Revisiting the Figure of Merit of Concentrated Solar Power Receivers

ABSTRACT

The figure of merit (FOM) is a widely used metric to characterize the performance of concentrated solar power (CSP) receivers by comparing the amount of solar thermal energy retained...
by the receiver to the incident concentrated solar radiation. However, the FOM is a strong function of the concentration factor and receiver temperature, thus direct comparison of FOM values measured under disparate operating conditions is inappropriate. To remedy this problem, the present study proposes a new metric called the receiver effectiveness calculated by normalizing the actual FOM with its theoretical maximum. The receiver effectiveness can be employed for comparing receiver performances regardless of their operating conditions, and can be treated as more-like the second law efficiency of thermodynamics. In addition, a theoretical limit of the CSP plant efficiency is also examined by combining the maximum FOM and the Carnot efficiency for different concentration factors and receiver temperatures. The calculated maximum CSP plant efficiency clearly indicate that optimizing FOM does not always lead to a better CSP plant performance. Along with the FOM, the proposed receiver effectiveness and maximum CSP system efficiency should be considered as complementary metrics to evaluate the performance of the CSP system.

1 Introduction

Concentrated solar power (CSP) is a technology that converts solar radiation into thermal energy, which is then used to drive turbines and generate electricity \cite{1, 2}. The efficiency of CSP plants strongly depends on the solar-to-thermal conversion efficiency, also called figure of merit (FOM), of the solar receiver. The FOM is defined as the amount of solar radiation absorbed and retained by the receiver divided by the total solar radiation incident on the receiver \cite{3-5}. Therefore, an ideal receiver should maximize the amount of solar absorption while minimizing thermal emission from the receiver. This can be achieved by spectrally selective surfaces that have large absorptivity within the short-wavelength solar spectrum and low emissivity within long-wavelength receiver emission spectrum \cite{6}. However, for receiver temperatures approximately equal to or larger than 500 K, which are typical in CSP plants, perfect spectral selectivity cannot be achieved because of the overlap between the solar and thermal emission spectra. This spectral overlap should be taken into account for the maximum FOM of a solar receiver. The simplest case of an ideal solar receiver could be realized by determining a cut-off wavelength, at which the receiver absorptivity transitions from unity to zero \cite{7}.

The FOM has been widely used to evaluate the performance of CSP receivers \cite{5, 8-12}. However,
direct comparison of FOMs calculated under disparate conditions of solar concentrations and temperatures results in misleading interpretation of CSP receiver performances. For example, Ambrosini et al. [5] measured the FOM of a solar receiver made of Pyromark 2500 to be 0.897 at a concentration factor $C = 667$ and a receiver temperature $T_r = 973$ K, while Kim et al. [11] reported a FOM of 0.903 for a copper-alloyed spinel black oxides receiver at $C = 1000$ and $T_r = 1023$ K (Here, a concentration factor is defined as the scalar multiple of the solar flux on earth’s surface). However, since they were measured in different operating conditions, it is not possible to objectively say that one receiver has a better performance than the other simply by comparing the FOM values. The objective of this work is therefore to revisit the interpretation of the FOM and to provide a novel metric, the receiver effectiveness, enabling a direct comparison of CSP receivers working under different concentration factors and temperatures. This is done by defining the receiver effectiveness as the ratio of the actual receiver FOM to the maximum FOM for the same concentration factor and temperature. In addition, the maximum CSP plant efficiency is introduced by combining the maximum FOM and the Carnot efficiency to show that the optimal concentration factor and receiver temperature should be selected not based on the FOM but based on the CSP plant efficiency.

2 Maximum FOM and Receiver Effectiveness

Figure 1 illustrates a CSP receiver illuminated by concentrated solar radiation. When concentrated solar radiation is incident onto the receiver, it is either absorbed or reflected. In addition, the receiver emits thermal radiation to the surroundings. The difference between the absorbed solar radiative flux $q_{abs}$ and the emitted radiative flux $q_{em}$ at the receiver temperature $T_r$ is the net energy that can be transferred to the cycle upon absorption. The receiver FOM is defined as this net solar thermal energy normalized by the incident solar radiative flux $q_{inc}$ [3–5]:

$$FOM = \frac{q_{abs} - q_{em}}{q_{inc}}$$ (1)

The incident solar radiative flux is calculated as $q_{inc} = C \int_0^\infty q_{sol,\lambda} d\lambda$, where $\lambda$ is the wavelength, $C$ is the concentration factor, and $q_{sol,\lambda}$ is the AM 1.5 standard spectral solar flux (“ASTM G173-03 Table”,
The absorbed and emitted radiative fluxes are computed using the following equations:

\[ q_{\text{abs}} = C \int_{0}^{\infty} \alpha_{\lambda} q_{\text{sol}, \lambda} d\lambda \quad (2) \]

and

\[ q_{\text{em}} = \int_{0}^{\infty} \varepsilon_{\lambda} E_{b, \lambda}(T_r) d\lambda \quad (3) \]

where \( \alpha_{\lambda} \) and \( \varepsilon_{\lambda} \) are respectively the spectral, hemispherical absorptivity and emissivity of the receiver. Here, it is assumed that the receiver is diffuse, such that the spectral, hemispherical absorptivity equals the spectral, hemispherical emissivity according to Kirchhoff’s law (i.e., \( \alpha_{\lambda} = \varepsilon_{\lambda} \)) [13]. For simplicity, the adjective hemispherical will be omitted in the rest of the text. In Eq. (3), \( E_{b, \lambda}(T_r) \) is the spectral blackbody emissive power at the receiver temperature [13]. It should be noted that the convective heat loss to the surrounding air is not typically considered in the FOM.

Owing to the overlap between the solar and emission spectra for receiver temperatures larger than 500 K, it is impossible to completely separate the absorption and emission spectra. Therefore, the FOM is maximized by defining a cut-off wavelength \( \lambda_{\text{cut}} \) beyond which further absorption of solar radiation is outweighed by emission losses. The spectral absorptivity of an ideal receiver having the maximum FOM is thus given by:

\[ \alpha_{\lambda} = \varepsilon_{\lambda} = \begin{cases} 1 & \lambda \leq \lambda_{\text{cut}} \\ 0 & \lambda > \lambda_{\text{cut}}. \end{cases} \quad (4) \]

Figure [2] shows the cut-off wavelength and the corresponding maximum FOM for five different combinations of concentration factors and receiver temperatures. In panels (a), (b), and (c), the concentration factor is fixed at 1000 while the receiver temperature increases from 500 K to 1500 K. As the receiver temperature increases, the emitted flux increases along with its spectrum shifting towards shorter wave-
lengths. The latter effect leads to a shift of the cut-off wavelength from 4 $\mu$m at $T_r = 500$ K to 1.78 $\mu$m at $T_r = 1500$ K owing to a larger overlap between the emission and solar spectra. A shorter cut-off wavelength reduces the solar flux absorbed by the receiver. As a result, a solar receiver at higher temperatures yields a lower FOM due to the diminution of solar absorption as well as the augmentation of thermal emission.

In panels (d), (b), and (e) of Fig. 2, the receiver temperature is fixed at 1000 K while the concentration factor increases from 100 to 2000. Varying the concentration factor does not affect the spectral distribution of solar radiation, whereas the same receiver temperature maintains the thermal emission spectrum as well. Yet, the cut-off wavelength is impacted by the concentration factor because of the competition between the absorbed solar flux and the emitted flux. Here, the cut-off wavelength increases from 1.78 $\mu$m to 2.48 $\mu$m for a rise in concentration factor from 100 to 1000. Although the emitted flux increases due to the longer cut-off wavelength, the ten-fold enhancement in the magnitude of the incident solar flux mitigates the negative impact of the emitted flux to yield a higher FOM at $C = 1000$. When the concentration factor increases from 1000 to 2000, the enhancement of the FOM is modest, and the cut-off wavelength remains the same. This is explained by the fact that the solar spectrum has a negligible amount of energy contained at wavelengths longer than 2.48 $\mu$m. Clearly, the receiver temperature has a more significant impact on the cut-off wavelength than the concentration factor.

Figure 3(a) shows the maximum FOM as a function of the concentration factor and receiver temperature. A higher concentration factor and lower receiver temperature mitigate the impact of emission losses and therefore lead to a larger maximum FOM. Figure 3(b) shows FOM values from various contemporary literature sources, measured at different concentration factors and receiver temperatures against the maximum FOM curves. Clearly, direct comparison of FOMs measured with different concentration factors and receiver temperatures is inappropriate and misleading. It is thus more meaningful to correlate the FOM to their respective maximum values, akin to the second law efficiency in thermodynamics. For this purpose, a novel metric called the receiver effectiveness is proposed and is defined
as

\[ e = \frac{\text{FOM}_{\text{act}}}{\text{FOM}_{\text{max}}} \]  

where \( \text{FOM}_{\text{act}} \) and \( \text{FOM}_{\text{max}} \) are respectively the actual and maximum FOM values. Table 1 compares the effectiveness values from the FOMs reported in the literature and their corresponding operating conditions. Although in general a solar receiver having a high FOM yields a high effectiveness, Table 1 clearly demonstrates that a higher FOM does not necessarily lead to a higher effectiveness unless measured at the same operating conditions. For example, FOMs of 0.895 and 0.882 have been reported by Moon et al. \[9\] and Avila-Marin et al. \[8\], respectively. Direct comparison of these FOMs would lead to the conclusion that Ref. \[8\] reported a better performing receiver than Ref. \[9\]. However, the effectiveness of the receiver in Ref. \[9\] is 0.9, which is slightly higher than the receiver effectiveness of 0.897 in \[8\]. Therefore, contrary to considering solely the FOM, this effectiveness formulation provides a different perspective for determining the performance of a receiver, and is useful for comparing receiver performances independently of their operating conditions.

3 CSP Plant Efficiency and Optimal Operating Conditions

The thermal energy retained by the receiver is supplied to a cycle for power generation (see Fig. 1). As such, the selection of the concentration factor and receiver temperature for optimal CSP plant operating conditions should not be solely based on the FOM. According to the Carnot efficiency, it is desirable to have a high hot-side temperature in order to maximize the cycle efficiency. However, a high temperature on the hot side of the cycle implies a high receiver temperature, which result in large emission losses. There should be an optimal balance between the cycle efficiency and the receiver FOM that results in the highest performances. The interplay between these two factors is quantified via the CSP plant efficiency (i.e., solar-to-electrical conversion efficiency) calculated as follows:

\[ \eta_{\text{plant}} = \text{FOM} \times \eta_{\text{Carnot}} = \frac{q_{\text{abs}} - q_{\text{em}}}{q_{\text{inc}}} \times \frac{T_r - T_c}{T_r} \]  

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Here, it is assumed that the hot reservoir temperature of the cycle is equal to the receiver temperature \((T_r)\), while the cold-side temperature \((T_c)\) of the cycle is equal to the surrounding temperature of 298K.

The maximum CSP plant efficiency is displayed as a contour plot in Fig. 4(a), and line curve in Fig. 4(b) as a function of the receiver temperature for different concentration factors. This is the theoretical limit of plant efficiency for a given set of operating conditions. Clearly, the plant efficiency cannot be maximized by arbitrarily selecting the concentration factor and receiver temperature. Figure 4(b) shows that there is an optimum receiver temperature maximizing the plant efficiency for a specific concentration factor. Moreover, it is evident that considering solely the FOM does not give a complete picture of CSP plant performance. If a low receiver temperature is maintained to enhance the FOM, the absorbed energy may not be usable for power generation that demands a high-temperature heat source. Conversely, if the receiver temperature exceeds the optimal point to just improve the cycle efficiency, a large thermal emission loss from the receiver ultimately degrades the CSP plant performance.

4 Conclusions

Although the FOM is a widely accepted metric to evaluate the performance of a CSP receiver, direct comparison between FOM values without careful consideration of operating conditions may lead to inaccurate assessment for CSP performance. In the present article, a novel metric called the CSP receiver effectiveness was defined as the ratio of the actual receiver FOM and its maximum value. The effectiveness enables direct comparison of CSP receiver performances under disparate operating conditions. In addition, the CSP plant efficiency was defined by combining the FOM and the Carnot efficiency. It was shown that the optimal combination of concentration factor and receiver temperature should be determined using the maximum CSP plant efficiency. The analysis presented in this paper provides guidelines for designing CSP receivers maximizing the overall solar-to-electrical conversion efficiency.

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Table 1. Literature reported FOMs, operating conditions, and corresponding effectivenesses

| References                  | $C$  | $T_r$ (K) | $FOM_{act}$ | $e$  |
|-----------------------------|------|-----------|-------------|------|
| Mey-Cloutier et al. [12]    | 838  | 1231      | 0.581       | 0.616|
| Moon et al. [9]             | 1000 | 1023      | 0.882       | 0.900|
| Avila-Marin et al. [8]      | 400  | 595       | 0.895       | 0.897|
| Ambrosini et al. [5]        | 667  | 973       | 0.897       | 0.916|
| Kim et al. [11]             | 1000 | 1023      | 0.903       | 0.922|
| Karas et al. [10]           | 1000 | 1023      | 0.912       | 0.931|
Fig. 1. Schematic of an optimized solar receiver and corresponding power cycle. The optimized receiver absorbs and radiates energy up to a certain cut-off wavelength based on its temperature and concentration factor. The resultant net energy is then supplied to the cycle, which generates electricity with an efficiency of Carnot cycle.
Fig. 2. Cut-off wavelength and corresponding FOM for: (a) $C = 1000$, $T_r = 500$ K, (b) $C = 1000$, $T_r = 1000$ K, (c) $C = 1000$, $T_r = 1500$ K, (d) $C = 100$, $T_r = 1000$ K, and (e) $C = 2000$, $T_r = 1000$ K. The cut-off wavelength was selected to maximize the FOM.
Fig. 3. Optimized FOM as a function of receiver temperature and concentration factor in the form of: (a) Contour plot, and (b) Line plot with literature data. The literature data consists of FOM values from Avila-Marín et al. [8], Moon et al. [9], Ambrosini et al. [5], Karas et al. [10], Kim et al. [11], and Mey-Cloutier et al. [12].
Fig. 4. Optimized plant efficiency in the form of: (a) Contour plot, and (b) Line plot as a function of receiver temperature and concentration factor.