Exergetic assessment of transmission-concentrated solar energy systems via optical fibres for building applications

Chafika Zidani*, Boumédiène Benyoucef and Nassima Madini

Unit of Research on Materials and Renewables Energies,
Tlemcen University,
13000, Republic of Algeria
Tel/Fax: 00 (213) 43 21 58 90 & 89
E-mail: Czidani10@yahoo.fr
E-mail: benyoucef_boumediene@yahoo.fr
E-mail: ma_nassima@yahoo.fr
*Corresponding author

Abstract: Optical fibressolar energy transmission and concentration provide a flexible way of handling concentrated solar energy. Solar lighting with Fibre Optic Bundles (FOBs) can be considered a promising option for energy-efficient green buildings. This study deals with the exergetic analysis and performance assessment of a system based on the idea of Transmission-Concentrated Solar Energy via Optical Fibres (TCSEvOF). A mathematical model is proposed for this study. The daily average exergy efficiencies are found to be 27% for the spring and autumn equinoxes, it is expected that the presented model would be beneficial to everyone involved in the design and performance evaluation of the solar lighting with FOB in building applications.

Keywords: solar lighting; concentrated solar energy; FOB; fibre optic bundle; exergy analysis; efficient buildings.

Reference to this paper should be made as follows: Zidani, C., Benyoucef, B. and Madini, N. (2012) 'Exergetic assessment of transmission-concentrated solar energy systems via optical fibres for building applications', *Int. J. Exergy*, Vol. 11, No. 2, pp.216–228.

Biographical notes: C. Zidani is working as a Teaching Assistant in the Department of Physical at Aboubakr Belkaid University in Algeria. He received his Magister in Physical Materials and Renewable Energy from the University in 2001. His research is in Unit of Research on Materials and Renewable Energies, University of Tlemcen. His research interests include renewable energy design optimisation, photo-thermal systems, optical fibres and solar concentrator.

B. Benyoucef is a Professor at Tlemcen University, Director of the Unit of Research on Materials and Renewable Energies, University of Tlemcen, Faculty of Science, Department of Physics. He received his PhD from Paris University in 1986. He has published more than 500 papers in different journals and conferences in the materials and renewable energy, heat transfer, solar cells, photo-thermal and photovoltaic systems.

N. Madini has been a PhD student at the Department of Physical at Aboubakr Belkaid University in Algeria. His research area includes semi-conductor, renewable energy and nano-materials.

1 Introduction

The main difficulty in using solar energy is its low density. To solve this problem, a concentrating system is commonly proposed. The concentrated solar energy is transformed to thermal energy and then transported or applied in a direct manner to produce the final energy form, which can be used.

Clearly, the inherent losses during conversion are an inconvenience. In direct applications, the solar beams, which might be blurred, and the requirement for complex structural design so that to follow up the sun trajectory are the main limitations.

For the sake of surpassing these limitations, 20 years ago Robieux (1975) proposed to use one rigid light guide jointly with a paraboloidal mirror to transport concentrated solar radiation. Later on, Kato and Nakamura (1976) studied the theoretical possibility of using fused silica optical fibres to transmit solar radiation. They reported an average attenuation of 25 dB km^{-1} for the solar spectrum in linear transmission, i.e., about 6% loss after a 10 m long path. The idea of Transmission of Concentrated Solar Energy via Optical Fibres (TCSEvOF) was put forward in 1980 by a group of French investigators. Owing to the unavailability of high-quality optical fibres and the high cost of their design, this project limited itself to theoretical analysis only. Nowadays, with the availability of the fibre-optic techniques, solar energy can be transmitted by high-quality optical fibres with large core diameter and large numerical aperture (Liang et al., 1998; Cariou et al., 1982).

The systems based on the idea of transmitting concentrated solar energy via optical fibres (TCSEvOF) provide flexible options for numerous implementations such as solar lighting, solar power generation, solar surgery, photobioreactors, hydrogen generation and photochemical reactions and solar pumped lasers.

Nowadays, optical fibre materials offer a lesser attenuation, thus modern optical fibres produce better optical efficiency (Jaramillo et al., 1999). They can transmit a higher radiative heat flux than could the optical fibres used 20 years ago.

There are numerous studies on thermal analysis and solar power generation by TCSEvOF systems. Jaramillo et al. (1999) developed a theoretical thermal study of optical fibres transmissing solar energy. It was indicated that the thermal study considered a wavelength-dependent absorption coefficient of the optical fibre core to obtain the radiative heat flux in the fibre. Kribus and co-workers (2000) presented a study on the potential use of optical fibres for solar thermal power generation.

Jaramillo et al. (2002) carried out a theoretical and experimental thermal behaviour study of optical fibres with a high-purity SiO_2 core transporting concentrated radiative energy. Kandilli and Ulgen (2009) and Kandilli (2007) made a detailed review of previous studies on TCSEvOF.

The classical energy analysis does not give the qualitative evaluation of the various losses occurring in the components. Therefore, the exergy analysis based on the second-law analysis is considered to obtain a detailed picture of the various losses quantitatively as well as qualitatively.

Exergy analysis has been widely used in the design, modelling and performance assessment of thermal systems. Singh et al. (2000) performed an exergy analysis of a solar thermal power system using a parabolic trough collector system to evaluate the actual exergy available for running a thermodynamic Rankine heat engine cycle for power generation. Tyagi et al. (2007) evaluated a theoretical exergetic performance of concentrating-type solar collector. Their evaluation was based on a parametric study using hourly solar radiation, by optimising the exergy output with respect to the inlet fluid temperature and computing the corresponding efficiencies.

In the present study, the exergy analysis of the systems based on the idea of TCSEvOF is performed. The studies on exergy analysis of TCSEvOF system are very limited in the open literature as far as the authors know.

This was the motivation behind the present study. The structural organisation of this study can be listed as follows. In Section 1, a brief introduction is given by emphasising on the aims of this study and comprehending usage and energy analysis of TCSEvOF systems as well as exergy analysis of solar concentrator systems. The objectives and the originality of the present study are also emphasised in this section.

The system description and the theoretical model for energy and exergy efficiencies are given in Section 2. The calculations and the obtained results by applying the model in different sites of Tlemcen are described and discussed in Section 3. The last section is concerned with different conclusions.

2 Mathematical model

Tlemcen, the third big city of Algeria, is located at a latitude of 34.56°N, longitude of –1.19°E and altitude of 800 m. Tlemcen is situated in the Mediterranean climate belt; it has hot and dry summers, cool and rainy winters.

In this section, the mathematical model for coupling the FOB and a paraboloidal dish is described and studied within the environment of this city. The optimal geometric parameters relating both the paraboloidal dish and the FOB are presented.

The paraboloidal concentrator with a specular reflecting surface allows one to concentrate the solar beams at the focus plane where the FOB is placed. Each optical fibre has a pure transparent inner core and a thin transparent outer cladding.

The phenomenon of total internal reflection allows the light to travel through the core. The fibre core has an index of refraction n_1, which is greater than that of the cladding n_2. The ratio of the core index and cladding index determines the acceptance angle of radiation $\theta_{\max}$ at which total internal reflection occurs (Hetch, 1990),

$$\sin\theta_{\max} = \left(n_1^2 - n_2^2\right)^{1/2}. \tag{1}$$

When an FOB with a fixed acceptance angle $\theta_{\max}$ and diameter D_C is used, the parameters of the paraboloidal mirror can be obtained by looking for an optimal coupling between the concentrator and the FOB. Then, the rim angle ϕ_r should be equal to or smaller than the optical fibre admission angle θ_i, i.e.,

$$\phi_r \leq \theta_i. \tag{2}$$

So that the maximum rim angle of the paraboloidal mirror ϕ_r is $\phi_r = \theta_{max}$.

For a paraboloidal mirror, the relationship between the focal length f and the aperture diameter D_a can be easily obtained from analytical geometry to be:

$$\frac{f}{D_a} = \frac{1}{4\tan(\phi_r / 2)}. \tag{3}$$

On the other hand, for a flat receiver in the focal plane of the paraboloidal concentrator the receptor diameter D_r is (Duffie and Beckman, 1991):

$$D_r = \frac{D_a \sin 0.267}{\sin\phi_r \cos(\phi_r + 0.267)}. \tag{4}$$

Taking into account that the concentration ratio is the ratio of the paraboloidal dish area of aperture A_a to the area of the receiver A_r, the maximum concentration is obtained by the interception of specular reflected radiation within the cone with an angle of 0.533°+δ (Duffie and Beckman, 1991):

$$C_{max} = \left(\frac{D_a}{D_r}\right)^2 = \frac{\sin^2\theta_{max}\cos^2(\theta_{max} + 0.2672° + \delta / 2)}{\sin^2(0.2672° + \delta / 2)} \tag{5}$$

where δ is a measure of the angular errors of the reflector surface and 0.267° is the half-angle of the incident beam cone of solar radiation. It is important to indicate that the receptor diameter D_r is replaced by the core diameter D_C at the input section of the FOB. Taking into account equations (3) and (5), we can write the optimal focal length f_0 as:

$$f_0 = \frac{D_c}{4\tan(\theta_{max} / 2)}(C_{max})^{1/2}. \tag{6}$$

Once we have established the geometrical parameters, we need to analyse the rate of energy hitting the end of the FOB. The energy rate on the focal plane, where the FOB is placed, is estimated on the basis of opto-geometrical parameters.

The rate of energy Q hitting a flat receiver of the paraboloidal concentrator was established by Siegel and Howell (1981):

$$Q = \pi f^2 \rho_m G_b (\sin^2\phi_r - \sin^2\phi_{min}) \tag{7}$$

where f is the focal length, ρ_m is the reflectance of the mirror surface, G_b is the solar beam irradiance, ϕ_r is the rim angle of the paraboloidal mirror and ϕ_{min} is the shading angle because of the receptor size.

At this level, we can define the concentration efficiency as (Simon, 1991):

$$\eta_c = \frac{\sin^2\phi_r - \sin^2\phi_{min}}{4\tan^2(\theta_{max} / 2)}\rho_m. \tag{8}$$

Assuming that there is a perfect image of the sun on the focal plane, i.e., we have an ideal concentrator.

Using equations (5) and (7), the maximum energy rate of the optical fibre bundle Q_{in} can be expressed as:

$$Q_{\text{in}} = (1-\rho_f)\frac{\pi D_c^2}{16\tan^2(\theta_{\max}/2)}C_{\max}\rho_m G_b(\sin^2\theta_{\max} - \sin^2\theta_{\min}) \tag{9}$$

where ρ_f is the unpolarised reflection of the radiation while it is passing from the environment to the core material (Modest, 1993). Therefore, the transmission losses at the beginning of the FOB caused by unpolarised reflection are taken into account by $1-\rho_f$.

Knowing that concentrated solar energy will be exposed some losses before entering into the FOB.

In concentrating collectors, solar energy is optically concentrated before being transferred into heat. The energy rate at focal plane Q_f is calculated from:

$$Q_f = Q_{\text{in}} + U_r A_{\text{of}}(T_r - T_o) \tag{10}$$

where U_r is the receiver-ambient heat transfer coefficient, while T_r and T_o are receiver and ambient temperatures, respectively.

On the other hand, from the definition of decibel losses per unit length (Hetch, 1990), the energy rate Q_{out} at the end of optical fibre can be expressed as (Hetch, 1990):

$$Q_{\text{out}} = 10^{-(LdB_{\text{loss}}/10)}Q_{\text{in}} \tag{11}$$

where L is the optical fibre bundle length and dB_{loss} is the optical fibre attenuation. In general, the attenuation function depends on the wavelength, so that, to perform a thermal analysis, we need to consider this aspect.

The system based on the idea TCSEvOF is evaluated by dividing into two subsystems, as shown in Figure 1. The first subsystem is to concentrate the solar energy coming to aperture of the collector, while the second one is to transfer this concentrated energy through the FOB. The TCSEvOF system does not store energy, and then the system can be assumed as steady flow.

Maximum efficiency ratio ψ is given by Petela (2005) as follows:

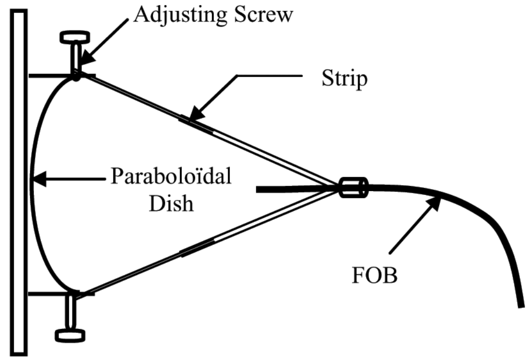
$$\psi = 1 + \frac{1}{3}\left(\frac{T_0}{T}\right)^4 - \left(\frac{4}{3}\right)\frac{T_0}{T} \tag{12}$$

where T_0 is the ambient temperature and T is the temperature of the exergy source. It can be defined as the exergy of the solar radiation by substituting $T = T_s$, apparent black body temperature of the sun, 6000 K.

Relating to the first subsystem, the exergy rate inflow coming from the solar radiation falling on the collector surfaces is given by:

$$Ex_{\text{in}} = G_b A_a \psi. \tag{13}$$

Figure 1 The coupling between the concentrator and the FOB



Relating to the second subsystem, if the concentrated solar energy on the receiver is assumed as the exergy source of the useful energy from the end of the FOB, the exergy flow transferred is given by:

$$Ex_{\text{out}} = Q_{\text{out}}\left(1 - \frac{T_0}{T_r}\right). \tag{14}$$

For the whole system, the energy and exergy efficiencies can be given as, respectively:

$$\eta = \frac{Q_{\text{out}}}{G_b A_a} \tag{15}$$

$$\varepsilon = \frac{Ex_{\text{out}}}{Ex_{\text{in}}}. \tag{16}$$

The system of transmission for concentrated solar energy via optical fibres is presented in Figure 1. From this system, the entry of FOB is placed on the focal point of the paraboloidal dish. Solar energy is concentrated on a spot whose size is equal to the surface of the inlet of the FOB.

In this system, the concentrated solar energy on the focal plane is not transported by using a fluid, but it is transferred via FOB directly. The light is scattered by Rayleigh dispersion effect at the entrance of the bundle. Besides, it can be absorbed by the holes between the cables. These effects can cause excessive heating and degradation of acrylic material. To minimise them, two types of optical fibres with different diameters (Type 1: 2.5 mm and Type 2: 3.0 mm) were used to bundle the fibres. Thirty-one pieces of Type 2 cables were installed in the centre of the bundle and 64 pieces of Type 1 cables were placed on the their surrounding. Spectral transmission properties of the FOB analysed before are very crucial for the system.

High reflective paraboloidal dishes previously referred to in the literature are covered by aluminium or silver (Kandilli et al., 2007). It can be made of glass mirrors. The paraboloidal mirrors made of glass can result in very high mechanical loads. Also, practically it may be difficult to protect and utilise the glass mirror paraboloidal dish. In the present study, the paraboloidal dish was adopted from a simple existing satellite antenna and processed by chrome to provide high reflectivity.

Table 1 indicates the important parameters of the system. FOB used in the present study consists of large core flexible polymethylmethacrylate (PMMA) optical fibres. The length of FOB is 4 m and the diameter is 0.03 m.

Table 1 Parameters of the system

Parameters of the system	
D_a (m)	1.04
D_r (m)	0.03
A_{of} (m^2)	0.00049
A_a (m^2)	0.85
f (m)	0.78
f_0 (m)	0.87
ϕ_r (°)	36.87
ϕ_{min} (°)	0
θ_{max} (°)	30.7
$\delta/2$ (°)	0.39
dB_{loss} (dB/m)	0.30
L (m)	4
C_{max}	1731
ρ_m	0.60
η (%)	0.32
ε (%)	0.27
T_0 (K)	298

The maximum admission angle of FOB is determined by equation (1). Rim angle of the dish is calculated by equation (3).

The attenuation of the optical fibre is indicated as 300 dB/km by the manufactured data.

For maximum concentration ratio, the rim angle is used in equation (5) and is found to be 1731.

3 Results and discussion

De Brichambaut (1984) developed a theoretical model (for the city of Tlemcen), which uses average values of the parameters influencing the solar radiation with emphasis on the concept of atmospheric mass. In the present study, this model is used to obtain the daily energy received by a panel (α, γ) for any orientation with: α and γ being the Azimuth and the inclination of the panel, respectively.

As it is illustrated in Figure 2, the daily energy gap becomes important between winter and summer. The maximum energy is given by the panel $(\alpha = 0, \gamma = 90° - 0°)$ and the minimum is for the panel $(\alpha = 0, \gamma = 90° - 90°)$ in the summer solstice, as GJ (max) ≅ 9000 Wh/m^2, GJ (min) ≅ 2000 Wh/m^2.

Similarly, Figure 3(a) illustrates the daily average received power for the paraboloidal dish proposed for the solstices and equinoxes. It can be understood from the graph that the received power can reach 324.70 W in solar noon for the winter solstice, 377.46 W for the spring equinox and the autumn equinox. For the summer solstice, the values exceed 394 W.

Figure 2 The daily energy received by different orientations for the panel

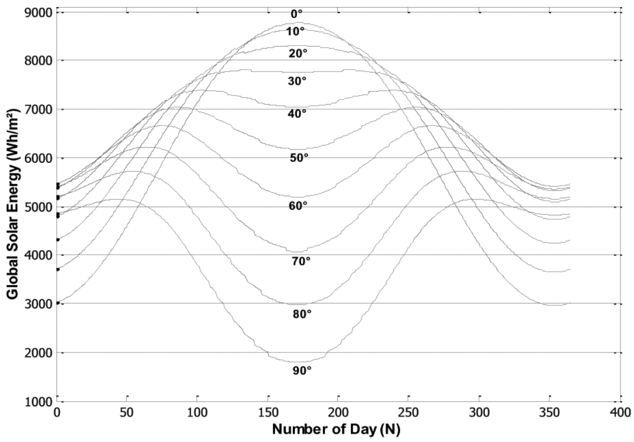


Figure 3(b) shows the daily average received power in the entrance of the FOB. It can be seen that the power is 83.21 W in solar noon for the winter solstice, 96.74 W for the spring equinox and the autumn equinox. The values exceed 101.03 W for the summer solstice in solar noon.

Concentrated solar energy will be exposed to some losses before entering into the FOB.

For 21 March (spring equinox), from 6h (sunrise) to 12 h (solar noon) the relationship between the heat flux (W/cm^2) and the length of the FOB is given in Figure 5. It is observed that the heat flux decreases, while the length values go up, although the attenuation increases with the length of the fibre.

It can be understood from the Figure 4 that the output power has the values of 100.77 W at the entrance. It decreases to 89.37 W at 4 m for the length of FOB.

The relationship between the global solar radiation (W/m^2) and the temperature of the receiver (K) is given in Figure 3. It is observed that the receiver temperatures increase, while the global solar radiation values go up.

A linear tendency is found between the global solar radiation and the receiver temperature.

Figure 6 illustrates the relationship between the global solar radiation (W/m^2) and the exergy efficiency of the system. It is found that there is a parabolic relation tendency between them.

In Figure 7, the hourly exergy efficiency variation for the TCSEvOF system from the solstices and the equinoxes are presented.

It is obvious from these figures that the exergy efficiency of the system varies between 2 and 26% in daytime for winter solstice, 4.7–27% for spring equinox and autumn equinox. Similarly, the exergy efficiency ranges between 5 and 28.5% for summer solstice.

On 21 March, at 12:00 a.m. at the local time, the global solar radiation was 1034 W/m^2, the solar beam radiation calculated is 914 W/m^2, the ambient temperature was about 298 K (25°C), and the wind speed was 2 m/s.

The receiver temperature is calculated to be 699 K (424°C). The energy and exergy efficiency values for the whole system were found to be 0.32 and 0.27, respectively.

Figure 3(a) The hourly power hitting a flat receiver of the paraboloidal dish (*W*) for equinoxes and solstices

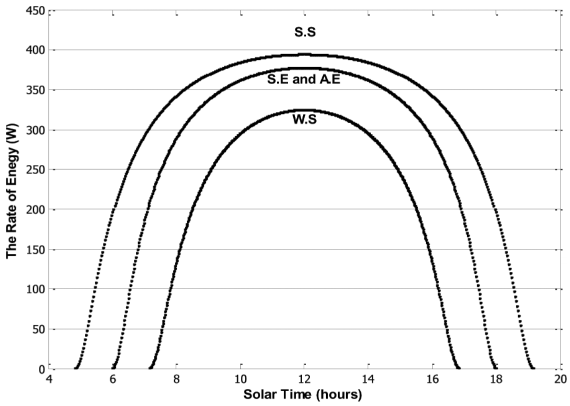


Figure 3(b) The maximum hourly power at the inlet of the FOB (*W*) for equinoxes and solstices

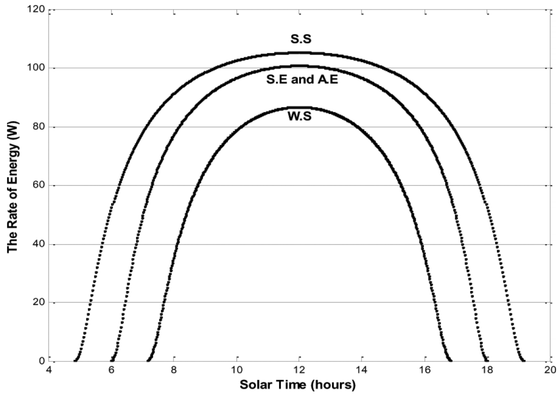


Figure 4 The energy rate transferred via FOB for spring equinox

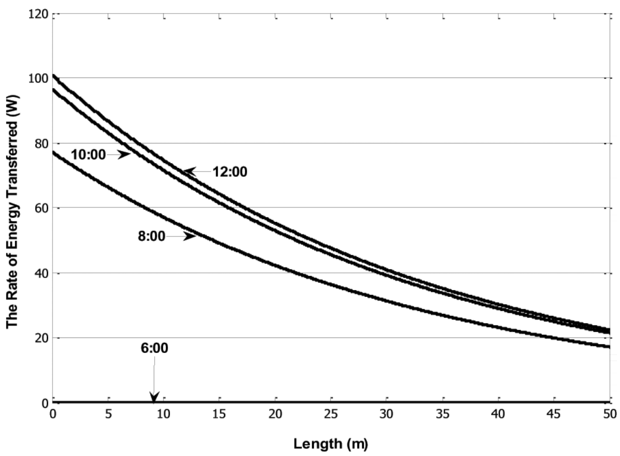


Figure 5 The relationship between the global solar radiation (W/m²) and the receiver temperature

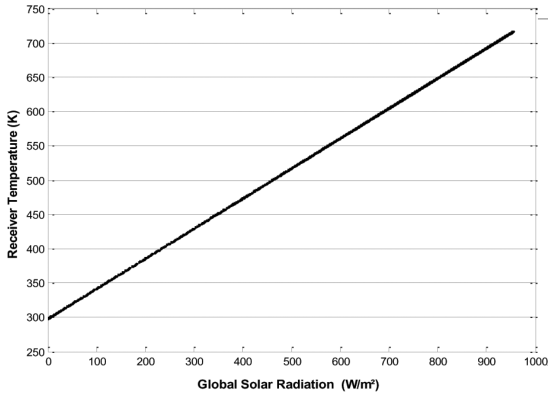


Figure 6 The relationship between the global solar radiation (W/m²) and the exergy efficiency of the system for the solstices and equinoxes

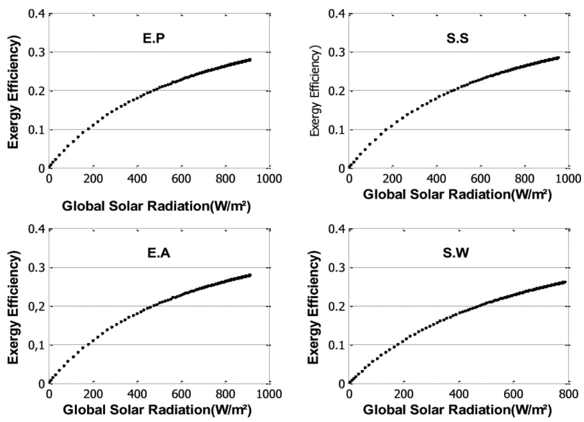
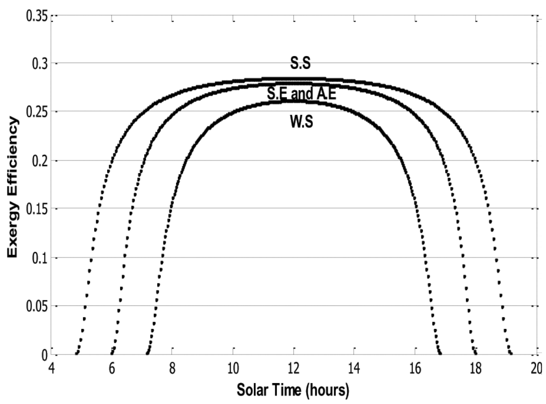


Figure 7 Average hourly exergy efficiency for the TCSEvOF system for the solstices and equinoxes



4 Conclusions

The exergy analysis of a low-cost, high reflective, tracking the sun along two axes offset paraboloïdal dish integrated FOB was made in this study. Although the main aim of the system was solar lighting to non-daylight areas, it could be possible to transform by additional components and some modifications for the further applications in buildings.

The obtained results show that the use of optical fibres as element in highly concentrated solar energy transmission in a real possibility that is worth investigating experimentally.

The main deductions, which can be done relating the obtained results, can be given as follows:

- Idea of TCSEvOF has been a source for numerous studies conducted on different areas since the 1980s.
- The efficiency of the system could be improved by utilising high reflective materials for the paraboloïdal dish.
- The type of the optical fibres, plastic, glass or liquid can be chosen for the aim of the study. Glass optical fibres show less attenuation feature than the plastical ones.
- The energy efficiency of the whole system is calculated to be 0.32, while the exergy efficiency is found to be 0.27 at a global solar radiation of 1034 W/m^2.
- The energy and exergy efficiencies of the system increased with the increase in the global solar radiation values and by finding a way to benefit all parts of the solar spectrum.

For further studies, it would be very essential to achieve higher temperatures and larger efficiencies. However, the durable material for the FOB against the high temperatures should be chosen to transfer the concentrated solar energy. It could be worth to test the fibres based on SiO_2 for the thermal application of TCSEvOF systems, even there would be hazard to lose flexible utilisation advantage of PMMA fibres. In this case, it could be a good solution to connect the PMMA-based fibres and silica-based fibres to benefit both fiexibility and durability properties.

However, plastical optical fibres are more flexible and can have larger core diameter, and it can be more suitable for solar lighting. On the other hand, the applications of solar can be more appropriate to use glass optical fibres. At present, the core diameter of glass optical fibres is very small compared with the plastical ones. Accordingly, great number of cables can be needed to bundle from the glass optical fibres. The holes between the optical fibres should be reduced as much as possible to minimise the losses during the bundling process. It can be provided by forming joining cables hexagonally in the entrance of the FOB or mixing the cables that have different core diameters.

Finally, TCSEvOF systems can have a great potential for solar energy application in a wide range of research area. The systems based on the ideal TCSEvOF can find significant opportunities to be used in some innovative and prospective studies with multidisciplinary research structure.

References

Cariou, J.M., Martin, L. and Dugas, J. (1982) 'Transport of solar energy with optical fibres', *Solar Energy*, Vol. 29, pp.397–406.

De Brichambaut, P. (1984) *The Energy Evaluation of a Solar Gisement*, Lavoisier Edition, Tec and Doc, Paris.

Duffie, J.A. and Beckman, W.A. (1991) *Solar Engineering of Thermal Processes*, Wiley-Interscience, New York.

Hetch, J. (1990) *Understanding Fibre Optics*, Howard Sams, USA.

Jaramillo, O.A., Del Rio, J.A. and Huelsz, G. (1999) 'A thermal study of optical fibres transmitting concentrated solar energy', *Journal of Physics. D. Applied Physics*, Vol. 32, No. 9, pp.1000–1005.

Jaramillo, O.A., Huelsz, G. and Del Rio, J.A. (2002) 'A theoretical and experimental thermal study of SiO_2 optical fibres transmitting concentrated radiative energy', *Journal of Physics D: Applied Physics*, Vol. 35, pp.95–102.

Kandilli, C. (2007) 'Design, constructing, testing of the active hybrid sunlight system and investigation of the parameters affecting its performance', *Ph.D. Thesis*, Ege University, September, Turkish.

Kandilli, C. and Ulgen, K. (2009) 'Review and modelling the systems of transmission concentrated solar energy via optical fibres', Renewable and Sustainable Energy Reviews, Vol. 13, pp.67–84.

Kandilli, C., Turkoglu, A.K. and Ulgen, K. (2007) 'Transmission performance of fibre optic bundle for solar lighting', in *CD-Proceedings of the Third International Energy, Exergy and Environment Symposium*, 1–5 July, E ´vora, Portugal.

Kato, D. and Nakamura, T. (1976) 'Application of optical fibers to the transmission of solar radiation', *J. Appl. Phys*., Vol. 40, pp.4528.

Kribus, A., Zik, O. and Karni, J. (2000) 'Optical fibres and solar power generation', *Solar Energy*, Vol. 68, pp.405–416.

Liang, D., Monteiro, L.F., Teixeira, M.R. Monteiro, M.L.F. and Collarespereira, M. (1998) 'Fibre-optic solar energy transmission and concentration', *Solar Energy Materials and Solar Cells*, Vol. 54, pp.323–331.

Modest, M.F. (1993) '*Radiance Heat Transfer*, McGraw-Hill, New York.

Petela, R. (2005) 'Exergy analysis of the solar cylindrical–parabolic cooker', *Solar Energy*, Vol. 79, pp.221–233.

Robieux, J. (1975) Patent 75-14582 (INPI), *International Classification*, F03g 7/02; 02 KX/G02b5/10.

Tyagi, S.K., Shengwei, W., Singhal, M.K., Kaushik, S.C. and Park, S.R. (2007) 'Exergy analysis and parametric study of concentrating type solar collectors', *International Journal of Thermal Sciences*, Vol. 46, No. 12, pp.1304–1310.

Siegel, R. and Howell, J.R. (1981) *Thermal Radiation Heat Transfer*, Wiley, New York.

Simon, A.W. (1958) 'Calculation of the concentration of energy at points outside the focal spot of a parabolic condenser', *Solar Energy*, Vol. 2, No. 2, pp.22–24.

Singh, N., Kaushik, S.C. and Misra, R.D. (2000) 'Exergetic analysis of a solar thermal power system', *Renewable Energy*, Vol. 19, pp.135–143.

Abbreviations

S.E	spring equinox
A.E	autumn equinox
S.S	summer solstice
W.S	winter solstice
NA	numerical aperture (dimensionless)
FOB	fibre optic bundle
TCSEvOF	transmission of concentrated solar energy via optical fibres
PMMA	polymethylmethacrylate.

Nomenclature

A	Surface area (m^2)
C_{max}	Max ratio of geometrical concentration
D	Diameter (m)
dB_{loss}	Attenuation of optical fibre (dB/m)
Ex	Exergy rate (W)
f	Focal length (m)
G	Solar beam irradiance
L	Fibre-optic bundle length (m)
n	Refraction index (dimensionless)
Q	Energy rate (W)
U	Heat transfer coefficient (W/m^2K)
T	Temperature (K)
Greek letters	
δ	Dispersion angle (°)
ε	Exergy efficiency (dimensionless)
η	Energy efficiency (dimensionless)
θ	Admission/acceptance angle (°)
ρ	Reflectivity (dimensionless)
ρ_f	Unpolarised reflection of radiation
ϕ_r	Paraboloidal dish rim angle (°)
ϕ_{min}	Paraboloidal dish shading angle (°)
ψ	Maximum efficiency ratio (dimensionless)