16èmes Journées Internationales de Thermique (JITH 2013)
Marrakech (Maroc), du 13 au 15 Novembre, 2013

Theoretical thermal limits of photothermal system based on the idea of transmission solar energy via optical fibers

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Abstract :

The aims of this study are to optimize the coupling of a paraboloidal dish, which concentrates direct solar irradiance with dual axes tracking component, and the optical fiber, which transmits concentrated solar energy. We present previous review studies on the transmission of concentrated solar energy via optical fibers (TCSEvOF), and provide a mathematical model for coupling paraboloidal dish and the optical fiber. We present the daily power obtained at the output of the optical fiber, the power supply is estimated to be 25 W at the end. Then we show that the energy transported is diffused until the enclosure then disperse inside it, this energy is absorbed by the receiver. Temperatures higher than 1600°K may be reached while maintaining very good efficiency. Such furnaces have the extra advantage of having temperature gradients which may be perfectly determined.

Keywords :
solar lighting, concentrated solar energy, optical fiber, solar furnace.

1. Introduction

Solar energy has been made widely available for thermal applications. Many kinds of solar collectors have been developed to operate from low to very high temperatures and many optical concentration systems have been investigated with the aim of reducing the cost of electricity generated.

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 [1] proposed to use one rigid light guide jointly with a paraboloidal mirror to transport concentrated solar radiation [2]. Later on, Kato and Nakamura [3] studied the theoretical possibility of using fused silica optical fibers to transmit solar radiation.

The idea of transmission of concentrated solar energy via optical fibers (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 it self to theoretical analysis only. Nowadays with the availability of the optical fiber techniques, solar energy can be transmitted by high-quality optical fibers with large core diameter and large numerical aperture [4] [5]. Nowadays, optical fiber materials offer a lesser attenuation, thus modern optical fibers produce better optical efficiency [6]. There are numerous studies on thermal analysis and solar power generation by TCSEvOF systems. Zidani et al. [7] presented the exergy analysis of the systems based on the idea TCSEvOF for the site of Tlemcen. In the present study, the thermal analysis of the systems based on the idea TCSEvOF is performed.

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 optical fiber 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 optical fiber are presented.

The energy rate on the focal plane, where the optical fiber 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 et al. [8]:

$$Q = \pi f^2 \rho_m G_b (\sin^2\phi_r - \sin^2\phi_{min}) \quad (1)$$

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.

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

The maximum energy rate of the optical fibre Q_{in} can be expressed as:

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

Where ρ_f is the unpolarized reflection of the radiation while it is passing from the environment to the core material [9], D_c is the core diameter of the fiber, The ratio of the core index and cladding index determines the acceptance angle of radiation θ_{max} at which total internal reflection occurs [10], and C_{max} is the maximum concentration.

Knowing that concentrated solar energy will be exposed some losses before entering into the optical fiber. On the other hand, from the definition of decibel losses per unit length, the energy rate Q_{out} at the end of optical fiber can be expressed as [10]:

$$Q_{out} = 10^{-(LdB_{loss}/10)} Q_{in} \quad (3)$$

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

3. The system proposed

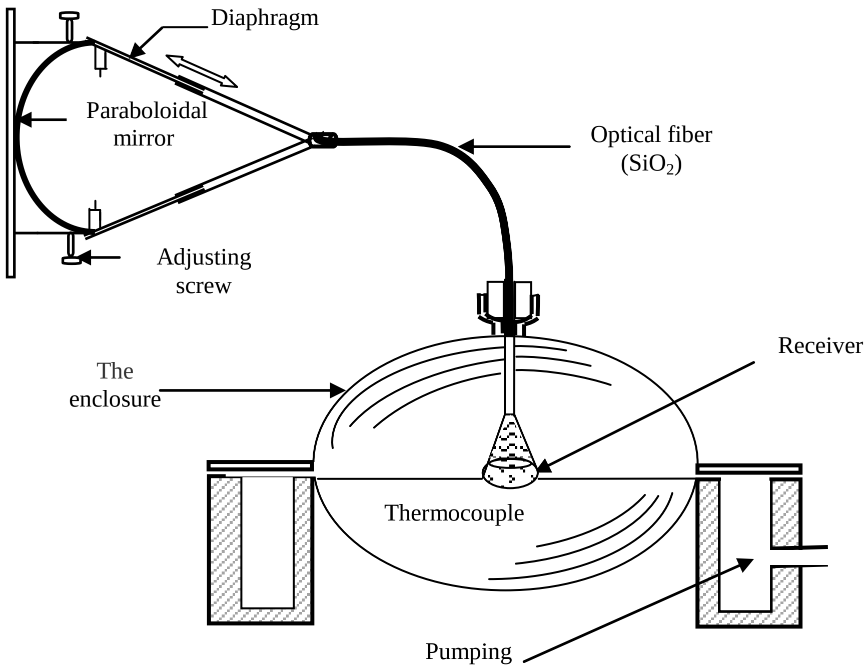

Figure.1: The coupling between the concentrator, the optical fiber and the solar furnace proposed

The system of solar furnace based on the idea TCSEvOF is evaluated by dividing it into two subsystems, as shown in figure 1. The first subsystem is to transport the concentrate solar energy by optical fiber, while the second one is to concentrate this energy in the receiver of the solar furnace. The previous results show the possibility of raising the receiver temperature to very high values. To evaluate its limit, we consider that the thermal take place only by radiation: the cone may be vacuum pumped and we may neglect the conduction losses through the receiver holder but the whole radiative power emitted by the receiver is lost because it may go out through the optical fibres ends.

The equilibrium temperature in the receiver is given as:

$$T_e^4 - T_a^4 = \frac{1}{\sigma S_r} \frac{\alpha_s}{\alpha_T(1-R)} \frac{1-R+\alpha_T R}{1-R+\alpha_s R} Q_{out} \quad (4)$$

Where T_a is the ambient temperature, σ the Stephan constant, α_s the solar absorptance coefficient from the receiver, α_T the solar absorptance coefficient from the receiver for temperature T, R is the reflectivity coefficient of the enclosure, and Q_{out} is the energy rate at the end of optical fiber .

Table 1: Parameters of the system

D_a (m)	0.218
D_r (m)	0.005
f_0 (m)	0.519
ϕ_r (°)	12
θ_{max} (°)	12
dB_{loss} (dB/m)	0.30
L (m)	3
C_{max}	1900
ρ_m	0.95
T_0 (K)	298

Table 1 indicates the important parameters of the system. The optical fiber used in the present study consists of large core SiO_2 optical fiber. The length of the optical fiber is 3m, the diameter is 5mm, and an aperture angle of 12°. The paraboloidal dish was adopted from a mirror covered by silver for providing high reflectivity, the diameter of the mirror is 21.8cm with a focal distance of 51.9cm. The attenuation of the optical fiber is indicated as dB/km by the manufactured data.

The receiver of the solar furnace was an aluminium ball, the surface of which has been blackened by an anodizing treatment. It was held by a quartz wire to minimize the conduction exchanges. The receiver may be surrounded by an enclosure with 20cm of diameter, it was constituted by glass bulbs freshly coated with a silver evaporation. A small hole was drilled to admit the optical fiber end. The tight between the enclosure and the optical fiber, made it possible to pump inside.

4. Results and discussion

Brichambaut [11] 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.

Figure.2 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 27.33W in solar noon for the winter solstice, 31.77W for the spring equinox and the autumn equinox. For the summer solstice the values exceed 33.18W. Concentrated solar energy will be exposed to some losses before entering into the optical fiber.

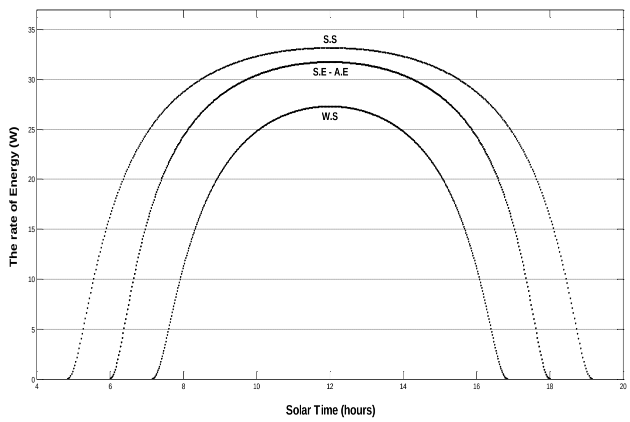

Figure.2 : The hourly power hitting a flat receiver of the paraboloidal dish (W) for equinoxes and solstices

For March 21st (spring equinox), from 6h (sunrise) to 12h (solar noon) the relationship between the heat flux (W/cm^2) and the length of the optical fiber is given in figure.3.

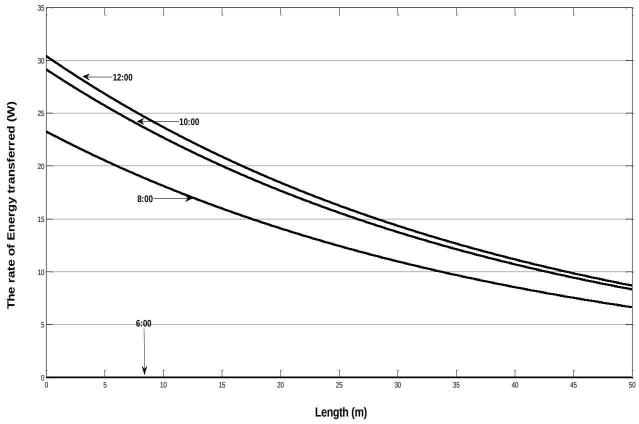

Figure.3: The energy rate transferred via optical fiber for spring equinox

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 graph that the output power has the values of 30.43W at the entrance, it decreases to 28.23W at 3m for the length of optical fiber.

After studying the transport of the solar power with the optical fiber, we present a study for a correct dimensioning of the solar furnace and assure the realization of high temperatures.

Similarly, in figure 4. we present the variation in the temperature of the receiver of the solar furnace according to its surface, for March 21st (Spring Equinox), from 6h (sunrise) we distinguish a decrease in equilibrium temperature which stabilized at the surface of 0.002 m^2. Between 8h and 12h a larger decrease of this temperature is observed. However, this decrease becomes less accentuated from a surface of 0.003 m^2.

Therefore, small areas of the receiver are more favourable for obtaining high temperatures.

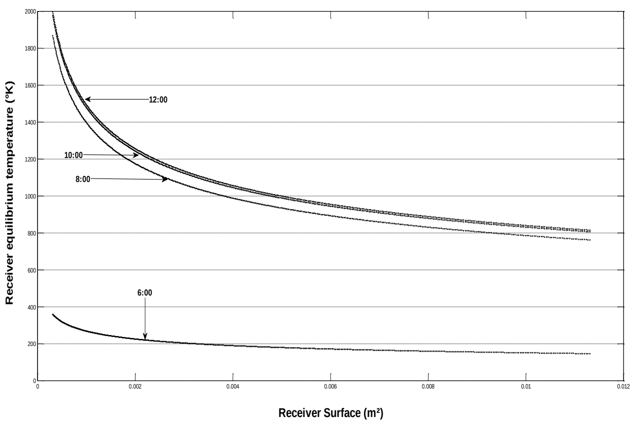

Figure.4: Variation in the temperature of the receiver of the solar furnace according to its surface

From the results mentioned in the figure 5. and in table 2., we conclude that the equilibrium temperature of the receiver increases with the increase of the global solar radiation. Also small areas of the receiver are more favorable for obtaining high temperatures.

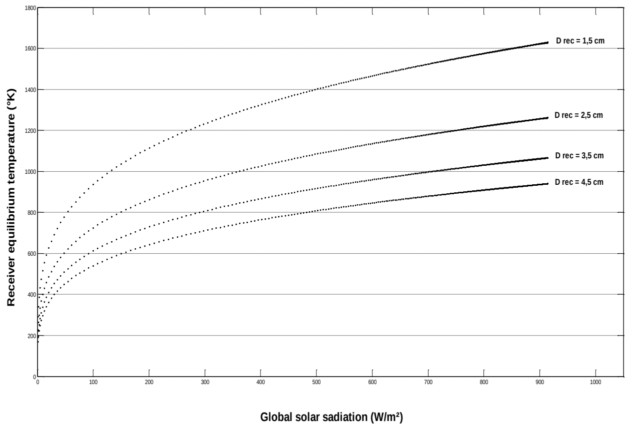

Figure.5: Variation in the equilibrium temperature of the receiver of the solar furnace depending on the global solar radiation for different diameters

Table 2: the variation in the temperature according of the diameter of the receiver

	100 W/m^2	**350 W/m^2**	**700 W/m^2**	**850 W/m^2**	**900 W/m^2**	**914 W/m^2**
D_{rec}=1,5 cm	938°K	1281°K	1523°K	1600°K	1623°K	1629°K
D_{rec}=2,5 cm	727°K	993°K	1180°K	1240°K	1257°K	1262°K
D_{rec}=3,5 cm	614°K	839°K	998°K	1048°K	1063°K	1067°K
D_{rec}=4,5 cm	542°K	740°K	880°K	925°K	937°K	940°K

In order to determine the best treatment for surface of the enclosure surrounding the receiver, allowing for better reflection of radiation, we propose a simulation that defines the change in the equilibrium temperature depending on the coefficient of the reference the inner wall of the enclosure surrounding the receiver. The latter has a diameter of 1.5cm optimized in order to obtain high temperatures.

For March 21st (spring equinox) at 12h (solar noon), simulation results of the variation in the equilibrium temperature of the receiver according to the coefficient of reflectivity of the inner wall of the enclosure are given on the following table.

Table 3: the variation in the temperature according of the coefficient of reflectivity of the inner wall of the enclosure

	0.1	**0.2**	**0.3**	**0.4**	**0.5**	**0.6**	**0.7**	**0.8**	**0.9**
6h (TSV)	169°K	174°K	180°K	187°K	196°K	207°K	222°K	246°K	293°K
8h (TSV)	880°K	906°K	937°K	974°K	1019°K	1078°K	1158°K	1282°K	1524°K
10h (TSV)	931°K	959°K	991°K	1030°K	1078°K	1140°K	1225°K	1356°K	1612°K
12h (TSV)	941°K	969°K	1002°K	1041°K	1090°K	1152°K	1238°K	1370°K	1629°K

We notice a slight increase in the equilibrium temperature of the receiver. It becomes more pronounced from a parameter value of the reference radiation of 0.6. Except at sunrise at 6o'clock, the equilibrium temperature of the receiver remains virtually unchanged. These values show that it must be possible to obtain a higher equilibrium temperature, by performing surface treatment of the inner wall of the enclosure best adapted.

5. Conclusion

Our aim of this paper is to show the limits of solar furnaces supplied by optical fibres. The obtained results illustrate that the use of optical fibres as element in highly concentrated solar energy transmission in a real possibility that is worth investigating experimentally.

We have considered the spherical geometrical shape because it resembles the ideal case where the sun’s surface temperature may be approached. We have presented the equilibrium temperature when the irradiance of the receiver was uniform.

For further studies, it would be very essential to achieve higher temperatures and larger efficiencies. However, the durable material for the optical fibres against the high temperatures should be chosen to transfer the concentrated solar energy. It could be worth to test the fibers based on SiO_2 for the thermal application of TCSEvOF systems.

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.

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Abbreviations

S.E, spring equinox; **A.E**, autumn equinox; **S.S**, summer solstice; **W.S**, winter solstice;
NA, numerical aperture (dimensionless); **TCSEvOF**, transmission of concentrated solar energy via optical fibers;