper, the comprehensive energy and exergy performances of these three novel HCEs in a real 72 m small-scale PTC system are further investigated by the mathematical models established. Additionally, the comparisons among overall performances of the proposed HCEs under different direct solar irradiances are also carried out. The results show that the simulated data yields good consistence with the experimental results, and that all three of the novel HCEs achieve superior overall performance compared with the conventional HCEs. The PTC system installing the novel HCEs with the IR-reflector coating which possesses the optimal cutoff wavelength has the best energetic and exergetic efficiencies, which are significantly improved by 25.2% and 28.1% compared with the conventional HCEs at the solar irradiance of 800 W/m² and inlet temperature of 580 °C. Moreover, the proposed novel HCEs have a much superior performance at lower solar irradiance. The performance-enhanced PTC system will play a significantly positive role in the performance improvement of the heating and cooling of buildings in the future.

Keywords: parabolic trough collector; CSP; solar receiver; efficiency; reflector

1. Introduction

At present, high-temperature solar-thermal conversion processing is accomplished mainly by the concentrated solar collection technologies [1,2], with the implementation forms including the parabolic trough collector system, tower collector system, dish collector system, and linear Fresnel collector system [3–5]. With the increasing market values, the concentrated solar collection
technologies develop fast and are popularly applied into solar-thermal utilizations such as solar heating/cooling in buildings, solar desalination, concentrated solar power (CSP) [6–8], etc.

The parabolic trough collector (PTC) is the most mature technology and is popularly employed all over the world. The PTC system is mainly composed of trough mirrors, heat collecting elements (HCEs), structural support, and a sun-tracking system [9]. In the heat collection process of the PTC system, solar rays projected on the trough mirrors are reflected and concentrated onto the HCEs, the most of rays would pass through the glass envelope, and are blocked and absorbed by the absorber tube deposited with solar selective-absorbing coating (SSC) [10], then the solar energy absorbed is eventually converted into the heat energy of heat transfer fluid (HTF) flowing inside of absorber tube. At present, the operating temperature of PTC system approximately reaches 400 and even 550 °C as the HTFs are therminol oil or molten salt [11–13]. Under such high temperatures, HCEs face with many challenges. Besides the structural deformation and poor reliability of HCEs at high operating temperatures [14], considerable heat loss is another knotty and urgent problem. According to the study conducted by National Renewable Energy Laboratory [15], the heat loss increases rapidly with the absorber temperature raised to fourth power, which accounts for almost 19.4% of solar irradiance by the HCE at absorber temperature of 550 °C, i.e., absolute decrease of thermal efficiency by 19.4% would occur in the PTC system due to excessive heat loss. Therefore, the reduction of heat loss in HCEs at high operating temperature is definitely vital for the further development of the PTC system.

Material properties enhancements of the key components in the HCE are the solutions popularly employed by researchers to reduce the heat loss of HCEs. For instance, SSC with lower emittance has been studied and developed for a long time. Up to now, the emittance of state-of-the-art SSC is about 0.09 at 400 °C [16]; the room for the further decrease of emittance is small because the absorptance of SSC would suffer much with the lower emittance. Therefore, the solution by enhancing the properties of materials hardly exerts effective role in reducing the heat loss. In our previous study [17], we discovered and proposed the negative thermal-flux region (negative energy-flow region) which occurs in approximately upper half of HCE; the discovery of the negative thermal-flux region (NTR) spawned novel optimization methods to effectively reduce the heat loss and improve the overall performance of HCEs. Taking the EuroTrough collector and Schott PTR70 solar receiver as an example [18]: due to the special structural characteristics of the PTC system, the HCE receives 80 times direct normal irradiance (80× DNI) at the approximately lower half of the HCE facing the trough mirrors, but only receives one direct normal irradiance (1× DNI) at the upper half of the HCE facing the sun as shown in Figure 1. This fact causes a phenomenon that the heat loss of the HCE in the upper half would exceed the absorbed solar energy in this part when the operating temperature is high enough. Consequently, the phenomenon of negative net heat gain in the upper half occurs, and this part in the HCE is thus named as the negative thermal-flux region (see literature [17] for more detail information). Therefore, the reduction of heat loss is vital for the improvement of the net heat gain of the HCE in the NTR. In this framework, an optimization method by depositing IR-reflector coatings on the glass envelope of the HCE in the NTR to reduce the heat loss in the NTR was proposed.
Figure 1. Schematic diagram of novel heat collecting elements (HCEs) with infrared (IR)-reflectors on the glass envelope in the negative thermal-flux region.

IR-reflective coating, which has high reflectance in the infrared wavelength band and high transmittance in the solar irradiance wavelength band, was employed and deposited on the inner and outer surfaces of glass envelope in the (NTR as shown in Figure 1 [19]. IR-reflective coating on the inner surface of glass envelope can effectively block the infrared emissive heat loss from the absorber tube in the NTR, and the IR-reflective coating on the outer surface of glass envelope can reduce the emissive heat loss from the glass envelope due to its low infrared emittance. However, the IR-reflective coatings would inevitably incur the solar irradiance loss due to the reduced transmittance of the glass envelope with IR-reflective coatings. Taking the actual transparent conductive oxide (TCO) film [20] as an example, the solar irradiance transmittance of this IR-reflective is 69.9%, which means approximately 30% of the incoming solar irradiance cannot pass through the TCO film, thus forming additional solar irradiance loss. Generally, an ideal IR-reflective is designed with a determined cutoff wavelength ($\lambda_c$) at which the spectral property of material, such as spectral transmittance, spectral reflectance, changes sharply (Figure 2). The value of $\lambda_c$ is usually selected as the fixed value of 2.5 μm to obtain the maximum solar transmittance in the case of lower service temperature. This is because the blackbody’s emissive power from the surroundings under lower temperature mainly locates in infrared wavelength band above 2.5 μm (such as 373 K exhibited in Figure 2), that coincides well with the spectral selectivity of IR-reflective with a fixed cutoff wavelength of 2.5 μm. In the case of high service temperature such as 400–550 °C in HCEs, a conventional ideal IR-reflective with the cutoff wavelength of 2.5 μm still enables the vast majority of solar irradiance to pass through, but the effectiveness of blockage of emissive heat loss of the HCE in the NTR is definitely reduced. This is because the emissive heat loss of the HCE at high temperatures explosively increases, and the main wavelength band at which blackbody’s emissive power from the absorber tube locates would shift to lower wavelength (such as 673 K exhibited in Figure 2) [21], these two factors result in the escape of a fair amount of heat loss below 2.5 μm from the absorber tube to the surroundings. In this framework, the cutoff wavelength of ideal IR-reflective coating was optimized and shifted to lower optimal cutoff wavelength ($\lambda_{opt}$) as shown in Figure 2. The optimized ideal IR-reflective coating optimally weighs the amount of transmitted solar irradiance and that of blocked emissive heat loss in the NTR, and thus maximizing the net heat gain in the NTR. The novel HCEs (NHCEs) with three kinds of IR-reflective (IRR) coatings, namely, TCO coating (NHCE-IRR-I), ideal IRR with a fixed cutoff wavelength of 2.5 μm (NHCE-IRR-II), and ideal IRR with optimal cutoff
wavelength (NHCE-IRR-III), were proposed, and the heat loss performance of three kinds of NHCEs was preliminarily analyzed in the previous work [19].

![Figure 2](image_url)

**Figure 2.** The selectivity characteristics of ideal IR-reflector coating.

To further verify their overall performances in a real PTC system and observe the maximum potential of IR-reflector coating on the performance enhancement of PTC system, in this study, three kinds of NHCEs (NHCE-IRR-I, NHCE-IRR-II, NHCE-IRR-III) are employed into a small-scale PTC field with a 72 m loop. The energetic and exergetic performances of different NHCEs are numerically investigated and compared by the established mathematical models. Additionally, the effects of two key parameters, namely, operating temperature and DNI, on the overall performance of the NHCE are also explored. Promisingly, the performance-enhanced PTC system with the NHCEs could contribute to the efficient building heating and cooling systems.

2. Models and Methodology

2.1. Characteristics of Three Kinds of IR-Reflector Coatings

The transparent conductive oxide (TCO) film (marked as IRR-I) used in this study mainly consists of In$_2$O$_3$:Sn, it possesses good thermal resistance and performance stability [22,23]. The spectral selective characteristics of TCO film are exhibited in Figure 3. The average solar irradiance transmittance and the average reflectance of emissive radiation heat from the absorber tube at the absorber temperature of 600 °C are 0.699 and 0.639, respectively.

![Figure 3](image_url)

**Figure 3.** Spectral characteristics of the TCO film.

The ideal IR-reflector coating with a fixed cutoff wavelength of 2.5 μm (marked as IRR-II) has high transmittance (set as 0.99) and low reflectance (set as 0.01) below 2.5 μm, which can allow vast
majority of solar irradiance pass through. In the wavelength band above 2.5 μm, opposite spectral characteristics of high reflectance and low transmittance appear as shown in Figure 2. In the case of an absorber temperature of 600 °C, the average transmittance of solar irradiance and average reflectance of emissive radiation heat are 0.99 and 0.607, respectively.

The optimal cutoff wavelength ($\lambda_{opt}$) mainly depends on the values of solar irradiance and absorber temperature. In the condition of ambient temperature of 25 °C and wind speed of 2.5 m/s, the values of $\lambda_{opt}$ under different values of DNI and absorber temperature are calculated and presented in Table 1 [19]. It is observed that the value of $\lambda_{opt}$ lowers with the increasing absorber temperature for intercepting more heat loss, by contrast, with the increasing DNI, the value of $\lambda_{opt}$ becomes higher for reducing the solar irradiance loss incurred by optimal IR-reflector coating (marked as IRR-III). In the case of absorber temperature of 600 °C and DNI of 800 W/m², the average transmittance of solar irradiance and average reflectance of emissive radiation heat are 0.929 and 0.946, respectively.

Table 1. Optimal cutoff wavelengths under different values of direct normal irradiance (DNI) and absorber temperature.

| $T_a$ (°C) | DNI = 400 W/m² | DNI = 600 W/m² | DNI = 800 W/m² |
|------------|----------------|----------------|----------------|
| 200        | 2.50           | 2.50           | 2.50           |
| 240        | 2.45           | 2.45           | 2.50           |
| 280        | 2.30           | 2.40           | 2.40           |
| 320        | 1.80           | 1.81           | 2.30           |
| 360        | 1.80           | 1.80           | 1.80           |
| 400        | 1.75           | 1.80           | 1.80           |
| 440        | 1.35           | 1.70           | 1.75           |
| 480        | 1.35           | 1.35           | 1.35           |
| 520        | 1.35           | 1.35           | 1.35           |
| 560        | 1.30           | 1.35           | 1.35           |
| 600        | 1.25           | 1.30           | 1.30           |

2.2. Specifications of HCE and PTC System

In this paper, the popular commercial Schott PTR70 solar receiver and EuroTrough collector are selected as the studied HCE and PTC system. By referring to the real outdoor testing conducted by Valenzuela et al. [24], the total length of small-scale PTC system is determined as 72 m, the detail specifications of the HCE and PTC system used in simulations are presented in Table 2. In addition, the other parameters used in simulations are same with the experimental parameters in literature [24], including optical efficiency ($\eta_o$) in the PTC system of 0.768, and ambient temperature ($T_a$) of 20 °C, with solar molten salt used as the heat transfer fluid in this paper.

Table 2. Specifications of studied HCE and parabolic trough collector (PTC) system.

| Parameter | Specification | Parameter | Specification |
|-----------|---------------|-----------|---------------|
| $L_{HCE}$ | 4.06 m        | $L_{local}$ | 1.7 m        |
| $D_h$     | 70 mm         | $L_{PTC}$  | 72 m         |
| $D_h$     | 125 mm        | $A_{ap}$   | 409.9 m²     |
| $W_{PTC}$ | 5.76 m        |            |              |

2.3. Energetic and Exergetic Efficiency Models

Detail heat loss models of conventional HCEs (CHCEs) and NHCEs have been presented in our previous study [25], thus no more repetitive introductions are conducted in this paper. Here, energetic and exergetic efficiency models used to simulate overall performance of NHCEs in a real PTC system are established by employing a volume unit method. The heat collecting process in the
72 m PTC system is exhibited in Figure 4, 72 m loop is divided into \( n \) control volumes \((n = 144)\) for accurately calculating overall performance of the HCEs in the PTC system. For per control volume \((i)\) under quasi steady state, the fluid temperature and absorber temperature are marked as \( T_f \) and \( T_s \) \((i = 1, \ldots, n)\), the heat loss \((HL)\) from the HCE and the amount of convection heat transfer between the absorber tube and the HTF are expressed as \( Q_{HL,i} \) and \( Q_{conv.s-f,i} \). \( Q_{conv.s-f,i} \) is written as follows [26]:

\[
Q_{conv,s-f,i} = h_j D_j \pi L_{PTC,i} (T_{f,i} - T_{f,j}) \quad (i = 1, \ldots, n),
\]

where \( L_{PTC,i} \) refers to the length of control volume \( i \), m. The heat gain of control volume \( i \) can be expressed as:

\[
Q_{gain,i} = m_j c_p (T_{f,i+1} - T_{f,i}) \quad (i = 1, \ldots, n).
\]

According to the principle of conservation of energy, the heat gain of control volume \( i \) equals to amount of convection heat transfer between the absorber tube and the HTF, that is:

\[
Q_{gain,i} = Q_{conv,s-f,i}.
\]

Consequently, heat gain of each control volume can be obtained, and the total heat gain throughout the full-length PTC system can be expressed as:

\[
Q_{gain} = \sum_{i=1}^{n} Q_{gain,i} \quad (n = 144).
\]

As a result, the energetic efficiency of the PTC system is calculated by:

\[
\eta = \frac{Q_{gain}}{Q_{solar}},
\]

where \( Q_{solar} \) is total available solar irradiance received by the full-length PTC system, W/m², which can be expressed as:

\[
Q_{solar} = A_p \cdot DNI \cdot \cos \gamma,
\]

where \( \gamma \) is the incidence angle of solar irradiance in the aperture plane of the PTC.
Figure 4. Heat collecting process in the PTC system.

Exergy is an important indicator to evaluate the process quality, high exergetic performance means low irreversibilities and considerable high-quality energy output. For observing the quality of the heat source obtained by the PTC system with different HCEs, the exergetic performance of the PTC system is simulated in this paper. The exergetic output of system \( E_{\text{gain}} \) can be expressed as the difference of the useful heat gain and irreversibilities, as shown in Equation (7):

\[
E_{\text{gain}} = Q_{\text{gain}} - m_f \cdot c_p \cdot (T_a + 273) \cdot \ln \left[ \frac{T_{\text{out}} + 273}{T_{\text{in}} + 273} \right].
\]  

(7)

Thus, the exergy efficiency \( \chi \) of an HCE can be calculated by the equation as follows:

\[
\chi = \frac{E_{\text{gain}}}{E_{\text{solar}}},
\]  

(8)

where \( E_{\text{solar}} \) is the exergy of solar irradiance, W/m², which is expressed as [27]:

\[
E_{\text{solar}} = Q_{\text{solar}} \cdot \left[ 1 - \frac{4(T_a + 273)}{3(T_{\text{out}} + 273)} + \frac{1}{3} \left( \frac{T_a + 273}{T_{\text{out}} + 273} \right)^4 \right],
\]  

(9)

where \( T_{\text{out}} \) represents the equivalent solar temperature.

3. Results and Discussions

3.1. Validation of Simulation Results

It has been proved in previous study that the simulated heat loss had a good agreement with experimental data carried out by National Renewable Energy Laboratory [15]. In this paper, the simulated energetic efficiency results implemented by the C++ language program (Visual C++ 11.0, Microsoft, Redmond, Washington, USA, 2012) are compared with experimental data from outdoor testing carried out by Valenzuela et al. [24]. All parameters used in simulation are same with parameters in experiments, namely, DNI of 864 W/m², ambient temperature of 32.8 °C, and HTF flow rate of 3 kg/s. The simulated and experimental energetic efficiencies are presented in Figure 5. It is...
noted that the units of variable of \((\Delta T)\) and \(Q_{solar}\) is °C and W/m², respectively. In this study, root-meansquare deviation (RMSD) and mean bias error (MBE) [28] are employed to verify the simulation precision. MBE is expressed as follows:

\[
MBE = \frac{\sum_{i=1}^{N} (X_{\text{simulated},i} - X_{\text{experimental},i})}{N},
\]

where \(X_{\text{simulated}}\) and \(X_{\text{experimental}}\) represent the simulated and experimental values, \(N\) refers to the total number of observations. It is calculated that the RMSD value remains within 6.0% and the MBE value is about ~0.8%, which demonstrates that the simulated result yields satisfactory consistence with the experimental data.

![Figure 5. Modeled energetic efficiency versus experimental data.](image)

### 3.2. Heat Loss Reduction

The heat losses in four HCEs and percentages of the reduced heat loss in NHCEs compared with the CHCE are presented in Figure 6. As explained in our previous study, three kinds of NHCEs, namely, NHCE with TCO film (NHCE-IRR-I), NHCE with ideal IR-reflector coating with a fixed cutoff wavelength of 2.5 μm (NHCE-IRR-II), and NHCE with ideal IR-reflector coating with optimal cutoff wavelength (NHCE-IRR-III), possessed superior heat loss performances. In particular, NHCE-IRR-III has the lowest heat loss, and the percentage of heat loss reduction increases with the elevation of absorber temperature. In contrast to the NHCE-IRR-III, the role of the IR-reflector in the NHCE-IRR-II in reducing the heat loss gradually decreases with the growing absorber temperature. This is because, with the increase of absorber temperature, more emissive heat from the absorber tube occurs in the wavelength band below 2.5 μm, but the IR-reflector with a fixed cutoff wavelength of 2.5 μm cannot block this part of emissive heat, which results in the eventual escape of this part of emissive heat from the absorber tube to the surroundings. Due to not so satisfactory spectral selectivity parameters in real TCO film in comparison with the ideal IR-reflectors, the heat loss performance in NHCE-IRR-I is inferior to the other two kinds of NCHEs. However, the NHCE-IRR-I still has superior performance compared with the CHCE, and the heat loss performance gets better with the increasing absorber temperature.
As shown in Figure 6b, the percentages of heat loss reduction in NHCE-IRR-I, NHCE-IRR-II, and NHCE-IRR-III reach 18.7%, 25.3%, and 43.8% at the absorber temperature of 600 °C, which demonstrate that the greatest potential of IR-reflector for the reduction of heat loss in HCE is 43.8% at this absorber temperature. Therefore, the application of IR-reflectors in the HCEs has great potential to improve the thermal performance.
3.3. Energy and Exergy Performance of NHCEs

The energy and exergy performances of NHCEs with the HTF of solar molten salt are calculated in this study. The DNI, ambient temperature, and mass flow rate are 800 W/m², 20.0 °C, and 3.0 kg/s, respectively, and the inlet temperature of the PTC system is assigned from 300 to 580 °C. The energetic efficiencies of the PTC system with different HCEs are exhibited in Figure 7, where it is observed that the NHCE-IRR-II and NHCE-IRR-III possess superior performance compared with the CHCE, and the former is the best. Additionally, the gap between the energetic efficiency of the NHCE-IRR-II and that of the NHCE-IRR-III widens with the increasing inlet temperature. The reason for this phenomenon is that the effectiveness of IR-reflector of NHCE-IRR-II to block the heat loss is reduced at high absorber temperature; by contrast, the effectiveness of IR-reflector of NHCE-IRR-III is strongly maintained because its adaptive spectral selectivity characteristic by shifting the cutoff wavelength greatly contributes to the optimal reduction of heat loss. In contrast to the NHCE-IRR-II and NHCE-IRR-III, the energetic efficiency of the NHCE-IRR-I is lower than that of the CHCE at the inlet temperature below 350 °C. This is because, though the TCO film in NHCE-IRR-I can intercept a partial amount of heat loss, a certain amount of solar irradiance is blocked by the TCO film, and this part of solar irradiance loss would surpass the amount of heat loss intercepted by the glass envelope with TCO film at lower operating temperatures or higher solar irradiance. In the case of the solar irradiance of 800 W/m², the solar irradiance loss is larger than the blocked heat loss until the inlet temperature reaches approximately 350 °C, at which the energetic efficiency of NHCE-IRR-I is same with that of CHCE. Furthermore, with higher inlet temperature, the energetic efficiency of NHCE-IRR-I gets much superior compared with CHCE.

![Figure 7. Energetic efficiency of PTC system with different HCEs versus inlet temperature.](image)

As shown in Figure 8, the percentages of energetic efficiency enhancement ($P_\eta$) of three NHCEs obviously grow with the increasing operating temperature; the percentage values in NHCE-IRR-I, NHCE-IRR-II, and NHCE-IRR-III reach 6.5%, 12.2%, and 25.7% at the inlet temperature of 580 °C.
Exergy is an important indicator to evaluate the maximum useful work possible during a process of heat collection of the PTC system. The exergetic efficiency of the PTC system versus different inlet temperatures is exhibited in Figure 9. As similar to the energy efficiency analyzed above, NHCE-IRR-III achieves the best performance among three kinds of NHCEs. The NHCE-IRR-II is inferior to NHCE-IRR-III, and the growing gap between the exergy efficiency of NHCE-IRR-III and that of NHCE-IRR-II appears at higher operating temperatures. This demonstrates that IRR-III achieves an exceptional ability in improving the useful work possible for the PTC system. For the NHCE-IRR-I, a reduced exergy efficiency compared with the CHCE occurs at lower inlet temperature, then its exergy efficiency is gradually enhanced and eventually surpasses that of the CHCE with the increasing operating temperature. The reason for this phenomenon is because that the solar irradiance loss incurred by TCO film in NHCE-IRR-I is larger than the blocked heat loss at lower operating temperature, thus causing the reduced exergy. With the increase of operating temperature, however, the blocked heat loss gradually gets higher and eventually exceeds the solar irradiance loss, which contributes to the enhanced exergy in NHCE-IRR-I compared with the CHCE.

As shown in Figure 10, the percentages of exergy efficiency enhancement ($P_{\eta}$) of three NHCEs obviously grow with the increasing inlet temperature, the percentage values of NHCE-IRR-I, NHCE-IRR-II, and NHCE-IRR-III reach 7.1%, 13.3%, and 28.1% at the inlet temperature of 580 °C, respectively.
3.4. Parameter Analysis of Solar Irradiance (DNI)

Effects of the IR-reflector on the performance of HCEs in the PTC system mainly depend on the operating temperature and solar irradiance. As explained above, higher operating temperatures contribute to a more effective role of the IR-reflector. In this part, the roles of different IR-reflectors in the NHCEs at the inlet temperature of 500 °C on the overall performance are investigated under different values of DNI.

The energetic efficiency of the PTC system with different HCEs versus DNI is shown in Figure 11. It can be seen that the gap between the energetic efficiency of NHCE and that of the CHCE is gradually reduced with the increasing DNI from 400 W/m² to 800 W/m², which is also proved in Figure 12. The percentages of energetic efficiency enhancement of NHCE-IRR-I, NHCE-IRR-II, and NHCE-IRR-III at the DNI of 800 W/m² are 4.3%, 6.7%, and 11.4%, respectively.
The exergetic efficiency of the PTC system with different HCEs versus DNI is shown in Figure 13. Similar to the energetic efficiency of the NHCE, the gap between the exergetic efficiency of NHCE and that of CHCE is gradually reduced with the increasing DNI, which demonstrates that role of IR-reflectors in the NHCEs in enhancing overall performance of PTC system is reduced at higher solar irradiance. As exhibited in Figure 14, the percentages of exergetic efficiency enhancement of NHCE-IRR-I, NHCE-IRR-II, and NHCE-IRR-III at the DNI of 800 W/m² are 4.8%, 7.4%, and 13.0%, respectively.
Figure 13. Exergetic efficiency of PTC system with different HCEs versus DNI.

Figure 14. Percentage of exergetic efficiency enhancement of NHCEs versus DNI.

4. Conclusions

Based on the proposed negative thermal-flux region in the heat collecting element (HCE), three novel HCEs (NHCEs) with different IR-reflector coatings, namely, real IR-reflector coating of transparent conductive oxide (TCO) film (IRR-I), IR-reflector with a fixed cutoff wavelength of 2.5 μm (IRR-II), and IR-reflector with optimal cutoff wavelength (IRR-III), were proposed. In this framework, to observe the actual overall performance of three kinds of NHCEs, a 72 m loop PTC system with different NHCEs is numerically investigated for evaluating the outdoor energetic and exergetic efficiencies of NHCEs. The simulation results based on the established mathematical models are verified with the experimental data, it is calculated that the RMSD value remains within 6.0% and the MBE value is about −0.8%, which demonstrates that the modeled results yield a satisfactory consistence with the experimental data. Additionally, the effects of solar irradiance on the performance of NHCEs are also studied in this paper. The results are summarized as follows:
Three kinds of NHCEs possess superior heat loss performance at higher temperature. The percentages of heat loss reduction of NHCE-IRR-I, NHCE-IRR-II, and NHCE-IRR-III reach 18.7%, 25.3%, and 43.8% at the absorber temperature of 600 °C, respectively.

Compared with the CHCE, three kinds of NHCEs achieve great overall performance at high operating temperatures, and the NHCE-IRR-III shows greatest potential for the enhancements of energetic and exergetic efficiencies in the PTC system. The percentages of enhancements of energetic efficiency and exergetic efficiency of NHCE-IRR-III reach 25.2% and 28.1% at the inlet temperature of 580 °C.

Direct normal irradiance (DNI) exerts an important impact on the performance of PTC system with the NHCEs. Higher value of DNI causes lower performance enhancement of PTC system with the NHCEs.

The performance-enhanced PTC system with the NHCEs would greatly contribute to the efficient building heating and cooling systems.

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Nomenclature

- \( a \): Ambient
- \( c \): Cutoff wavelength, \( \mu \text{m} \)
- \( c_p \): Specific heat of fluid, J/(kg·K)
- \( f \): fluid
- \( g \): Glass envelope
- \( h \): Heat transfer coefficient, W/(m\(^2\)·K)
- \( m \): Mass flow rate, m/s
- \( s \): Absorber tube
- \( A \): Area, m\(^2\)
- \( D \): Diameter, mm
- \( L \): Length, m
- \( P \): Percentage, %
- \( Q \): Net heat flux, W/m\(^2\)
- \( T \): Temperature, °C
- \( W \): Width, m
Greek Symbols

\( \lambda \)  Wavelength, \( \mu \)m
\( \gamma \)  Incidence angle, rad
\( \eta \)  Energetic efficiency
\( \chi \)  Exergetic efficiency

Abbreviation and Subscripts

HCE  Heat collecting element
CHCE  Conventional HCE
NHCE  Novel HCE
HTF  Heat transfer fluid
PTC  Parabolic trough collector
CSP  Concentrated solar power
SSC  Solar selective absorbing coating
TCO  Transparent conductive oxide
HL  Heat loss, W/m
DNI  Direct normal irradiance, W/m^2
ap  Aperture
conv  Convection
opt  Optimal
in  inlet
out  outlet

References

1. Romero, M.; Steinfeld, A. Concentrating solar thermal power and thermochemical fuels. *Energy Environ. Sci.* 2012, 5, 9234–9245.
2. Liu, M.; Tay NH, S.; Bell, S.; Belusko, M.; Jacob, R.; Will, G.; Saman, W.; Bruno, F. Review on concentrating solar power plants and new developments in high temperature thermal energy storage technologies. *Renew. Sustain. Energy Rev.* 2016, 53, 1411–1432.
3. Fuqiang, W.; Ziming, C.; Jianyu, T.; Yuan, Y.; Yong, S.; Linhua, L. Progress in concentrated solar power technology with parabolic trough collector system: A comprehensive review. *Renew. Sustain. Energy Rev.* 2017, 79, 1314–1328.
4. Tian, Y.; Zhao, C.Y. A review of solar collectors and thermal energy storage in solar thermal applications. *Appl. Energy* 2013, 104, 538–553.
5. Zhu, G.; Wendelin, T.; Wagner, M.J.; Kutscher, C. History, current state, and future of linear Fresnel concentrating solar collectors. *Sol. Energy* 2014, 103, 639–652.
6. El Fadar, A.; Mimet, A.; Pérez-Garcia, M. Modelling and performance study of a continuous adsorption refrigeration system driven by parabolic trough solar collector. Sol. Energy 2009, 83, 850–861.
7. Xiao, C.; Luo, H.; Tang, R.; Zhong, H. Solar thermal utilization in China. Renew. Energy 2004, 29, 1549–1556.
8. Yang, H.; Wang, Q.; Huang, Y.; Gao, G.; Feng, J.; Li, J.; Pei, G. Novel parabolic trough power system integrating direct steam generation and molten salt systems: Preliminary thermodynamic study. Energy Convers. Manag. 2019, 195, 909–926.
9. Wang, Q.; Li, J.; Yang, H.; Su, K.; Hu, M.; Pei, G. Performance analysis on a high-temperature solar evacuated receiver with an inner radiation shield. Energy 2017, 139, 447–458.
10. Zhang, Q.C. Recent progress in high-temperature solar selective coatings. Sol. Energy Mater. Sol. Cells 2000, 62, 63–74.
11. 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. Energy Convers. Manag. 2018, 156, 388–402.
12. Zhang, C.; Xu, G.; Quan, Y.; Li, H.; Song, G. Optical sensitivity analysis of geometrical deformation on the parabolic trough solar collector with Monte Carlo Ray-Trace method. Appl. Therm. Eng. 2016, 109, 130–137.
13. Ruegamer, T.; Kamp, H.; Kuckelkorn, T.; Schiel, W.; Weinrebe, G.; Nava, P.; Riffelmann, K.; Richert, T. Molten salt for parabolic trough application: System simulation and scale effects. Energy Procedia 2014, 49, 1523–1532.
14. Maccari, A.; Bissi, D.; Casubolo, G.; Guerrini, F.; Lucatello, L.; Luna, G.; Rivaben, A.; Savoldi, E.; Tamano, S.; Zuanella, M. Archimed Solar Energy molten salt parabolic trough demo plant: A step ahead towards the new frontiers of CSP. Energy Procedia 2015, 69, 1643–1651.
15. Burkholder, F.; Kutscher, C. Heat Loss Testing of Schott’s 2008 PTR70 Parabolic Trough Receiver; National Renewable Energy Lab. (NREL): Golden, CO, USA, 2009.
16. Kalogirou, S.A. A detailed thermal model of a parabolic trough collector receiver. Energy 2012, 48, 298–306.
17. Wang, Q.; Yang, H.; Zhong, S.; Huang, Y.; Hu, M.; Cao, J.; Yang, H.; Pei, G. Quantitative analyses and a novel optimization strategy on negative energy-flow region in parabolic trough solar receivers. Sol. Energy 2020, 196, 663–672.
18. Pfänders, M.; Lüpfert, E.; Pistor, P. Infrared temperature measurements on solar trough absorber tubes. Sol. Energy 2007, 81, 629–635.
19. Wang, Q.; Hu, M.; Yang, H.; Cao, J.; Li, J.; Su, Y.; Pei, G. Performance evaluation and analyses of novel parabolic trough evacuated collector tubes with spectrum-selective glass envelope. Renew. Energy 2019, 138, 793–804.
20. Das, R.; Ray, S. Zinc oxide—A transparent, conducting IR-reflector prepared by rf-magnetron sputtering. J. Phys. D: Appl. Phys. 2002, 36, 152.
21. Incropera, F.P.; Lavine, A.S.; Bergman, T.L.; DeWitt, D. P. Fundamentals of Heat and Mass Transfer; Wiley: Hoboken, NJ, USA, 2007.
22. Li, X.; Zhu, Y.; Cai, W.; Borysiak, M.; Han, B.; Chen, D.; Piner, R. D.; Colombo, L.; Ruoff, R S. Transfer of large-area graphene films for high-performance transparent conductive electrodes. Nano Lett. 2009, 9, 4359–4363.
23. Granqvist, C.G.; Hultåker, A. Transparent and conducting ITO films: New developments and applications. Thin Solid Films. 2002, 411, 1–5.
24. Valenzuela, L.; López-Martin, R.; Zarza, E. Optical and thermal performance of large-size parabolic-trough solar collectors from outdoor experiments: A test method and a case study. Energy 2014, 70, 456–464.
25. Wang, Q.; Hu, M.; Yang, H.; Cao, J.; Li, J.; Su, Y.; Pei, G. Energetic and exergetic analyses on structural optimized parabolic trough solar receivers in a concentrated solar–thermal collector system. Energy 2019, 171, 611–623.
26. Padilla, R.V.; Demirkaya, G.; Goswami, D.Y.; Stefanakos, E.; Rahman, M. M. Heat transfer analysis of parabolic trough solar receiver. Appl. Energy 2011, 88, 5097–5110.
27. Kara, O.; Ulgen, K.; Hepbasli, A. Exergetic assessment of direct-expansion solar-assisted heat pump systems: Review and modeling. Renew. Sustain. Energy Rev. 2008, 12, 1383–1401.
28. Jiang, Y. Estimation of monthly mean daily diffuse radiation in China. Appl. Energy 2009, 86, 1458–1464. © 2020 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (http://creativecommons.org/licenses/by/4.0/).