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Thermal Study of Optical Fibers Transmitting Concentrated Solar Energy

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***Abstract*—Fiber-optic solar energy transmission and concentration (TCSEvOF) provide a flexible way of handling concentrated solar energy. The high flux solar energy transmission by a flexible fiber-optic bundle (FOB) and the research on the associated compound parabolic concentrator will largely expand the existing field of applications of solar energy concentrators. In this study, it is aimed to optimize the coupling of a low-cost offset paraboloidal dish, which concentrates direct solar radiation with two axes tracking component, and the fiber-optic bundle, which transmits concentrated solar energy. A mathematical model of paraboloidal dish system is described. A Q.S.F. 1000 flexible fiber-optic solar energy transmission and concentration scheme by using one single fiber bundle is reported. The objective is to design a new light collector system for hot water production with considerably higher efficiency. Transmission efficiency of FOB is found as 75 per cent at optimum conditions.**

Keywords-simulation; solar thermal conversion; solar energy concentration; optical fibers; conception

I. INTRODUCTION

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 fibers and the high cost of their design, this project limited itself to theoretical analysis only. With the present day availability of fiber-optic techniques, solar energy can be transmitted by high-quality optical fibers of large core diameter and large numerical aperture [1,2]. The systems based on the idea of transmission of concentrated solar energy via optical fibers (TCSEvOF) provide flexible options for numerous implementations such as solar lighting [3], solar power generation [4], solar surgery [5], photo-bioreactors [6], hydrogen generation [7] and photochemical reactions [8] and solar pumped lasers [9].

The objective of this study was to design a new light collector system for hot water production with considerably higher efficiency (Y. MENNI [10]). The paper is organized as follows: Section 1 includes a brief review, comprehending usage and energy analysis of TCSEvOF systems. The system description is presented in Section 2, while the theoretical model is given in Section 3. The data used in the calculations and the results of the model application in different sites of Tlemcen in Republic of Algeria, are covered in Section 4, while the last section gets conclusions.

II. SYSTEM DESCRIPTION

The system of transmission-concentrated solar energy via optical fibers is illustrated in Fig. 1, while the detailed description of this system has been given in more detail elsewhere [1,2]. In this study, it is aimed to optimize the coupling of a low-cost offset paraboloidal dish, which concentrates direct solar radiation with two axes tracking component, and the type-Q.S.F. 1000 fiber-optic bundle (FOB), which transmits concentrated solar energy.

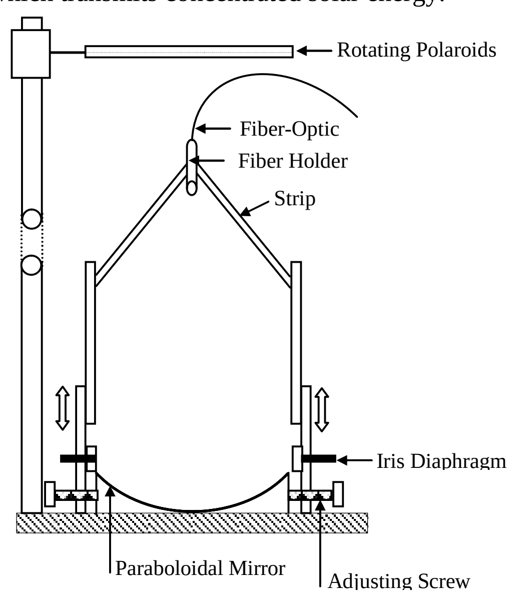


Figure 1. Schematic drawing of the testing system [1,2]

The mirror is a telescope-like glass mirror, silver (Ag) or aluminum (Al) coated with a 0.068 m diameter, a 0.0366 m radius and a 0.1038 m focal length [1].

The fiber holder is constituted by three thin vertical metal strips which are soldered on to an adjustable screw bearer to ensure the best adjustment of the fiber end in the focal plane of the mirror and to measure the effects of determined shifts. A large iris diaphragm is set in front of the mirror to change the angular aperture of the incident beam. Finally, two rotating polarizes may be put before the whole system to reduce the solar incident intensity and to make it possible to look at the quality of adjustment without any dazzle. This system is borne by an equatorial mount continuously oriented to track the sun.

We tested either 0.001 m or 0.0006 m core diameter silica fibers manufactured by Quartz and Silice. Their cladding is a silicone resin with the refractive mean index n_2=1.405, while silica index is n_1=1.4585. Their theoretical angular aperture is 23° but they are only guaranted for about 20°. The mean attenuation of this fiber-optic is α =2.10^{-2} dB/m on all solar spectrum.

III. Mathematical Modeling

In this section, the mathematical model for coupling of the FOB and a low-cost offset paraboloidal dish were studied. The optimal geometrical parameters to couple offset paraboloidal dish and FOB were analyzed. Each optical fiber has a pure transparent inner core and a thin transparent outer cladding. The total internal reflection allows guiding the sun light through the fiber. The fiber core has an index of refraction n_{cor}, which is greater than that of the cladding n_{clad}. The ratio of the core index and cladding index determines the acceptance/admission angle of radiation θ_{max} at which total internal reflection occurs:

$$NA = \sin\theta_{max} = \left(n_{cor}^2 - n_{clad}^2\right)^{1/2} \quad (1)$$

where NA is the numerical aperture indicating a measure of the admission angle θ_{max} of the fiber-optic bundle. It can be considered that the FOB is a concentrated solar energy transportation pipe.

It is important to mention that the rim angle Φ_{rim} should be equal to or smaller than the optical fiber admission angle. Under the optimum conditions, to ensure that the whole radiation gets in the fiber bundle, the maximum rim angle of the paraboloidal dish must be

$$\Phi_{rim} = \theta_{max} \quad (2)$$

that corresponds to the maximum admission angle of the optical fiber. The focal length f and the aperture diameter D_a for the paraboloidal dish are related by

$$\frac{f}{D_a} = \frac{1}{4\tan\left(\Phi_{rim}/2\right)} \quad (3)$$

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

$$Q_f = A_{of}\,\rho\, G_b F C_{max} \quad (4)$$

where A_{of} is the area of the input fiber-optic bundle, ρ is reflectivity of the collector surface, G_b is solar beam radiation coming to collector aperture. C_{max} is the maximum ratio of geometrical concentration and F is the view factor for a flat receiver of paraboloidal mirror:

$$F = \frac{\sin^2\theta_{max} - \sin^2\Phi_{shade}}{4\tan^2\left(\theta_{max}/2\right)} \quad (5)$$

where Φ_{shade} is shading angle for the receiver of the paraboloidal dish.

$$C_{max} = \frac{A_a}{A_{of}} = \frac{\sin^2\theta_{max}\cos^2\left(\theta_{max} + 0.267° + \delta/2\right)}{\sin^2\left(0.267° + \delta/2\right)} \quad (6)$$

where A_a is the aperture area of the paraboloidal mirror, δ is dispersion angle as a measure of the angular errors of the reflector surface and 0.2678° is the half-angle of the incident beam cone of the solar radiation.

Concentrated solar energy will be exposed some losses before entering into the FOB. The energy rate considering the heat losses at the inlet of the FOB $Q_{in,of}$ is

$$Q_{in,of} = Q_f - U_r A_{of}\left(T_r - T_0\right) \quad (7)$$

where U_r is the receiver-ambient heat transfer coefficient, while T_r and T_0 are receiver and ambient temperatures, respectively.

The energy rate transferred via FOB $Q_{out,of}$ is

$$Q_{out,of} = Q_{in,of} \times 10^{-l dB/10} \quad (8)$$

where l is the length of the bundle and dB is the decibel loss (dB/m) of the bundle.

IV. Results and Discussion [10]

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

Perrin De 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. 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 Fig. 2, the daily energy gap becomes important between winter and summer. The maximum energy is given by the panel (α = 0, γ = 90° - 0°) and the minimum is for the panel (α = 0, γ = 90° - 90°) in the summer solstice, as GSE (max) ≈ 9000 Wh/m^2, GSE (min) ≈ 2000 Wh/m^2.

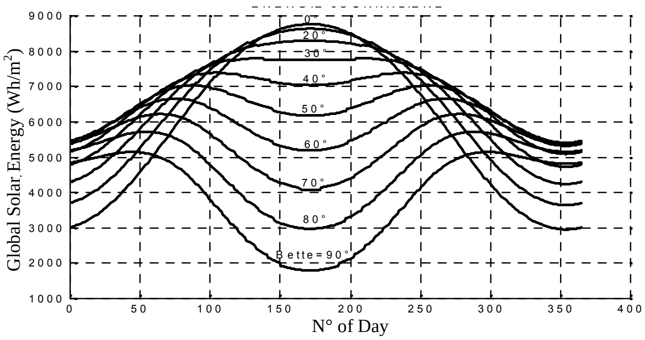


Figure 2. The daily energy received by different orientations for the panel.

To estimate realistic system performance, we reduce the theoretical limits by the following factors:

- Numerical aperture θ_{max}=20°.
- A FOB transmission efficiency of 75% is found at following conditions [1]: an absorptive loss in the dish mirror of 5% (ρ_m=95% for the Ag-coated mirror); Fresnel reflective losses on each end of the fiber: 3.5% (ρ_f=93%); losses in lines: 10% (I=90%); and concentrator-fiber interface losses: 0% (η=1).

For the estimation of the thermal energy at the inlet and outlet of the solar fiber, we modeled the solar radiation and we have developed a simulation program of the sun course.

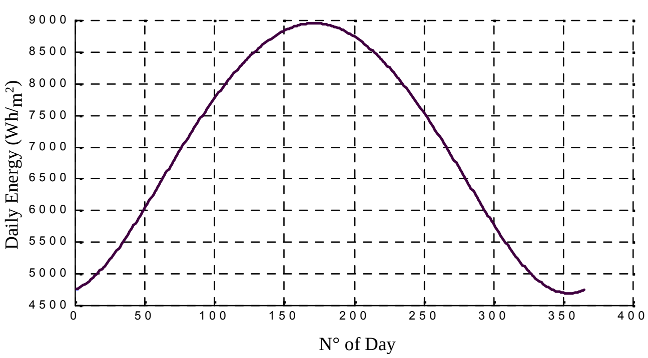


Figure 3. The daily energy hitting a flat receiver of the paraboloidal concentrator using Tlemcen solar irradiance data (the mirror is Ag-coated, the sky is clear blue).

Fig. 3 present monthly average daily output power for the offset paraboloidal dish proposed. It can be understood from the graph that the output power can reach 8956 Wh/m^2 in solar noon for the summer solstice (N°=171) which corresponds to 21 June.

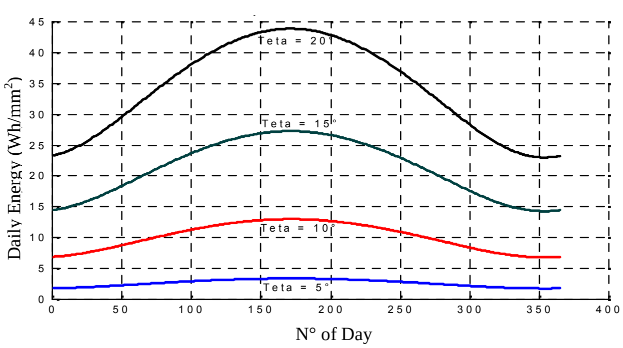


Figure 4. The daily energy at the inlet of the Q.S.F. 1000 optical fiber versus the concentrator aperture using a Ag-coated mirror and a clear blue sky for the city of Tlemcen.

Fig. 4 shows the concentrator aperture influence on the daily energy estimation at the inlet of the optical fiber bundle (Q.S.F. 1000 fiber). For a good adaptation of the paraboloidal mirror, the aperture of the latter must be equal to the numerical aperture of the FOB (θ_{max}=20°). A fiber-optic adapted to the concentrator aperture transports a solar energy maximum of 44 Wh/mm^2 for the summer solstice and a minimum of 24 Wh/mm^2 for the winter solstice at Tlemcen by using the hotel clear sky model. It can be understood from the Fig. 4 that the outlet measured daily energy has the values of 44 Wh/mm^2 in solar noon for the summer solstice at the entrance. It decreases to 32.59 Wh/mm^2 at 5 m for the length of Q.S.F. 1000 fiber-optic, while for the winter solstice does not exceed 18 Wh/mm^2, as shown in Fig. 5.

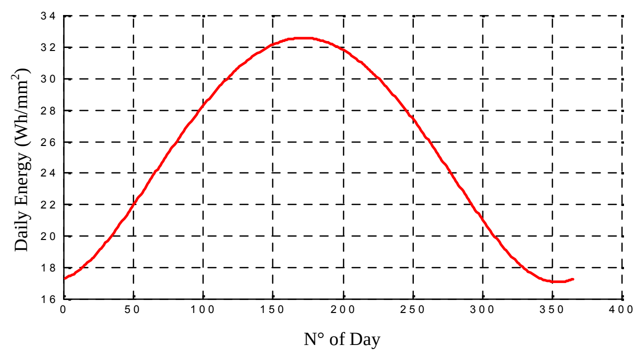
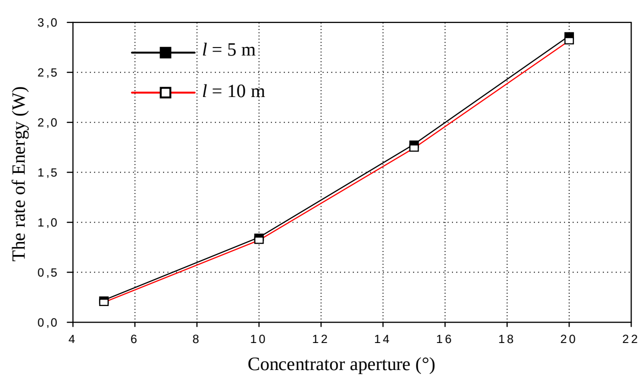


Figure 5. Outlet measured daily energy using an Ag-coated mirror and a 5 m long Q.S.F. 1000 fiber-optic

The variation of the energy rate transferred via Q.S.F. 1000 FOB with concentrator aperture values for two different lengths of fiber-solar is depicted in Fig. 6. In the figure, it is interesting to note that the energy rate at the fiber end tends to increase with the rise of concentrator aperture for all fiber length cases. For using the fibers, the increase in the length value gives rise to the reduction of output energy rate. From the figure, it appears that the fiber transmittance depends on the beam aperture. This result may be interpreted with the reflection losses which inevitably exist in the "total reflections" along the fiber and which increase when the incident beam is wider open.



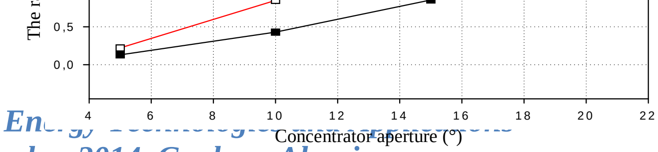


Figure 6. The energy rate transferred via Q.S.F. 1000 FOB versus the concentrator aperture for two different lengths of fiber (the mirror is Ag-coated).

In this study, the results have been obtained using a silver-coated mirror, the reflectivity of which being about 0.95. However, in order to observe and to verify the place taken by the mirror reflectivity in the efficiency calculation, we took some measurements using a recently coated aluminum mirror. The mean value of its reflectivity along the whole solar range may be evaluated at about 0.80. For a 5 m long, 1 mm diameter fiber, the results obtained for various concentrator apertures are given in Fig. 7. The thermal performance of the Ag-coated mirror is found to be higher than that of the Al-coated mirror for all values of concentrator apertures used.

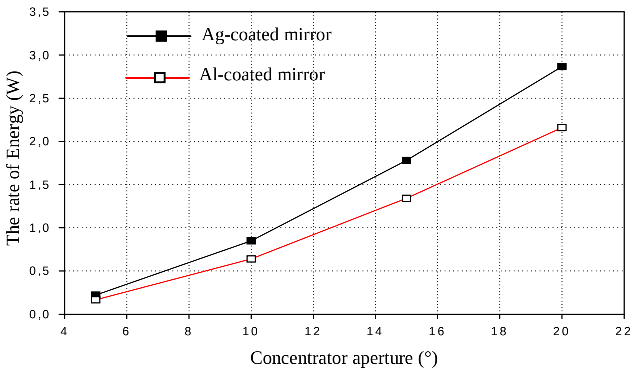


Figure 7. The energy rate transferred via Q.S.F. 1000 FOB as a function of the concentrator aperture for various mirrors.

Concerning the effect of the Q.S.F. solar fiber diameter on the outlet measured power, it can see from Fig. 8 that: the upper curve corresponds to a 1 mm diameter fiber (Q.S.F. 1000 fiber-optic), the lower to a 0.6 mm diameter (Q.S.F. 600 fiber-optic). Moreover, it seems that the small fiber has a slightly inferior transmittance than the thicker one for the large apertures. This is due to the larger number of reflections in the small fiber.

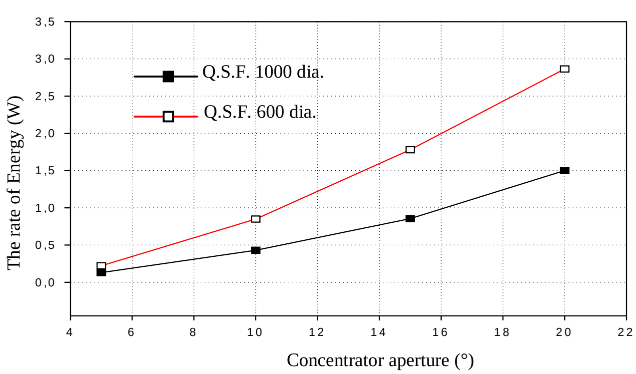


Figure 8. The energy rate transferred via Q.S.F. 1000 FOB as a function of the concentrator aperture for various FOB diameters using a Ag-coated mirror and a 5 m long solar fiber.

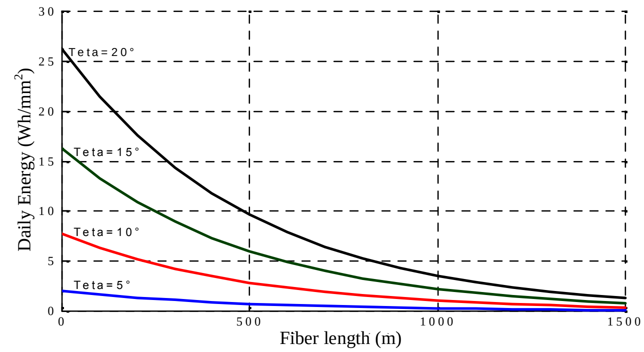


Figure 9. The daily energy transferred via Q.S.F. 1000 FOB as a function of the concentrator aperture for equinoxes and various FOB lengths using a Ag-coated mirror and a 1 mm dia. solar fiber.

It can be understood from the Fig. 9 that the output daily energy variation for spring equinox has the values of 2.4; 7.5; 16; 26.5 (unit: Wh/mm^2) at the entrance for the concentrator aperture values of 5°; 10°; 15° and 20°, respectively. It decreases, approaching 0 Wh/mm^2 at 1500m for the length of FOB. It is observed that the heat flux decreases, while the length values go up, although the attenuation increases with the length of the fiber.

Fiber attenuation may be divided into two parts: the first, due to the quality of the core material, only depends on the length and that is what we considered in our theoretical investigation. The second depends on the aperture of the incident beam, on the number of reflections into the fiber and consequently on the fiber length. The mean attenuation coefficient $\bar{\alpha}$ is not an intrinsic characteristic of fibers, but has to be taken in a form $\bar{\alpha}$ (θ, l).

TABLE 1. NUMERICAL VALIDATION FOR VARIOUS FIBER LENGTHS

	$Q_{out,fo}$ (unit: W)	
Fiber-optic	***Our numerical simulation* [10]**	***Experimental data* [1]**
l=5 m	2.8652	2.8
l=15 m	2.8014	2.42

Q.S.F. 1000 fiber, Ag-coated mirror;

For an aperture of θ_{max}=20°, a FOB transmission efficiency equal to 75%, the same geometrical characteristics of the paraboloidal concentrator, we present the results obtained various investigated cases are given in Tables 1 and 2.

TABLE 2. NUMERICAL VALIDATION FOR VARIOUS MIRRORS.

	$Q_{out,fo}$ (unit: W)	
Mirror	**Our numerical simulation [10]**	**Experimental data [1]**

Ag-coated	2.8652	2.8
Al-coated	2.1587	2.25

Q.S.F. 1000 fiber, l=5m;

It is clear from the tables that the results are exhibited good agreement. And, this allows us to validate our numerical model. Thus, it is jumped to next step to get different results from the numerical study.

In order to reduce losses before heat of a photo-thermal collector and to increase considerably the temperature of the absorber, in order to reduce the thermal losses of working fluid of a photo-thermal collector, in order to use the photo-thermal conversion to a very precise place, our work consists in a new light collector system for hot water production with considerably higher efficiency.

The studied light collector system for hot water production, which is outlined in Fig. 10, contains:

- The solar concentrator is a telescope-like glass, high reflective, tracking the Sun along two axes offset paraboloidal dish, silver coated with a 0.068 m diameter and a 0. 1038 m focal length.
- Q.S.F. 1000 fiber-optic bundle: that has the following geometrical and optical characteristics: length l=5 m; 0.001 m core diameter silica fiber manufactured by Quartz and Silica; numerical aperture θ_{max}=20°, and mean attenuation α =2.10^{-2} dB/m on all solar spectrum.

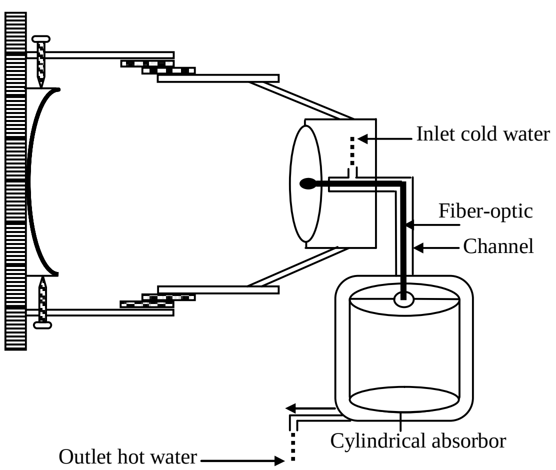


Figure 10. Water flow cylindrical-shaped photo-thermal collector with optical fibers

- Cylindrical storage tank composed with: Radius R_c=0.25 m, height h_c=2R, internal surface S_c=2.π.$R_c h_c$-S_{of} (where S_{of} is the inlet section area of FOB). It is composed of a black painting on a copper substrate with absorption and emission coefficients α=0.95 and ε=0.18, respectively. The cylinder is fed in its summit by the type-Q.S.F.1000 BFO. Besides, the entire cylinder & fiber is insulated with the glass wool.

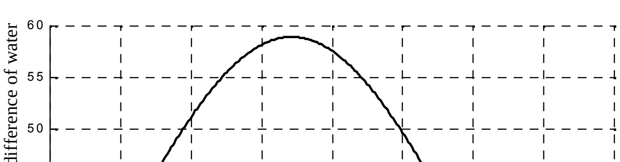


Figure 11. Evolution of the daily temperature difference transported by water, city of Tlemcen with a clear blue sky.

The concentrated heat inside the cylindrical absorber can be transported by water working fluid. The inlet-outlet temperature difference, ΔT=T_{out}-T_{in} for water flow can be obtained by

$$Q_{out,of} = h.S_c.\Delta T \tag{9}$$

where

$$\Delta T = Q_{out,of} / h.S_c \tag{10}$$

and

$$h = Nu.\lambda / D \tag{11}$$

with

$$Nu = 0{,}0259\,.\left(\mathrm{Re}^{4/5}\right) \tag{12}$$

and

$$\mathrm{Re} = U.D/\nu \tag{13}$$

with

λ=0.143 cal/s.m.°C, μ=$0.985.10^{-6}$ m^2/s, U=1 m/s, and D=0.02 m are the water characteristics. Where Re=20304, Nu=72.33 and h=517.16 cal/m^2°C.

After the determination of the output power quantity transported by the optical fiber to the storage tank, where it is absorbed then transmitted by the selective surface, the inlet-outlet temperature difference as shown in Fig.11 can reach 58°C in the summer and 32°C in the hiver.

V. Conclusion

The thermal study of a low-cost, high reflective, tracking the sun along two axes offset paraboloidal dish integrated FOB was made in this study. Moreover, this paper was reported on a numerical realization and field testing of a recently proposed solar fiber optic mini dish light concentrator connected to a hot water accumulator. The prototype dish was 68 mm in diameter. In repeated test the collected and concentrated sunlight was transported in a one millimeter diameter optical fiber to a selective surface in the shaped-cylindrical storage tank. This surface absorbs the radiation which remains trapped inside as it heat exchanges with tank fluid which temperature can reach 58°C at the summer solstice and 32°C at the winter solstice with an transmission efficiency greater than 75% at optimum conditions.

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