# DIRECT CONVERSION OF SOLAR ENERGY TO ELECTRIC ENERGY

# **Evaluation of Exergy and Energy Efficiencies** of Photothermal Solar Radiation Conversion<sup>1</sup>

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Abstract—In this paper, a new thermodynamic model for photothermal solar radiation conversion into mechanical through a heat engines is proposed. The developed equations allow for the energy and exergy contents of solar radiation to be found, as well as the energy and exergy efficiencies corresponding to concentration type solar-thermal heat engines operating under a range of conditions. The calculation method remains accurate to other published models when their assumed conditions are imposed to the newly developed model. The heat flux absorbed by the receiver (which is assumed to be a grey body and is placed in the focal point of the solar concentrator) depends on the hemispherical absorptivity and emissivity, concentration ratio and receiver temperature. The model is used to conduct a parametric study regarding the energy and exergy efficiencies of the system for assessing its performance. The use of a selective grey body receiver (having a reduced emissivity and a high absorptivity) for enhancing the conversion efficiency is also studied. If the absorptivity approaches one and the emissivity is low enough the photothermal conversion efficiency becomes superior to the known black body receiver limit of 0.853. It is found that in the limit of receiver emissivity tending to zero and absorptivity lending to one, the present model gives the exergy content of solar radiation because the work generated reaches its maximum. In this situation the energy efficiency approaches the exergy efficiency at  $1 - T_0/T_s$  where  $T_s$  and  $T_0$  are the sun and ambient temperatures, respectively. The influence of the ambient temperature on the exergy and energy efficiencies becomes apparent, with effects of up to 15%, particularly for high absorptivity and low emissivity. The heat transfer conductances at sink and source of the heat engine have a considerable impact on the efficiency of solar energy conversion. The present model is developed in line with actual power system operations for better practical acceptance. In addition, some irreversibility parameters (absorptivity, emissivity, heat transfer conductivity, etc.) are studied and discussed to evaluate the possible photothermal solar radiation conversion systems and assess their energy and exergy efficiencies.

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Solar energy is expected to play a key role as the most abundant renewable source. It is the only one that is omnipresent over the terrestrial surface delivering an annual incident normal radiation of 1600–2800 kW h for each square meter (Romero-Alvarez and Zarza, 2008). The solar radiation consists of a flux of photons covering a spectrum of energies from infrared to ultraviolet.

Although the sun's temperature is often considered constant, the reality is that it varies and can be determined indirectly by measurements of the solar radiation spectrum at the outer edge of the terrestrial atmosphere. One finds that  $T_s = 5762$  K is the sun's surface temperature that fits the Planck's blackbody radiation spectrum best. Therefore, the energy emitted by the sun's surface has an impressive intensity at source given by  $\sigma T_s^4 = 63$  MW/m<sup>2</sup>, where  $\sigma = 5.67 \times 10^{-8}$  W/m<sup>2</sup> K<sup>4</sup> is the Stefan-Boltzmann constant. However, the radiation intercepted by earth is much less intense than at the source because the emitted radiation disperses in space. The

reduction factor is given by the ratio of sun's surface area and the area of the ellipsoid described by the terrestrial orbit around the sun.

According to some scientists, including De Vos (2008), the average radius of the terrestrial orbit (assumed spherical) is  $R_0 = 150$  Gm and the sun's radius is  $R_s = 696$  Mm, thus the reduction factor of solar radiation intensity is  $f = (R_s/R_0)^2 = 2.16 \times 10^{-5}$  which gives an extraterrestrial solar radiation flux of  $I_{SC} = f\sigma T_S^4 = 1353$  W/m<sup>2</sup> (known as the solar constant). Due to various effects (e.g., variation of earth orbit radius and of sun's temperature), the solar constant may fluctuate by about 6.9% around the year.

Several phenomena occur in the terrestrial atmosphere that may diminish the solar radiation intensity, which can be intercepted at the earth's surface, namely, direct (albedo) reflection, wind formation, evaporation and water vapour rising, rains, lightning, scattering, greenhouse effect etc. Understanding these phenomena is critically important not only for climatologists but also for renewable energy engineers who are interested

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in developing systems to harvest solar radiation and convert it in useful forms such as electricity, heating, cooling, synthetic fuels (e.g., hydrogen) etc.

An example is the albedo of the earth, where  $\sim 30\%$ of the direct beam radiation is reflected back to the extraterrestrial space which means that the part of solar radiation that is actually incident on the planet surface is of the order 950 W/m<sup>2</sup> except for the case of clear sky condition when, locally and temporarily, the albedo and diffuse radiation effects may be negligible and the INcident SOLar radiATION (known by the short name as "insolation") can be higher (De Vos, 2008). As a consequence of the albedo, the concentrating solar thermal power systems (CSP) in general, are designed for a normal incident beam radiation of 800-900 W/m<sup>2</sup> (see Romero-Alvarez and Zarza, 2008). These systems use optical devices (mirrors or lenses) to concentrate the direct solar beam to a small spot (called a receiver) where the radiation is converted into heat at high temperature. Subsequently, the heat can be converted into work by a heat engine. It is estimated that by 2020 the contribution of CSP to global energy generation would be 30 TWh (Romero-Alvarez and Zarza, 2008).

There are numerous studies published in the open literature with regards to the maximum obtainable photothermal conversion efficiency of solar energy into work through a man-made system. The simplest approach is by Müser (1957) and it was further developed and analysed, e.g., by Castañas (1976), Jeter (1981), De Vos and Pauwels (1981), Würfel (2005), Bejan (2006) and De Vos (2008). In all these approaches, a blackbody collector placed on the ground is coupled through radiation heat transfer with the solar disk only. The solar receiver has a temperature  $T_r$ , at a value between the planet's environment and the sun's temperature, and essentially receives radiation from the sun at  $T_s$  and emits radiation toward the sun at  $T_r$ . The difference between the received and emitted fluxes of radiation is delivered to a Carnot heat engine which operates between the collector (source) and environment (sink) temperatures and produces useful work at its shaft. The heat flux received by the heat engine is  $\sigma(T_s^4 - T_r^4)$  while the Carnot engine efficiency is  $1 - T_0/T_r$ , where  $T_0$  is the standard temperature on earth ( $T_0 = 289$  K, as documented by De Vos, 2008).

Therefore, the work retrieved at the engine shaft per unit of collector area is a function of collector temperature, namely  $W(T_r) = \sigma(T_s^4 - T_r^4)(1 - T_0/T_r)$ . If the collector temperature is low, then the second factor has a low value, while if  $T_r$  is high the first factor is low such that in the two extremes (low and high  $T_r$ ) the produced work is low. A maximum work can be found at an intermediate collector temperature that can be determined by equating  $dW/dT_r = 0$ . The solution found for the terrestrial system is  $T_r^{opt} = 2443$  K for which the generated work is 53.3 MW per m<sup>2</sup> of solar receiver and the incident radiation  $\sigma T_4^S = 62.5$  MW per m<sup>2</sup> of solar receiver. Therefore, the maximum photothermal energy efficiency of insolation is therefore  $\eta_{max} = 53.3/62.5 = 0.853$ .

In order to obtain this maximum efficiency, the solar radiation must be concentrated at maximum so that the receiver sees only the sun. The concentration ratio is then introduced here as the ratio of the actual radiation focused on the solar receiver to the solar radiation incident on the earth:

$$C = \frac{I_{conc}}{I_{db}} \cong \frac{A_a}{A_r},\tag{1}$$

where  $I_{conc}$  indicates the concentrated flux that is actually focused on the solar receiver,  $I_{db}$  represents the direct beam radiation in a direction normal to the sun rays,  $A_a$  is the aperture area of the solar concentrator and  $A_r$  is the effective area of the solar receiver.

From a thermodynamic point of view, the upper limit of the concentrated radiation intensity cannot be higher than the intensity of the radiation at source, that is  $I_{conc, \max} = \sigma T_s^4$ . On the other hand the direct beam radiation incident on the solar concentrator cannot be higher than the solar constant, that is  $I_{db, \max} = I_{sc} =$  $f\sigma T_s^4$ . Therefore, based on Eq. (1), the maximum achievable concentration ratio thermodynamically becomes  $C_{\max} = 1/f = 46.300$ . In general, the concentrated radiation is  $I_r = CI_{db}$ , where because  $C < C_{\max}$  one has  $\eta < \eta_{\max}$ .

There are some studies in the literature that analyse the photothermal solar energy conversion accounting for various losses like the hemispherical absorptivity and emissivity of the solar receiver, heat losses at the receiver and heat engine source and sink, the temperature of the environment etc. For example, De Vos (2008) shows that if no concentration is used (C = 1), the conversion efficiency drops to  $\sim 13\%$ . Furthermore, if one uses special coatings on the receiver surface that do not emit radiation at low energy spectrum (so-called: selective black body coatings), the efficiency can then be maximized to reach  $\eta_{max} = 0.54$ , when no concentrator is used (see Castañs, 1976; Platz, 1978; De Vos, 2008; Bejan, 2006). Using appropriate coatings, the ratio between hemispherical absorptivity and emissivity can be set up to 10 : 1, fact that leads to obtaining about double receiver temperature with respect to nonselective coatings (see Romero-Alvarez and Zarza, 2008). Apart from thermal radiation losses there are convective heat losses at the receiver. The maximum energy efficiency of photothermal solar radiation conversion considering both convective and thermal radiation losses at the solar receiver were analysed e.g., by Howell and Bannerot (1977), Lee and Kim (1991). Some modeling studies considered the type of heat engine. For example Singh et al. (1997) studied the effect of solar collector design parameters on the operation of solar Stirling power system.

The majority of the studies published on photothermal solar energy conversion focus on energy analysis, i.e., thermodynamic analysis based on the first law of thermodynamics. Some second law analyses regarding the efficiency of solar energy conversion were initiated by Bejan et al. (1981) and relevant contributions in this direction are revised in Bejan (2006).

The scope of this paper regards both the energy and exergy efficiencies of photothermal conversion of solar radiation. Exergy efficiency is a qualitatively superior parameter than energy efficiency when quantifying the effectiveness of processes because exergy is based on the second law of thermodynamics. Exergy represents the maximum work that can be obtained when a thermodynamic system is brought to equilibrium with its environment. Several examples of exergy analysis and design are presented by Dincer and Rosen (2007). In principle, the exergy efficiency of a process is defined as the ratio of useful exergy output to the input exergy.

For the study of exergy efficiency it is important to obtain a model through which one can derive the exergy content of solar radiation. The scientific and engineering communities have struggled for the last 60 years to answer the question; how much work can one extract from solar radiation? In this respect, one has to imagine a solar energy conversion system (not necessarily photothermal) able to produce shaft work at most. Several models based on so-called enclosed isotropic blackbody radiation theory are published in the literature. A photonic model of the electromagnetic radiation is adopted in this respect for which it is assumed that photons can be described with the kinetic theory of monoatomic gases. The photons are enclosed in a deformable cavity with perfectly reflecting walls and are initially at an elevated temperature. After the expansion of the cavity, the photons are released to a lower temperature.

It may be argued that the work delivered by this system is the maximum achievable and therefore adopted by many as the exergy of the solar radiation. In function of the irreversibilities considered (e.g., at filling, emptying of the cavity etc) several expressions for the exergy of solar radiation are published in the literature, e.g., Spanner (1974), Landsberg and Mallinson (1976), Press (1976), Jeter (1981), Badescu (2000), Petela (2003), Bejan (2006). Other recent approach to determine the exergy of insolation has been proposed by Zamfirescu and Dincer (2009). Interestingly, solar exergy maps for USA and India have been developed by Joshi et al. (2009).

In this paper a model of photothermal energy convertor that assumes radiation losses at the solar receiver and thermal losses at sink and source of the heat engine due to finite temperature differences is proposed. Other peculiarities of the present study refer to the solar receiver which not a black body but rather a grey body with a given hemispherical absorptivity and emissivity,

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Fig. 1. Thermodynamic model and for solar energy conversion.

allowing for the use of the incident beam radiation as a study variable. A sensitivity analysis is conducted to determine the thermodynamic upper bound and the practical conversion limits.

#### ANALYSIS

We start by introducing the thermodynamic model with the help of the diagram from Fig. 1 which consists of a device that converts the incident solar radiation into work with various losses. The system is comprised of a solar concentrator, as illustrated in the form of a segmented sphere at the upper part, suggesting a lens or mirror-kind collector. Note that in the general practice of photothermal energy conversion with solar concentrating paraboloidal mirrors are commonly used. This is justified by the fact that the sun rays are almost parallel for a reasonable size of concentrator. However, it should be recalled that in reality the solar rays are divergent.

The solar concentrator shown in Fig. 1 captures the incident direct beam radiation  $I_{db}$  and focuses it on the solar receiver. The focus is obtained by the optical system by increasing the solid angle under which the solar receiver sees the sun. The increase in solid angle is the same as the concentration ratio, therefore  $\Omega_c = C\Omega_s$ , where  $\Omega_s = \pi \sin^2 \omega$  is the solid angle under which the solar receiver sees the sun when the concentrator is used (see Fig. 1), and  $\Omega_s = \pi (R_s/R_0)^2$  is the solid angle under which the solar receiver sees the sun if no concentrator is used. One gets that

$$\sin^2 \omega = fC. \tag{2}$$

The aperture factor under which the solar receiver sees the sun is given by the ratio (see De Vos, 2008)

$$a_s = \frac{\int_0^{\omega} (\cos \nu) (2\pi r \sin \nu) (r d\nu)}{\int_0^{\pi/2} (\cos \nu) (2\pi r \sin \nu) (r d\nu)} \sin^2 \omega, \qquad (3)$$

where the parameters r, v,  $\omega$  are defined graphically in Fig. 1. The aperture factor under which the receiver sees the environment that is the rest of the hemisphere; as shown in Fig. 1 it becomes

$$a_0 = \frac{\int_{\omega}^{\pi/2} (\cos v) (2\pi r \sin v) (r dv)}{\int_{0}^{\pi/2} (\cos v) (2\pi r \sin v) (r dv)} = 1 - \sin^2 \omega.$$
(4)

Introducing the direct beam radiation factor  $\zeta = I_{db}/I_{sc}$  (as an integrative factor that accounts for various optical loses in the atmosphere and at the level of solar concentrator, e.g., reflectance, transmittance, cloudiness, haziness, etc) and using Eqs. (2), (3) one obtains the actual direct beam radiation incident on the receiver

$$I_{r,db} = a_s \varsigma \sigma T_s^4 = C \varsigma f \sigma T_s^4 = C \varsigma I_{sc}.$$
 (5)

The radiation impacting the receiver from the environment is, according to Eqs. (2), (4), as follows:

$$I_{r,0} = a_0 \sigma T_0^4 = (1 - Cf) \sigma T_0^4, \tag{6}$$

while the radiation emitted by the grey body receiver having the hemispherical emissivity  $\varepsilon$ , modeled as a grey body radiation at receiver's temperature  $T_r$ , is given by

$$I_{r,e} = \varepsilon \sigma T_r^4. \tag{7}$$

Based on the energy balance, the heat absorbed by the receiver becomes

$$(Q_r = \alpha (I_{r,db} + I_{r,0}) - I_{r,e}) \quad or$$
  
$$Q_r = \alpha [C\zeta I_{sc} + (1 - Cf)\sigma T_0^4 - \chi \sigma T_r^4].$$
 (8)

In the above expression it has been introduced the selective grey body factor defined by  $\chi = \varepsilon/\alpha$ .

Coupled to the solar receiver is the heat engine as illustrated in Fig. 1. The heat engine assumes linear heat transfer irreversibilities (e.g., convection, conduction) at source and sink. Therefore, with reference to Fig. 1 the heat fluxes at source and sink are, respectively

$$Q_H = U_H(T_r - T_H); Q_L = U_L(T_L - T_0),$$
(9)

where  $U_{H, L}$  denotes a heat transfer conductance in W/K at source and sink, respectively. If one introduces

$$U = U_H U_I / (U_H + U_I)$$
(10)

and remarks that  $Q_r = Q_H$ , it is straightforward to demonstrate that the work generated by a Carnot heat

engine operating between  $T_H$  and  $T_L$  (see Fig. 1) is given by

$$W = Q_r \left( 1 - \frac{T_0}{T_r - Q_r/U} \right).$$
(11)

One introduces now some dimensionless temperatures, namely  $\theta_0 = T_0/T_s$ ,  $\theta_r = T_r/T_s$  and  $U = \sigma T_s^3/U$  and combining Eqs. (8), (11) it results

$$= C\zeta I_{sc} \alpha \left(1 + \frac{1 - Cf}{\zeta Cf} \theta_0^4 - \frac{\chi}{\zeta Cf} \theta_r^4\right) \left[1\right]$$

$$- \frac{\theta_0}{\theta_r - \theta_U \zeta Cf \alpha \left(1 + \frac{1 - Cf}{\zeta Cf} \theta_0^4 - \frac{\chi}{\zeta Cf} \theta_r^4\right)}\right].$$
(12)

Having now the general expression (12) for the work resulted from solar radiation conversion, one asks the question what is the exergy of insolation? The exergy of insolation is the maximum possible work obtainable from solar radiation incident on earth. By looking to Eq. (12) one remarks that the unit for *W* is in Watt per surface area of receiver. Therefore, the work generated per square meter of earth surface illuminated by sun becomes W/C. In order to obtain the maximum possible work, the system described in Fig. 1, and modelled by Eq. (12) must have a series of peculiarities, as follows:

—It operates at maximum possible concentration ratio ( $Cf \rightarrow 1$ ).

—The emitted radiation by the receiver tends to zero ( $\chi \rightarrow 0$ ).

—The receiver adsorbs all radiation ( $\alpha \rightarrow 1$ ).

—Since the concentration is maximum, and the receiver does not emit, its temperature tends to sun's temperature ( $\theta_r \rightarrow 1$ ).

Based on all these assumptions, the exergy of insolation  $(\max\{W/C\})$  becomes

$$E_x = I_{sc} \zeta \left( 1 - \frac{T_0}{T_s} \right). \tag{13}$$

One must remark here that the insolation exergy derived from the photothermal solar radiation conversion model introduced in Fig. 1 is the same as that proposed by Bejan (2006) which in fact reformulates the Jeter (1981) approach.

The efficiency of the conversion system can be defined in terms of first (energy) and second (exergy) laws. The energy efficiency is based on the work output given by Eq. (12), and the concentrated radiation incident on the receiver  $C\zeta I_{sc}$  and is defined by

$$\eta = \frac{W}{C\zeta I_{sc}}.$$
 (14)

In the limit of  $\zeta \longrightarrow 0$ , that is dark sky conditions (no solar radiation) the receiver enters in equilibrium with the environment ( $\theta_r = \theta_0$ ) and there is no work production since the Carnot factor of the heat engine vanishes. The numerator of Eq. (12) tends faster to zero than  $\zeta$  at the denominator. Consequently, the energy efficiency tends to zero as the solar light turns off. From Eqs. (12), (14) it results the final expression for energy efficiency as follows:

$$\eta = \alpha \left( 1 + \frac{1 - Cf}{\zeta Cf} \theta_0^4 - \frac{\chi}{\zeta Cf} \theta_r^4 \right) \left( 1 - \frac{\theta_0}{\theta_r - \frac{Q_r}{UT_s}} \right). \quad (15)$$

Using Eqs. (12), (13) one can define the exergy efficiency of photothermal solar radiation conversion into work as the ratio of useful over consumed exergies, that is

$$\Psi = \frac{W/C}{E_x}$$
$$= \alpha \left(1 + \frac{1 - Cf}{\zeta Cf} \theta_0^4 - \frac{\chi}{\zeta Cf} \theta_r^4\right) \left(1 - \frac{\theta_0}{\theta_r - \frac{Q_r}{UT_s}}\right) / (1 - \theta_0).$$

From Eqs. (13), (15) it results that the ratio between energy and exergy efficiency is:

$$\frac{\eta}{\Psi} = 1 - \theta_0. \tag{17}$$

The energy and exergy efficiencies are functions of the following kinds of parameters:

—climatologic parameters  $\rightarrow \theta_0$  (average environment temperature),  $\zeta$  (which is a measure of the direct beam radiation as defined above);

—optical parameters of the solar collector  $\rightarrow C$ (concentration ratio),  $\alpha$  (hemispherical absorptivity of the solar receiver),  $\chi$  (ratio of hemispherical emissivity and absorptivity of solar receiver);

—heat engine parameters  $\longrightarrow U$  (geometric mean of heat transfer resistance at sink and source).

In addition, the exergy efficiency depends on the receiver temperature  $\theta_r$  which for the purpose of this study represents a variable for optimization.

## **RESULTS AND DISCUSSION**

The model developed in the previous section, as expressed through Eqs. (13), (16) is used further to conduct a parametric study regarding the efficiency of photothermal solar energy conversion with the device proposed in Fig. 1. As a first step of the present study we compare our model with other theoretical ones, with the purpose of validating the present results. The comparison is done for the case of a perfect black body receiver ( $\alpha = 1, \chi = 1$ ), perfectly clear sky ( $\zeta = 1$ ) and

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no heat transfer resistance at the source and sink of the heat engine  $(U = \infty)$ . In this particular situation, our model becomes similar with that proposed by De Vos (2008). Imposing  $\alpha = 1$ ,  $\chi = 1$ ,  $\zeta = 1$  and  $U = \infty$  in Eq. (15) one obtains

$$\eta = \left[1 + \left(\frac{1}{fC} - 1\right)\theta_0^4 - \frac{1}{fC}\theta_r^4\right] \left(1 - \frac{\theta_0}{\theta_r}\right).$$
(18)

For the same conditions one can apply also the energy efficiency model by Würfel (2005). In the Würfel's model, the radiation received from the background is neglected. The receiver is a black body that receives the incident direct beam radiation from the sun which is seen under the solid angle  $\pi Cf$ ; the receiver itself emits black-body radiation in the hole hemisphere (solid angle  $\pi$ ). It results that

$$\eta = \left(1 - \frac{\theta^4}{Cf}\right) \left(1 - \frac{\theta_0}{\theta}\right).$$
(19)

Another model for energy efficiency is given by Romero-Alvares and Zarza (2008) and assumes that the energy emitted is by the receiver under the same solid angle as the incident radiation coming from the surroundings (i.e., the view factor is one). The receiver is considered a grey body and the direct beam radiation is attenuated (with respect to the solar constant). In such conditions, the heat absorbed by the solar receiver becomes

$$Q_r = \alpha [C\zeta I_{sc} - \sigma \chi (T_r^4 - T_0^4)].$$
 (20)

Based on Eq. (20) and a Carnot heat engine, the energy efficiency, as defined by Romero-Alvares and Zarza (2008), becomes

$$\eta = \alpha \left[ 1 - \frac{\chi}{Cf\zeta} (\theta_r^4 - \theta_0^4) \right] \left( 1 - \frac{\theta_0}{\theta_r} \right).$$
(21)

The efficiencies given by Eqs. (18), (19), (21) are studied for a range of receiver temperatures and three concentration ratios, and fixed ambient temperature of 288 K, i.e.,  $\theta_0 = 0.05$ . In the introduction, the existence of a maximum of energy efficiency at certain receiver temperature has been discussed. This known result is retrieved, as demonstrated in Fig. 2a, by all analysed models. Würfel (2005) model returns the lowest values for the energy efficiency. This is explained by the fact that the model does not incorporate the effect of the diffuse radiation. For higher concentration ratios, the effect of diffuse radiation diminishes because the receiver is mainly influenced by the concentrated beam radiation.

If in Eq. (21) one sets  $\alpha = 1$ ,  $\chi = 1$ ,  $\zeta = 1$ , the models given in Eqs. (18) and (21) provide very close predictions, especially for concentration ratios over 5, according to the results shown in Fig. 2. The model by Romero-Alvares and Zarza (2008) assumes that the solid angle under which the receiver sees the environment is the same as the solid angle under which the



Fig. 2. Photothermal solar radiation conversion predicted by three models for  $\theta_0 = 0.05$  [dashed line: present model—Eq. (17), solid line: Würfel (2005)—Eq. (18), diamonds: Romero-Alvarez and Zarza (2008)—Eq. (20)].

environment sees the receiver—that is the view factor for thermal radiation heat exchange between receiver and the environment is equal to unity. In fact this is only an approximation, because in reality, the receiver is "shaded" by the solar concentrator, and therefore, it sees the environment emitting diffuse radiation under a smaller solid angle. The model expressed by Eqs. (15), (18) takes into account this difference in solid angle and it is therefore more accurate. However, in the hypothesis discussed in the above paragraph (blackbody receiver), the difference in predictions by models (18) and (21) is negligible (see Fig. 2a). The difference between the quantity  $\eta/\alpha(1 - \theta_0/\theta_r)$  as predicted by our model (Eq. (15)) and as predicted by Eq. (21) when  $U = \infty$  is of the order of  $-\theta_0^4/\zeta$ .

In Fig. 2b we plot on a dual y-axis diagram the optimal value of receiver temperature  $Q_{r, opt}$  for which the efficiency of the photothermal solar radiation convertor is maximized (left y-axis). The other y-axis shows the maximum receiver temperature,  $\theta_{r, max}$ . The maximum receiver temperature occurs when the emitted radiation balances all incident radiation and therefore no heat is left for the heat engine which, in this condition, does not produces any work. The analysis shown in Fig. 2b refers to low concentration ratio where the predictions of Würfel (2005) model are significantly lower that predicted by other model, again due to the effect of neglecting the diffuse radiation.

In brief said, the model proposed in this paper gives better confidence because it agrees well with past works that assume black body receiver. We now go ahead and conduct a parametric study on energy and exergy efficiencies using the formulas given by Eqs. (15), (16) which incorporate the more general case of grey body receiver and other additional irreversibilities. The next part of the study regards the maximum efficiency of the convertor in the hypotheses of no irreversibilities at the heat engine  $(U = \infty)$  and full beam radiation ( $\zeta = 1$ ). One considers however, that the receiver has a hemispherical emissivity that can be different from the absorptivity. A radiation selective coating can be applied on the receiver surface so that the emissivity becomes smaller than the absorptivity. The factor  $\chi$ defined in the above section can take practical values from 0.1 to 1 (see the discussion in the Introduction and Romero-Alvares and Zarza, 2008). We extended however the study toward lower values of  $\gamma$  that approach zero in order to obtain an idealistic upper limit of the conversion efficiency. The results are shown in Fig. 3a in terms of efficiency as a function of receiver dimensionless temperature.

The reported energy efficiency in Fig. 3a is divided by the hemispherical absorptivity  $\alpha$  that is considered a constant parameter. For each concentration ratio, the efficiency curve presents a maximum that is identified with the dotted line. A bundle of doted lines are superimposed on the same plot. These are the lines that unite the maxima of energy efficiency, and are drawn for various the selective grey body receiver factors,  $\chi$ . The curve for  $\chi = 1$  shows a maximum efficiency of 0.853 for  $\theta_0 = 288$  K, which is the known result recalled in the Introduction. In addition to this, from the plot one yields that, if the receiver is more selective ( $\chi$  is lower) the maximum reachable efficiency increases. For example at  $\chi = 0.1$ ,  $\eta_{max} = 0.91$ , and at  $\chi = 0.015$ ,  $\eta_{max} =$ 0.93—this last value representing an ideal one of solar energy conversion, higher than 0.853, due to the



Fig. 3. Energy efficiency (a) and optimal receiver temperature (b) for  $\theta_0 = 0.05$ , assuming a receiver defined by a selective grey body factor  $\chi$ .



Fig. 4. Maximum energy (a) and exergy (b) efficiency for  $\theta_0 = 0.05$ , assuming a receiver defined by a selective grey body factor  $\chi$ ; the heat transfer conductance is  $U = \infty$ .

assumption of negligible emissivity. The corresponding optimal values of receiver temperature (for which the efficiency is maximized) are reported in Fig. 3b.

One also shows in Fig. 4 the maximum exergy and energy efficiencies.

In Figs. 5 and 6 the results regarding the optimal performance (or maximum efficiency) of the photothermal conversion system are presented, assuming  $U = \infty$  and  $\theta_0 = 0.05$ .

Figure 5 shows the variation of the optimal receiver temperature for the full theoretical range of the selective grey body factor  $\chi$ . The  $\theta_{r,opt}$  profiles are shown for

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six concentration ratios covering the full range of variation of this parameter, i.e., from 1 (no concentration) to 1/f (theoretical maximum concentration). For every concentration ratio we plot a bundle of four curves corresponding to four values of the direct beam radiation diminishing factor  $\zeta$ , namely 0.25, 0.50, 0.75 and 1.00. The effect of  $\chi$  is more important at high concentration ratios.

Figure 6 shows the corresponding energy efficiencies.

In Fig. 7 we present the influence of the ambient temperature on energy and exergy efficiencies of solar energy conversion. The covered range of ambient tem-



**Fig. 5.** Optimum dimension less receiver temperature at  $\theta_0 = 0.05$  for full theoretical range of selective grey body factor  $\chi$  and various concentration ratios and four values of direct beam radiation factor  $\zeta$ ; the heat transfer conductance is  $U = \infty$ .



Fig. 6. Maximum energy efficiency of photothermal solar radiation conversion at  $\theta_0 = 0.05$  for full range of grey body receiver factor  $\chi$  and various concentration ratios and four values of direct beam radiation factor  $\zeta$ ; the heat transfer conductance is  $U = \infty$ .



Fig. 7. Photothermal energy (a) and exergy (b) efficiencies of solar radiation conversion for maximum (theoretical upper limit, C = 46300) and technical achievable (C = 10000) concentrations for the range of ambient temperatures on the earth; the heat transfer conductance is  $U = \infty$ .

perature is from -50 to  $+50^{\circ}$ C. On the plots, two cases are presented from which the first regards the theoretical upper bound of conversion efficiency obtained when the concentration ratio is maximum and the sky is completely clear such that  $\zeta = 1$ . The second is a more

practical case where the incident beam radiation is assumed to be 80% of the solar constant and the concentration ratio is 10000. When the heat engine is a Carnot-based one, the profiles shown in this figure could be taken as theoretical upper limits.



Fig. 8. Energy efficiency maxima at maximum concentration for various heat transfer conductances U, and selective grey body factor  $\chi$ .

The influence of heat transfer conductances at sink and source is investigated in Fig. 8 based on Eq. (15) for the case of maximum concentration; also one assumes clear sky condition ( $\zeta = 1$ ), selective black body receiver ( $\alpha = 1, \chi = \{0, 0.2, 0.4, 0.6, 0.8, 1.0\}$ ) and standard ambient temperature ( $\theta_0 = 0.05$ ). This analysis demonstrates that there is a minimal threshold for the receiver temperature, higher than  $\theta_0$ , over which the thermodynamic cycle behaves as a heat engine.

The temperature threshold increases with the decrease of the heat engine conductance defined by Eq. (10). For the limit of infinite conductance (no heat transfer resistance,  $U = \infty$  or  $\theta_U = 0$ , the efficiency profile approaches the one calculated in Fig. 3a, for which the maximum efficiency is 0.853. If the selective blackbody factor  $\chi$  is reduced the efficiency increases even more. The optimal receiver temperature displaces toward higher values and the efficiency profile becomes flatter around the maximum.

The global maximum solar intensity is obtained for the hypothetical case when  $\chi = 0$ , and it is  $(1 - \theta_0)$ . This value can be obtained from Eq. (15) if one introduces  $\alpha = 1, \theta_r = 1, \zeta = 1, \chi = 0$  and corresponds to the exergy of solar radiation (the receiver's temperature reaches the temperature of the sun). In this extreme situation the exergy of the solar radiation is retrieved. Obviously, such a theoretical limit can never be reached in practice, since any body at a temperature higher than that of zero Kelvin emits radiation, but it has a theoretical value as an upper bound of solar energy conversion.

Figure 9 illustrates the maximum energy efficiency for a range of insolations. Three values of hemispherical absorptivity and three values of heat transfer conductance (or dimensionless temperatures  $\theta_U$ ) were considered for calculations. The calculations were repeated for two concentration ratios, i.e., 1000 and 5000. In Fig. 10 the maximum energy (a) and exergy (b) efficiencies for a range of ambient temperatures and several *U*'s and *C*'s are also presented.



Fig. 9. Maximum energy efficiency for a range of insolations ( $\zeta$ ) and several hemispherical absorptivities ( $\alpha$ ) of the solar receiver and heat transfer conductances of the heat engine ( $\theta_{I/}$ ).



Fig. 10. Maximum energy (a) and exergy (b) efficiency as function of ambient temperature, for various heat transfer conductances and concentration ratios.

#### CONCLUSIONS

In this paper, we present a thermodynamic model for photothermal solar radiation conversion into work with a maximum efficiency, which includes irreversibilities at the solar receiver (radiation losses, non-black body—i.e., selective grey body receiver) and at the heat engine (finite heat transfer conductances). The results are presented in the paper in the form of diagrams which may be found useful for the design and assessment of photothermal solar energy conversion systems and their applicability. The relevant parameters for conducting a sensitivity study, among which one notes the dimensionless temperature  $\theta_U = \sigma T_s^4/U$ , were identified. We can extract some particular conclusions from this study:

—The results from the present model agree considerably well with the prediction of consecrated models.

—Theoretical energy efficiency limit of 0.853 of photothermal solar radiation conversion with black body receiver can be overcome by using a selective receiver.

—At the hypothetical limit when the receiver only absorbs ( $\alpha = 1$ ), but does not emit ( $\varepsilon = 0$ ) radiation all the solar radiation exergy is retrieved.

—The optimal receiver temperatures increase in a quasi-logarithmic form with an increase in concentrations.

—The heat transfer conductances at sink and source have major influences on both energy and exergy efficiencies. —The exergy and energy efficiencies at optimal operation are hardly influenced by the ambient temperature of the earth, which affects them with up to 15%.

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